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Winding capacitance dividing scheme for a high-voltage cable-wound generator

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ABSTRACT

This paper presents a method which can equivalently arrange the capacitance distribution along with the winding of the generator on the terminal and neutral respectively in a reasonable partition, particularly for a type of high-voltage graded insulated cable-wound generator, powerformer. This method can be used to compensate the capacitive current wholly to improve the reliability of the differential protection. It is proved that the capacitive current in the case of normal operation, external fault and internal fault can be calculated using the same dividing method. The formula of the partition coefficient is provided and the characteristic of the coefficient is explored by MATLAB software.

1. Introduction

In the protection zone of the differential protection, the currents of some branches possibly cannot be measured, like the capacitive current of direct earth capacitances of the long transmission lines, which will lower the reliability of the protection. The differential relay can compensate this charging current to improve the stability of the protection, which has been implemented in the protection of the long transmission line for many years. Actually, large conventional generators are confronted with the problem of the increasing capacitive charging current as well [1].

At the end of the 21th century, a new type of high-voltage generator, powerformer, was invented by Dr. Mats Leijon et al. at ABB power company for eight years research and development. The stator windings of the high-voltage generator make use of cable. This novel generator is called powerformer and it offers a direct connection of the power network without the need for a step-up transformer. Some experts in this field praise this technique as the power generation technique of the 21th century [2–4].

As far as protection of power systems is concerned, some theories and criteria should be optimized so that they can adapt to the change of the ideal of generator winding design. The method using to compensator capacitive current for long transmission line has been implemented for many years. And hence for protection of generators, this problem was not very important in the past. However, with the development of generator capacity and the application of new technique, generator differential protections are confronted whit the problem of the increasing capacitive charging current as well [1]. The windings of the powerformer make use of cross-linked polyethylene cable that formerly used in the transmission lines. The cable of powerformer can be considered as a capacitor with charges on the electrodes which are, in this case, the inner and the outer semiconducting layers [5]. On the other hand, the electrical charge on a phase winding of the powerformer at voltage maximum is 30 times larger than the charge on a phase winding of a conventional generator with the same rated apparent power [6]. Therefore, the impacts on the reliability of differential protection should no longer be negligible.

There are some literatures available in the field of compensated differential protection [7,8], but most of them focus on the charging current compensation for long transmission line, instead of for generator. The winding capacitive current contributes to the differential current during normal operation. The differential protection for generator rarely considers the influence of capacitance in the protection zone because the current differential protection itself has already met the requirement of conventional AC electrical machines, where the value of the direct earth capacitance is quite low. Similar to the analysis of the capacitance of the transmission line, the equivalence of winding capacitance of the generator can refer to [9], in which the capacitance distribution along with the winding is represented by lump capacitance with 50% at the phase terminal and 50% at the neutral point. This assumption is suitable for the cases of capacitance evenly distributing, like the transmission line and the winding of conventional generator. However, it will lead to errors for analyzing the stator winding of the powerformer in that the winding capacitance does not actually distribute evenly along with the stator winding. As known, the winding of the powerformer adopts graded insulation, which leads to the various cable thicknesses in different portion of the winding, and thus, the uneven capacitance distribution [10]. A scheme is proposed in [6]

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to cope with this problem. In this scheme, the winding capacitance is divided into two portions in lump parameter. One portion ρC_ω of the total phase-to-earth capacitance of the winding C_ω can be associated with the voltage at the neutral end of the phase winding while the rest $(1-\rho)$ C_ω can be associated with the voltage at the line terminal of the winding. This makes it possible to represent a winding with graded insulation. With this arrangement, the capacitive current can be calculated with the above lump equivalent capacitance and the voltages of the terminal and neutral, as the compensated differential protection of the transmission line does.

Therefore, some fundamental work must be done before this scheme is implemented. Firstly, the above equivalent partition of the winding capacitance must be proved. Secondly, the coefficient ρ must be calculated or measured in advance before the protection is put into service.

This paper proves that the capacitive current in the case of normal operation, external fault and internal fault can be calculated using the same dividing method. The formula of the partition coefficient is provided and the characteristic of the coefficient is explored by MATLAB software [11,12].

2. Capacitance equivalence of the powerformer cable

As for the powerformer, the outer semiconductor of the cable used in the winding is grounded at regular intervals [10]. Hence, it is normally a good approximation to assume that the voltage on the outer semiconductor is almost at ground potential. This means that the electric field driven by the voltage differences in the winding is concentrated between the inner and outer semiconducting layers of the cable. The electric field is very low outside the cable so that there is almost no electricity coupling between the turns in cable-wound generator, which is different from the conventional generator. In this case, turn-to-turn and coil-to-coil or phase-to-phase coupling capacitances, which are important in capacitive current of long transmission line, can be ignored when analyzing the powerformer [5]. According to the above assumption, the electric field in the winding is concentrated between the inner and outer semiconducting layers of the cable. Hence, in the coaxial insulation system, normally only the capacitance between the inner and outer semiconductor ought to be considered. The capacitance per unit length C_0 between the inner and outer semiconductor can be calculated from the formula for two cylindrical coaxial tubes, which is given by

$$C_0 = 2\pi\varepsilon_0\varepsilon_r/\ln(r_2/r_1) \tag{1}$$

where ε_0 = 8.854e-12; relative permittivity $\varepsilon_r = 2 \sim 3$ [13]; r_1 is the outer radius of the inner semiconducting layer and r_2 is the inner radius of the outer semiconducting layer, as shown in Fig. 1.

A discrete lumped circuit, representing the displacement current in the cable, can be replaced by a more compact one by a Taylor expansion [14]. The capacitance between the conductor and ground for a piece of cable between two grounded points of the outer semiconductor can be represented by just a capacitor. However, C_0 should be different at different position of the winding when the insulation thickness of cable of the powerformer increases stepwise from the neutral to the terminal, as described by (1).

Assume that each segment of the cable with the same insulation thickness can be modeled as a π network, as shown in Fig. 2, which illustrates the equivalent circuit of capacitance of the powerformer cable with N segments.

Note that the voltage distribution within the stator winding is still linear along with the winding and is proportional to the turn number of the winding, we can assume that the voltage at any point inside the winding can be equivalent as the linear combination of the voltages of two terminals, the $\dot{U}_0$ and $\dot{U}_N$. It is no harm to let

$$\dot{U}_i = k_{2i+1}\dot{U}_0 + k_{2i+2}\dot{U}_N \tag{2}$$

where k_{2i+1}, k_{2i+2} are both real numbers.

From Fig. 2 and Eq. (2) the capacitive current of phase a, $\dot{I}_{ca}$, can be related to the cable capacitance C_i and the voltages of both terminals, as follows:

$$\begin{aligned}\dot{I}_{ca} &= j\omega\sum_{i=0}^{N} C_i\dot{U}_i = j\omega\sum_{i=0}^{N} C_i\left(k_{2i+1}\dot{U}_0 + k_{2i+2}\dot{U}_N\right) \\ &= j\omega\left(\dot{U}_0\sum_{i=0}^{N} k_{2i+1}C_i + \dot{U}_N\sum_{i=0}^{N} k_{2i+2}C_i\right)\end{aligned} \tag{3}$$

Where C_i is the real distributed capacitance at point i, which can be regarded as a portion of the total winding capacitance. Let C_ω be the total distributed capacitance of a stator winding, we will prove the following assumption:

The capacitance combination $\sum_{i=0}^{N} k_{2i+2}C_i$, is a portion of the C_ω, namely ρC_ω and the $\sum_{i=0}^{N} k_{2i+1}C_i$, is the residual portion of C_ω, namely $(1-\rho)C_\omega$ as described in Eq. (3), where ρ is a partition coefficient. In this case, Eq. (3) can be rewritten as below:

$$\dot{I}_{ca} = j\omega[(1-\rho)C_\omega\dot{U}_0 + \rho C_\omega\dot{U}_N] \tag{4}$$

Three typical scenarios of the generator operation states, namely the normal operation, the external fault and the internal fault, were analyzed to prove the above assumption. During the analysis, a N-segment cable is taken to set up the cable model of powerformer winding as the example. A schematic representation of N-segment cable during normal operation is shown in Fig. 3. Among which, neutral voltage and terminal voltage are referred as $\dot{U}_n$ and $\dot{U}_t$. C_{01}, $C_{02...}C_{0N}$ is the capacitance per unit length of first segment, second segment...N segment, respectively. The total length of winding is referred as l. It is easy to know:

$$\begin{aligned} &0 \leqslant \alpha_1 \leqslant \alpha_2 \leqslant \cdots \leqslant \alpha_{N-1} \leqslant 1 \\ &\alpha_N = 1 \end{aligned} \tag{5}$$

The winding voltage of per unit length of phase a, $\dot{E}_{0a}$, is related to the neutral and terminal voltages as follows:

$$E_{0a}l = U_t - U_n \tag{6}$$

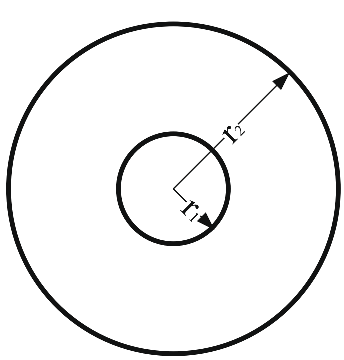

Fig. 1. Cross-section of the cable used in the powerformer.

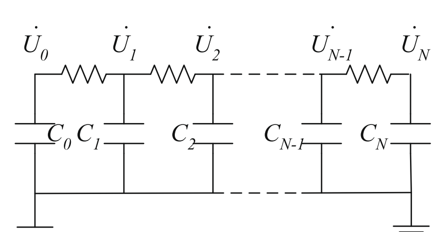

Fig. 2. Equivalent circuit of capacitance of the powerformer cable.