Parameter Sensitivity Analysis on DC Transients between MMC Station and Cable

H. Saad, P. Rault, M. Goertz, S. Wenig

***Abstract*-- In MMC based HVDC transmission systems, DC and internal converter faults lead to transient overvoltages and overcurrents that have an impact on DC cable design and ageing. Hereafter, an Electromagnetic transient (EMT) type tool is used, as this presents the most appropriate and most accurate option to investigate such behaviors. In this paper, sensitivity analysis on the main HVDC parameters is performed using a simple but efficient screening approach. The studied case is based on the generic MMC-HVDC link according to Cigré TB604 to provide a general overview. These set of results allow an increased understanding of the impact of HVDC parameter variations on DC transients at converter/cable interface. In addition, related deeper insights allow the identification of input parameters that cause significant DC transients and should, therefore, be in the focus for HVDC projects.**

***Keywords*: DC transient behavior, EMT-Type, HVDC transmission, MMC, sensitivity analysis, switching overvoltage.**

I. INTRODUCTION

Application of voltage source converters (VSCs) in power systems is rapidly growing due to advantages such as absence of commutation failures, ability of independently controlling active and reactive power, and fast dynamic response. VSC based on Modular Multilevel Converter (MMC) topology has become the most attractive solution, mainly due to their higher performances and lower cost compared to early VSC implementations.

MMC technology does not require the inversion of the voltage polarity when reversing the power flow direction. This has made the utilization of extruded insulation cables (XLPE) easier for DC applications. Since then, the number of extruded insulation cables, used in combination with VSCs, has increased for HVDC power transmission applications. Even if VSC does not require the inversion of the voltage polarity (during normal operation), several events can cause transients on cables that are not covered by standard tests. To fill this gap, an ongoing CIGRE JWG B4/B1/C4.73 investigates surges and extended overvoltage testing for DC cable systems to provide recommendation for upcoming HVDC projects and improve cable testing standards [1].

The impact of MMC station's transients on DC cable are evaluated during the design phase of each HVDC project. To provide an overview on such DC transient impact at converter/cable interface, a sensitivity analysis on the main system parameters is provided in this paper. Related findings provide insights on system behavior during DC transients and the influential parameters that should be considered during the design phase of HVDC projects.

Circuit configuration of a converter station can vary depending on project specification and selected manufacturer. In order to present analysis and results without revealing any confidential information for a specific project, a generic HVDC-MMC link based on [2] and on Cigré TB604 benchmark [3] is considered.

DC transients (i.e. overvoltage and overcurrent) during converter faults leads to non-linear behavior and, thereby, are difficult to predict using analytical tools. Therefore, EMT simulations are commonly used to predict overvoltage and overcurrent transients because these provide the most accurate and reliable results. Transient overvoltages are studied in [1]; focus is made on DC system behavior during converter internal faults. In [4] and [5], a thorough analysis of the DC pole-to-ground fault and the impact on cable overvoltage is performed. The impact of project dependent parameters on cable overvoltages is analyzed in [12] and [13] by means of parametric study approaches. Overcurrent behavior during DC pole-to-pole and pole-to-ground faults are investigated in [6]. In [6], the IGBT withstand level during DC pole-to-ground faults is analyzed. In most of these works, sensitivity analysis using EMT simulations are performed by running a limited number of simulations. Hence, a limited indication on sensitivities of the main HVDC parameters is provided. Such constraints are due to:

- Computational time of one single run of the model requires a significant amount of time.
- The model has a large number of input parameters. Sensitivity analysis is usually performed by running the model many times and the number of runs may grow exponentially in size with the number of variable inputs.
- Correlated inputs and system nonlinearity can lead to difficulties in result interpretation. HVDC system behavior can be complex. As a result, its relationships between inputs and outputs may be poorly understood.

This paper addresses these three challenges, by adopting the screening method. Indeed, sensitivity analysis approach such as the variance-based analysis is not affordable when a big number of input parameters is considered. In this work, the elementary effect (EE) method [7] and [8] is applied. EE approach is more adequate because it tends to have a relatively low computational cost when compared to other methods [8]. This method

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provides qualitative sensitivity analysis measures, i.e. measures that allow to rank the input parameters in order of importance and allow the identification of non-influential inputs, but do not quantify exactly the sensitivity relative importance of the input parameters. Therefore, this work provides the identification of inputs parameters that have significant impact on DC transients and should, therefore, be considered in HVDC projects for further detailed analysis. These results and studies are useful for researchers and engineers, who are involved in HVDC projects and in the interface between converter station and DC cable.

The paper is organized as follow: Section II introduces the MMC-HVDC generic model used in this study. Section III describes the parametric test setup considered for running transient fault studies. Section IV presents the EE method used to conduct the sensitivity analysis. Finally, section V displays and analyses the EE sensitivity of DC transients (overvoltage and overcurrent).

II. HVDC SETUP

In order to present analysis and results without revealing any confidential information specific from one project, generic data for cables and converters are used in this work. A generic monopolar HVDC point-to-point link, based on the Cigré brochure B4-57 [3] and described in [2], is considered (Fig. 1). The ac grids (50 Hz) are presented as equivalent sources with a short-circuit level (SCL). The transmission capacity of the link is 1,000 MW. The DC cable is rated ± 320 kV and is implemented using the frequency dependent model. A MMC 201-level (200 SMs/arm) is considered with a time step of 25 µs. To obtain accurate transient results when simulating converter internal faults, detailed MMC model must be considered [3]. Non-linear IGBT/diodes model are used in the converter valves, defined as Model #3 in [2], to account for switching surges when the MMC blocks [2]. Control system details are reported in [3]. Parametric studies are performed with EMTP-RV software [9] in this work.

To protect the converter station and DC cable after fault occurrence, the protection system initiates a trip order, i.e. the converter is blocked first (few microsecond) and the AC circuit breaker is opened (few cycles). In order to account for telecommunication and mechanical delays between protection system and power circuit equipment, artificial delays are added between the order reception and the action: blocking delay is varied between 20 and 400 µs and AC circuit breakers opening is set to 40 ms (BRK1 and BRK2 in Fig. 1). The protection implementation can be found in [10] and a model validation against other commercial EMT-type software is shown in [1].

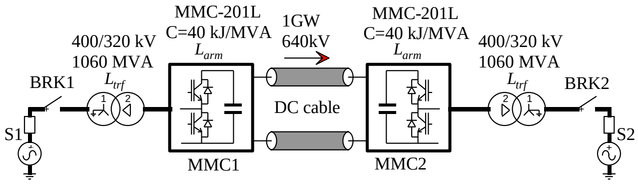

Fig. 1. MMC-HVDC transmission system

A. Parametric study framework

The investigated fault locations as well as the considered voltage/current measurement locations are depicted in Fig. 2. Based on the previous work [10], the highest DC overvoltage transients, at converter/cable interface, recorded are related to the DC pole-to-ground (F8) and the single-phase-to-ground (F1) fault. Therefore, for overvoltage transients, in this article, the parameter sensitivity studies are focusing on these two exemplary fault types. For overcurrent transients, the short-circuit current contribution comprises cable discharge and converter station feed-in. Because this study is focusing on converter/cable interface, only short-circuit current contribution supplied by the converter station is considered. DC pole-to-ground (F8) and DC pole-to-pole (F9) faults are considered, since they are the most severe events within the scope of this analysis (see [8] and [15]). Solid faults are considered because they intend to generate the highest transients.

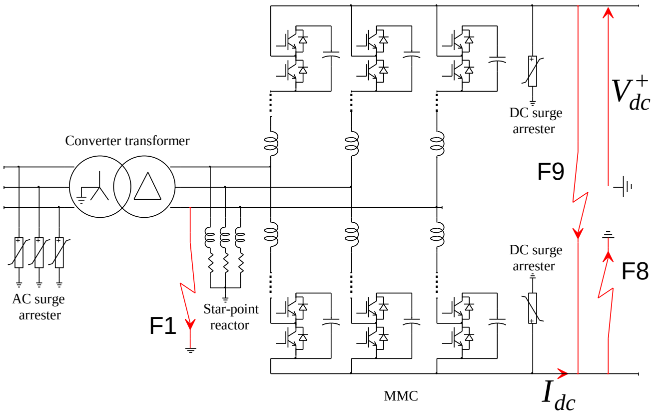

Fig. 2. Faults and measurement locations

The input parameters that are investigated cover the main converter stations, AC networks and cable parameters that usually vary in HVDC project and are suspected to have an impact on DC transients. Table 1 summarizes the considered parameters and the selected value ranges:

- Four control system parameters: active/reactive power direction, outer control configuration and blocking delay time of converter. The blocking delay parameter account indirectly to the protection activation speed (therefore the influence of such parameter provide also indication on the protection speed impact).
- Three parameters regarding HV equipment in converter stations: DC surge arrester characteristics, transformer and arm inductances.
- Two parameters that covers the fault topology: fault location and fault instant occurring on the AC point on wave.
- Two parameters regarding the HV equipment connected to the station: DC cable length and SCL of AC grid.

With respect to Table 1, note that the considered parameter values are realistic themselves, but the resulting set might be extreme in some combinations. This comprises for instance: long duration of blocking delays (400 µs) with low arm inductance value (L_{arm} = 0.11 pu). In practice, if the blocking delay of a converter is high the arm inductance will be designed in consequence to have rather a high value to decrease the d*i*/d*t* slope and, hence, to prevent an IGBT damage. Therefore, such combination might not be realistic to find plausible maximum overvoltage and overcurrent, but it is useful to compute parameter sensitivities, which is the main scope of this work.

It should be noted, that in this work, the circuit breaker opening speed is not covered, because such parameter has an impact on the energy dissipation of the DC surge arrester and does not have an impact on the switching/temporary overvoltage/overcurrent values. Therefore, such parameter is not relevant for the scope of this study.

TABLE I
SETUP CONFIGURATION FOR PARAMETER SENSITIVITY STUDY

Parameters	Symbols	Parameter values
Active power transmission	P_{dir}	*+1000* and *-1000 MW*
Reactive power transmission	Q_{dir}	*+300* and *-300 MVar*
Outer control configuration	Outer-Ctrl	DC voltage control and P control
Blocking delay time of converter	Blk-Delay	*20* and *400 µs*
Arm reactor	L_{arm}	*0.11* and *0.19 pu*
Transformer reactor	L_{trf}	*0.14* and *0.22 pu*
SIPL of DC surge arrester for 1kA	ZnO-type	*Type 1 = 1.55 pu* *Type 2 = 1.85 pu*
Fault location	Flt-loc	At the terminal of the considered station and at the terminal of the other station
Fault instant	Flt-inst	Fault instant at zero crossing and maximum peak secondary voltage
Short circuit level	SCL	*50* and *3 GVA*
Cable length	Cable-Lgth	*50* and *200 km*

In order to analyze the transient behavior at the DC side terminals of the converter; the two output measurements shown in Fig. 2 are processed. These measurement data is only extracted from station MMC1, because the link is symmetrical. The measurement data is evaluated with respect to:

- Maximum switching overvoltage values:

$$V^{+}_{dc_{\max}} = \max\left(\left|V^{+}_{dc}(t)\right|\right) \qquad (1)$$

- Maximum temporary overvoltage values :

$$V^{+}_{dc_{RMS}\max} = \max\left(\sqrt{\frac{1}{period}\int_{t-period}^{t}\left(V^{+}_{dc}(t)\right)^{2}dt}\right) \qquad (2)$$

- Maximum switching overcurrent values:

$$I_{dc_{\max}} = \max\left(\left|I_{dc}(t)\right|\right) \qquad (3)$$

- Maximum temporary overcurrent values:

$$I_{dc_{RMS}\max} = \max\left(\sqrt{\frac{1}{period}\int_{t-period}^{t}\left(I_{dc}(t)\right)^{2}dt}\right) \qquad (4)$$

III. SENSITIVITY COMPUTATION METHOD

In this section, the sensitivity computation method is described.

A. *Main concept*

Sensitivity computation of the HVDC system is based on screening approach. The Elementary Effect (EE) method, as described in [7] and [8], is adapted for the considered system. This approach is adapted for non-linear system and is efficient to provide a general overview on parameter sensitivity. Furthermore, it helps identifying the uninfluential parameters and enables ranking the input parameters in order of importance.

To reduce the number of runs, several sampling approaches are suggested in [7] and [8]. In this study, since high nonlinearities are important, to enhance the precision of the results and avoid any misleading interpretation, the classical factorial sampling is used. Therefore, for each type of fault, all combination presented in Table 1 are simulated; i.e. the number of parameters investigated is eleven with two variations for each parameter, hence, the total number of runs is $2^{11} = 2048$.

1) Elementary effect computation

Assuming the EMT system represented by a mathematical model with the *k* input parameters. Let *y* be the output of interest (i.e. $V^{+}_{dc_{\max}}$, $V^{+}_{dc_{RMS}\max}$, $I_{dc_{\max}}$ or $I_{dc_{RMS}\max}$):

$$y(\mathbf{X}) = y\left(X_1, X_2, ..., X_k\right) \qquad (5)$$

where $X_i, i = 1,...,k$ are the input parameters (in the considered study, $k = 11$).

Each input parameter takes two values, from Table 1, let X_i be the first value and $X_i + \Delta_i$ be the second one. In classical EE approach, the choice of input values is sampled randomly [7]. However, for the considered input parameters of the HVDC system, some values as Outer-Ctrl and Flt-loc can neither be set randomly neither have a real value. For the remaining input parameters, the two extreme values have been considered (Table 1). Such approach allows us to cover the sensitivity boundary for each parameter. For instant, the input parameter P_{dir}, has the following set of values: $X_1 = +1000MW$ and $X_1 + \Delta_1 = -1000MW$. Note that Δ_i is considered fictive for parameters such as Outer-Ctrl, Flt-loc and Flt-inst (i.e. for Outer-Ctrl; $X_3 = \text{DC voltage control}$ and $X_3 + \Delta_3 = \text{P control}$).

From [7], the EE of the *i*th input parameter is defined as:

$$d_i(\mathbf{X}) = y(\mathbf{X} + \mathbf{e}_i\Delta_i) - y(\mathbf{X}) \qquad (6)$$

where $\mathbf{e}_i$ is a vector of zeros but with unit as its *i*th component.

For each input parameter, *r* elementary effects are estimated $d_i\left(\mathbf{X}^{(1)}\right), d_i\left(\mathbf{X}^{(2)}\right), ..., d_i\left(\mathbf{X}^{(r)}\right)$, where $\mathbf{X}^{(j)}, j = 1,...,r$. In the considered study, *r* is equal to 1024 and includes the combinations of the ten remaining parameter variation.

In order to normalize the results, the EE of *i*th input is divided by the mean average of the total runs:

$$d_i^{\%}\left(\mathbf{X}^{(j)}\right)=\frac{d_i\left(\mathbf{X}^{(j)}\right)}{\frac{1}{r}\sum_{j=1}^{r}\left(\frac{y\left(\mathbf{X}^{(j)}\right)+y_j\left(\mathbf{X}^{(j)}+\mathbf{e}_i\Delta_i\right)}{2}\right)}(\%) \tag{7}$$

To deduce the influence of each input, two sensitivity measures are computed: the mean of the absolute values [10]:

$$\mu_i^*=\frac{1}{r}\sum_{j=1}^{r}\left|d_i\left(\mathbf{X}^{(j)}\right)\right| \tag{8}$$

which assesses the overall influence of the input on the output and the standard deviation σ_i, which highlights the non-linear effects and correlation (or interactions) with other inputs:

$$\sigma_i=\sqrt{\frac{1}{r-1}\sum_{j=1}^{r}\left(d_i\left(\mathbf{X}^{(j)}\right)-\mu_i\right)^2} \tag{9}$$

These two sensitivity measures provide an insight to determine the effect of X_i on y [7]; (a) negligible when μ_i^* is close to zero, (b) linear and additive when μ_i^* is constant, or (c) non-linear or involved in interactions with other input when σ_i is high.

As highlighted in [8], the objective of the EE method is rather to identify which inputs are contributing significantly to the output results, rather than exactly quantifying sensitivity. Table 2 illustrates the different steps to compute the parameter sensitivities for each type of fault.

TABLE 2 SENSITIVITY COMPUTATION STEPS

1.	Run the 2048 EMT simulations
2.	Acquire all results : i.e. $y(\mathbf{X})$ and $y(\mathbf{X}+\mathbf{e}_i\Delta_i)$
3.	For each parameter, compute $d_i^{\%}\left(\mathbf{X}^{(j)}\right)$ from eq. (6) and (7)
4.	For each parameter, compute and plot μ_i^* and σ_i from eq. (8) and (9)

IV. SENSITIVITY RESULTS

The EE sensitivity results are presented in this section. The ratio σ_i/μ_i^* provides an additional indicator of linearity (or non-linearity) of the input [11]; for each input parameter, a true linear response correspond to $\sigma_i/\mu_i^*=0$. Hence, for a complex system, the ratio $\sigma_i/\mu_i^*<0.1$ can be considered linear. Moreover, when the ratio $\sigma_i/\mu_i^*<1$, the input factor can be considered almost monotonic. On the other hand, when $\sigma_i/\mu_i^*>1$, this means that the factor is non-monotonic and/or has interactions with other factors. In order to discriminate between almost monotonic and non-linear effect, a solid blue line with a slope $\sigma/\mu^*=1$ is plotted in each EE result figure.

A. DC overvoltage results

In this section, parameter sensitivity analysis on DC switching and temporary overvoltage is presented first for a DC pole-to-ground fault and then for a single-phase-to-ground fault.

1) EE sensitivity for DC pole-to-ground fault

The EE sensitivity results on $V_{dc\max}^{+}$ and $V_{dcRMS\max}^{+}$ for fault F8 is presented in Fig. 3 and Fig. 4, respectively. For the three main parameters that have an impact on overvoltages, exemplary DC voltage waveforms with related parameter variations are presented in Fig. 5 - Fig. 7.

For both EE sensitivity on $V_{dc\max}^{+}$ (Fig. 3) and $V_{dcRMS\max}^{+}$ (Fig. 4), we can notice that the predominant input parameter is the DC surge arrester's type (ZnO-type). The ratio σ/μ^* is close to 0.1, which implies that this parameter has almost a linear impact on the switching and temporary overvoltage results. As can be expected, overvoltages will increase linearly when the SIPL of DC surge arresters increases, as can be seen in Fig. 5.

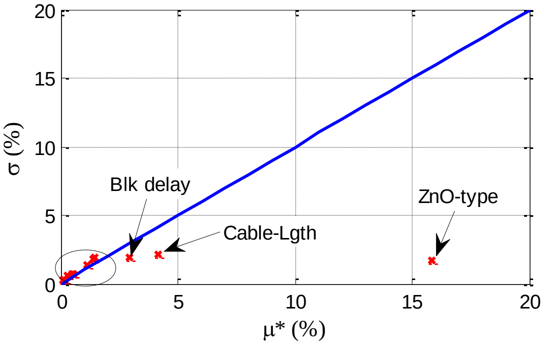

Fig. 3. EE sensitivity results on $V_{dc\max}^{+}$ for F8 fault

On the other hand, a comparison of EE sensitivity results for switching and for temporary overvoltages (Fig. 3 and Fig. 4) shows that cable length and converter blocking delay have an impact only during switching overvoltage. This can be seen from the typical waveforms Fig. 6 and Fig. 7, where the effect of such parameters are mainly during the first milliseconds after fault occurrences. The remaining parameters have negligible impact since the EE sensitivity results show that there μ_i^* is lower than 2.5%.

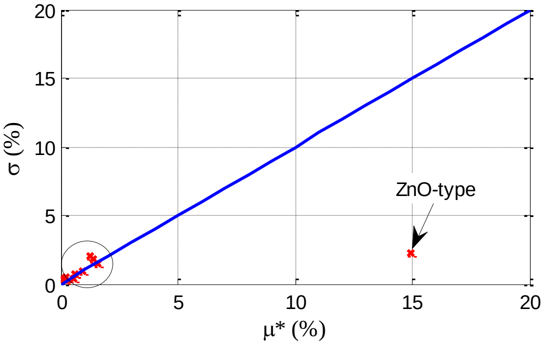

Fig. 4. EE sensitivity results on $V_{dcRMS\max}^{+}$ for F8 fault

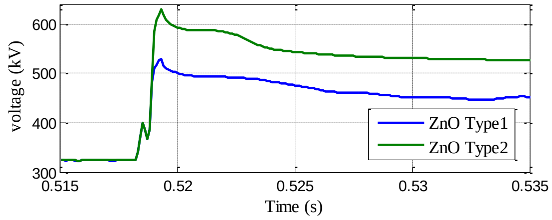

Fig. 5. Impact of ZnO-type on V_{dc}^{+} for F8 fault

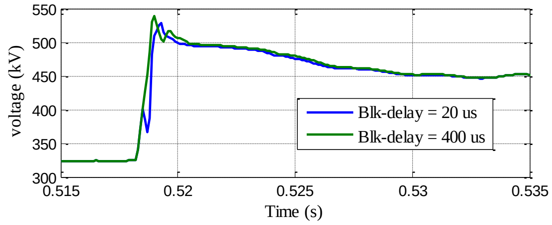

Fig. 6. Impact of blocking delay on V_{dc}^{+} for F8 fault

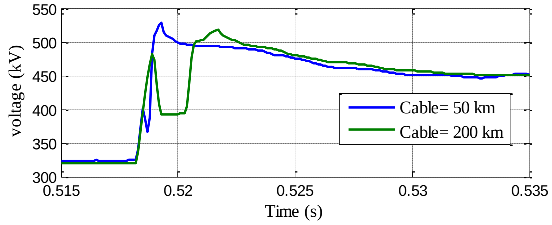

Fig. 7. Impact of cable length on V_{dc}^{+} for F8 fault

2) *EE sensitivity for secondary phase-to-ground fault*

The EE sensitivity results on $V_{dc\max}^{+}$ and $V_{dcRMS\max}^{+}$ for the F1 fault is presented in Fig. 8 and Fig. 9, respectively. For the three main parameters that have an impact on overvoltages, exemplary DC voltage waveforms with related parameters variations are presented in Fig. 10 - Fig. 12.

From EE sensitivity results obtained in Fig. 8 and Fig. 9, we can notice that several parameters have an impact on DC overvoltages. Regarding switching overvoltages (Fig. 8), the surge arrester type has the predominate influence with a nearly linear impact. However, the following parameters: cable length, AC short-circuit level, fault location, active and reactive power direction, have also an impact but with non-monotonic and/or interactions with each other. Therefore, we can state that all these parameters should be considered in a specific study. However, it is not possible to identify a linear impact of these parameter values on DC overvoltage. Such correlation between parameters SCL and Cable-Lgth is illustrated in Fig. 10.

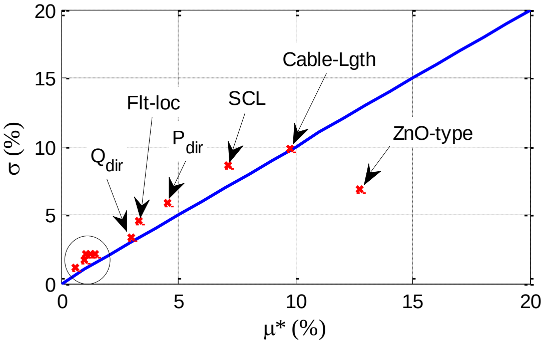

Fig. 8. EE sensitivity results on $V_{dc\max}^{+}$ for F1 fault

Comparison between EE sensitivity results for temporary overvoltages (Fig. 9), with the one for switching overvoltage (Fig. 8) shows that (essentially) two parameters have a considerable change of influence:

- Fault location (Flt-loc) effect becomes predominant with a monotonic behavior. When the fault is close to the converter station, the temporary overvoltage tends to be higher, as can be seen in Fig. 12.
- μ_i^* of the fault instant becomes higher than 2.5% (with σ=7.5%), which means that this parameter becomes non-negligible, but with highly non-linear effect on temporary overvoltages.

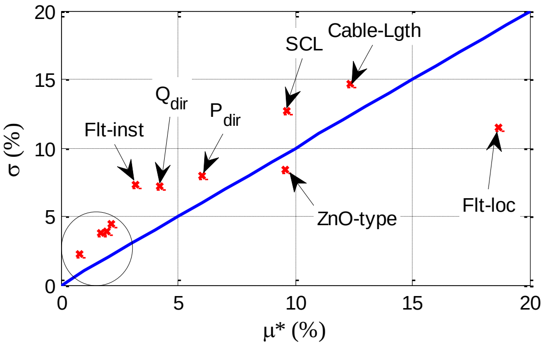

Fig. 9. EE sensitivity results on $V_{dc\max}^{+}$ for F1 fault

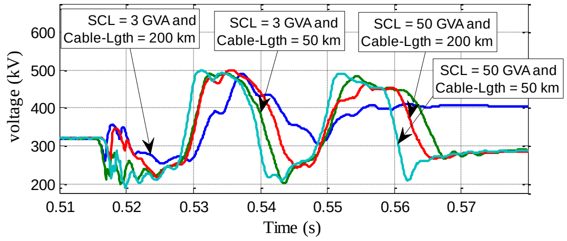

Fig. 10. Impact of Cable Lentgh and SCL on V_{dc}^{+} for F1 fault

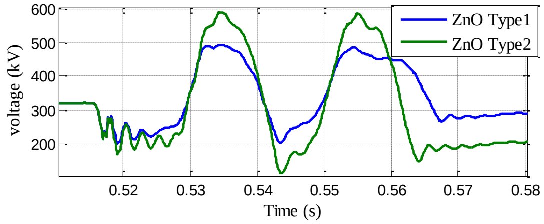

Fig. 11. Impact of surge arresters on V_{dc}^{+} for F1 fault

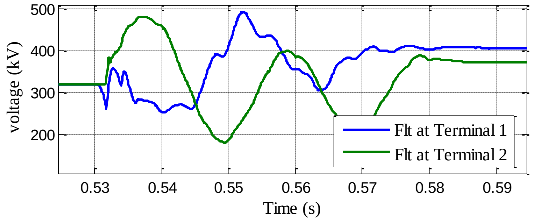

Fig. 12. Impact of fault location on V_{dc}^{+} for F1 fault

B. *DC overcurrent results*

1) *EE sensitivity for DC pole-to-ground fault*

EE sensitivity results on $I_{dc_{\max}}$ and $I_{dc_{RMS}\max}$ for F8 faults are presented in Fig. 13 and Fig. 14, respectively. For the three main parameters that have an impact on overcurrents, exemplary DC current waveforms with related parameters variations are presented in Fig. 15 - Fig. 17.

For pole-to-ground faults (Fig. 13) sensitivity results reveal that blocking delay (Blk delay) and active power direction (P_{dir}) have the highest influence on the DC switching overcurrent ($\mu^* = 31\%$) with monotonic behavior. The illustrative waveform comparison (Fig. 15 and Fig. 17) shows that when blocking delay increases and/or active power direction becomes positive (i.e. inverter mode), overcurrent increases. Arm inductance value has also an influence on the overcurrent value with linear effect ($\mu^* = 16\%$ and $\sigma = 11\%$). From Fig. 16, one can notice that when arm inductance increases, the d*i*/d*t* decreases and the blocking instant will occur earlier, which reduces the overcurrent. The three other parameters: cable length, fault location and surge arrester's type, also play a role on the switching overcurrent; however, their impact seems slightly less important and is nonlinear and/or non-monotonic. The remaining parameters do not have an impact on the results.

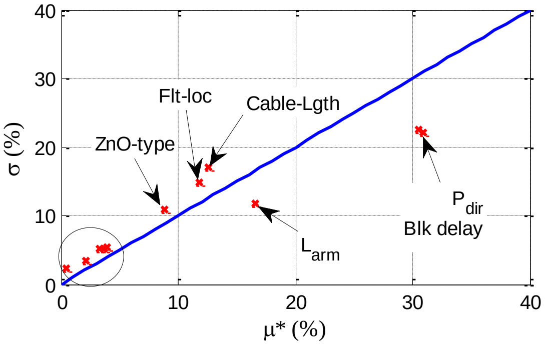

Fig. 13. EE sensitivity results on $I_{dc_{\max}}$ for F8 fault

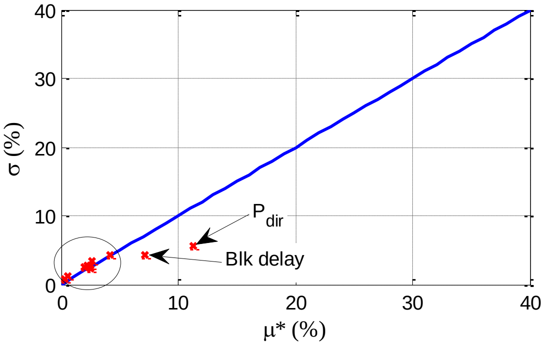

Fig. 14. EE sensitivity results on $I_{dc_{RMS}}$ for F8 fault

From EE sensitivity results of the temporary overcurrent in Figure 14, it is interesting to note that the impact of all parameters is drastically reduced. Only two remaining parameters, (blocking delay and active power direction) can be identified showing an influential behavior on the temporary overcurrent.

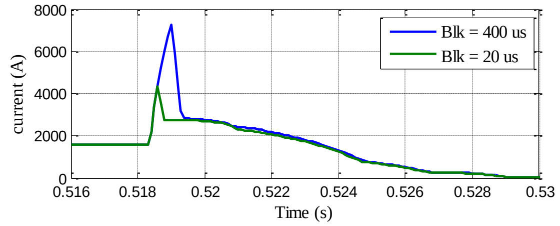

Fig. 15. Impact of blocking delay on I_{dc} for F8 fault

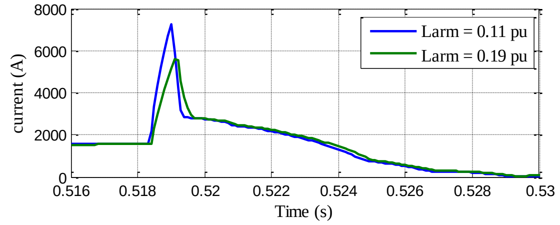

Fig. 16. Impact of Larm on I_{dc} for F8 fault

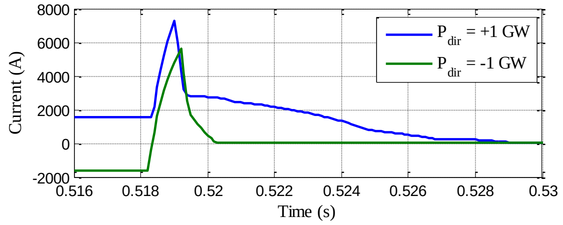

Fig. 17. Impact of active power direction on I_{dc} for F8 fault

2) *EE sensitivity for DC pole-to-pole fault*

The EE sensitivity results on $I_{dc_{\max}}$ and $I_{dc_{RMS}\max}$ for the F9 faults are presented in Fig. 18 and Fig. 19, respectively. For the three main parameters that have an impact on overcurrents, exemplary DC current waveforms with related parameters variations can be found in Fig. 20 - Fig. 22.

Results in Fig. 18 show that fault location and AC SCL value has a major impact on the overcurrent during pole-to-pole fault. The impact tends to be linear; i.e. when the SCL is high the overcurrent peak is high and, the closer is the fault located towards converter side, the higher is the overcurrent value. The following four parameters also play a role on such overcurrent: arm inductance, transformer inductance, blocking delay and cable length. It is assumed that when arm inductance/transformer increase the overcurrent will decrease and when the blocking delay and cable length increase the overcurrent will increase. Nevertheless, there ratio σ_i / μ_i^*, for both switching and temporary overcurrent, are close to one, which means that the impact of such inputs are non-linear or have interdependencies with other inputs.

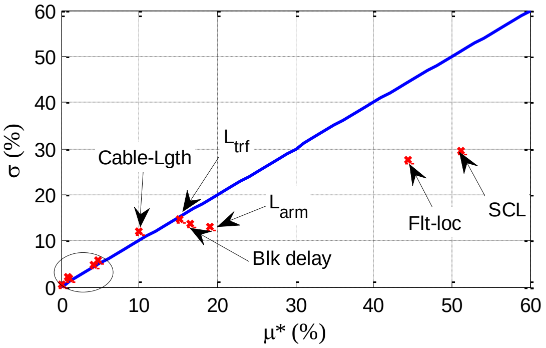

Fig. 18. EE sensitivity results on $I_{dc_{\max}}$ for F9 fault

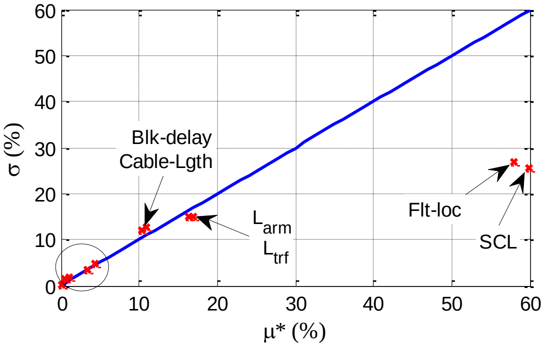

Fig. 19. EE sensitivity results on $I_{dc_{RMS}}$ for F9 fault

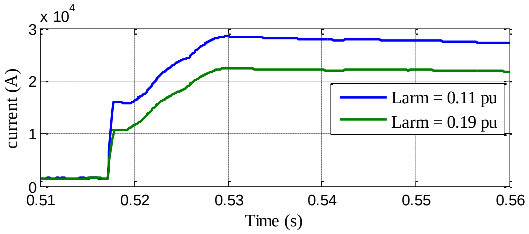

Fig. 20. Impact of arm reactor value on I_{dc} for F9 fault

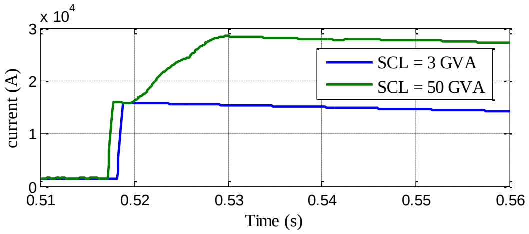

Fig. 21. Impact of SCL value on I_{dc} for F9 fault

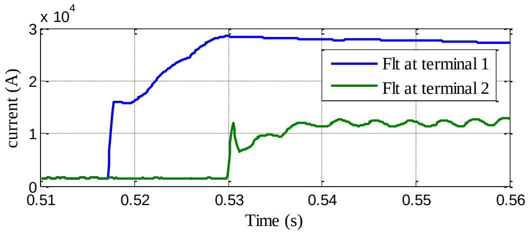

Fig. 22. Impact of fault location on I_{dc} for F9 fault

V. CONCLUSION

This paper provides an efficient approach to evaluate the impact of the main HVDC system parameters on DC transient behavior. Such approach helps identifying the uninfluential parameters and ranking the input parameters in order of importance. Because the system is highly non-linear, the elementary effect approach has been adapted and a factorial sampling is used (instead of random sampling) to cover the extreme boundaries of HVDC system. The EE sensitivity results have shown that:

- For DC pole-to-ground faults, DC overvoltages are mainly influenced by the DC surge arresters. However, blocking delay and cable length has also an impact during switching transients.
- For a single-phase-to-ground fault, there are several parameters that play a role in terms of overvoltage: the main one for switching overvoltage is the DC surge arrester type, and fault location parameter for the temporary overvoltage. However, four other parameters play a role, but with non-monotonic behavior. Therefore, it is difficult to identify a simple correlation on how those impact the overvoltage. During the design stage of a HVDC project, variation of these parameters should be considered in order to tackle the worst DC transient.
- For DC pole-to-ground faults, DC overcurrents are mainly important during switching transient. Two main groups exists: the predominant group, which shows monotonic behavior, is the active power, blocking delay and arm inductance values. The second group of influence, with non-monotonic behavior, are cable length, fault location and DC surge arrester type.
- For the DC pole-to-pole faults, switching and temporary overcurrents are mainly affected by the fault location and short-circuit level of the AC grid. The second group of influence comprises arm inductance, transformer inductance, blocking delay and cable length.

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