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An analytical circuit based nonlinear thermal model for capacitor banks

Haoran Wang*, Huai Wang

Center of Reliable Power Electronics (CORPE), Aalborg University, Denmark

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ABSTRACT

The thermal couplings among capacitors in a bank could significantly alter the reliability performance compared to a single capacitor. The impact of thermal coupling is becoming stronger for high power density systems due to more stringent constraint in volume. Prior-art studies take into account the thermal coupling effects of a capacitor bank by either Finite Element Method (FEM) or experimental characterization, which are case dependent and time-consuming. This paper proposes a nonlinear mathematical model for capacitor banks based on physics of thermal conduction, convection, and radiation. A simplified version of the model is also obtained and represented by an RC circuit network, which enables computational-efficient thermal stress modeling. The proposed models are convenient to use to support model based sizing of capacitor banks and is scalable for multi-cell rectangle layout. A case study with experimental testing is discussed to verify the accuracy of the models.

1. Introduction

Capacitors are widely used in electrolytic systems to buffer the pulsation power, filter the harmonics and support voltage for stable operation. For these applications where single capacitor cannot fulfil the voltage rating or capacitance requirements, capacitor bank is always used as the energy buffer by connecting several capacitors in parallel for larger capacitance, or in series for higher voltage rating [1]. With more stringent reliability constrains brought by automotive, aerospace and energy industries, capacitor bank is one kind of the stand-out components in terms of failure rate in field operation electronic systems.

The efforts to overcome the above challenges can be divided into three categories: a) obtain the accurate temperature and lifetime distribution in the design phase [2]; b) optimal capacitor bank design solutions to achieve proper robustness margin and cost-effectiveness [3]; c) adopt novel longer lifetime capacitor technologies [4]. For the three categories, accurate and time efficient temperature estimation is the basic. The existing methods to estimate the temperature distribution of the capacitor banks is by using experiment or FEM simulation, however, it always take long time to acquire the results in the original design phase. Although constant thermal resistance based mathematical thermal models for single capacitor have been explored, which offer a fast way to estimate the status of the capacitors [2], it cannot be used for a capacitor bank directly to acquire the temperature distribution. Several issues need to be overcome: a) one issue is the uneven temperature distribution among the capacitors inside the bank due to thermal coupling effect [5]. The temperature estimation based on a single capacitor becomes useless; b) thermal resistance extraction for temperature estimation consumes much time in either FEM simulation or experiment. An accurate, fast and efficient mathematical model to acquire the thermal resistance as well as the 3-D temperature distribution is highly valuable.

Although researchers have developed a mathematical model for capacitor bank [3], it cannot estimate the detailed hot-spot temperature of each cell, because it packages the capacitor bank as a cuboid module for a rough estimation and ignores the nonlinear thermal behavior inside the module. This paper aims to propose a 3-D nonlinear thermal model for capacitor bank, where the conduction, convection and radiation heat transfer among the cells are considered to acquire the hot-spot temperature of each cell. Without the time-consuming FEM simulation or experiment, thermal resistance as well as the critical temperature distribution can be fast characterized from circuit simulators (e.g., Simulink, PLECS, Pspice). Scalable circuit design guideline is also studied.

The rest of this paper is as follows: Section 2 introduces the general structure and fundamental theory of nonlinear thermal model; Section 3 studied the circuit based nonlinear thermal model and the scalable design guideline; Section 4 demonstrates a case study of a capacitor bank to verify the accuracy of the proposed thermal model.

2. A general nonlinear thermal model

A diagram of the proposed nonlinear thermal model is shown in

* Corresponding author.
E-mail address: hao@et.aau.dk (H. Wang).

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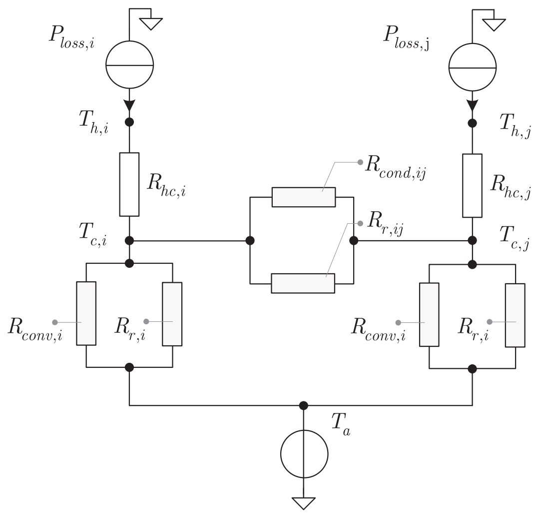

Fig. 1. Thermal model of two capacitors in a bank.

Fig. 1. $P_{loss,i}$ and $P_{loss,j}$ are the power loss of the capacitor *i* and *j*, respectively. $T_{h,i}$, $T_{h,j}$, $T_{c,i}$, $T_{c,j}$ and T_a are the hot-spot temperature, case temperature and ambient temperature of the capacitor *i* and *j*, respectively. $R_{hc,i}$ and $R_{hc,j}$ are the thermal resistance of the capacitor *i* and *j*, respectively, from hot-spot to case which are determined by the physical structure and assumed constant in different operating conditions (e.g., electrical loading and thermal loading), and locations. $R_{conv,i}$ and $R_{conv,j}$ are the thermal resistance of the capacitor *i* and *j*, respectively, for convection heat transfer. $R_{r,i}$ and $R_{r,j}$ are the thermal resistance of the capacitor *i* and *j*, respectively, for radiation heat transfer. The thermal model for convection and radiation heat transfer cannot be obtained by linear thermal resistor and capacitor, while they follow the nonlinear formulas as shown in Eqs. (A.1) and (A.2) which are terminal temperature dependent and effective surface area related. In the multi-cell capacitor bank, since the impact from neighboring cells is significant, additional aspects need to be considered in the thermal modeling:

A) Thermal coupling resistance

The case temperature of the capacitor is not only determined by power loss and thermal resistance of the capacitor itself, but is also related to the neighboring cells in the bank. A new path for heat transfer among cells which contains heat conduction and radiation thermal resistances connected in parallel from capacitor *i* to capacitor *j* should be considered. $R_{cond,ij}$ and $R_{r,ij}$ are the thermal coupling resistance between capacitor *i* and *j* for conduction and radiation heat transfer through the air. For simplicity, assuming the distance between cells is very small, the complicated heat convection process among cells is ignored and considered as heat conduction through air.

B) Variance of self-heating thermal resistance

Another difference between single capacitor and capacitor bank thermal model is the convection and radiation heat transfer coefficient of self-heating thermal resistance for each cell. Taking capacitor *i* as an example, these two thermal resistances are the nonlinear function of $T_{c,i}$, T_a and the effective surface area to ambient air. When capacitor *i* locates in a bank, the thermal resistance for self-heating is no longer constant, because the effective surface area to ambient air is no longer the whole surface, which should be the whole surface area subtracts the area faced to the neighboring cells. In the thermal model of a capacitor bank, except for the linear thermal resistance from hot-spot to case, the other thermal resistances are always adaptively changed with the layout as well as the effective surface area.

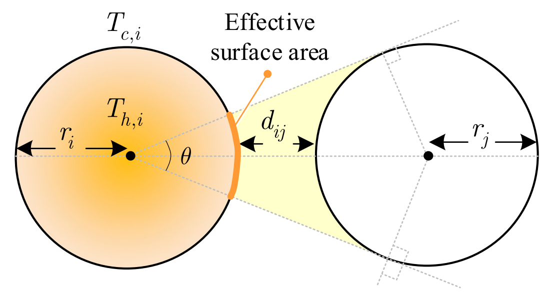

Fig. 2. Diagram to illustrate the view factor calculation for the efficient surface area.

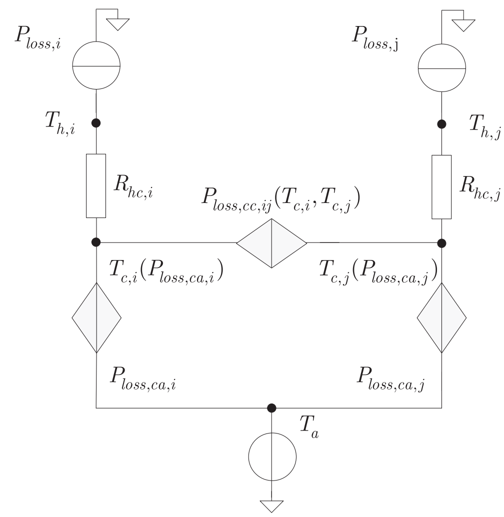

Fig. 3. Circuit based thermal model diagram for two capacitors.

C) Effective surface area

Effective surface area is a key coefficient to acquire the thermal resistances, which are adaptively changed with the capacitor dimension and layout. For example, as a single capacitor *i*, all the surface exposes in the ambient air, so that the effective surface area in heat convection and heat radiation are the whole surface. Different from that, for the capacitor *i* in a bank with two cells, only a part of the surface exposes to the ambient air, other parts are faced to the capacitor *j*. The effective surface area is defined in Fig. 2, which can be written as

$$S_{effect} = \underbrace{2\pi r_i^2}_{top/bottom} + \underbrace{\frac{\theta}{2\pi} 2\pi r_i H}_{lateral\ area} = 2\pi r_i^2 + \theta r_i H \tag{1}$$

where H is the height of the capacitor. A view factor θ is used to obtain the effective surface area from the lateral area, which is shown as

$$\theta = 2\arcsin\left(\frac{r_j}{r_i + d_{ij} + r_j}\right) \tag{2}$$

3. Circuit based nonlinear thermal model

Basic modules for building up the thermal model in circuit simulator is discussed firstly in this section, followed by the guideline to illustrate how to implement the thermal model for different application by using the scalable module in circuit simulator.

A) Basic circuit modules of the thermal model

As an example, the circuit based thermal model for a capacitor bank