Electric Power Systems Research 144 (2017) 107–114

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Application of resistive superconducting fault current limiters in offshore oil production platforms

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ARTICLE INFO

Article history:
Received 27 May 2016
Received in revised form 11 October 2016
Accepted 6 November 2016

Keywords:
Superconducting fault current limiters
Power system dynamics
Industrial power systems
Offshore installations

ABSTRACT

This manuscript presents an analysis of the integration of superconducting fault current limiters (SFCL) in floating, production, storage, and offloading (FPSO) platforms. Short-circuit studies based on dynamic simulations of an FPSO power system with an integrated SFCL were carried out. The simulation model used to reproduce the transient behavior of the SFCL device is based on the so-called thermal-electrical analogy. The results show that SFCLs are reliable devices for maintaining fault current levels within typical equipment ratings of the FPSO power system.

1. Introduction

Modern offshore oil and gas production platforms are typically being delivered as FPSOs because of their suitability for deepwater (300–1500 m) and ultra-deepwater wells (beyond 1500 m) [1,2].

A typical FPSO power system presents voltage ratings of up to 13.8 kV [3], with many high-power motor loads installed in the production facility. Due to its high power density, fault currents in the FPSO electric system tend to present severe levels, which may exceed the typical fault current ratings of switchgears of 50 kA_{rms} and 130 kA_{peak}. To overcome this problem, the division of the main medium-voltage switchgear busbar in interconnected sections by fault current limiters is usually proposed [1,4,5].

Pyrotechnic fault current limiters (P-FCL) are widely used in offshore oil and gas production facilities in order to maintain fault current levels within the typical ratings of medium-voltage switchgears [6,7]. However, if triggered, the P-FCL may lead to plant downtime due to the replacement of the blown part [8].

SFCLs recently became commercially available, and many device concepts are under development [9–16]. Some of these devices have already been installed in real grids with voltage and current ratings up to 12 kV and 800 A [17]. The use of resistive SFCLs (R-SFCLs) in FPSO systems is preferable, since they present the simplest design.

This work presents a study using a detailed dynamic simulation model of the power system [5]. To simulate the R-SFCL device, a model based on an analogy between thermal and electrical circuit differential equations has been used. Such a model is called thermal-electrical analogy, and it will be introduced in the next section.

The main contribution of this paper is to prove the technical feasibility of an SFCL device in terms of the fault current limitation applied to FPSO electric power systems.

2. The resistive SFCL

2.1. Design

Among all concepts of SFCL devices, the R-SFCL is the simplest one [18]. The R-SFCL is connected in series with the electrical circuit to be protected, as shown in Fig. 1a. Under normal conditions, the superconducting material presents negligible impedance, and there are no significant losses. In the case of a fault, the SFCL is subjected to currents higher than the critical current (I_c) of the superconducting material. Thus, a phase transition to the normal state takes place, and the R-SFCL starts to present a significant resistance. This characteristic provides an interesting effect on fault current asymmetry mitigation, which is a function of the X/R ratio at the fault point.

Another interesting characteristic of the R-SFCL is that it does not present fault current distortion when compared to some other devices' fault current waveform [9,19,20]. The fault current

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http://dx.doi.org/10.1016/j.epsr.2016.11.006
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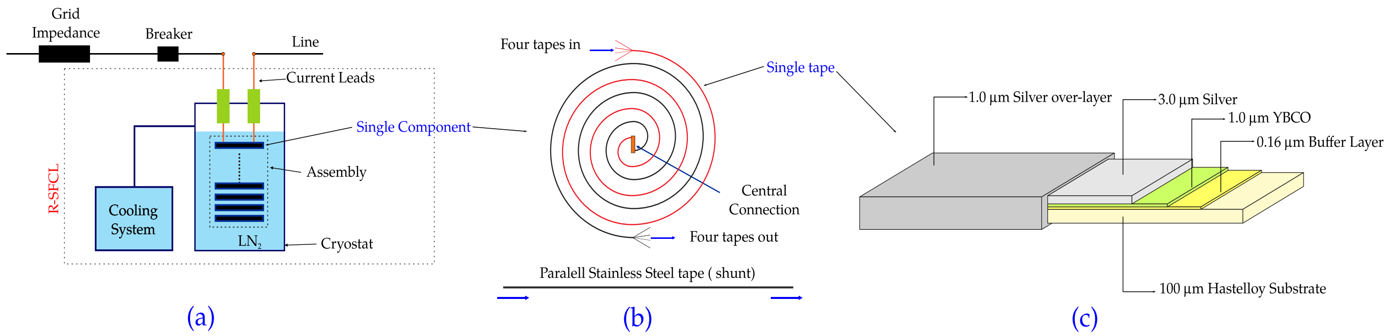

Fig. 1. (a) The R-SFCL connected in series with the system to be protected, (b) design of the coil, and (c) architecture of each YBCO 2G tape.

distortion may cause negative effects on typical protective relays settings, such as miss-coordination, depending on the fault current magnitude measurement techniques [21].

The considered R-SFCL consists of shunted coils of second generation (2G) tapes. Eight tapes with a length of 4.3 m each compose a single component, and there is an additional central contact, connecting the tapes. The tapes are arranged in an anti-parallel manner, as shown in Fig. 1b. The stainless steel pancake executes the function of a shunt element and is made by a bifilar spiral of stainless steel tapes. For the design of the R-SFCL device, one can arrange these elements in series and in parallel in order to satisfy current and voltage ratings of the specific application [15].

Each coil of the R-SFCL is based on YBCO tapes (2G tapes). Each tape consists of several layers of different materials, as shown in Fig. 1c. One of these layers is the superconducting material (YBCO). Dimensional characteristics were obtained from [22,23].

2.2. Simulation model

To simulate the transient behavior of the R-SFCL, it is mandatory to calculate the temperature rise of the tapes during the fault period. For that, an analogy between thermal and electrical systems was used. The use of such an analogy to simulate the temperature rise of each layer during the short-circuit makes the simulations easier to be implemented, since the coupling between the electrical circuit and the heat conduction differential equations becomes a straightforward task. A numerical solution is obtained by using the classical lumped approximation, i.e., the temperature is assumed to be spatially uniform within each layer during the transient. Such an assumption is reasonable if the thicknesses of the layers are very small. According to [24,25], a network composed of T sections can be used to represent the thermal model. Fig. 2 represents an equivalent network that describes the thermal behavior of the R-SFCL component. The shunt component is represented apart from the tapes, since it is not in direct contact with the 2G tapes in the R-SFCL component.

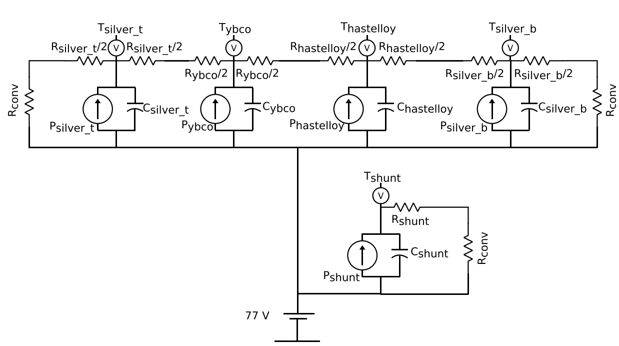

Fig. 2. Thermal-electric analogy for simulated tapes.

The thermal resistances $R_{material}$ are related to the heat conduction of the material, whereas the capacitors $C_{material}$ are related to the thermal capacity of the material. Eqs. (1)–(4) show the conversion from thermal to electrical quantities. The index i refers to the respective indexed layer. The thermal resistance R_{conv} is calculated as presented in (4), considering h_c as 0.2 W/cm^2 K.

$$R_i = \frac{l_i}{\lambda S} \tag{1}$$

$$C_i = d_i c_i l_i S \tag{2}$$

$$P_i = I_i^2 R_{e,i} \tag{3}$$

$$R_{conv} = \frac{1}{(h_c S)} \tag{4}$$

The physical parameters l_i, c_i, d_i, λ, S, and h_c are, respectively, layer depth, specific heat, specific mass, thermal conductivity, contact surface between layers, and convective heat transfer. The quantity P_i is the heat dissipated in each layer, which is a function of the current in each layer, I_i, and the resistance of each layer, $R_{e,i}$.

This model is considered suitable to predict the transient behavior of the R-SFCL device to be performed in this work, since it has been extensively tested and validated in the literature [22,23,26–28].

The resistance of the YBCO layer is a strong function of temperature and current. The temperature is calculated by means of the previously mentioned thermal-electrical analogy. Eq. (5) describes the characteristic $E \times J$ curve (electric field versus electrical current density) of the YBCO layer. It describes the transition from the superconducting state to the normal state, and it is often called a power law, divided into three stages: flux creep, flux flow, and normal state [29].

$$E = E_c \left[\frac{J}{J_c(T_{sp})} \right]^n \tag{5}$$

In (5), E, E_c, $J_c(T_{sp})$, and n denote, respectively, the electromagnetic field in V/cm, the critical field, the critical current at the current temperature, and the exponent for the operating stage of the superconducting material. Values of n vary according to the operating stage of the superconductor, as in [26].

Simulations done in this work consider all tapes to be homogeneous, i.e., all tapes present the same critical current on the whole tape length and among tapes.

The resistivity of normal conductors (further layers) are linearly dependent on the temperature [30].

3. FPSO power system

The FPSO main electric power generation consists of 4 turbogenerators, driven by dual-fuel (gas and diesel) turbines connected to