# A Resistance Model of Fault Current Limiting Magnets under DC Impact


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## Abstract

The short-circuit fault current on the DC side affects the operation safety of the multi-terminal flexible HVDC transmission system (MTDC) seriously. At the same time the superconducting fault current limiter (SFCL) has received extensive attention in limiting the DC impact current due to its characteristics such as fast response speed, good current limiting effect and zero impedance at steady state. At present, the error of simulations of the resistance of YBCO tapes under DC impact is relatively larger, which affects the design accuracy of SFCLs. In this paper, the characteristics of DC fault current are studied. The resistance and other parameters of YBCO samples under DC impact are measured by use of a DC impact platform. The heat transfer process of YBCO tapes under DC impact is researched and two different modeling methods are obtained. Finally, these methods are improved considering the characteristics of the fault current limiting (FCL) magnet and the correctness is verified by comparison with the experimental results of FCL magnets. The advantages and disadvantages of two modeling methods are compared. This research aids in simulation analysis and optimization design of DC SFCLs.


## Experiment of YBCO tapes under DC impact

- The transient process in the short circuit of the MTDC system is similar to the capacitor discharge.
- The voltage variation of the 10 cm YBCO specimens under different impact conditions (different impact duration and different impact current) is measured. Resistance and power curves are obtained.

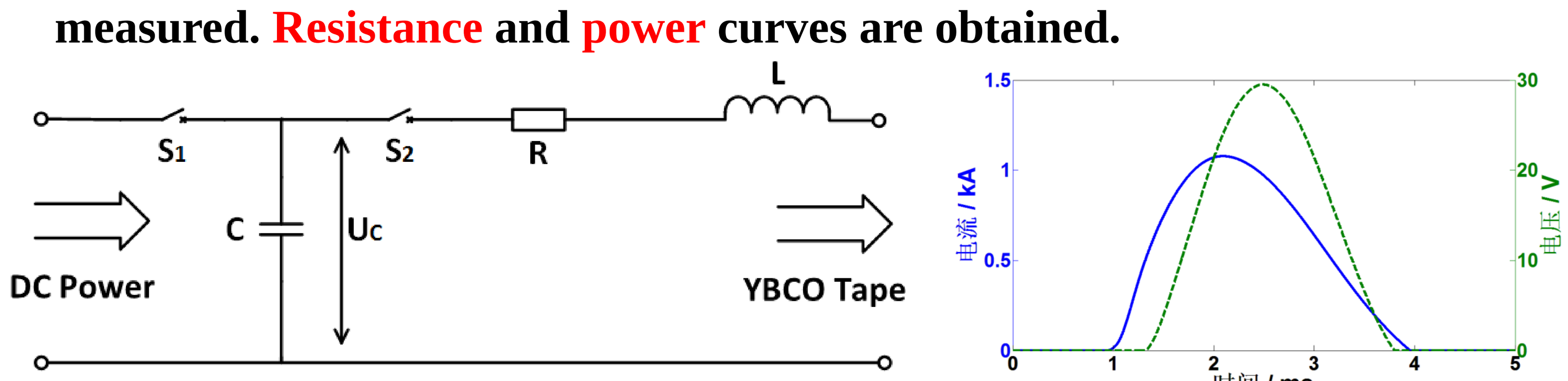



Fig. 1. The DC impact platform and experiment data

## Resistance-joule heat fit model (R-Q FM)

- Resistivity is a function of temperature, meanwhile the area of each layer in the YBCO tape is determined and known. The resistance of the tape is also a function of temperature.
- In the process of DC impact, the initial temperature of the YBCO tape is known. The temperature of each layer of the tape can be uniquely determined by joule heat.
- The resistance of the YBCO tape is a function of joule heat of the tape.

$$r_{per} = \frac{1}{\sum \frac{1}{r_{per,n}}} = \frac{1}{\sum \frac{A_n}{\rho_n}} \qquad r_{per} = f(T_n) = g(q)$$

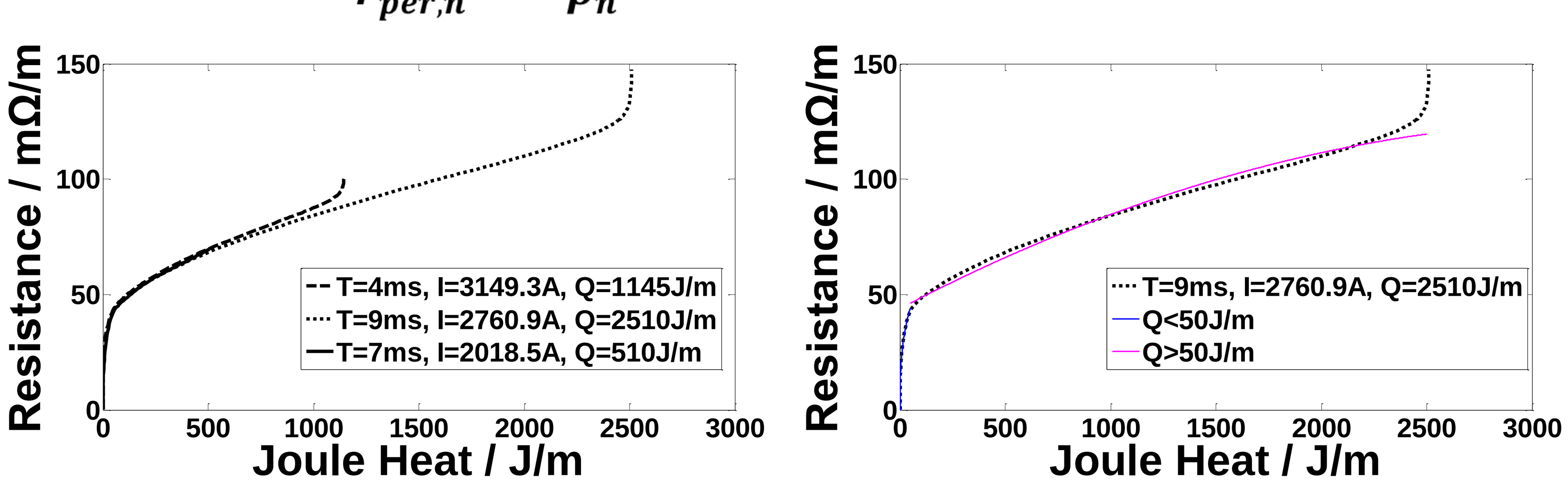



Fig. 2. R-Q curves of YBCO specimens and the R-Q FM

$$r_{per} = 10^{-3} \times \begin{cases} 10.984q^{0.3554} \\ -7\times 10^{-6}q^2 + 0.0478q + 43.801 \end{cases}$$

- **Advantages**
  - simple, constant, easy to calculate.
- **Disadvantages**
  - The selection of parameters is not objective enough. The structure of the expression and the values of the constant parameters in the model are selected by observing the direction of R-Q curves and the $R^2$ values.
  - there is an upper limit of the applicable scope. The second part of the expression in the model is part of a quadratic function, in which there is a maximum point. Simulation results show that when q>3000 J/m, the error of R-Q FM is large.
  - the influence of liquid nitrogen on heat dissipation is not considered. YBCO tape samples is short and fixed in length, which is why it can be considered that the heat dissipation of liquid nitrogen is negligible, or only related to the joule heat of the tape. This is not applicable in the simulation of FCL magnets.

## Lumped parameter model (LPM)

- **Assumptions**
  - YBCO tapes are quenching at the same time in the current direction.
  - The solder is considered to be adiabatic.
  - The liquid nitrogen is stationary and its region is large enough.
  - Thermal radiation from external environment can be ignored.
  - The contact resistance is ignored.

$$\rho c L_x L_y \frac{dT}{dt} = 2hL_x(T_\infty - T) + p \qquad \rho c L_x L_y \frac{dT}{dq} = \frac{2hL_x(T_\infty - T)}{p} + 1$$

$$T(t+\Delta t) - T(t) = \frac{2h\left(T_\infty - T(t)\right)\Delta t}{\rho c L_y} + \frac{p(t)\Delta t}{\rho c L_x L_y} \qquad T(q+\Delta q) - T(q) = \frac{2h\left(T_\infty - T(q)\right)\Delta q}{\rho c L_y p(t)} + \Delta q$$

- A(T) is defined as equivalent heat capacity parameter
- B(T) is defined as equivalent heat dissipation parameter

$$A(T) = \rho c(T) = \frac{(p(t)_1 - p(t)_2)\Delta t}{\left(T(t+\Delta t)_1 - T(t+\Delta t)_2\right)L_x L_y} \qquad B(T) = \frac{h(T)}{\rho c(T)} = \frac{\left(T(q+\Delta q)_1 - T(q+\Delta q)_2\right)L_y}{2\Delta q(T_\infty - T(q))\left(\frac{1}{p(t)_1} - \frac{1}{p(t)_2}\right)}$$

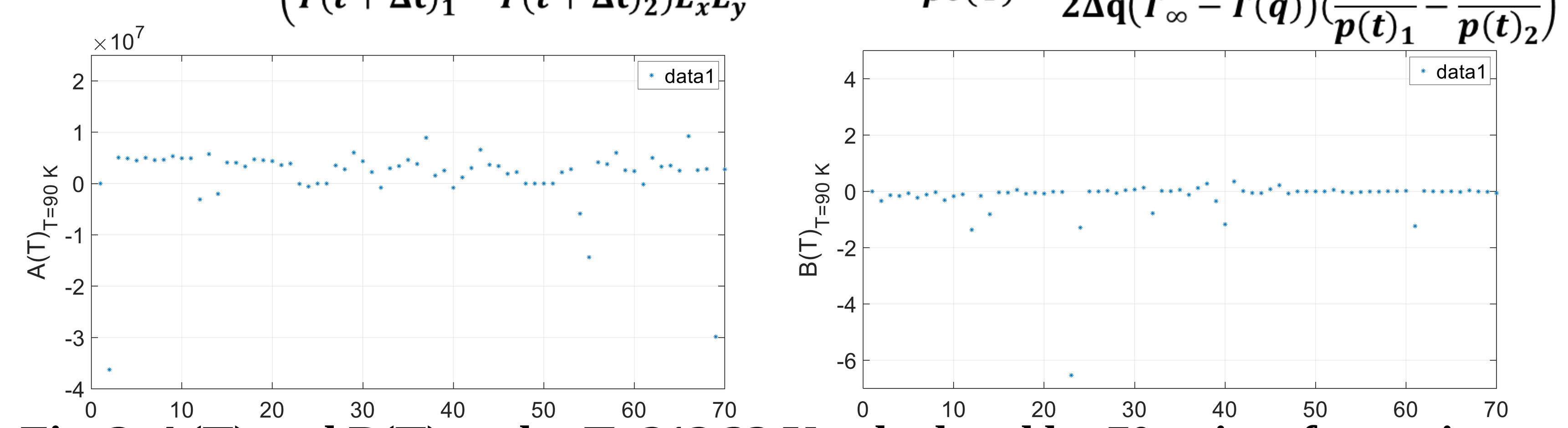



Fig. 3. A(T) and B(T) under T=212.33 K calculated by 70 pairs of equations

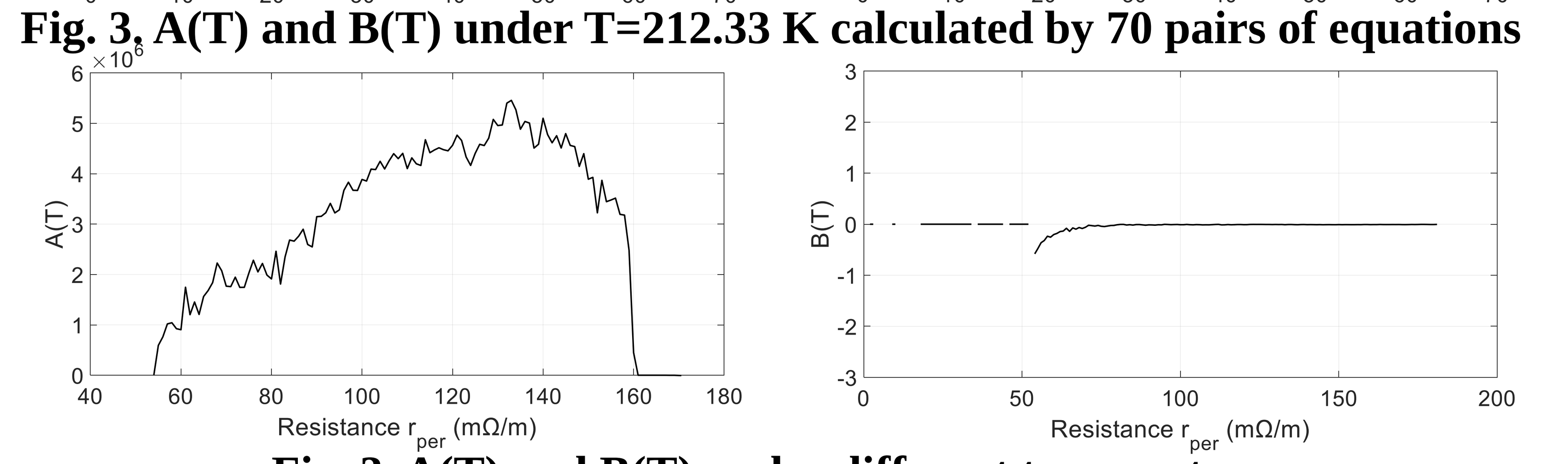



Fig. 3. A(T) and B(T) under different temperature

$$T(t+\Delta t) = T(t) + \frac{(p(t)\Delta t}{A(T)L_x L_y} + \frac{2B(T)\left(T_\infty - T(t)\right)\Delta t}{L_y}$$

## Verification on FCL magnets

- The end of the resistance curve measured by the platform have the phenomenon of smooth upwarping.
- thermal equilibrium point can be regarded as the credible boundary of the resistance curve in the DC impact

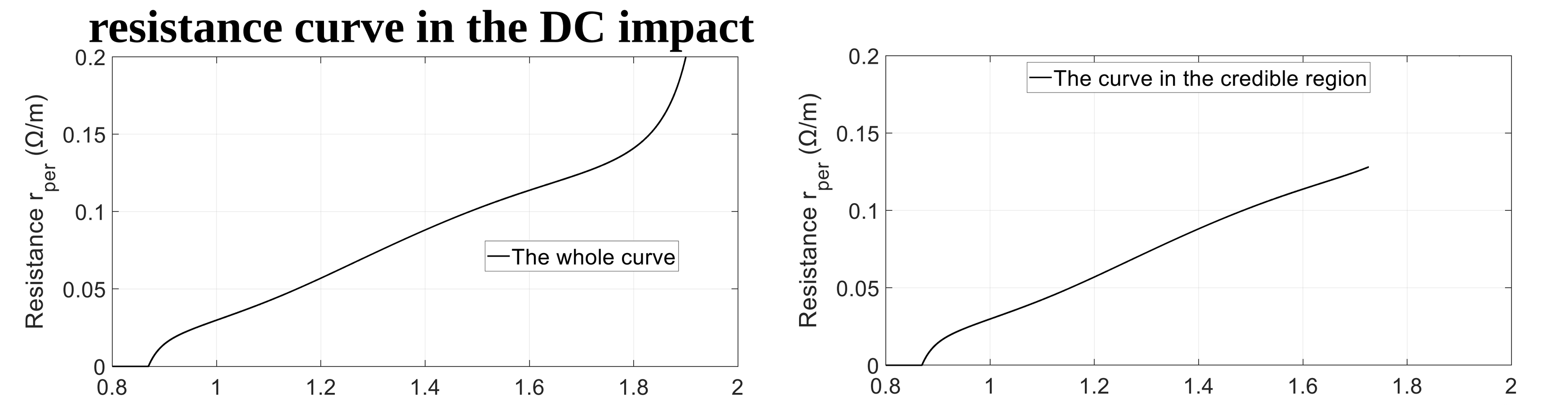
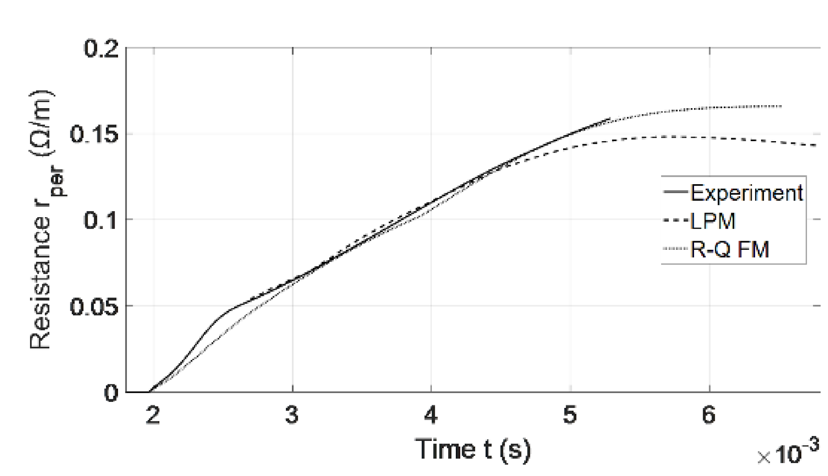



Fig. 4. Comparison between the whole curve and the credible region




- LPM can fit resistance inflection point at the beginning and with high accuracy in the middle stage, but low accuracy in lower maximum resistance.
- R-Q FM can fit the maximum resistance that the FCL magnet can reach, but the inflection point is not obvious.

## Conclusion

- YBCO tape voltage data under different impact conditions are measured on the DC impact test platform, from which the resistance and power curves are processed. The R-Q FM is obtained by direct fitting.
- The recursive formula of the LPM is given. The equivalent heat capacity parameter and the equivalent heat dissipation parameter are proposed.
- A method by taking the thermal balance point during the DC impact as the credible boundary of the resistance curve is proposed.
- The accuracy of the R-Q FM and the LPM is verified by independent DC impact test data of FCL magnets.


## Acknowledgement

This work was supported in part by National Natural Science Foundations of China (51577179, 51721005), National Key Basic Research Program of China (973 Program) (2015CB251005) and Key Frontier Research Program of Chinese Academy of Sciences (QYZDJ-SSW-JSC025).