Analyzing Sensitivities in HVDC Cable Joint Materials

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ABSTRACT

Sensitivity analysis allows engineers to identify the most important design parameters affecting the performance of cable joints and to improve their design accordingly. This paper presents the adjoint variable method for coupled nonlinear electrothermal problems as an efficient approach to calculate sensitivities of high voltage direct current cable joints with respect to a large number of design parameters. This method has, in contrast to the commonly used direct sensitivity method or finite differences, computational costs that are nearly independent of the number of considered design parameters.

KEYWORDS

Adjoint variable method, HVDC, Cable joint, Sensitivity analysis, EQS, EQST

INTRODUCTION

Cable joints are the most vulnerable part of high voltage direct current (HVDC) systems [1-4]. The insulation system of cable joints must be able to safely handle field stresses in the range of several kV/mm both in direct current (DC) operation as well as during transient overvoltages. Cable joints hence rely heavily on the principle of field grading. One field grading approach is the insertion of a nonlinear resistive field grading material (FGM) layer between the cable insulation and the joint's main insulation [2, 5-7]. The strongly nonlinear conductivity of an FGM balances the electric field stress, similar to the overvoltage clipping of high voltage (HV) surge arresters [8].

Thanks to advances in material science, it is now possible to customize the nonlinear conductivity characteristic of an FGM to fit the respective application [9,10]. An essential tool in the design process are finite element (FE) simulations that provide detailed insight into the internal field- and temperature-distribution. However, so far, only few systematic investigations, e.g. [5, 10-12], studied the different design parameters of the FGMs.

The key to making the influence of individual design parameters more tangible without extensive parameter sweeps are sensitivities. Sensitivities describe how and how strong a quantity of interest (QoI) is influenced by a design parameter. Their information can be used to identify the most influential parameters and thereby reduce the number of further considered design parameters. Furthermore, applying sensitivities in gradient-based optimization tools can reduce the number of time-consuming simulation runs during optimization [13].

The most common methods for sensitivity computation, such as finite differences or the direct sensitivity method (DSM), have the disadvantage that their computational costs scale with the number of parameters [14, 15]. The adjoint variable method (AVM) on the other hand has computational costs that are nearly independent of the number of parameters [14-16]. In the field of HV engineering, tha AVM has recently been presented for linear electroquasistatic (EQS) problems in frequency domain [17], nonlinear EQS problems in time domain [18] as well as stationary nonlinear coupled electrothermal problems [19]. However, to achieve a full characterization of the capacitive-resistive-thermal behavior of a cable joint during transient overvoltages, a coupled electroquasistatic-thermal (EQST) analysis is necessary. Thus, in this work, the AVM is formulated and solved numerically for coupled transient EQST problems with nonlinear media. The method is implemented in the Python-based FE framework *Pyrit* [20] and validated using results obtained via the DSM as a reference.

ELECTROTHERMAL MODELING

The capacitive-resistive-thermal behavior of cable joints can be described by the combination of the transient EQS equation and the transient heat conduction equation [21]. The transient EQS problem reads

$$\operatorname{div}(\boldsymbol{J}) + \operatorname{div}(\partial_t \boldsymbol{D}) = 0 \qquad t \in [0, t_f], \boldsymbol{r} \in \Omega; \qquad [1a]$$

$$J = \sigma E \qquad t \in [0, t_f], \boldsymbol{r} \in \Omega; \qquad [1b]$$

$$D = \varepsilon E \qquad t \in [0, t_f], \boldsymbol{r} \in \Omega; \qquad [1c]$$

$$\boldsymbol{E} = -\operatorname{grad}(\phi) \qquad t \in [0, t_f], \boldsymbol{r} \in \Omega; \qquad [1d]$$

$$\phi = \phi_{\text{fixed}} \qquad t \in [0, t_f], \boldsymbol{r} \in \Gamma_{\text{D,el}}; \qquad [1e]$$

$$(J + \partial_t D) \cdot n_{\text{el}} = 0 \qquad t \in [0, t_f], \boldsymbol{r} \in \Gamma_{\text{N,el}}; \qquad [1f]$$

$$\phi = \phi_0 \qquad t = 0, \quad \boldsymbol{r} \in \Omega. \qquad [1g]$$

where $\boldsymbol{D}$ is the electric displacement field, $\boldsymbol{J}$ is the electric current density, $\boldsymbol{E}$ is the electric field and ϕ is the electric scalar potential. σ and ε represent the electric conductivity and permittivity, respectively. The position vector is denoted as $\boldsymbol{r}$, the time as t. The computational domain in space and time are denoted as Ω and $[0, t_f]$, respectively. ϕ_{fixed} is the fixed voltage at the Dirichlet boundaries,

$\Gamma_{\text{D,el}} \neq \emptyset$. $\boldsymbol{n}_{\text{el}}$ is the unit vector at the magnetic boundaries, $\Gamma_{\text{N,el}} = \partial\Omega \setminus \Gamma_{\text{D,el}}$. ϕ_0 denotes the initial condition of the electric potential, i.e. the steady state before the transient event. The transient heat conduction equation reads

$$c_{\text{V}}\, \partial_t T - \operatorname{div}(\lambda \operatorname{grad}(T)) = \dot{q} \qquad t \in [0, t_f], \boldsymbol{r} \in \Omega; \qquad [2a]$$

$$T = T_{\text{fixed}} \qquad t \in [0, t_f], \boldsymbol{r} \in \Gamma_{\text{D,th}}; \qquad [2b]$$