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DC Grid Stabilization using a Resistive Superconducting Fault Current Limiter

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Abstract

The present work deals with the stabilization of DC grid using a resistive superconducting fault current limiter (r-ScFCL) in association with a classical RLC filter. Superconducting fault current limiters have been proposed to provide overcurrent protection during fault conditions in DC grids. However, in the present work, we focus on the behavior of the fault current limiter during unstable operation but never in fault condition. More specifically, we show that a r-ScFCL can provide a stabilizing power filter functionality when operated around its critical current I_c. This is done by means of numerical simulations considering a simplified DC grid and several r-ScFCL models: piecewise linear model and power law model. It is important to note that the models used here are valid only below and around I_c, and that future works will have to include a more detailed modeling of the r-ScFCL. The present results could nevertheless be useful for preliminary design of r-ScFCLs so that they can provide both current limiter and power filter functionalities in DC grids.

I. Introduction

In a DC grid, the connection of constant-power loads, such as inverter-fed actuators, batteries with charge controllers and drives, can be the source of bus voltage instabilities [1–3]. This can be addressed using active and passive stabilization. Active stabilization consists in redesigning the source/load converter control [4–9]. This approach can be very effective, but may increase the complexity of the controller and/or require additional sensors. Passive stabilization is achieved by adding resistive damping circuits [10, 11]. It is simple but it lacks flexibility, increases the system footprint and reduces the overall efficiency [12].

In parallel, resistive superconducting fault current limiters (r-ScFCL) have been proposed in order to mitigate the effects of fault currents in DC grids and to improve the system stability *during fault conditions* [13–20]. Our concern here is different: we are looking at the behavior of the r-ScFCL during unstable operation but *never in fault condition*. It is suggested that in these particular conditions, a r-ScFCL can be used in association with a classical RLC filter to obtain a passive stabilizer [21]. It would operate in the non-limiting region around its critical current I_c (in average). Indeed, well below I_c the device presents negligible resistance, but around I_c it starts dissipating power and increases its effective resistance thus providing stabilization.

The purpose of this article is to demonstrate, by means of numerical simulations, that a r-ScFCL can provide a stabilizing power filter functionality in DC grids. Various r-ScFCL models are compared, thus offering a better understanding of the various parameters that play a role in the operation of such device.

II. Stability limit of a DC grid

Fig. 1 shows the DC grid under consideration in this section. A constant voltage source V_e models the output of a generic power source which is connected in series with a classical RLC filter and a constant power load $P_s = v_s i_s$. The parameters of this grid are summarized in Table 1.

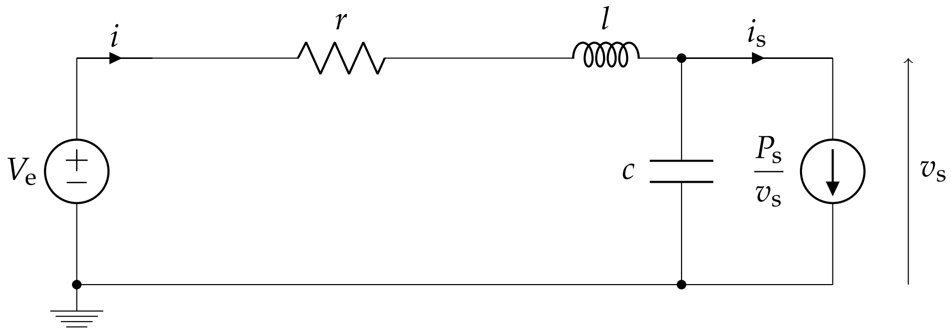


Figure 1: DC grid with a constant power load.

Table 1: DC grid parameters

Symbol	Parameter	Value
V_e	source voltage	5 kV
r	resistance	40 mΩ
l	inductance	0.6 mH
c	capacitance	1.4 mF

1. Analytical stability region

Because the constant power load behaves like a negative resistance, it reduces system damping and can lead to instability. The topic has been extensively addressed in the literature (see [3] for example), and therefore we directly give here the expression for the stability region. It is supposed that the system is operating around the point of operation $(i_{\rm s},v_{\rm s})=(I_{\rm s0},V_{\rm s0})$. The DC voltage grid is stable if,

$$P_{\rm s} \leq \frac{rc}{l} V_{\rm s0}^2 \tag{1}$$

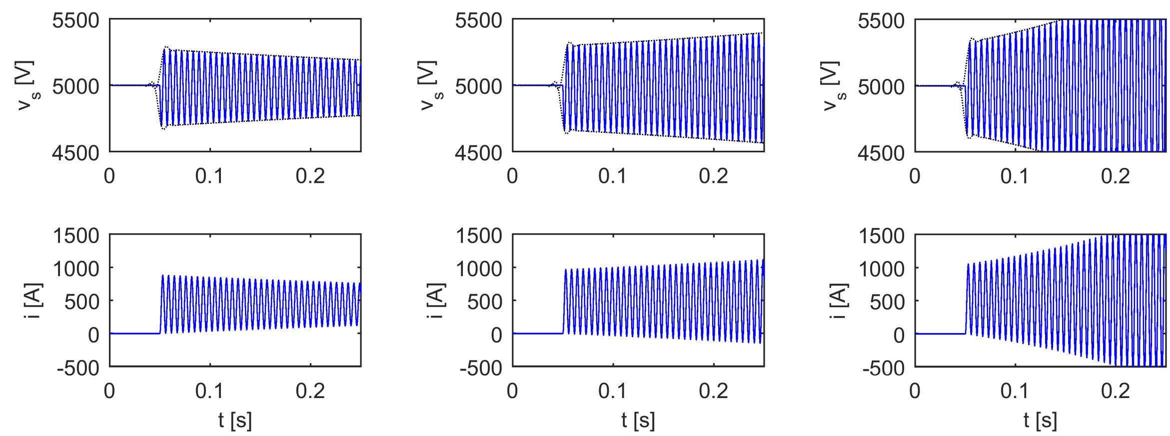
Assuming that the voltage drop across the RLC filter stays small, the average value of $v_{\rm s}$ around the given point of operation $V_{\rm s0}$ is approximately equal to $V_{\rm e}$. The stability region can then conveniently be approximated by,

$$P_{\rm s} \leq \frac{rc}{l} V_{\rm e}^2 \tag{2}$$

In the present case, the maximum power at which the stability holds is 2.33 MW.

2. Numerical analysis

The DC grid of Fig. 1 with the parameters of Table 1 is simulated using Matlab/Simulink and the SimPowerSystem toolbox. Fig. 2(a) shows the load voltage and source current for a load power step from 0 to 2.2 MW: the DC grid is stable[1]. Figs. 2(b) and 2(c) show the grid behavior for load power steps from 0 to 2.4 and 2.6 MW: the DC grid is unstable.



(a) $P_{\rm s} = 2.2$ MW: stable (b) $P_{\rm s} = 2.4$ MW: unstable (c) $P_{\rm s} = 2.6$ MW: unstable

Figure 2: Simulated load voltage and source current for various load power steps, without r-ScFCL.

To widen the stability region, one could for example increases the RLC filter resistance r [12] according to (2). But even in nominal operation, the power losses would increase. This issue can be solved by using a r-ScFCL in series with the RLC filter. In nominal operation for which the $I_{\rm c}$ of the device is much larger than the operating current i, there is no dissipation introduced in the system. However during unstable

[1]To evaluate numerically the stability of the DC grid, we consider the envelope of the grid voltage. If after an event, the derivative of the upper envelope is positive, the grid is unstable. If the derivative is negative, the grid is stable. The simulations are made using Matlab/Simulink and the SimPowerSystem toolbox.

operation, the operating current oscillates approaching I_c, the r-ScFCL resistance increases and damps the fluctuations to reach a new stable point of operation as shown in the next sections.

III. Improved stability of a DC grid with a r-ScFCL

Fig. 3 shows the circuit under consideration in this section. A r-ScFCL made of (Re)BCO tapes is connected in series with the classical RLC filter. The parameters of the system are summarized in Tables 1 and 2. The reactance of the r-ScFCL is neglected.

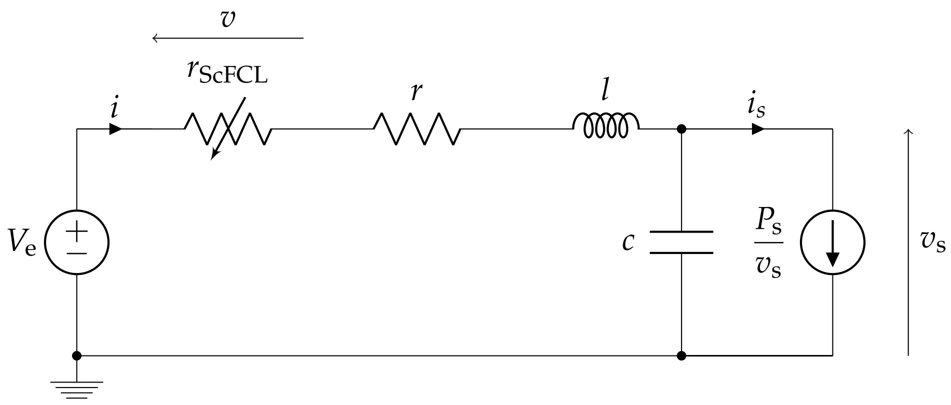


Figure 3: DC grid with a constant power load and a r-ScFCL.

Table 2: r-ScFCL parameters

Symbol	Parameter	Value
E_c	critical current criterion	10^{-4} V/m
I_c	r-ScFCL critical current	550 A
n	power law exponent	38
l_{sc}	r-ScFCL length	1000 m
r_{sh}	shunt resistance	10 mΩ

1. Current limiter mode and power filter mode

In the present work, we are not interested in the current limiter mode. The r-ScFCL stays in its superconducting state for $i \leq I_c$ (we neglect here the current oscillations around its average value). This gives a limit to the load power to stay in the power filter mode,

$$P_s \leq V_{s0}\ I_c \tag{3}$$

Assuming that the voltage drop across the r-ScFCL and the RLC filter stays small, the average value of v_s around the given point of operation V_{s0} is approximately equal to V_e. The power filter mode region can then conveniently be approximated by,

$$P_s \leq V_e\ I_c \tag{4}$$

Using Eqs. (2) and (4), we obtain the limiter mode and power filter mode regions of the r-ScFCL as a function of I_c (Fig. 4). The goal of the following numerical analysis is to determine if the DC grid voltage stability region is extended when using a r-ScFCL (Is the grid voltage stable above the dashed line?).

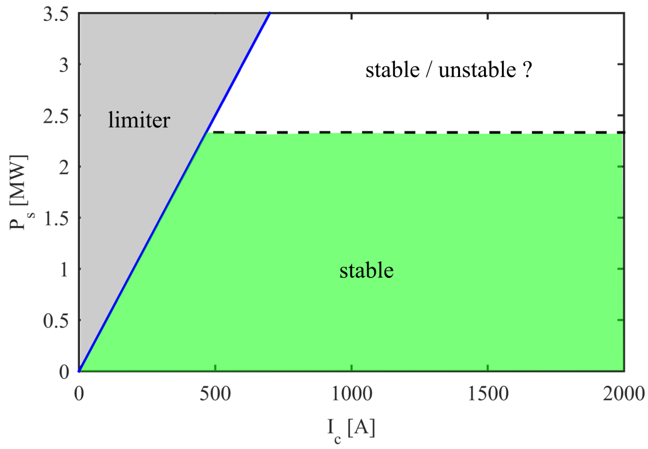


Figure 4: Current limiter mode and power filter mode regions of the r-ScFCL. The dashed line is the stability limit without r-ScFCL according to (2).

2. r-ScFCL model

The r-ScFCL is, to make simple, a superconducting element in parallel with a shunt resistor. In this article, as a first step, we assume that the superconducting element resistance r_{sc} is a non-linear function depending only on the transport current i. By neglecting the thermal dependence, we are assume that the cooling power is sufficient enough to keep the temperature constant. This would be true only outside of the current limiter mode and for a sufficient cooling power. The resistivity of the superconducting element is then modeled by the classical power law [22],

$$\rho(j) = \frac{E_c}{J_c} \left| \frac{j}{J_c} \right|^{n-1} \tag{5}$$

where J_c is the critical current density, $E_c = 10^{-4}$ V/m is the critical current criterion, and n is a material parameter that describes the steepness of the transition from superconducting to normal-resistive state. The corresponding lumped parameter model of the superconducting element is,

$$v\,(i) = \frac{V_c}{I_c} \left| \frac{i}{I_c} \right|^{n-1} i \tag{6}$$

where $V_c = E_c l_{sc}$, l_{sc} is the r-ScFCL length and I_c is the r-ScFCL critical current. In a real design, I_c dictates the number of conductors to be connected in parallel to obtain the limiting current functionality.

The shunt resistor lumps the metallic stabilizer of the superconductor with an optional external shunt resistance. The metallic stabilizer can ensure that the superconductor does not quench when operated around its critical current. The shunt resistance is typically used as a by-pass to the current in case of a superconducting-to-resistive transition of the superconductor. The usefulness of the external shunt resistance will be discussed later. To take into account the effect of the shunt resistor here, the r-ScFCL resistance r_{ScFCL} is taken equal to the superconducting element resistance r_{sc} but limited to the shunt resistance r_{sh},

$$r_{\mathrm{ScFCL}} = \min\left(r_{\mathrm{sc}}, r_{\mathrm{sh}}\right) \tag{7}$$

We compare here the two models of the r-ScFCL to determine which one is the most suitable for stability studies.

a) Piecewise linear model

From (6), by linearization around I_c, a piecewise linear model of the superconducting element resistance can be obtained,

$$r_{\mathrm{sc}} = \begin{cases} 0, & \text{if } i \leq \frac{n-1}{n} I_c \\ \frac{v_c(1-n)}{i} + \frac{n v_c}{I_c}, & \text{if } i > \frac{n-1}{n} I_c \end{cases} \tag{8}$$

The r-ScFCL resistance r_{ScFCL} is then obtained from (7) (blue line in Fig.5).

b) Power law model

From Eq.(6), a power law model of the superconducting element resistance can be directly obtained,

$$r_{\mathrm{sc}} = \frac{V_{\mathrm{c}}}{I_c} \left| \frac{i}{I_{\mathrm{c}}} \right|^{n-1} \tag{9}$$

The r-ScFCL resistance r_{ScFCL} is then obtained from (7) (red line in Fig.5).

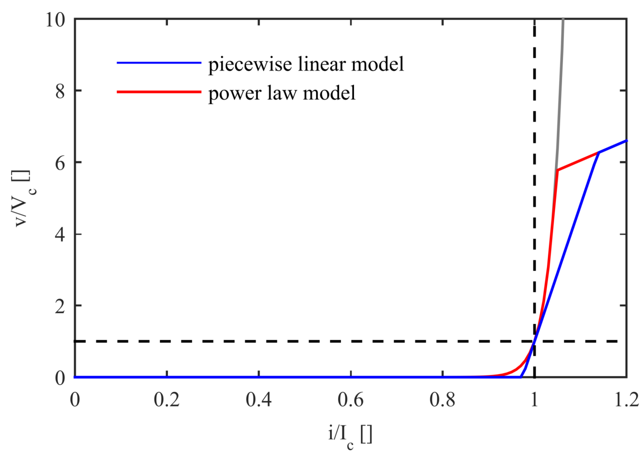


Figure 5: r-ScFCL models. r_{sh} = 1 mΩ here, for illustration purpose.

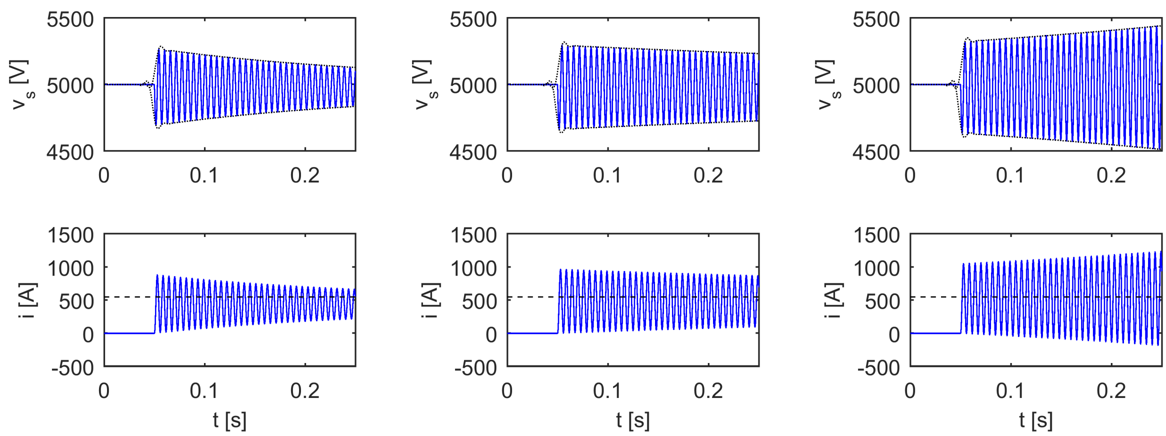
3. Numerical analysis

The DC grid of Fig. 3 with the parameters of Tables 1 and 2 is simulated. We remind that, without the r-ScFCL, the stability limit was 2.33 MW (see section 2.).

a) Piecewise linear model

Fig. 6 shows the load voltage and source current for a various load power steps. For a step from 0 to 2.2 MW, the DC grid is stable. Note that the stabilization is faster than without r-ScFCL. For a step from 0 to 2.4 MW, the DC grid is now stable. This demonstrates that in principle the r-ScFCL can provide a stabilizing power filter functionality. For a step 0 to 2.6 MW, the DC grid is unstable.

By running simulations for various values of I_c and P_s, one can obtain the stability region of the DC grid with a r-ScFCL. Results are shown in Fig. 7. A small improvement (above the dashed line) is observed for source currents near i_c (near the blue line). The question remains as to whether the piecewise linear model is accurate enough for stability study?



(a) $P_s = 2.2$ MW: stable (b) $P_s = 2.4$ MW: stable (c) $P_s = 2.6$ MW: unstable?

Figure 6: Simulated load voltage and source current for various load power steps, with a r-ScFCL (piecewise linear model). The dashed line represents the r-ScFCL critical current.

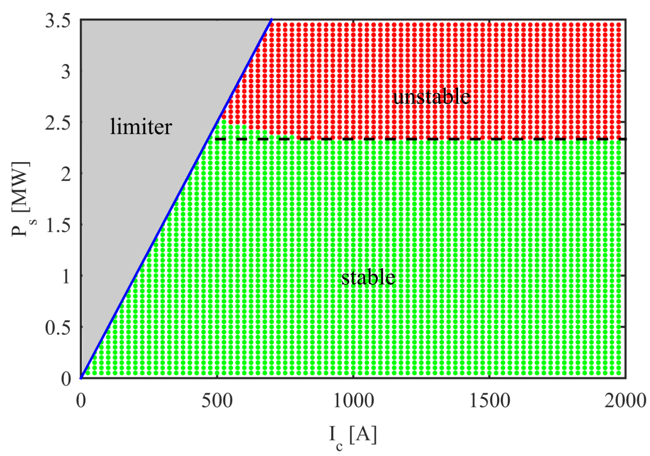
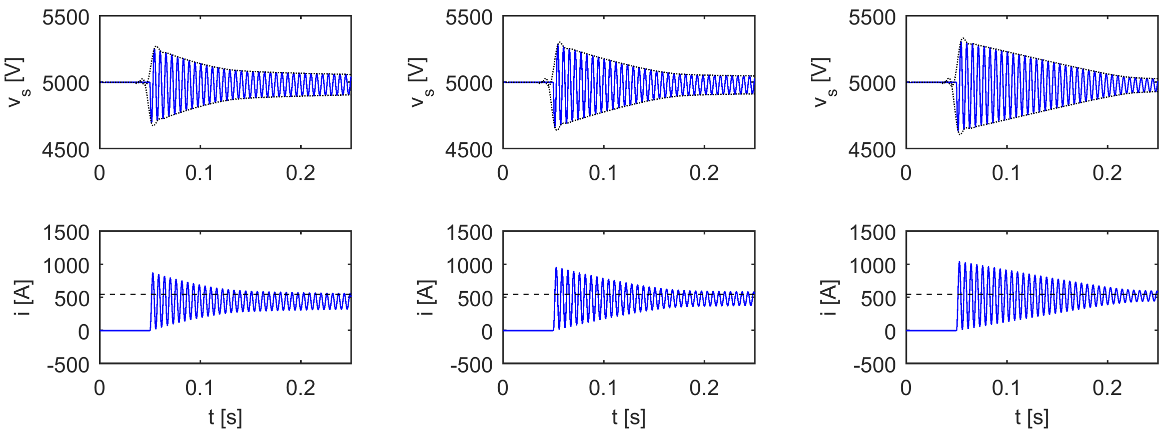


Figure 7: Stability region as a function of the r-ScFCL critical current (piecewise linear model). The dashed line is the stability limit without r-ScFCL according to (2). The green dots correspond to stable operation points. The red dots correspond to unstable operation points. In the gray region, the r-ScFCL is in current limiter mode.

b) Power law model

Fig. 8 shows the load voltage and source current for load power steps from 0 to 2.2, 2.4 and 2.6 MW: the DC grid is stable. This confirms the previous results: a r-ScFCL can provide a stabilizing power filter functionality in DC grids. Note that the stabilization is faster in comparison with the piecewise linear model. In addition, the damping seems to have two time constants: fast when the current oscillations are going above I_c and slow then.

The stability region of the DC grid obtained with this model is shown in Fig. 9. A significant improvement (above the dashed line) is observed for source currents near i_c (near the blue line).



(a) $P_s = 2.2$ MW: stable (b) $P_s = 2.4$ MW: stable (c) $P_s = 2.6$ MW: stable

Figure 8: Simulated load voltage and source current for various load power steps, with a r-ScFCL (power law model). The dashed line represents the r-ScFCL critical current.

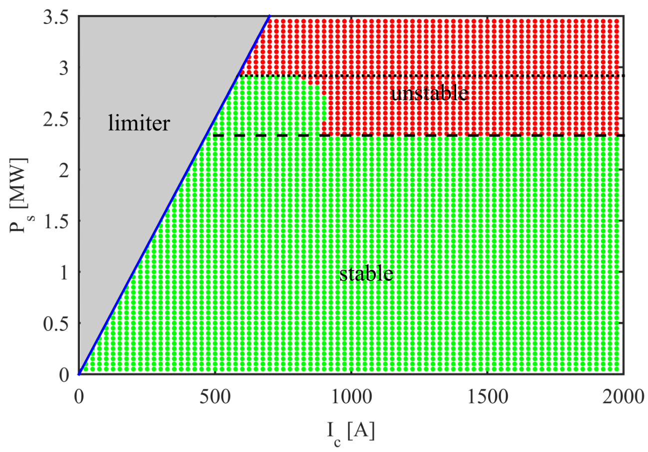


Figure 9: Stability region as a function of the r-ScFCL critical current (power law model). The dashed line is the stability limit without r-ScFCL according to (2). The dotted line is the upper stability limit according to (10). The green dots correspond to stable operation points. The red dots correspond to unstable operation points. In the gray region, the r-ScFCL is in current limiter mode.

4. Discussion

We observe an important discrepancy between the stability regions obtained with the two models. The stability region predicted by the r-ScFCL piecewise linear model is narrower than the one obtained with the power law model. It is concluded that the piecewise linear model is not adapted for stability study. A proposed explanation is that the critical current criterion E_c is arbitrary, and therefore a linearization around (V_c,i_c) doesn't provide necessarily a good physical model. The observation of the shape of the stability region obtained with the power law model demonstrates the importance of the shunt resistance. Indeed, the value of the upper stability limit (dotted line in Fig. 9) can be predicted from (2) by considering the shunt resistance r_{sh} of the r-ScFCL,

$$P_s \leq \frac{(r + r_{sh})\,c}{l} V_e^2. \tag{10}$$

A higher shunt resistance would therefore allow one to widen even more the stability region of the DC grid.

IV. Conclusion

In this article, we studied the possibility of using a resistive superconducting fault current limiter (r-ScFCL) together with a classical RLC filter to passively stabilize a DC grid above the limit offered by the RLC filter alone. This power filter functionality is obtained by using the r-ScFCL below but around its critical current. One advantage of the proposed solution, in comparison with conventional passive stabilization, is that the efficiency of the system is not reduced in nominal operation. We compared here two lumped-parameter electrical models of the r-ScFCL, neglecting thermal effects. It is shown that a piecewise linear model obtained by linearization of the superconductor equation around its critical current is not adapted for stability studies. The power law model seems proper. It enabled us to predict the stability region of a DC grid with a constant power load and a r-ScFCL. Further studies should clarify the limitations of the power law model and include detailed thermal analysis. Only then it will be possible to evaluate the technical and economic feasibility of using a r-ScFCL as a power filter.

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