Auxiliary Short-Circuit Fault Classification for HVDC Systems Based on VCO

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***Abstract*— One of the great challenges of HVDC systems is the protection against short-circuit faults. The propagation of the fault effects in DC systems is faster than in AC networks mainly because to the low resistance, so a new breed of detection algorithms is required, much faster and more effective, with operation times to 10 milliseconds. This work proposes a step-forward scheme to detect and classify high and low resistance pole-to-pole and pole-to-ground short circuit faults in a MMC-HVDC system by combining the use of Voltage Controlled Oscillator (VCO) modules with a smoothing reactor. Case studies to verify the effectiveness of the proposed strategy are performed in PSCAD/EMTDC with a point-to-point HVDC system.**

Keywords*— *HVDC; DCCB; Short-circuit; VCO; MMC; PSCAD; DC protection.

TABLE I. ACRONYM TABLE

Acronym	**Description**
AC	Alternating Current
DC	Direct Current
HVDC	High Voltage Direct Current
P2P	Point-To-Point
MMC	Modular Multilevel Converter
SM	Sub-Module
PTP	Pole To Pole
PTG	Pole To Ground
HRPP	High Resistance Pole to Pole
HRPG	High Resistance Pole to Ground

I. INTRODUCTION

The integration of large blocks of renewable energy into power systems has several transmission challenges. One of them is the transmission from the power source to the AC power grid. For distances in the order of several hundred kilometers, transmission based on High Voltage Direct Current (HVDC) is an increasingly attractive option. In point-to-point MMC-HVDC systems, or VSC-HVDC the most common [1], in a short circuit condition in the DC line, the DC overcurrent can flow through the anti-parallel diodes of the IGBTs of any station even if the converter is blocked [2]. Due to the absence of current zero crossing and the low inductance and resistance of a dc system, the short circuit DC current rate rump up fast, in the order of tenths of milliseconds despite the smoothing reactors in the line. Therefore, the potential damage to various primary equipment is high and a fault release time of less than 10 ms is recommended [3].

The Direct Current Circuit Breaker (DCCB) technology can isolate short-circuit faults, but under the condition that this device is timely triggered up by a trip signal sent by an ultra-fast and reliable fault detection algorithm. There are several recent proposals dedicated to the detection of short-circuit fault available in the specialized literature. However, the set of these proposals gives a pivotal role to the rate of change of the fault current as it is use as parameter. Nevertheless, this rate cannot be used as criterion to discriminate between faulted and non-faulted conditions because in this situation the detection becomes dependent on the system topology and parameters (resistance and inductance) [4-5]. This dependability turns these options less reliable. For instance, faults occurring in a highly resistive or inductive context, the algorithm will not send the trip signal to the DCCB, as shown in Figure 1.

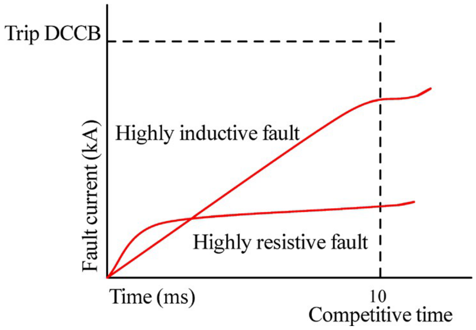


Figure 1. Current behavior of highly resistive and inductive faults.

Regarding protection algorithms for HVDC system, various techniques has been proposed for the detection, even the identification, of fault conditions. Two of these are traveling waves and evaluation of voltage changes in smoothing reactors. Although there are plenty of experiences using traveling wave in AC power systems, in DC systems the use of traveling waves has various weak points. First, the fault location and the resistance of the line affect the performance of the algorithm. Second, it is unable to detect double-pole-to-ground faults. Additionally, the structure of the algorithm is complex and computationally demanding [6-9]. Also, considering that high impedance faults account for about 5% to 20% of the total number of faults, then in this condition the traveling wave technique may perform poorly [10].

The auxiliary systems associated to main protection schemes are central to the proper operation of protection schemes, however, few works finger in this direction. The effective selection of this auxiliary system can improve the response speed of the algorithm as well as improve fault location, discrimination of healthy lines or identify the type of fault.

In this work a Voltage Controlled Oscillator (VCO) filter is proposed to be use as part of an auxiliary protection scheme. The role of the VCO helps in the identification of the type of fault (high or low resistance) on the DC lines. The proposed main protection scheme is based on evaluating the voltage change across the smoothing reactors which, after processing, has the information to trigger the DCCB [11]. The proposed scheme is validated in the PSCAD/EMTDC.

The following sections of this paper described as follows, section two describes the short-circuit study that determines the parameters that feed the VCO and the DCCB trip. Section three presents the cases of study pole-to-pole (PTP), pole-to-ground (PTG), high-resistance pole-to-pole (HRPP) and high-resistance pole-to-ground (HRPG) faults. At final section, conclusions are presented.

II. PROTECTION AND SCHEME FOR HVDC LINES

A. General Description

This section presents the general structure of the proposed protection algorithm for an HVDC system implemented based on the voltage change rate across the smoothing reactor. The proposed detection algorithm evaluates the behavior of this voltage and send the tripping signal to the DCCBs if the fault condition is positive. Using the voltage change as parameter the sensitivity and speed in the detection of a fault greatly improves compared to other proposals. Despite its relative advantages, this approach still has high sensitivity, and therefore inaccurate for classifying high resistive faults.

To improve further the algorithm, a VCO (Voltage Controlled Oscillator) filter is included in the algorithm as an auxiliar tool in the short-circuit fault classification. The frequency of the output signal of the VCO is directly proportional to the magnitude of the input voltage signal, as shown in Figure 2.

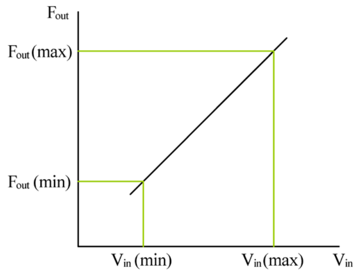


Figure 2. Proportional response of the VCO.

B. Measurement scheme

The measurement of voltage across smoothing reactors is taken at both poles of the DC system through the voltage meter that feeds the VCO filter as well as the DCCB trip comparator, as shown in Figure 3.

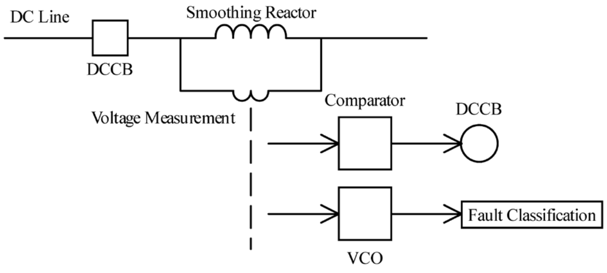


Figure 3. Measurement scheme for VCO and DCCB.

C. Operation principle of the DCCB

During temporary stages, such as large load changes, or transitory conditions such as short-circuit faults or resonances the changes in the voltage of the smoothing reactors, responding to $vv = LL\frac{dddd}{dddd}$. A trip signal condition for the DCCB based on this voltage change is fast and reliable for fault isolation within a transmission line.

To determine the voltage value that triggers the opening signal of the DCCBs, it is necessary to perform a short-circuit study and evaluate the maximum and minimum transient values in the smoothing reactors.

D. Operation principle of the VCO filter

The frequency of the output signal of the VCO filter is proportional to the magnitude of the voltage signal at its input. Then, the proposed algorithm evaluates the response of this VCO filter to the transitory voltage across the smoothing inductor during.

The VCO filter output frequencies evaluated in the DC short-circuit study establish two classification zones, where each zone is associated with DC short-circuit fault resistance values. As well as, a steady state classification zone where there is no DC short circuit fault, as shown in Figure 4.

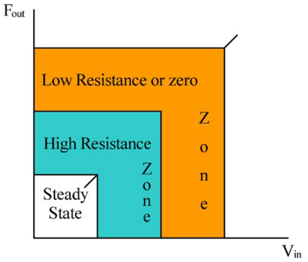


Figure 4. VCO filter short-circuit classification zones.

III. HVDC SYSTEM SHORT-CIRCUIT STUDY

For the case of this work, a short-circuit study in a 200 km point-to-point MMC-HVDC system, shown in Figure 5, is carried out.

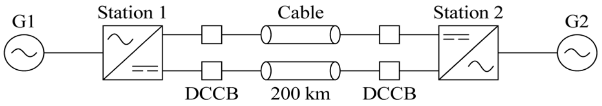


Figure 5. Point-To-Point HVDC system.

The short-circuit study is performed considering a pole-to-pole fault, pole-to-ground faults, high-resistance pole-to-pole fault and high-resistance pole-to-ground fault in the positive pole. The parameters of the system are in Table II.

TABLE II. SYSTEM PARAMETERS UNDER STUDY TO BE IMPLEMENTED IN PSCAD.

Parameter	Value
DC voltage	± 400 kV
AC voltage	250 kV
Power rating	100 MVA
SMs per arm	200 units
MMC topology	Half-bridge
SMs capacitance	29.3 µF
Arm Inductance	84.4 mH
Cable resistive equivalent	2.2e-5 Ω/km
Cable inductance	1.29 mH
Smoothing reactor	200 mH
High resistance fault	50 Ω

A. Smoothing reactors transient voltage evaluation

The voltage profile in the smoothing reactor during 5 to 6 ms short-circuit fault is illustrated in Figure 6.

The maximum voltage magnitudes in the smoothing reactors are listed in Table III. Furthermore, the voltage value reached by the smoothing reactor at 1ms VV_{ssss} after the fault is captured to establish the reference value for the DCCB trip, as well as for the voltage range to be evaluated in the VCO for the fault type designation, where LR is Low or zero zone and HR is High Resistance Zone.

TABLE III. VOLTAGE VALUES IN THE SMOOTHING REACTOR AND VCO VOLTAGE RANGE

Short-circuit Fault	**Maximum value at 5 ms (kV)**	**Value at 1 ms (VV_{ssss})(kV)**	**Voltage range for VCO filter (V)**
PTP	268.54	266.1	141.72 < LR < 268.54
PTG	257.89	254.4	
HRPP	141.72	126.4	46.16 < HR < 141.72
HRPG	71.63	46.16	

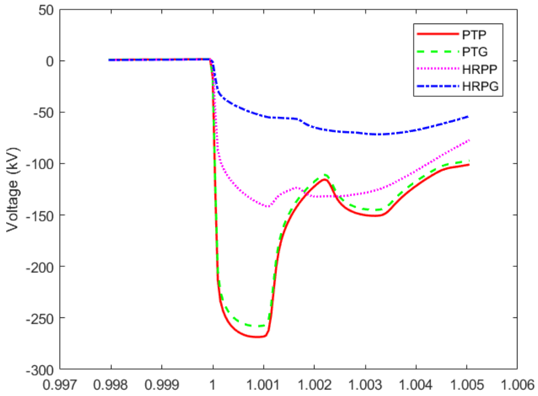


Figure 6. Transient voltages in the smoothing reactor in a short-circuit fault.

B. VCO filter frequency proportional response

During the short-circuit study, the maximum transient frequency values up to 6 ms of the VCO proportional to the input voltage of the smoothing reactors are determined, as shown in Figure 7.

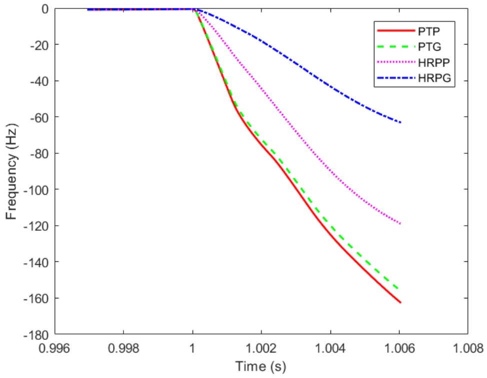


Figure 7. Proportional transient frequency values in the VCO.

Similarly, the frequency value that reaches 2ms (FF_{ssss}) after the fault is taken for the fault type classification, as well as for the frequency range that classifies the fault type, as shown in Table IV.

TABLE IV. FREQUENCY PROPORTIONAL VALUE AND FREQUENCY RANGE FOR VCO

Short-circuit Fault	Maximum value at 6 ms (Hz)	Value at 2 ms (FF_{sss})(Hz)	Frequency range for VCO filter (Hz)
PTP	162.66	62.99	162.66 < LR < 119.07
PTG	156.15	60.4	
HRPP	119.07	32.94	12.85 < HR < 119.07
HRPG	63.16	12.85	

C. Short-circuit fault classification criteria

During a pole-to-ground or high-resistance pole-to-ground fault, the ungrounded pole has a transient frequency response almost equal to zero, compared to the grounded pole with a frequency much greater than zero.

Although it is already possible to define whether the type of fault is high or low resistance depending on the frequency value, to determine which pole is failing, a difference of the frequencies is calculated and evaluated in the VCO. To facilitate this evaluation, it is considered that the positive pole (P+) is the one that always fails to ground.

Considering that the frequency of the negative pole (P-) is almost zero during a ground fault, the result of the difference should be relatively equal to the frequency of P+, as shown in (1). In contrast, when the fault involves both poles, the frequency difference is relatively zero, as shown in (2).

$$\Delta ff = |ff_{PP+} - ff_{PP-}| \approx |ff_{PP+}| \rightarrow \text{PTG fault} \tag{1}$$

$$\Delta ff = |ff_{PP+} - ff_{PP-}| \approx 0 \rightarrow \text{PTP fault} \tag{2}$$

IV. STUDY CASES

For all study cases, the HVDC system in Figure 4 is used, as well as the parameters in Table II. All short-circuit faults are evaluated in the transmission line at 80 km from the station 1 at $tt = 1$s from system startup until fault insulation through DCCBs triggered by the smoothing reactor voltage signal measured at 1 ms after the short-circuit fault, as well as the VCO frequency measured at 2 ms after the short-circuit fault for short-circuit fault classification. Also, the current signal on the DC transmission line is illustrated to observe the isolation of the short-circuit fault through the DCCBs which has a delay of 5 ms.

The flowchart presented in Figure 9 shows the main protection algorithm as well as the auxiliary short-circuit fault classification algorithm based on the VCO filter.

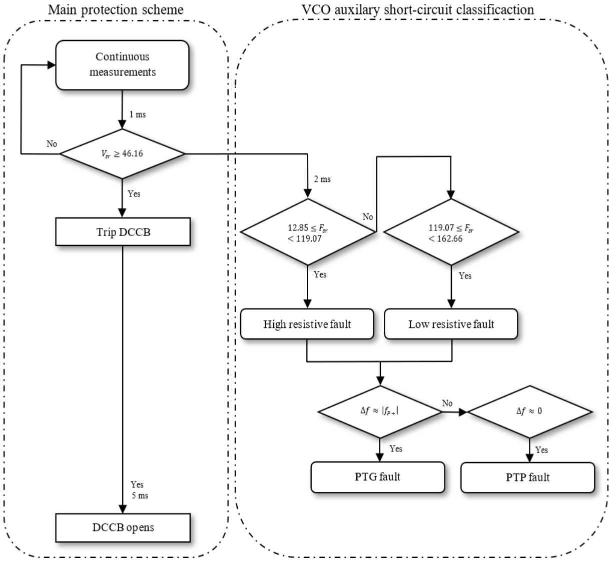
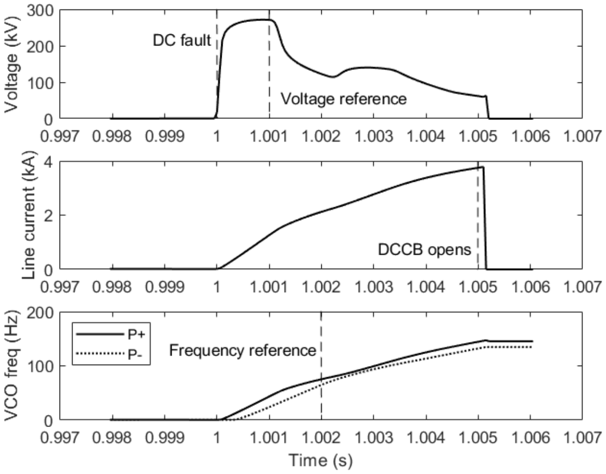
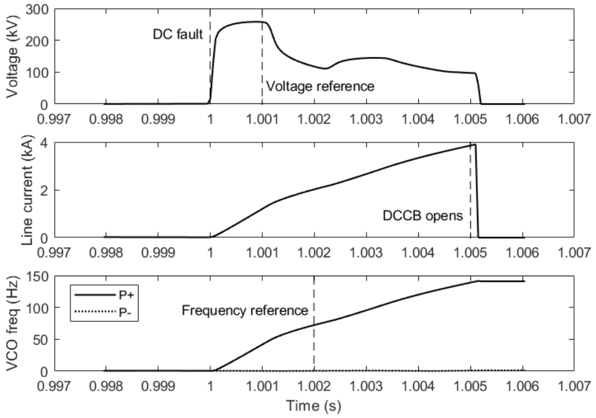


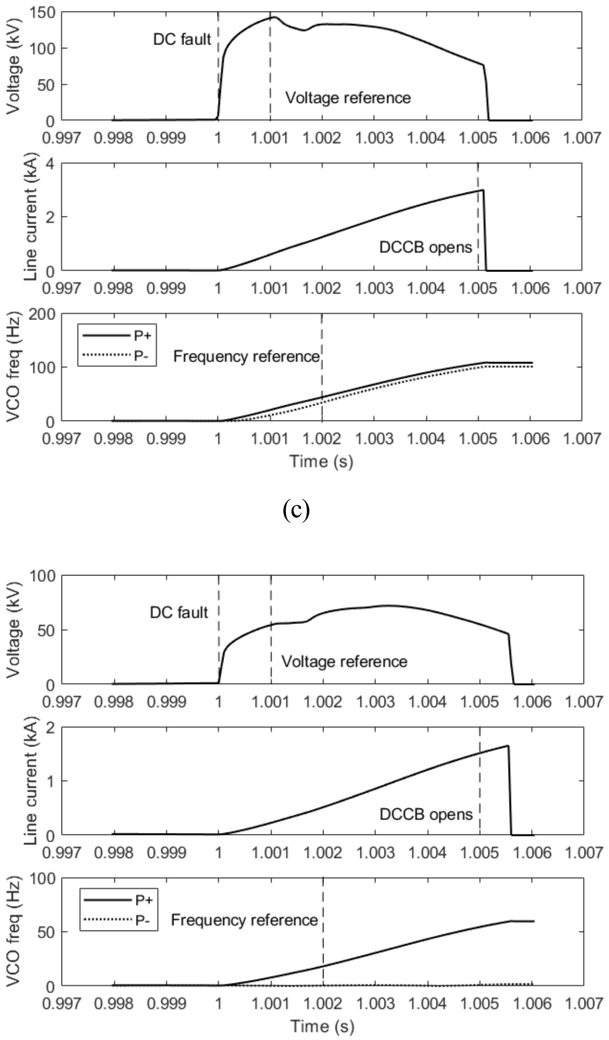
Figure 7. Full protection scheme flowchart.



(a)



(b)



(c)

(d)

Figure 8. Transient voltage, current and frequency signals in a short-circuit fault. (a) PTP. (b) PTG. (c) HRPP. (d) HRPG.

During a short-circuit fault on the DC side, the smoothing reactor has a fast transient response which ranges from 46 to 268 kV. As well as the transient frequency proportion of the VCO filter that reaches values from 12 to 162 Hz. Furthermore, the short-circuit transient line current has an almost linear response delayed by the smoothing reactors. The short-circuit transient line current reaches up to a maximum of 3.8 kA until it is isolated through the DCCB. All the transient magnitudes of the above-mentioned signals depend on the type of fault the point-to-point HVDC system was exposed to, as shown in Figure 8. The magnitudes of voltage, frequency, as well as the fault classification are listed in Table V.

TABLE V. DC SHORT-CIRCUIT FAULT EVALUATION AND CLASSIFICATION

W_{sss} **(kV)**	ff_{PP+} **(Hz)**	ff_{PP-} **(Hz)**	Δff **(Hz)**	**Fault classification**
266.1	62.99	62.92	0.07	PTP fault
254.4	60.4	0.4	60	PTG fault
126.4	32.94	33.08	0.14	HRPP fault
46.16	12.85	0.18	12.67	HRPG fault

V. CONCLUSIONS

The VCO filter as an auxiliary short-circuit fault scheme has shown its capability for discriminating high and low resistance faults, as well as pole-to-pole and pole-to-ground faults within a range established through a short-circuit study in a point-to-point HVDC system. In turn, it is possible to combine it with different main protection schemes based on the transient voltage of smoothing reactors, where the transient voltage response is a fast and reliable signal for the isolation of a short-circuit fault through a DCCB. The protection algorithm processes all information in approximately 5ms, which is an excellent time response for DC fault isolation in point-to-point HVDC systems.

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