

2 DC equivalent model of rectifier module

The equivalent circuit with the series resistor which is located in the 10kVAC side is shown in Fig.2.

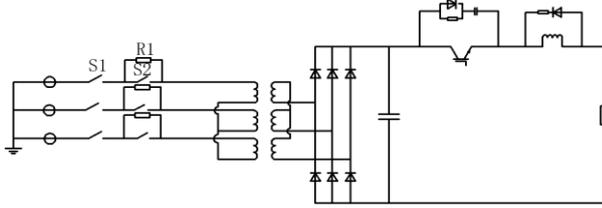


Fig. 2. The equivalent model of rectifying module.

The AC source charges the capacitor through the soft-start resistor, transformer, and three-phase uncontrolled rectifier, and then the DC output of the rectifying module is controlled by the IGBT switch. The process of charging the filter capacitor is called the soft start process. The parameters of each branch are equal, mutual influence can be ignored, and the current and voltage on each branch are approximately equal, so the model in Fig.2 can be simplified as DC equivalent circuit which is shown in Fig.3.

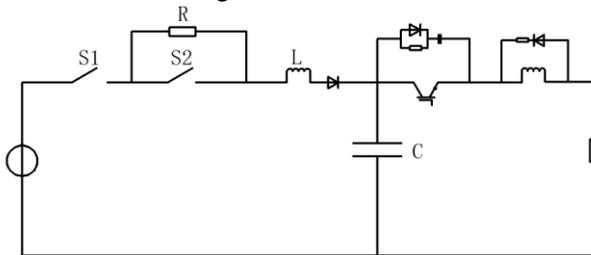


Fig. 3. The DC equivalent circuit of rectifying module.

The basic parameters of multi-winding transformer are shown in Table 1.

Table 1. The basic parameters of multi-winding transformer.

	Primary side	Secondary side
Rated power S_N	3150kVA	
Rated voltage U_{NL}	10kV	600V
Number of Winding	1	44
Short-circuit impedance U_K	4%	
Field current I_f	0.73A	

When the leakage inductance is converted to DC side, the leakage inductance can be calculated by the conventional method of transformer. The leakage inductance is expressed as follow equation:

$$L' = \left[\frac{\left(\frac{U_{2NL}}{\sqrt{3}} \right)^2}{\frac{S_N}{3N}} \right] U_K \quad (1)$$

U_{2NL} : line voltage of secondary side
 N: number of secondary winding

Because the current always flows over two phases, when the filter capacitor is charged, the DC side resistor is two times of it in the AC side.

Equivalent inductance:

$$L = 2L' \quad (2)$$

Equivalent resistor:

$$R = \frac{2NR_{soft}}{K^2} \quad (3)$$

R_{soft} : soft-start resistor

3 The analysis of soft-start process

The soft-start process consists of two steps:

1) The first step is that the soft-start resistor is connected into the circuit, the filter capacitor is charged to the first steady state value through the soft-start resistor.

2) The second step is that the soft-start resistor is removed, so the filter capacitor is charged to the second steady state value.

3.1. The charging process with the soft-start resistor

The charging equivalent circuit with the soft-start resistor is shown in Fig.4.

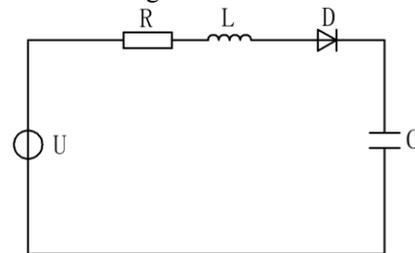


Fig. 4. The charging equivalent circuit with the soft-start resistor.

The transfer function of the filter capacitor voltage and step excitation is established as follow equation.

$$\frac{U_C(s)}{U_i(s)} = \frac{1/LC}{s^2 + s(R/L) + (1/LC)} \quad (4)$$

And the characteristic equation of transfer

function is $s^2 + s(R/L) + (1/LC) = 0$, so

$$\Delta = (R/L)^2 - 4 \frac{1}{LC}$$

When $\Delta < 0$, the equivalent resistor satisfies $R < 2\sqrt{\frac{L}{C}}$, the circuit is underdamped. It will cause overshoot of the output voltage. In order to avoid overshoot, Δ should be more than zero, the equivalent resistor should satisfy $R > 2\sqrt{\frac{L}{C}}$, so that the circuit is overdamped. Take note of (3), the soft-start resistor can be defined by:

$$R_{soft} > \frac{K^2}{N} \sqrt{\frac{L}{C}} \quad (5)$$

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If the resistor is large enough to satisfy $R \gg 2\sqrt{\frac{L}{C}}$, the RLC circuit can be equivalent to a RC circuit, so,

$$\begin{cases} U_C(t) = U(1 - e^{-\frac{t}{RC}}) \\ i_C = \frac{U}{R}e^{-\frac{t}{RC}} \end{cases} \quad (6)$$

U: Input voltage of DC equivalent circuit

The peak current of charging is express as follow equation:

$$i_{max1} = \frac{U}{\frac{2NR_{soft}}{K^2}} \quad (7)$$

In order to ensure that the rectifying bridge and capacitor can withstand maximum current, the charging current must be less than 300A, therefore the soft-start resistor should satisfy:

$$R_{soft} > \frac{K^2U}{2N \times 300} \quad (8)$$

According to (5), when $N=1$, $\frac{K^2}{N}\sqrt{\frac{L}{C}}$ get the maximum $K^2\sqrt{\frac{L}{C}}$, so the soft-start resistor satisfy:

$$R_{soft} > K^2\sqrt{\frac{L}{C}}$$

The circuit is simulated by selecting different soft-start resistor, the results are shown in Figure 5. According to the design of the module, the simulation parameters are set as follows:

- 1) Input voltage of DC equivalent circuit U: 1000V.
- 2) Equivalent inductance of DC equivalent circuit L: 2mH.
- 3) Filter capacitor C: 10mF.

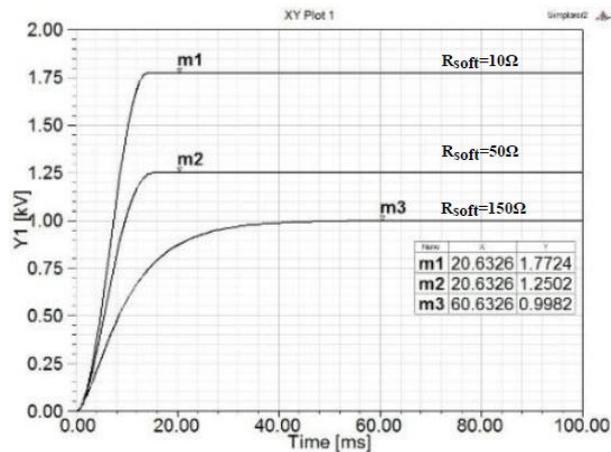


Fig. 5. The capacitor voltage of different soft-start resistor.

Table 2. The Influence of soft-start resistor on charge voltage.

R _{soft} (Ω)	Steady time T(ms)	Steady voltage U _C (V)
10	14	1772
50	16	1250
150	60	998

According to Fig.5 and Table 2, when the soft-start resistor is less than $K^2\sqrt{\frac{L}{C}}$ which is equal to 124Ω

according to the simulation parameters, the circuit is underdamped, the steady voltage of filter capacitor is larger than 1000V, and furthermore, the overshoot voltage is smaller with the increase of the soft start resistor. When the soft-start resistor is larger than $K^2\sqrt{\frac{L}{C}}$ which is equal to 124Ω, the circuit is over damped, the steady voltage of filter capacitor is about 1000V, and the capacitor is charged without overshoot.

3.2 The charging process of removing the soft-start resistor

When the filter capacitor is charged to the first steady state value, the voltage is less than the rated value because of soft-start resistor voltage drop, so the soft-start resistor must be removed to get the rated value and reduce the power loss. The soft-start resistor is removed by closing S2 in Fig.3, then the capacitor will be charged again to the rated value. The equivalent circuit is shown in Fig.6.

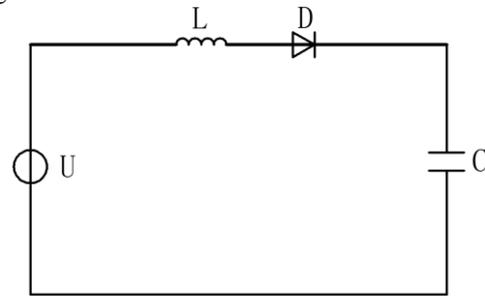


Fig. 6. The removing process of soft-start resistor.

The voltage drop of soft-start resistor which is produced by transformer magnetizing current is $\Delta U = I_f R_{soft}$, the excitation can be equivalent to:

$$u_i = \frac{\sqrt{2}\sqrt{3}I_f R_{soft}}{K} = \frac{\sqrt{6}I_f R_{soft}}{K}$$

The time domain expression is established as follow equation.

$$LC \frac{d^2 u_C}{dt^2} + u_C = u_i \quad (9)$$

According to the initial condition of filter capacitor: $u_C = U - \frac{\sqrt{6}I_f R_{soft}}{K}$, $C \frac{du_C}{dt} = 0$, the capacitance voltage and current are expressed as follow:

$$\begin{cases} u_C = U - \frac{\sqrt{6}I_f R_{soft}}{K} \cos \frac{t}{\sqrt{LC}} \\ i_C = \frac{\sqrt{6}I_f R_{soft}}{K} \sqrt{\frac{C}{L}} \sin \frac{t}{\sqrt{LC}} \end{cases} \quad (10)$$

According to (10), the voltage increment of filter capacitor is:

$$\Delta u_C = \frac{2\sqrt{6}I_f R_{soft}}{K} \quad (11)$$

The peak current is expressed as follow equation:

$$i_{max2} = \frac{\sqrt{6}I_f R_{soft}}{K} \sqrt{\frac{C}{L}} \quad (12)$$

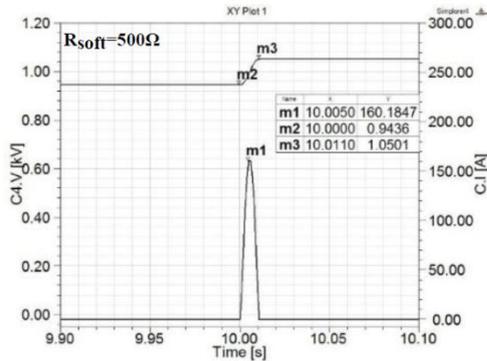
In order to ensure that the charging current is less than 300A, the soft-start resistor should satisfy:

$$R_{soft} < \frac{300K}{\sqrt{6}I_f} \sqrt{\frac{L}{C}} \quad (13)$$

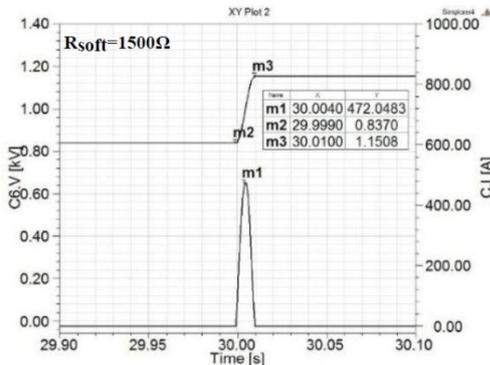
The circuit is simulated by selecting different soft-start resistor, the selection of resistor need to guarantee that the circuit is over damped. According to the simulation parameters, the soft-start resistor must

be $R_{soft} > K^2 \sqrt{\frac{L}{C}}$ and the simulation parameters are set as follows:

- 1) Input voltage of DC equivalent circuit U: 1000V.
- 2) Equivalent inductance of DC equivalent circuit L: 2mH.
- 3) Filter capacitor C: 10mF.



(a) $R_{soft}=500\Omega$



(b) $R_{soft}=1500\Omega$

Fig. 7. The capacitor voltage of removing different soft-start resistor.

Table 3. The Influence of soft-start resistor on charge voltage and current.

$R_{soft}(\Omega)$	$I_{max2} (A)$	$U_1 (V)$	$U_2 (V)$	ΔU
500	160	943	1050	107
1500	472	837	1150	313

I_{max2} : Maximum charging current of removing the soft-start resistor.

U_1 : The initial voltage of the filter capacitor before removing the soft-start resistor.

U_2 : The steady voltage of the filter capacitor after removing the soft-start resistor.

ΔU : The voltage change of the filter capacitor by removing the soft-start resistor.

According to (13), when the soft-start resistor is less than $\frac{300K}{\sqrt{6}I_f} \sqrt{\frac{L}{C}}$, which is equal to 968Ω , the rectifying bridge and capacitor can withstand maximum current 300A. Take note of Table 3, when $R_{soft}=500 < 968\Omega$, $I_{max2}=160 < 300A$, and when $R=1500 > 968\Omega$, $I_{max2}=472 > 300A$. According to (12) and Table 3, I_{max2} will enlarge with the increase of the soft-start resistor, and according to (11) and Table 3, ΔU will enlarge with the increase of the soft-start resistor. So in order to reduce voltage fluctuation of filter capacitor, the soft-start resistor should be reduced as far as possible.

According to the analysis, the design of the soft-start resistor must meet the following conditions.

(1) In order to avoid overshoot, the soft-start resistor must satisfy:

$$R_{soft} > K^2 \sqrt{\frac{L}{C}}$$

(2) In order to ensure that the rectifying bridge and capacitor can withstand the maximum charging current, the soft-start resistor must satisfy:

$$\frac{K^2 U_i}{2N \times 300} < R_{soft} < \frac{300K}{\sqrt{6}I_f} \sqrt{\frac{L}{C}}$$

4 The resistor design of HVPS for ECRH system

According to the multi-windings transformer parameters in the HVPS for 140GHz ECRH system, the leakage inductance of transformer can be calculated as follow:

$$L_1 = \frac{\left[\frac{(U_{2N})^2}{\sqrt{3}} \right] X_N \%}{2\pi f} = \frac{\left(\frac{600}{\sqrt{3}} \right)^2 \times 4\%}{2\pi \times 50} = 0.6mH$$

So the equivalent inductance is:

$$L = 2L_1 = 1.2mH$$

To ensure that the output voltage ripple is less than 1%, the filter capacitor is selected as follow:

$$C = 10mF$$

According to condition (1), in order to avoid voltage overshoot the soft-start resistor must satisfy:

$$R_{soft} > K^2 \sqrt{\frac{L}{C}} = 111\Omega$$

According to condition (2), in order to limit the maximum charging current the soft-start resistor must satisfy:

$$5\Omega = \frac{K^2 U_i}{2N \times 300} < R_{soft} < \frac{300K}{\sqrt{6}I_f} \sqrt{\frac{L}{C}} = 1118\Omega$$

Actually the soft-start resistor is designed for 300Ω in the HVPS for ECRH system. Some experiment results are shown in Fig.8 and Fig.9.

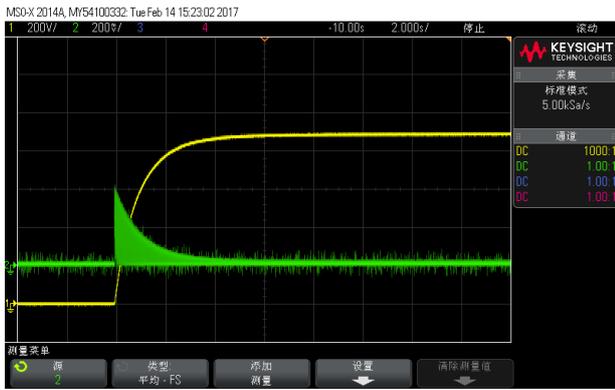


Fig. 8.The capacitor charging waveform with the soft-start resistor.

X-axis: 2s/div
 Y-axis: 200V/div, 8A/div

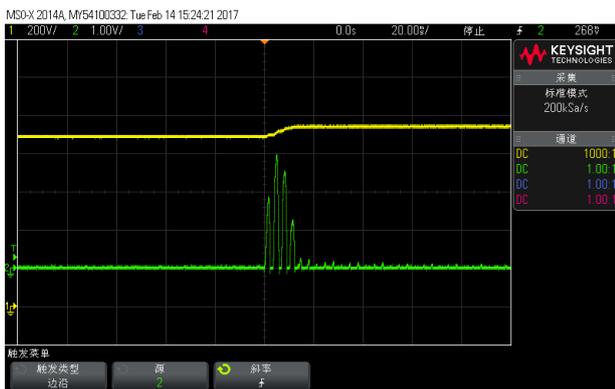


Fig. 9.The capacitor charging waveform of removing the soft-start resistor.

X-axis: 2s/div
 Y-axis: 200V/div, 40A/div

In Fig.8, the maximum value of charging current with the resistor is 16A and the first steady state voltage is 870V. In Fig.9, the maximum current value of removing the resistor is 110A and the second steady state voltage is about 930V. The voltage change of the capacitor is about 60V.

According to (7) and (12), the calculation for the maximum value of charging current is 11A and 93A for different process. According to (11), the voltage change is 64V. The experimental results are in agreement with the theoretical analysis.

5 Conclusion

The soft-start process of HVPS based on PSM technology is studied in this paper. A simplified DC equivalent model is proposed, and the transient and steady state responses of the soft-start process are analysed in detail. The qualifications are obtained and proved by simulation results. The soft-start resistor has been designed for the HVPS of the 140GHz ECRH system, and the final experimental results show that it is coincident with the theoretical analysis.

This work was supported by the National Magnetic Confinement Fusion Science Program of China under contract No. 2015GB103000, the National Key Research & Development Plan 2017YFE0300401, and CAS Key Technology Talent Program.

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