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METHODS

A Strategy for Enhanced Post-FRT Active Power Recovery in Expandable Point-to-Point VSC-HVdc Links

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ABSTRACT This paper proposes a non-linear DC power modulation strategy for expandable point-to-point (PtP) high-voltage DC (HVDC) systems. The goal is to enhance the active power management during post-fault conditions of the interconnected AC networks. The proposed strategy is developed by defining exponentially decaying functions, which, depending on the HVDC network configuration of the expandable HVDC system, alter the active current reference in a voltage source converter (VSC) affected by an AC network's disturbance, without utilizing proportional-integral (PI) controllers. Furthermore, it is investigated whether the produced alteration can fulfill the post-fault active power recovery (PFAPR) requirements of VSC-HVDC systems, even in situations when no communication protocols between the VSC units are used. Lastly, it is demonstrated, through simulation experiments, that the expandable HVDC system (working in a point-to-point (PtP) or a multi-terminal (MT) network configuration), shows a better performance (in terms of the PFAPR profile and the DC voltage response) when the proposed strategy is utilized instead of conventional main-supplementary or droop control strategies.

INDEX TERMS Expandable PtP HVdc system, fault-ride-through, post-fault active power recovery, voltage source converters.

I. INTRODUCTION

Nowadays, the electrical power systems are experiencing a transformation, in which high voltage DC systems based on the voltage source converter (VSC-HVDC) technology are playing a significant role in facilitating large-distance interconnections between different transmission networks [1], [2]. For instance, the VSC-HVDC technology has been reported to be a feasible solution for enabling the point-to-point (i.e. PtP-VSC-HVDC) connection of large (offshore) wind power generation with high voltage (onshore) transmission networks [3], [4]. On the other hand, the VSC-HVDC technology can also facilitate the regulation of the power flows between several VSC units connected through multi-terminal high voltage DC (i.e. MT-VSC-HVDC) systems [5].

These characteristics of the VSC-HVDC are motivating revisions and upgrades of grid code requirements for different real systems [6] in order to specify the way in which the VSC-HVDC systems must react when an electrical fault occurs in the power system. The specifications demanded by the transmission system operators to the VSC-HVDC systems (when a fault event occurs) can be grouped and described as AC voltage and active power support functions. The AC voltage support, a.k.a. low voltage (fault) ride through (or FRT) function, essentially defines the levels of reactive current supplied by VSC unit during an AC fault period [7]. On the other hand, the active power support function essentially defines the way in which the pre-fault active power condition is reestablished into the affected AC network during the post-fault period. This is why it is also known as the post-fault active power recovery (PFAPR) function [6].

In most of the PtP-VSC-HVDC systems, the FRT function is usually studied by assuming that the PTP-VSC-HVDC systems are used as a means of integrating offshore wind power into transmission networks [8], [9],

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[10], [11], [12]. This assumption usually leads to considering that the activation process of the FRT function eventually generates DC over-voltage problems across the HVDC cable when an electrical fault occurs in the AC network onshore. However, substantial research effort is still needed to examine the way in which the DC voltage response can be regulated during activation of the FRT function in PtP-VSC-HVDC systems interconnecting two onshore transmission networks. This is because, unlike the DC overvoltage problems caused by the wind power supply into the HVDC system (during the fault period), the activation of the FRT function in PtP-VSC-HVDC systems connecting two onshore transmission networks can also cause serious DC undervoltage issues across the HVDC cable. This is especially true if the activation of the FRT function occurs at the AC side of the rectifier VSC unit of the HVDC system [13]. Additionally, the regulation of the DC voltage response during the fault period is even more challenging task if there are no communication protocols facilitating the interchange of information about the operational states between the VSC units in the PtP-VSC-HVDC system. On the other hand, for MT-VSC-HVDC systems, the FRT activation can seriously alter the power flow conditions of the entire HVDC network [11]. Nevertheless, these alterations are usually handled by the DC voltage regulation functions of each VSC unit (e.g. a generalized voltage droop) [14], or less commonly, by dedicated power electronic devices (e.g., DC-DC converters) performing DC power flow regulation functions [15].

In terms of the PFAPR function, some researchers have proposed that during the post-fault period, VSC-HVDC systems should use a very fast (higher than 1 pu/s) active power recovery ramp rate to restore pre-fault active power conditions [11], [16]. Moreover, other authors have pointed out that post-fault active power modulation can be done based on communication-based phasor measurement signals to improve the stability limits in power systems dominated by power electronics devices [17], [18]. However, some efforts are currently devoted to the design and coordination between the FRT and the PFAPR function in PtP-VSC-HVDC systems connecting offshore wind power plants to offshore transmission networks [19]. However, the need to design methodologies to coordinate the FRT and PFAPR functions in PtP-VSC-HVDC that connects two onshore transmission systems is still an open research gap. Considering the organic growth envisaged for VSC-HVDC systems in [20] and the introduction of new concepts such as Flexible DC Grids [21] or Expandable PtP-VSC-HVDC links [22], the design of the FRT and PFAPR functions becomes an even more relevant issue.

This paper proposes a non-linear DC power modulation strategy to regulate the active power recovery process in a VSC unit (which belongs to an expandable PtP-VSC-HVDC system) when its contiguous AC network is affected by an electrical fault. The proposed strategy is expected to prevent DC voltage collapse during fault periods, while ensuring compliance with the PFAPR requirements (based on real VSC-HVDC system specifications) in VSC-HVDC systems connecting two onshore transmission networks. Additionally, the effectiveness of this strategy is tested on an expandable HVDC system operating in a PtP and in a three-terminal (MT) VSC-HVDC network configuration, demonstrating its superior performance against a conventional droop control to perform coordination between the FRT and the PFAPR functions. The limitations of the proposed method and its potential solutions are also tested and discussed.

The paper is organized as follows. Section II presents the requirements for the FRT and PFAPR functions of an expandable PtP-VSC-HVSC system. Section III presents the developmental aspects of the proposed non-linear DC power modulation. Section IV presents the considered simulation experiments, in which the proposed nonlinear DC power modulation strategy is assessed in terms of the PFAPR requirements in an PtP or an expanded PtP (multi-terminal) VSC-HVDC system. Finally, conclusions are given in Section V.

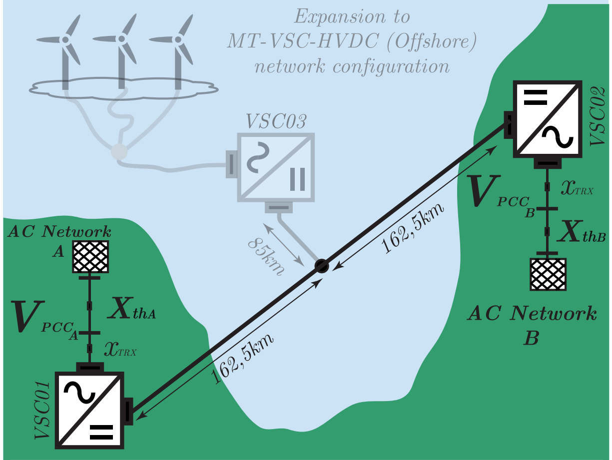
II. REQUIREMENTS FOR EXPANDABLE PTP-VSC-HVDC INTERCONNECTORS IN FAULT CONDITIONS

As introduced in [22], the expandability of a PtP-VSC-HVDC system is defined as *the ability of such a system to ensure MT-VSC-HVDC operation when a VSC unit is connected (added) to the existing PtP-VSC-HVDC link* as shown in Fig. 1.

As indicated in [23], this ability can be achieved without performing major changes in the control systems and network elements of the original PtP-VSC-HVDC network if the access to modify the DC voltage reference of the VSC units in the HVDC system is guaranteed. This means that if the access to modify the DC voltage reference is not guaranteed, then, modifications in the VSC units' control systems and/or addition of HVDC network elements should be envisaged to ensure the multi-terminal (MT) operation of an existing PtP-VSC-HVDC system as discussed in Section III-B.

However, independently of the considered VSC-HVDC system configuration (i.e. MT or PtP), the VSC-HVDC system must include dedicated functions (i.e. FRT and PFAPR) to support any of the AC networks, when they are affected by an electrical fault. The purpose of the FRT function is to provide voltage support when an AC network is affected by an electrical disturbance (e.g. three-phase fault), and the purpose of the PFAPR function is to guarantee the reestablishment of the pre-fault active power levels (provided by the VSC unit to the disturbed AC network) when the fault period has finished [6]. Traditionally, the voltage support given by the FRT function is carried out by prioritizing the reactive current injection over the active current injection during the fault period, whereas the PFAPR function modulates the active current reference to restore (after the fault period) the active power provided to the AC network. This means that the action of both functions (i.e. PFAPR and FRT) should be carefully coordinated since they occur in a sequential manner. A graphical description of the FRT and the PFAPR functions requirements can be observed

Expandable PtP-VSC-HVDC (System Data)			
Functional Specification	PtP-VSC-HVDC (Onshore) [2]		Expansion to MT-VSC-HVDC (Offshore) [22][26]
	VSC01	VSC02	VSC03
Active Power (MW)	±700		+800
DC Voltage (kV)	±320		±320
Reactive Power (MVAr)	±230		N/A



AC Networks (Systems Data)			
AC Network Parameters	AC Network (Onshore) [2]		AC Network (Offshore) [26]
	X_{thA}	X_{thB}	Based on the AC network layout shown in [22] and the Wind Turbine (RMS) model in[27].
Equivalent Network Impedance (Ω)	4,58	28,77	
AC Voltage (kV)	405		

FIGURE 1. Expandable PtP-VSC-HVDC network [22]. The PtP-VSC-HVDC network configuration represented by the elements highlighted in black color and the MT-VSC-HVDC expansion represented by the elements highlighted in gray color.

in Fig. 2. In Fig. 2a, it can be seen that as defined in [24], the level of voltage dip experienced in an AC network (and measured at the point of common coupling (PCC)) defines the level of reactive current injection demanded in a VSC unit during a fault condition. On the other hand, in terms of the PFAPR requirement it can be seen in Fig. 2b that as soon as the V_{PCC} voltage level starts to be restored, the active power supplied by the VSC unit is also increased. As shown in Fig. 2b, as soon as 90% of the AC network voltage (i.e. V_{PCC}) is recovered (from its pre-fault voltage condition), the converter must restore (within a 200ms time window) at least 90% of the pre-fault active power condition within the specified time window.

This coordination process is even more critical when a PtP-VSC-HVDC system is expanded into a MT-VSC-HVDC system, since, the consequences of activating the FRT function in a PtP-VSC-HVDC system or in a MT-VSC-HVDC system can be substantially different in terms of the DC voltage response. For instance, if the FRT function is activated in the VSC unit controlling the DC voltage in the PtP-VSC-HVDC system shown in Fig. 1, then, a low voltage DC problem is expected to occur due to the unidirectional power flow characteristics of this type of HVDC system. On the other hand, if the FRT function is activated in a VSC unit operating within a MT-VSC-HVDC system (cf. Fig. 1), the DC voltage response will depend on the pre-fault DC power flow conditions and the settings of the control modes (e.g. droop control) used by the VSC units in the MT-VSC-HVDC system.

III. DESIGN METHODOLOGY FOR FRT AND PFAPR FUNCTIONS COORDINATION IN EXPANDABLE PTP-VSC-HVDC SYSTEMS

In this work, if an electrical disturbance (e.g. three-phase fault) affects one of the onshore AC networks shown in Fig. 1, the coordination of the FRT and PFAPR functions is developed based on a non-linear DC power modulation strategy that will ensure the reestablishment of the pre-fault active power levels independently of the VSC-HVDC network configuration used in Fig. 1.

A. PTP-VSC-HVDC

In the PtP-VSC-HVDC network configuration, the non-linear DC power modulation protects the HVDC system (even if there are no communication channels between the onshore stations) against the low DC voltage excursions generated when the FRT function is activated in the rectifier VSC station. This low DC voltage excursion occurs because, as assumed in this work, the DC power always flows from the rectifier VSC station to the inverter VSC station during steady-state conditions. In the proposed non-linear DC power modulation strategy, it is necessary to know the minimum operational DC voltage level (or low DC voltage threshold (i.e. LVT)) that the PtP-VSC-HVDC system can use. Once the LVT is known, the proposed mathematical expressions (1), (2) are utilized to modify (during the fault and the post-fault periods), the active current reference (i.e. $I_{d_{REF}}$) in the inverter VSC unit. Furthermore, it is important to note that the active current reference generated by the active power controller of the inverter VSC unit is represented by $I_{AP_{REF}}$ in (1).

The rationale behind the mathematical expression (2) has been inspired by the inverse transformation of Laplace for a (linear time-invariant (LTI)) first-order transfer function. In this inverse transformation, an asymptotic time-domain function (based on an exponential term) defines the dynamic response of the LTI system as shown in Fig. 4. The essential change presented in (2) w.r.t. to the inverse transformation of Laplace in (3), is the replacement of the time domain dependency of the LTI system for a dependency linked to a DC voltage deviation level. This replacement can be understood as a way to emulate the well-known dynamic response of a first-order transfer function (LTI system) based on the response of the DC voltage deviation occurring in the HVDC system.

$$I_{d_{REF}} = \lambda_{MOD} * I_{AP_{REF}} \tag{1}$$

$$\lambda_{MOD} = 1 - e^{-\alpha(DC_{meas_{LIM}} - LVT)} \tag{2}$$

$$f(t) = (1 - e^{-\alpha t}) = \mathcal{L}^{-1}\{\frac{\alpha}{s+\alpha}\} \tag{3}$$

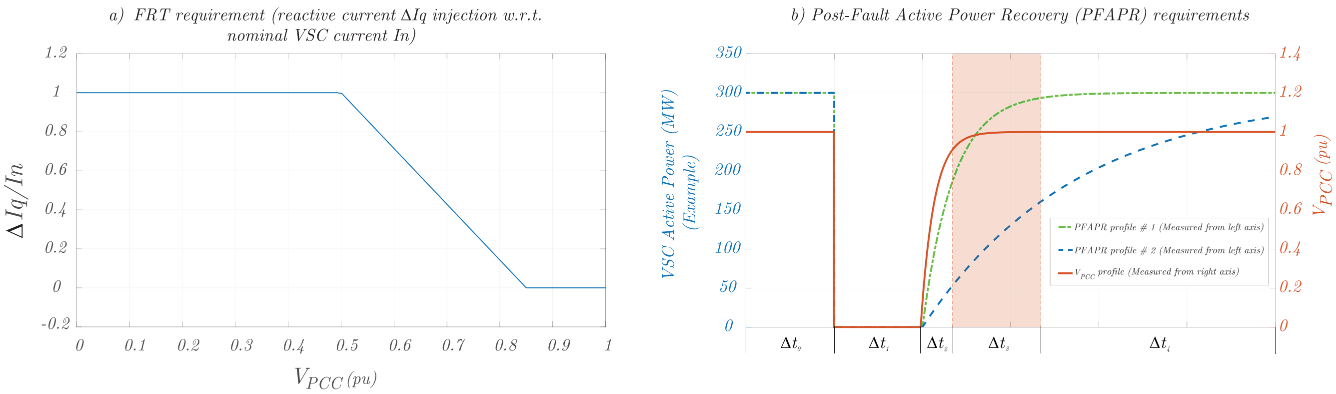


FIGURE 2. VSC unit requirements for the FRT and the PFAPR function. Fig. 2a shows the level of reactive current injection (ΔIq w.r.t to the nominal In VSC AC current) depending on the voltage (V_{PCC}) dip experienced in the AC network. Fig. 2b shows active powers and V_{PCC} voltage profiles during a pre-fault (Δt_0), fault (Δt_1), and post-fault (Δt_2, Δt_3, Δt_4) time periods.

The I_{dREF} modification is generated by introducing a modulation factor λ_{MOD} that basically reduces the active current reference $I_{AP_{REF}}$ as shown in (1). As indicated in (1) and (2), the modulation factor λ_{MOD} essentially represents a non-linear gain that depends on the LVT parameter, the scaling factor α and the variable $DC_{meas_{LIM}}$.

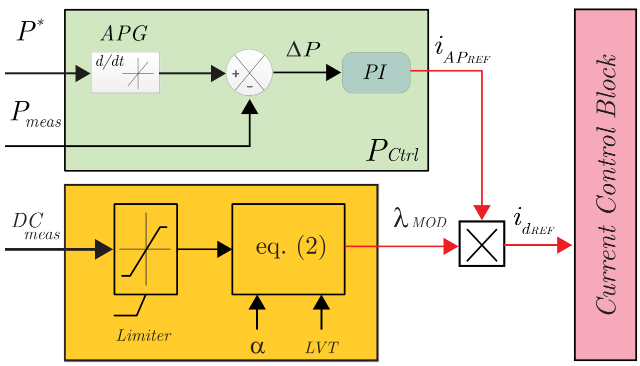


FIGURE 3. Graphical description of proposed non-linear DC power modulation at the inverter VSC unit.

The $DC_{meas_{LIM}}$ variable in (1) represents the (per unit) voltage measured at the DC side terminals of the VSC unit regulating the active power level transmitted through the PtP-VSC-HVDC system. If the difference between LVT and $DC_{meas_{LIM}}$ is negative, λ_{MOD} will be negative. This would generate a transient DC power reversal response within the PtP-VSC-HVDC link, preventing a DC voltage collapse issue during the FRT activation at the rectifier VSC unit. However, as I_{dREF} units are typically in per unit (p.u.), it is recommended to set DC_{meas} limit as close as possible to the LVT value. Furthermore, a graphical description for the proposed non-linear DC power modulation strategy is shown in Fig. 3.

The curves in Fig. 4 are shown to highlight the speed in which the modulation factor λ_{MOD} can modify the I_{dREF} value in (1). Note in Fig. 4 that for all the α values considered, the modulation factor λ_{MOD} asymptotically converges to one,

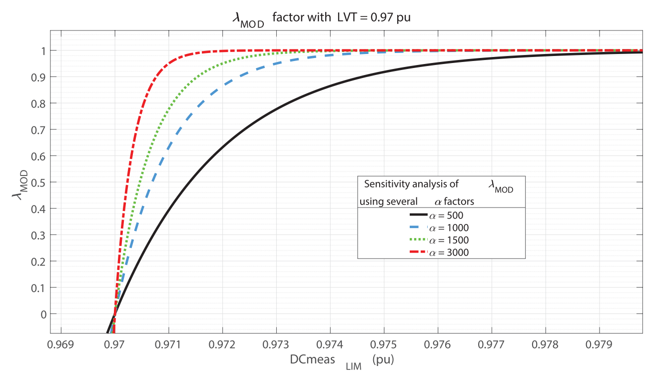


FIGURE 4. Exponential response presenting the non-linear relationship between λ_{MOD} and $DC_{meas_{LIM}}$ for different α values.

when the DC voltage (measured at the DC terminals of the inverter VSC unit) is higher than 0.979 pu. This means that if there is not an event that generates a sudden decrement (e.g. below 0.98 pu) in the DC voltage of the PtP-VSC-HVDC system, then, the I_{dREF} will be equal to $I_{AP_{REF}}$ (c.f. (1)). On the other hand, it is observed that as soon as the DC voltage starts to get close to the LVT level presented in Fig. 4, the rate of change of λ_{MOD} is increased when the pre-defined value of α is also increased. This implies that a fast reduction of the active power is expected in the PtP-VSC-HVDC system, when the DC voltage value is closer to the LVT level and when high α values are utilized in (2), as shown by the red-dashed curve plotted in Fig. 4.

The fast active power reduction in a PtP-VSC-HVDC system experiencing a critical DC voltage reduction is a desirable characteristic for keeping the stability of the HVDC system. Nevertheless, the consequences of using higher α values (e.g. above 3000) in a real power electronic converter application would require the use of real-time processors able to compute the λ_{MOD}'s value in a time frame smaller than 1 ms. Besides, the use of lower α values (e.g. below 500) is not recommended since its decrement can seriously affect the performance of the PtP-VSC-HVDC system during its steady-state operation.

B. MT-VSC-HVDC

As mentioned at the beginning of Section II, there are two options for developing the expansion of a PtP-VSC-HVDC system into a multi-terminal system. In the first option, the expansion is developed by enabling the access for modifying the DC voltage references of the VSC units of the MT-VSC-HVDC system. In the second option, this access is not ensured and then, the expansion is developed by adding network elements (e.g. DC choppers) to the MT-VSC-HVDC as discussed in Section III-B2.

1) FRT AND PFAPR FUNCTIONS COORDINATION BASED ON DC VOLTAGE REFERENCES MODIFICATION.

The access for modifying the DC voltage references of the onshore VSC units presented in Fig. 1, allows to establish the DC power flow conditions in the MT-VSC-HVDC system. The modification of the DC voltage references is usually developed by a multi-terminal DC voltage controller (MTDCVC) which for simplicity in this work will define the steady-state operation of the MT-VSC-HVDC system in Fig. 1, based on a conventional DC droop control (*Droop Ctrl*) mode. This conventional *Droop Ctrl* essentially alters the DC voltage reference (w.r.t an initial DC voltage steady-state condition V_{DC_0}), based on the deviation of the active power ΔP experienced by each onshore VSC unit when, the amount of offshore (wind) power coming from VSC03 (c.f. Fig. 1) increases. Additionally, the DC voltage reference deviation is also affected by the K parameter which defines in a proportional manner, the amount of DC voltage deviation expected depending on the ΔP experienced in the HVDC system as shown in (3).

The influence of the non-linear DC power modulation strategy is expressed by the term $V_{DC_{MOD}}$ in (4) which only affects the DC power flow if a fault event occurs in any of the onshore AC networks presented in Fig. 1. During the fault event, the low AC voltage level in the AC network activates FRT function in the corresponding onshore VSC unit, sending in that way a trigger a signal to the MTDCVC. The MTDCVC receives this trigger signal to register the DC voltage levels $V_{DC_{PreFault}}$ and the active power $P_{P_{PreFault}}$ transmitted by the affected VSC unit during the pre-fault period. The parameters $P_{P_{PreFault}}$ and $V_{DC_{PreFault}}$ that are used to define the term $V_{DC_{MOD}}$, and consequently the DC voltage error $\Delta V_{DC_{error}}$ utilized by the DC voltage control (i.e. *DC Ctrl*) of the affected VSC unit as expressed in (4) and (5).

$$V_{DC_{REF}} = V_{DC_0} - K\Delta P - V_{DC_{MOD}} \tag{4}$$

$$V_{DC_{MOD}} = \Delta V_{DC_{MEM}}(1 - e^{-\alpha(P_{PreFault} - P_{meas})}) \tag{5}$$

$$\Delta V_{DC_{MEM}} = V_{DC_{PreFault}} - V_{DC_{meas}} \tag{6}$$

The expressions (4)-(6) reveal that during the post-fault period, the DC voltage error $\Delta V_{DC_{error}}$ used by the DC control system (of the affected VSC unit) is influenced by the term $V_{DC_{MOD}}$, which according to (4) is defined as a DC voltage deviation modulated by an exponential function. The exponential function in (5) is based on the same principle explained in Section III-A for (2) but instead of using the DC voltage, it utilizes the active power deviation (scaled by the α factor) to define the behavior of $V_{DC_{MOD}}$ during the post-fault time period. In other words, the arguments of the exponential functions in (2) and (5) contain the variables critically affected by the FRT function activation, and the obtained result (i.e. λ_{MOD} or $V_{DC_{MOD}}$) represents the factor utilized to restore the pre-fault conditions in the corresponding VSC-HVDC system configuration. This modulation technique can also be interpreted as a way to redefine (during the post-fault period in a disturbed AC network) the shape of the trajectory used by the droop line tracking method proposed in [23] for the compliance of the PFAPR requirements. The performance analysis of the PFAPR in the MT-VSC-HVDC system of Fig. 1 using a conventional *Droop Ctrl* and the non-linear DC power modulation strategy is presented in Section IV-B1.

2) FRT AND PFAPR FUNCTIONS COORDINATION BASED ON THE INCORPORATION OF ADDITIONAL NETWORK ELEMENTS

In this case, the access for modifying the DC voltage reference is not guaranteed. This means that the DC power flow regulation in an expanded PtP-VSC-HVDC system (i.e. MT-VSC-HVDC system) would be based on the original power flow controllers of the PtP-VSC-HVDC system. As discussed in [25], this DC power flow regulation strategy is only feasible, if the multi-terminal DC system is relatively small (e.g. three-terminal system as the one presented in Fig. 1). However, if such DC power flow regulation strategy is applied in the MT-VSC-HVDC system presented in Fig. 1, the activation of the FRT function can cause serious DC over-voltage problem. This is especially true when the activation of the FRT function occurs in the onshore VSC unit controlling the DC voltage of the system while the amount of the active power demanded by the other onshore VSC unit is relatively low w.r.t. the one provided by the offshore wind generators (VSC03 unit) in Fig. 1. Consequently, as the non-linear power modulation strategy presented in (1) and (2) is exclusively designed to prevent undervoltage problems in the HVDC system, the addition of a DC chopper would constitute a feasible technical solution for mitigating DC over-voltages in the MT-VSC-HVDC system of Fig. 1. The sequences of events that lead into the operation of the DC chopper (in the MT-VSC-HVDC system of Fig. 1) will be described in detail in the Section IV-B2.

IV. SIMULATION SETUP AND RESULTS

The analysis of the expandable PtP-VSC-HVDC system is carried out in this work by performing simulation experiments under a quasi-stationary (or RMS) simulation time frame in DIgSILENT PowerFactory 2018 SP1. The modelling assumptions described in [26] for the outer controllers of a VSC unit are used for implementing a

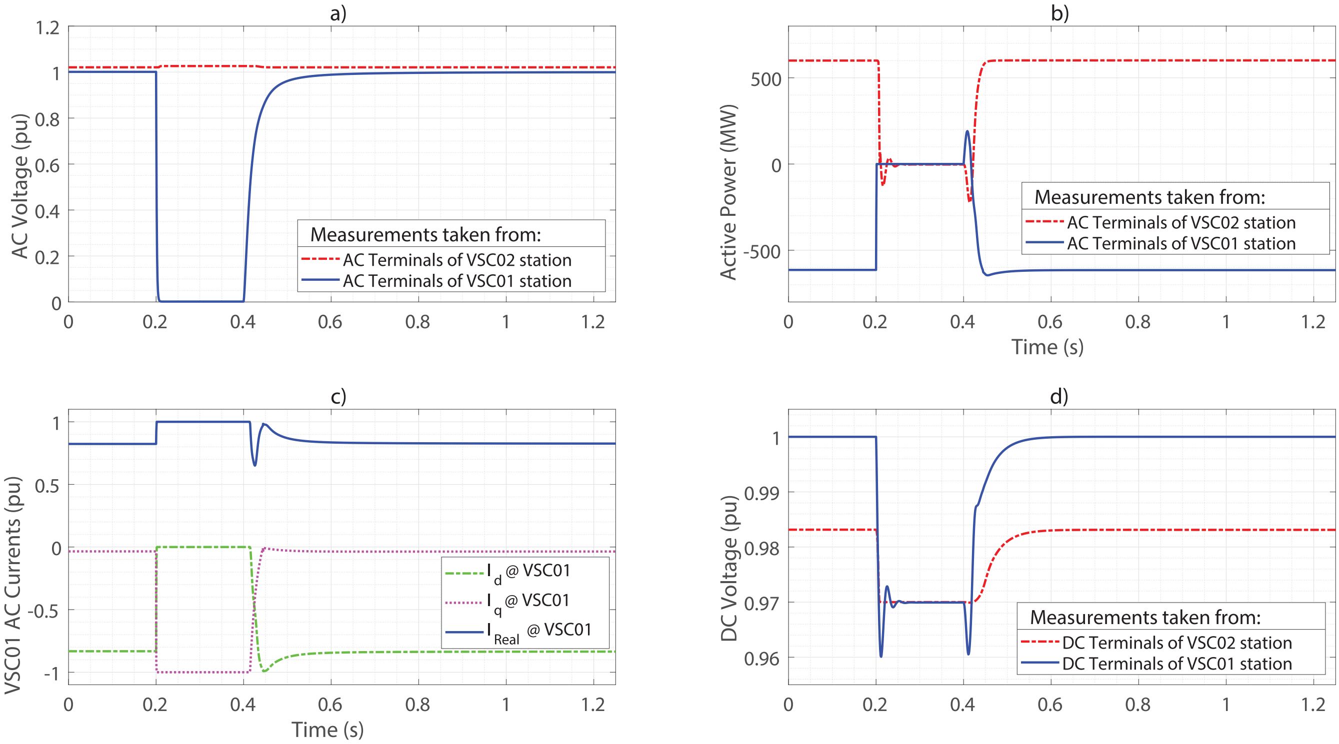


FIGURE 5. The PtP-VSC-HVDC system of Fig. 1 experiencing an AC fault (at t = 0.2 s V_{PPC_A} Fig. 4a) in the rectifier station VSC01. The injection of reactive current at VSC01 during the fault period is presented in Fig. 4c. Additionally, the active power and DC voltage responses are presented in Fig. 4b and Fig. 4d respectively.

700MW PtP-VSC-HVDC system connecting two onshore AC networks (c.f. Fig. 1) and its expansion is generated by the addition of an 800 MW (offshore) VSC unit connecting a group of wind generators as described in [27]. The analysis of the non-linear modulation strategy for the PFAPR function starts by considering a 200 ms three-phase onshore fault for each of the simulation-based experiments developed for the VSC-HVDC system configurations presented in Fig. 1. Based on real PtP-VSC-HVDC requirements [2], it is assumed that the time limit for reestablishing the pre-fault active power levels (i.e. PFAPR criteria) should not be bigger than 200 ms after the fault period has finished (i.e. after 90% of the pre-fault network voltage level has been restored).

A. PtP-VSC-HVDC

For the PtP-VSC-HVDC system configuration in Fig. 1, the three-phase fault occurs at the AC terminals (i.e. PCC bus) of the of the VSC01 station which regulates the DC voltage level in the HVDC system, while the VSC02 station provides 600 MW to AC network B. For the simulation experiments carried in this section, the parameters values utilized indicated in (2) for α and the LVT are 1500 and 0.97 respectively. The three-phase fault experienced by the AC network A at t = 0.2s presented in Fig 3a generates a serious deviation of the active power transfer through the HVDC link as shown in Fig. 5b. During the fault period, the FRT function gets activated prioritizing (in the VSC02 unit) the reactive current injection (i.e. I_q) over the active current injection (i.e. I_d) as presented in Fig. 5c. The prioritization of the reactive current during the fault period directly jeopardizes the operation of the DC voltage control (i.e. the AC/DC power conversion balance) in the VSC01 unit, creating in that way a critical reduction of the DC voltage as shown in Fig. 5d.

However, as shown in Fig. 4, as soon as the DC voltage in the DC terminals of the VSC02 units gets close to the LVT level, the proposed non-linear DC power modulation strategy generates a reduction in the active power in VSC02. This reduction in the active power in VSC02 helps to stabilize the DC voltage in the HVDC and it also produce a boosting action in the DC voltage by generating an automatic change in the direction of the active power flow demanded by the VSC02 unit. The automatic change in the active power flow direction is a consequence of the negative values generated in (2) when the DC voltage at the DC terminals of the VSC02 unit goes to levels below the LVT as observed in Fig. 4. As shown in Fig. 5d, the non-linear DC power modulation strategy allows stabilizing the DC voltage in the entire HVDC system during the fault period which means that the forfeit of the DC voltage regulation in the VSC01 does not lead into the collapse of the stability of the HVDC system.

As seen in Fig. 5a, the voltage at the PCC bus of VSC1 starts to recover at t = 0.4s. However, the priority of the active current over the reactive current in VSC01 is progressively

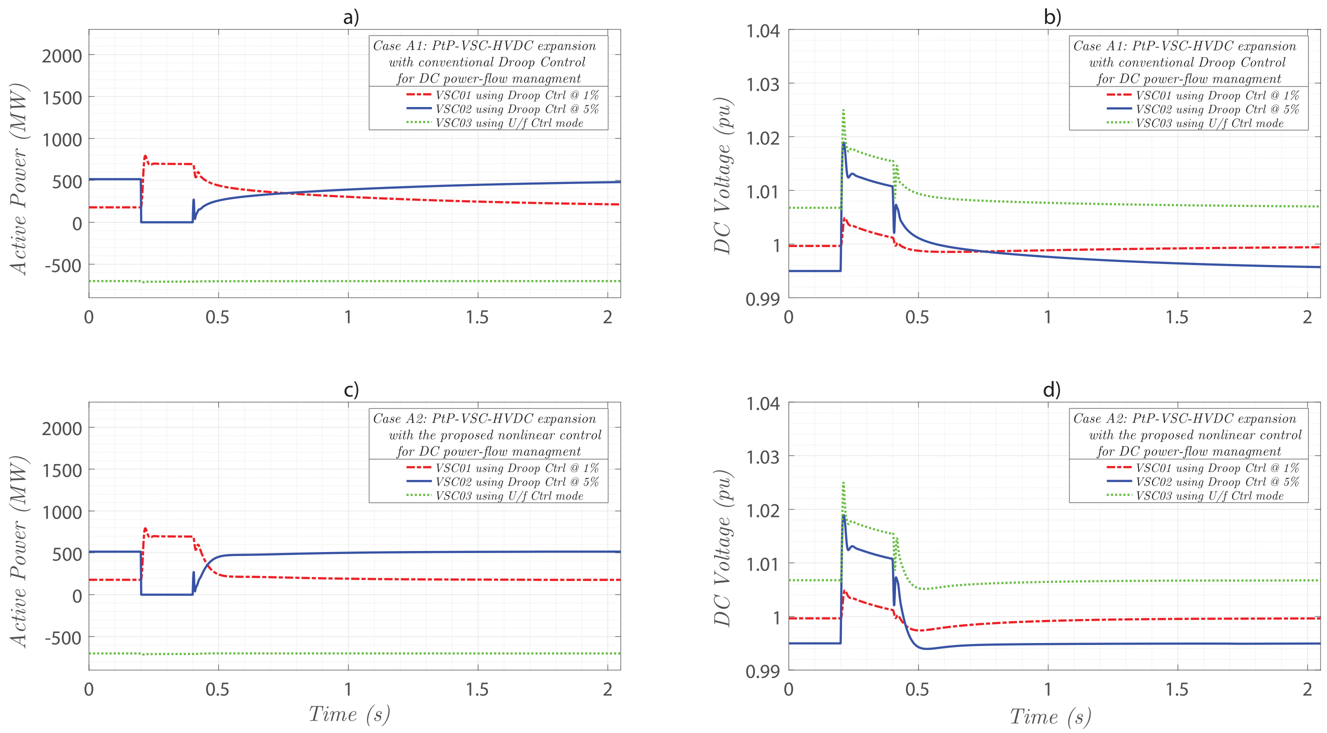


FIGURE 6. The Expanded PtP-VSC-HVDC system of Fig. 1 experiencing an AC fault (at t = 0.2 s) in the VSC station working with $Droop_{Ctrl}$ at 5%. Case A1 presenting active powers and DC voltage responses in the VSC units utilizing a conventional $Droop_{Ctrl}$ in Fig. 5a and Fig. 5b respectively. Case A2 presenting active powers and DC voltage responses in the VSC units utilizing the proposed non-linear method (defined in (5)) in Fig. 5c and Fig. 5d respectively.

given back, as soon as the AC voltage level surpasses 50% of the pre-fault voltage level in AC network A. This post-fault FRT reactive current criteria implies that, during the recovering process of the AC voltage, the difference between the DC and AC voltage magnitudes in the VSC01 terminals will induce a transfer of active power towards the AC network A. However, as indicated by the FRT (active and reactive current injection) requirements in [24], once the AC voltage level surpasses 50%, the injected active current starts to progressively increase (c.f. Fig. 5c), which means that the DC voltage control in VSC01 begins to be restored increasing the level of DC voltage to its pre-fault condition as shown in Fig. 3d. As the DC voltage starts to recover at the VSC01 terminals, the DC current in the HVDC system is also increased, producing in that way an increment in the power (DC current) sent towards the AC network B. Likewise, due to the electrostatic energy storage characteristics of the DC cable, the increment of the DC current (during the post-fault period) generates an increment in the voltage levels registered at the DC terminals of VSC02 as shown in Fig. 5d. The progressive DC voltage recovery in the DC terminals of VSC02 generates an increment of λ_{MOD} in (B) that can be interpreted as the gradual way in which the P_{Ctrl} is reestablished in VSC02. Finally, this analysis demonstrates that the recovery process of the DC voltage level developed by the DC_{Ctrl} in VSC01 mainly defines the PFAPR time (less than 200 ms, c.f. Fig. Ab), and the non-linear DC power modulation strategy regulates the DC voltage recovery process in HVDC system during the post-fault period as shown in Fig. 5d.

B. MT-VSC-HVDC

The expansion of the PtP-VSC-HVDC system into a MT-VSC-HVDC system is developed in this work by the addition of an 800MW offshore VSC unit connecting a wind power plant as shown in Fig.1. The analysis of the PFAPR in the expanded HVDC system is carried out by considering two cases. In the first case (i.e. Case A), the onshore VSC units (of the PtP-VSC-HVDC system in Fig. 1) allows access for modifying their corresponding DC voltage references based on (4)-(6), and for the second case (i.e. Case B), such access is not allowed.

1) CASE A

The Case A is divided in two simulation experiments (i.e. A1 and A2) where, a conventional *Droop Ctrl* method (Case A1) is compared against the non-linear DC power modulation (defined in (4)) in order to demonstrate the superior performance of the proposed strategy in terms of the influence over the PFAPR response. This analysis is carried out by considering a 200 ms three-phase fault occurring at t = 0.2 s in the VSC02 station during a power flow scenario in which 700 MW are supplied by the offshore VSC unit (i.e. VSC03 in Fig. 1) and unequally distributed (approx. 500 MW and 200 MW, respectively) between the onshore VSC units as shown in Fig. 6a and Fig. 6c. This unequal distribution of the active power is generated by the different *Droop* gains (i.e. cf. K in (4)) used for each VSC unit as indicated in Fig. 6a and Fig. 6c. The DC voltage responses for the Case A1 and Case A2 are shown in Fig. 6b and Fig. 6d, respectively.

It can be seen that as soon as the three-phase fault occurs, the active power the level in VSC02 is seriously affected and in an identical manner for either the Case A1 or either the Case A2. Due to the *Droop Ctrl* characteristics in VSC01, the active power distribution in the HVDC system is modified during the fault period, creating a transient boosting in the active power transferred to the VSC01 unit. Moreover, as the DC voltage control in VSC02 is disabled during the fault period (due to its FRT function activation), the DC voltage levels in the HVDC system increases as shown in Fig. 6b and Fig. 6d. However, during the post-fault period (i.e. from t = 0.4 s) relevant differences between the Case A1 and Case A2 can be noticed. Firstly, the active power in Fig. 4a is restored approximately at t = 2 s, exceeding in that way the 200 ms limit for the PFAPR period which was defined at the beginning of Section IV. This delay in the PFAPR period for the Case 1 occurs because of the inability of the conventional *Droop Ctrl* to promptly restore the DC voltage levels occurring in the affected VSC unit (i.e. VSC02) before the fault period, as shown in Fig. 6b. Nevertheless, the non-linear DC power modulation strategy (represented by the addition of the $V_{DC_{MOD}}$ term within conventional *Droop Ctrl* in (C)), can bring back the pre-fault active power level in VSC02 as shown in Fig. 6c. This result is a consequence of the DC voltage reference modulation driven by $V_{DC_{MOD}}$, which accelerates the DC voltage restoration process as shown in Fig. 4d. The faster restoration of the DC voltage in VSC02 is a consequence of the proposed non-linear DC power strategy which can be interpreted (from the DC network point of view) as an active power dependent DC voltage source which is generated during the post-fault period in the VSC02 unit.

2) CASE B

The Case B is also divided in two simulation experiments where, the PFAPR is analyzed considering that the access for modifying the DC voltage references of the onshore VSC units is not allowed. This consideration implies that the DC power flow regulation in the three terminal (MT-VSC-HVDC) system of Fig. 1 is governed by the same active power and the DC control modes (i.e. *P Ctrl* and *DC Ctrl*) of the original PtP-VSC-HVDC system. Thus, the simulation experiments developed aim at highlighting the relevance of having the non-linear DC power flow modulation strategy implemented in the original PtP-VSC-HVDC system (Case B1) and the relevance of incorporating a DC chopper into the expanded HVDC system (Case B2).

During the steady-state operation of the Case B1, the VSC01 unit regulates the DC voltage of the MT-VSC-HVDC system of Fig. 1, while the VSC02 unit is in charge of delivering 600 MW towards the AC network B as shown in Fig. 7a. As the offshore VSC unit (i.e. VSC03) is suppling 450 MW to the HVDC system, the VSC01 injects the necessary 150 MW (into the HVDC system) to satisfy the power requirements defined by the *P Ctrl* in VSC02. However, at t = 0.2 s a 200 ms three-phase fault occurs at the AC terminals of the VSC01 station (i.e. rectifier VSC unit) creating in that way a DC power unbalance in the HVDC system. This DC power unbalance generates a decrement in the DC voltage of the HVDC system since the *DC Ctrl* mode in VSC01 gets deactivated (since the FRT function is enabled) while VSC02 unit still demands the 600 MW described at the beginning of this paragraph. However, as the non-linear DC power modulation strategy is implemented in VSC02, if the DC voltage starts to get closer to the LVT level, the active current modulation starts to be generated as described in (1) and (2).

Unlike the PtP-VSC-HVDC system, the three terminal HVDC system (addition of VSC03) introduces an injection of active power during the fault period. This means that although the DC voltage in the HVDC system decreases (c.f. Fig. 7c), the active power in VSC02 is correspondingly adjusted by the proposed strategy (cf. (1) and (2)) to the power level supplied by VSC03 as shown in Fig. 7a. Next, as soon as the post-fault period starts (i.e. t = 0.4 s), the *DC Ctrl* mode in VSC01 is progressively reactivated. This reactivation process basically entails the restoration of the pre-fault AC current prioritization in VSC01, i.e. the active current injection over the reactive current injection as defined in [24]. This restoration basically generates the abrupt change in the active power presented in Fig. 7a. that is a consequence of a combination of events that occurs simultaneously: the progressive AC voltage increment in the transmission network, the saturation of modulation index, and the change in the converter (VSC01) current priorities during the post-fault period.

In any case, the abrupt change during the post-fault period in the active power is quickly regulated since the non-linear DC power modulation progressively adjusts the active current $I_{d_{REF}}$ of VSC02, generating in that way a smooth DC voltage recovery rate of the MT-VSC-HVDC system as illustrated in Fig. 7c. The smooth DC voltage recovery generated in VSC02 and the fast recovery of the DC voltage experienced in VSC01 guarantee a short PFAPR time (i.e. fast DC current change) and a progressive return to the DC voltage levels during the pre-fault condition in the MT-VSC-HVDC system.

For the Case B2, the amount of DC power supplied by VSC03 to the MT-VSC-HVDC system during the steady-state period is identical to the one described for the Case B1. Nevertheless, the power distribution between the onshore VSC units has changed to 200 MW for VSC02 (operating in *P Ctrl* mode) and (approximately) 250MW for VSC01 (operating in *DC Ctrl* mode). This means that for the simulation experiment Case B2, the VSC units concurrently provide active power towards the onshore AC networks. Like

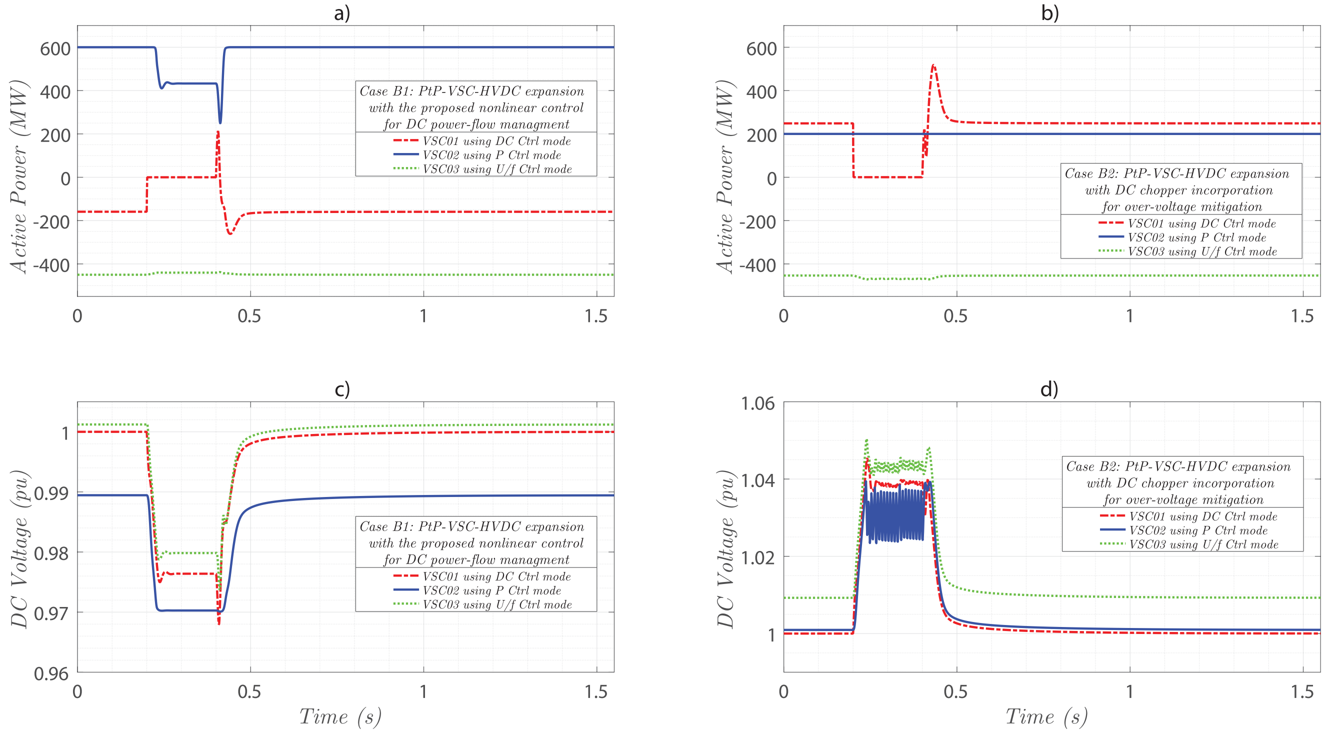


FIGURE 7. The Expanded PtP-VSC-HVDC system of Fig. 1 under fault scenarios. Case B1 showing a fault in the rectifier VSC01 station in Fig. 6a and Fig. 6c respectively. Case B2 presents a fault in the inverter VSC02 station in Fig. 6b and Fig. 6d respectively.

in Case B1, a 200 ms three-phase fault occurs at the rectifier station (VSC01) at t = 0.2 s, creating in that way an DC power unbalance in the HVDC system as shown in Fig. 7b. As presented in (B), the proposed non-linear DC power modulation strategy has been designed to alter the active current (i.e. active power) reference in a VSC unit operating in *P Ctrl* mode, when a serious DC voltage reduction is detected at its DC terminals. However, the DC power unbalance created by the three-phase fault in Case B2, produces an increment of the DC voltage that cannot be handled by the proposed non-linear DC power modulation strategy since the exponential function in (B) is not sensible to the increments in the DC voltage in the VSC station. For this reason, the incorporation of a DC chopper within the MT-VSC-HVDC system would help to limit the DC over-voltages created by the three-phase fault at the VSC01 station as shown in Fig. 7d. It is important to point out that during the fault period in Fig. 7b, the VSC02 unit maintains the active power (200 MW) supply towards the AC network B because the DC chopper limits the rise of the DC voltage by absorbing the surplus of DC power delivered by VSC03. Likewise, this limitation is generated by the DC chopper through switching actions that basically connect and disconnect resistive elements into the HVDC system. These switching events produce oscillatory patterns in the DC voltage response during the fault period that affect the response of active power during the initial period of the post-fault condition as shown in Fig. 7d. When the post-fault period starts (i.e. t = 0.4 s), the *DC Ctrl* in VSC01 begins to be restored and it detects that the DC chopper has limited the rise of the DC voltage, but it is still in a higher condition than the one required by the HVDC system. Consequently, the *DC Ctrl* in VSC01 produces a transient increment in the active power sent towards AC network A, in order to extract electrostatic energy from the HVDC system to promptly decrease the DC voltage level existing in the HVDC system. Nevertheless, this prompt decrement of the DC voltage does not harm the compliance of the PFAPR in terms of the time period requested by the HVDC sy stem owner as shown in Fig. 7b.

V. CONCLUSION

In this work, a non-linear DC power modulation strategy has been proposed to regulate the pre-fault active power recovery process in a VSC unit (affected by a three-phase fault) during the post-fault period. The strategy is aligned to cooperatively work with the low voltage (fault) ride through (FRT) function and it is also aligned with the post-fault active power recovery (PFAPR) requirements of a VSC-HVDC system. The strategy can successfully comply with the PFAPR requirements in VSC units belonging to an expanded point-to-point (PtP) VSC-HVDC (i.e. multi-terminal) system or for VSC units belonging a PtP-VSC-HVDC system. The implications of expanding a PtP-VSC-HVDC system are discussed to give insight into the ways in which the non-linear DC power modulation strategy can be implemented, taking into account that the access to the DC voltage reference regulation (in the VSC units conforming the expandable system) can be guaranteed or not. Moreover, it has been found that for the PtP-VSC-HVDC systems, the strategy proposed effectively alters the DC power flow in order to maintain (within an acceptable 3% range) the DC voltage levels in the HVDC system, even if the *DC Ctrl* mode is suppressed (in the rectifier VSC unit) during the activation of the FRT function. In terms of the multi-terminal (MT) VSC-HVDC systems allowing the modification of its DC voltage references, the non-linear DC power modulation strategy exhibits a superior performance in terms of the PFAPR requirements when it is compared against a conventional *Droop Ctrl* method. However, when the expansion of the PtP-VSC-HVDC system does not contemplate the modification of the DC voltage references of their VSC units, the effectiveness of the non-linear DC power modulation strategy is subjected to the power flow conditions in the HVDC system before the three-phase fault occurs. This power flow dependency constitutes a limitation of the proposed non-linear method (that occurs only if the modification of the DC voltage reference is not allowed), which can be easily overcame if a DC chopper is installed to protect the HVDC system against potential over voltages risks. Nevertheless, the installation of a DC chopper constitutes a costly solution that partially limits the increment in the DC voltage level in the HVDC system during the fault period. Consequently, a transient boosting in the active power transmitted by the affected VSC unit is generated during the post-fault period in order to comply with the time restrictions associated to the PFAPR requirements. The extension of the non-linear DC power modulation strategy for tackling overvoltage risks during fault periods in the VSC-HVDC system is a work that will be addressed in a future publication.

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