A Unified Analytical Model for Characterization of Cable Faults in VSC DC Systems

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1. Introduction – DC systems are being investigated as an emerging technology for efficient and smart power transmission and distribution. However, the proper development of DC systems requires solving challenges such as fault protection study and power quality issues [1].

The lack of mature DC circuit breakers makes cable faults (i.e., pole-to-pole and pole-to-ground short circuits) one of the main concerns of DC systems since VSCs are not capable of withstanding fault overcurrent and, in addition, converter loss can lead to dangerous high DC voltages. The main challenge regarding protections is that transient overcurrent can reach very high values (above 15 pu, approximately) in a few milliseconds (4 – 6 ms). For this reason, DC system behaviour under fault conditions must be studied in order to design protections for prompt interruption and isolation of faults [2 – 5]. Most works present methods and algorithms for locating and isolating faults based on simulations only [2 – 4]. Unlike them, [5] proposes a theoretical analysis of DC cable faults which provides fault overcurrent and voltage expressions and a location method validated by simulations. The main drawback of this work is that pole-to-pole and pole-to-ground short circuits are studied separately and fault resistance is considered for the latter only. Moreover, the fault overcurrent and voltage expressions obtained in [5] which can be used for characterizing pole-to-pole short circuits are only applicable in scenarios of under-damped (i.e., oscillating) circuit natural response. By contrast, those also obtained in [5] which can be used for characterizing pole-to-ground short circuits are only applicable in scenarios of over-damped (i.e., aperiodic) circuit natural response.

This paper presents a theoretical study of two-level VSC DC system response to DC cable faults using circuit analysis and contributes a unified analytical model which can be used for characterizing pole-to-pole and pole-to-ground short circuits for any value of fault resistance. Furthermore, this model is applicable in any of the two most likely scenarios, namely under-damped (i.e., oscillating) or over-damped (i.e., aperiodic) circuit natural response. A characterization procedure for cable faults in VSC DC systems based on the unified analytical model is also described to show its applicability.

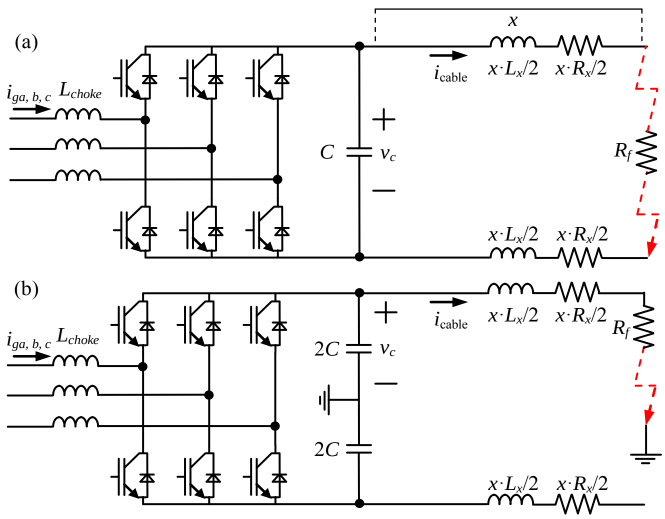

Figure 1. Cable faults in VSC DC systems: (a) Pole-to-pole short circuits. (b) Pole-to-ground short circuits.

2. Cable Faults in VSC DC Systems - Pole-to-pole and pole-to-ground short circuits are the typical DC system cable faults (see Figure 1(a) and (b)). They generally result in fast discharge of the DC-link capacitor through the DC circuit, leading to transient overcurrent, which can damage system components. Besides fault type and DC system parameters (namely, DC-link capacitor C and cable distributed parameters R_x, L_x), transient response also depends on fault distance x and fault resistance R_f. VSC DC systems are helpless against these DC faults because IGBTs are blocked for self-protection during the fault, leaving freewheel diodes subject to overcurrent. Thus, VSC DC system behaviour during faults must be examined and simulated for an effective system protection design. Additionally to simulations, analytical models for the characterization of cable faults in VSC DC systems are needed [5]. As an example, Figure 2(a) and (b) plot the MATLAB/Simulink waveforms of the DC-link capacitor voltage v_c and the cable current i_{cable} of pole-to-pole and pole-to-ground short circuits considering zero and nonzero fault resistance, respectively. As observed, the evolution of fault waveforms can be divided into several stages, the first of which corresponds to the discharge of the DC-link capacitor C on the DC cable and fault impedance ($R = R_x \cdot x$, $L = L_x \cdot x$ and R_f) [5]. This stage defines the response of the circuit and its study allows identifying the main DC fault characteristics. The natural response of the first stage voltage and current waveforms is obtained for the two types of faults by solving the two first order differential equation system of the first stage circuit by the Laplace transform.

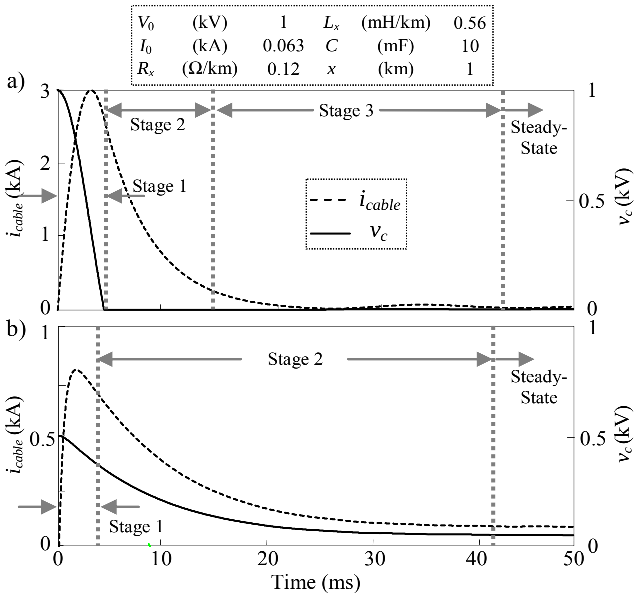

Figure 2. Simulations of DC cable faults in VSC DC systems: a) Pole-to-pole short circuit (R_f = 0 Ω). b) Pole-to-ground short circuit (R_f = 0.5 Ω).

3. A Unified Analytical Model for Characterization of DC Cable Faults in VSC DC Systems – In this section, the modelling of DC cable faults in VSC DC systems is studied and a unified analytical model of stage 1 (capacitor discharge stage) in pole-to-pole and pole-to-ground short circuits is provided.

The analysis of Figure 1(a) reveals that the equations characterizing the current i_{cable} and the voltage v_c of stage 1 in pole-to-pole short circuits are

$$\begin{cases} i_{cable}(t) = -C\dfrac{dv_c}{dt} \\ v_c(t) = \left(R_f + x\cdot R_x\right) i_{cable}(t) + x\cdot L_x \dfrac{di_{cable}}{dt} \end{cases} \Rightarrow \begin{cases} \dfrac{dv_c}{dt} = -\dfrac{1}{C} i_{cable}(t) \\ \dfrac{di_{cable}}{dt} = \dfrac{1}{x\cdot L_x} v_c(t) - \dfrac{R_f + x\cdot R_x}{x\cdot L_x} i_{cable}(t) \end{cases}, \quad (1)$$

Likewise, the analysis of Figure 1(b) shows that the equations characterizing the current i_{cable} and the voltage v_c of stage 1 in pole-to-ground short circuits are

$$\begin{cases} i_{cable}(t) = -2\cdot C\dfrac{dv_c}{dt} \\ v_c(t) = \left(R_f + x\cdot \dfrac{R_x}{2}\right) i_{cable}(t) + x\cdot \dfrac{L_x}{2} \dfrac{di_{cable}}{dt} \end{cases} \Rightarrow \begin{cases} \dfrac{dv_c}{dt} = -\dfrac{1}{2\cdot C} i_{cable}(t) \\ \dfrac{di_{cable}}{dt} = \dfrac{2}{x\cdot L_x} v_c(t) - \dfrac{2\cdot (R_f + x\cdot R_x/2)}{x\cdot L_x} i_{cable}(t) \end{cases}, \quad (2)$$

After comparing (1) and (2), the equations characterizing the current i_{cable} and the voltage v_c of stage 1 in both pole-to-pole and pole-to-ground short circuits can be unified as

$$\begin{cases} \dfrac{dv_c}{dt} = -\alpha_1 \cdot i_{cable}(t) \\ \dfrac{di_{cable}}{dt} = \alpha_2 \cdot v_c(t) - \alpha_3 \cdot i_{cable}(t) \end{cases}, \quad (3)$$

where

$$\alpha_1 = \frac{1}{C}, \qquad \alpha_2 = \frac{1}{x \cdot L_x}, \qquad \alpha_3 = \frac{R_f + x \cdot R_x}{x \cdot L_x}, \quad (4)$$

are the pole-to-pole short circuit parameters, and

$$\alpha_1 = \frac{1}{2 \cdot C}, \qquad \alpha_2 = \frac{2}{x \cdot L_x}, \qquad \alpha_3 = \frac{2 \cdot (R_f + x \cdot R_x/2)}{x \cdot L_x}, \quad (5)$$

are the pole-to-ground short circuit parameters.

The unified expressions of the current and voltage waveforms, $i_{cable}(t)$ and $v_c(t)$, are obtained after solving the two first order differential equation system in (3) under the initial conditions at the fault starting time t_0 ($i_{cable}(t_0) = I_0$ and $v_c(t_0) = V_0$) by using the Laplace transform. The obtained expressions can be written as follows:

$$\begin{gathered} i_{cable}(t) = A(s_2) \cdot e^{s_2 \cdot (t - t_0)} - A(s_1) \cdot e^{s_1 \cdot (t - t_0)} \\ v_c(t) = B(s_2) \cdot e^{s_2 \cdot (t - t_0)} - B(s_1) \cdot e^{s_1 \cdot (t - t_0)} \\ A(s) = \frac{\alpha_2 \cdot V_0 + s \cdot I_0}{s_2 - s_1} \qquad B(s) = \frac{(s + \alpha_3) \cdot V_0 - \alpha_1 \cdot I_0}{s_2 - s_1} \\ s_{1,2} = -\frac{\alpha_3}{2} \pm \sqrt{\left(\frac{\alpha_3}{2}\right)^2 - \alpha_1 \cdot \alpha_2}, \end{gathered} \quad (6)$$

The main contributions of the expressions $i_{cable}(t)$ and $v_c(t)$ in (6) over the corresponding expressions in [5] are

- Consideration of fault resistance not only for pole-to-ground short circuits, but also for pole-to-pole short circuits.

- Ability to characterize both types of short circuits in a unified way and in any of the two most likely scenarios, namely under-damped (i.e., oscillating) or over-damped (i.e., aperiodic) circuit natural response.

4. Characterization of Cable Faults in VSC DC Systems - In order to design protections for prompt interruption and isolation of DC system cable faults, it is important to determine fault characteristics (i.e., fault type, distance and resistance) from voltage and overcurrent measurements. This can be done by following a four-step protocol:

- Step 1. The analytical expressions of the fault overcurrent peak value (or of any other current value in stage 1), occurrence time and voltage at this time must be obtained from (6).

– Step 2. The measured values of the above three variables must be obtained from voltage and overcurrent measurements.

– Step 3. The parameters α_1, α_2 and α_3 must be determined from the analytical expressions obtained in Step 1 when equated to the corresponding measured values obtained in Step 2. The resulting non-linear equation system must then be solved.

– Step 4. DC cable fault characteristics must be determined from (4) and (5).

This protocol is currently under investigation by the authors and will be addressed and improved in future work.

5. Conclusions - This paper theoretically studies two-level VSC DC system behaviour during pole-to-pole and pole-to-ground short circuits by circuit analysis. The main findings are as follows:

– It is possible to obtain a unified analytical model to characterize voltage at DC-link capacitor terminals and overcurrent through the DC cable. This unified model considers fault resistance for both pole-to-pole and pole-to-ground short circuits, but it is also useful for characterizing both types of short circuits in any of the two most likely scenarios, namely under-damped (i.e., oscillating) or over-damped (i.e., aperiodic) circuit natural response.

– This model can also be used to characterize fault type, distance and resistance for further DC system protection design.

6. References

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