CIGRE US National Committee
2016 Grid of the Future Symposium

Insulation Coordination of FREEDM Solid State Transformers

Xuening Rong, Dongdong Zhang, George Karady, Gerald Heydt

School of Electrical, Computer and Energy Engineering
Arizona State University, Tempe, AZ 85287

This work is supported by the National Science Foundation

Outline

- Background

  Introduction of FREEDM SST structure and functions

- Simulation Method and Result

  Overvoltage and overcurrent response on each element in SST

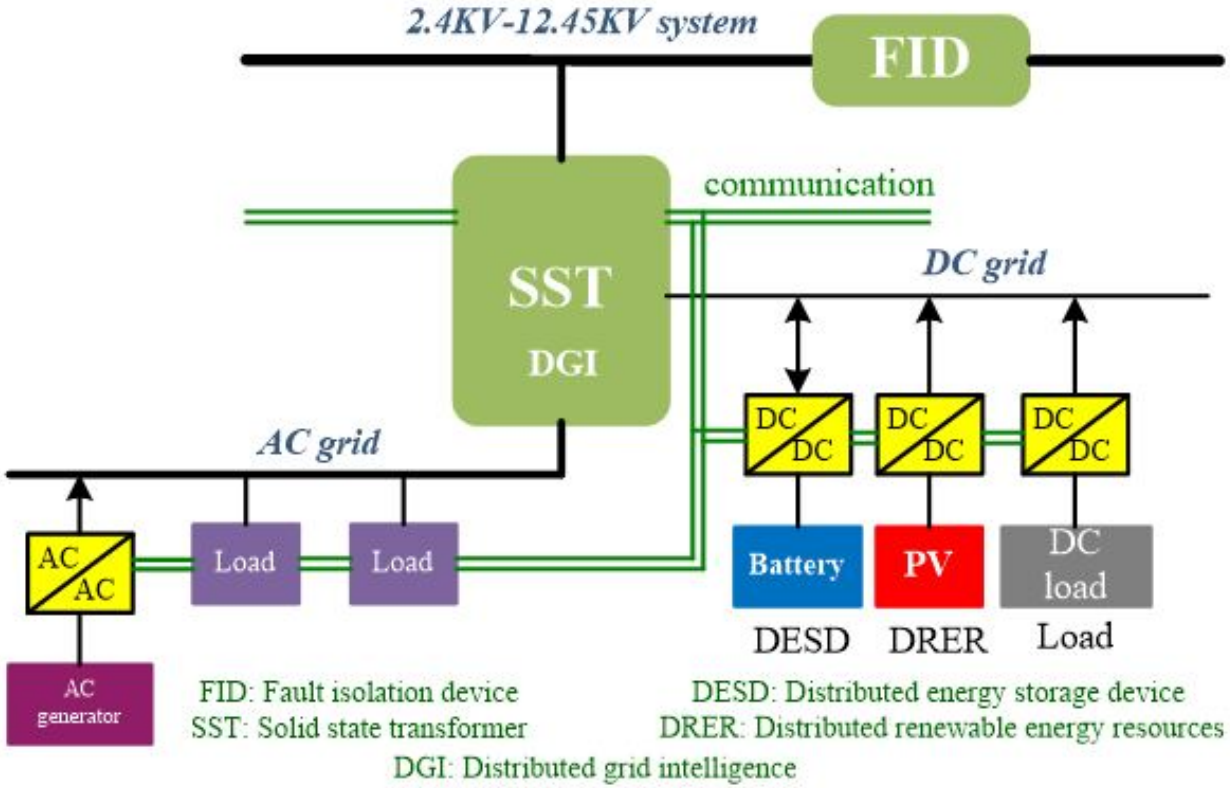
- MOA Protection Analysis

  Circuit diagram and performance of SST before and after the implementation of MOA

- Conclusion and Future Work

Background

FREEDM -- Future Renewable Electric Energy Delivery and Management (FREEDM) system



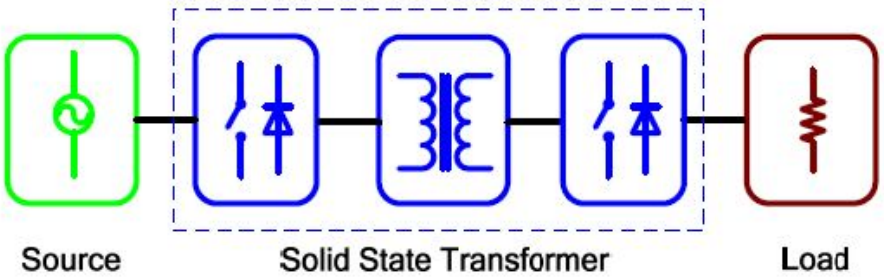
https://freedm.wordpress.ncsu.edu/sst/

Background

Solid State Transformer -- an integral and important asset in the FREEDM System.

SST is a smart transformer that consists of:

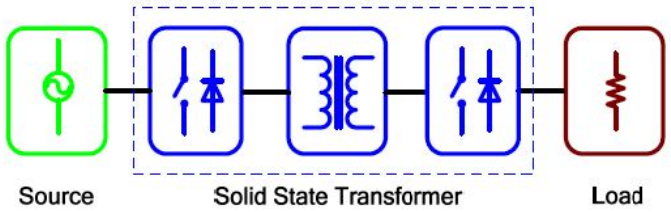
- High-powered semiconductors
- High-frequency transformers
- System providing flexible control to power distribution networks
- Communication capability



https://freedm.wordpress.ncsu.edu/sst/

Background

SST Function -- Voltage conversion



SST Advantage compared with traditional transformer

- Reduced physical size and weight
- Actively change power characteristics
- Power flow control
- Power factor correction
- Energy storage

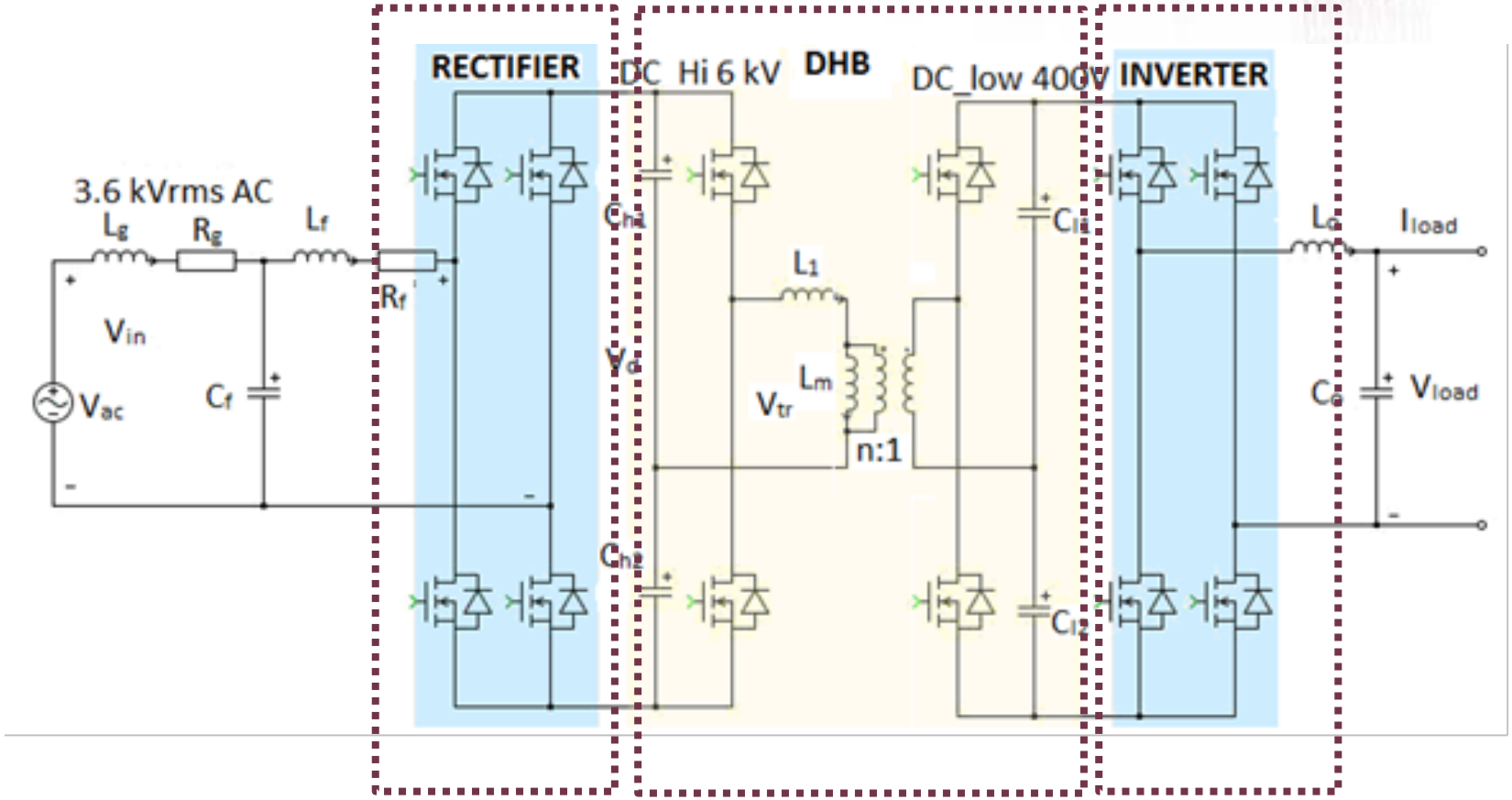
But the protection of the SST under lightning strikes remains an open topic.

Topics already discussed:

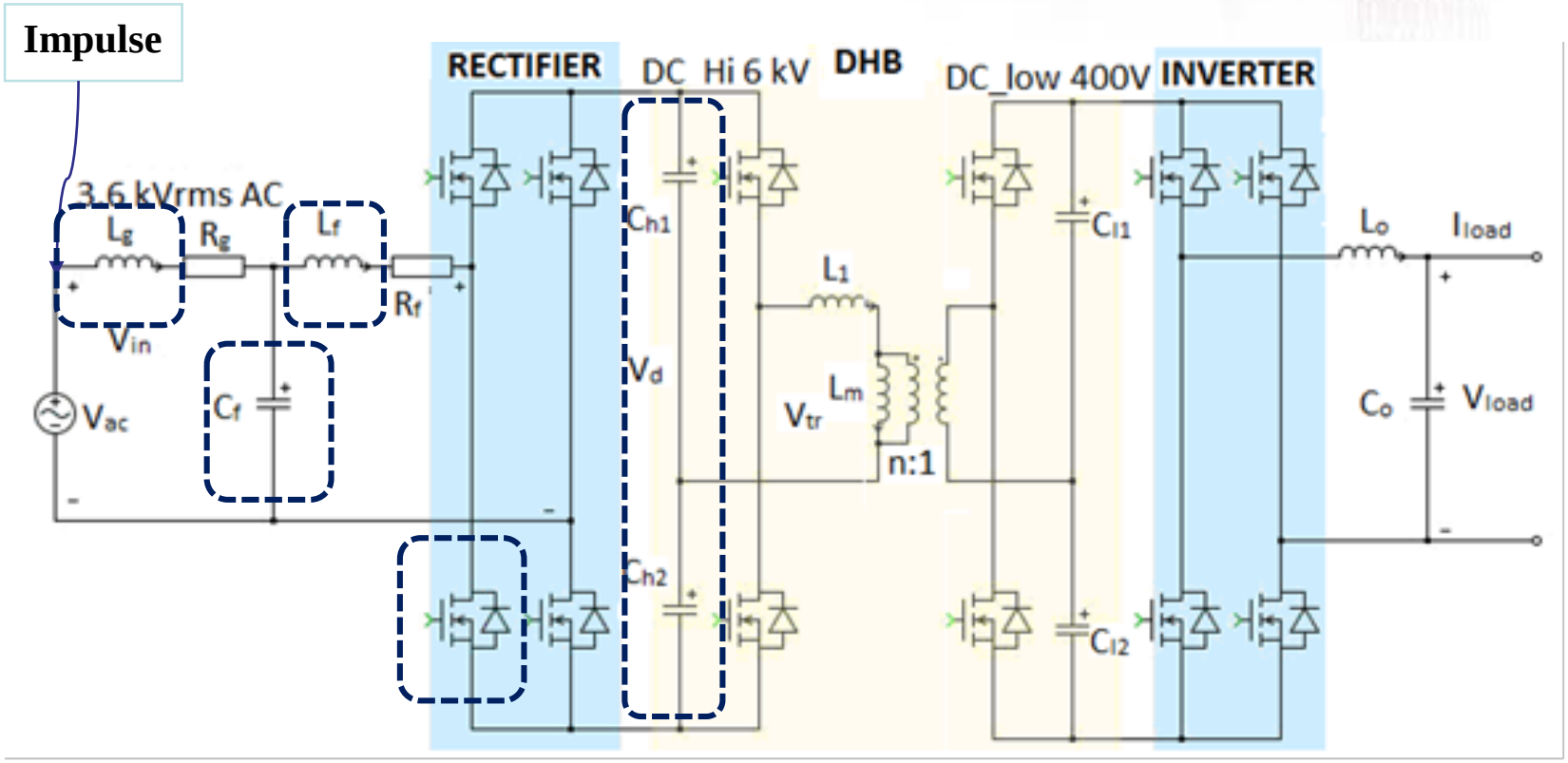
- The design and control of the SST
- Fast acting devices to isolate faults (fault current limiter)

https://freedm.wordpress.ncsu.edu/sst/

Switching Model of SST



Switching Model of SST



Simulation Method

The single-phase SST is simulated under ***non-operating*** condition

- The source voltage V_{ac} is set as ***zero***.
- The control of rectifier, DHB and inverter is ***shut down***.

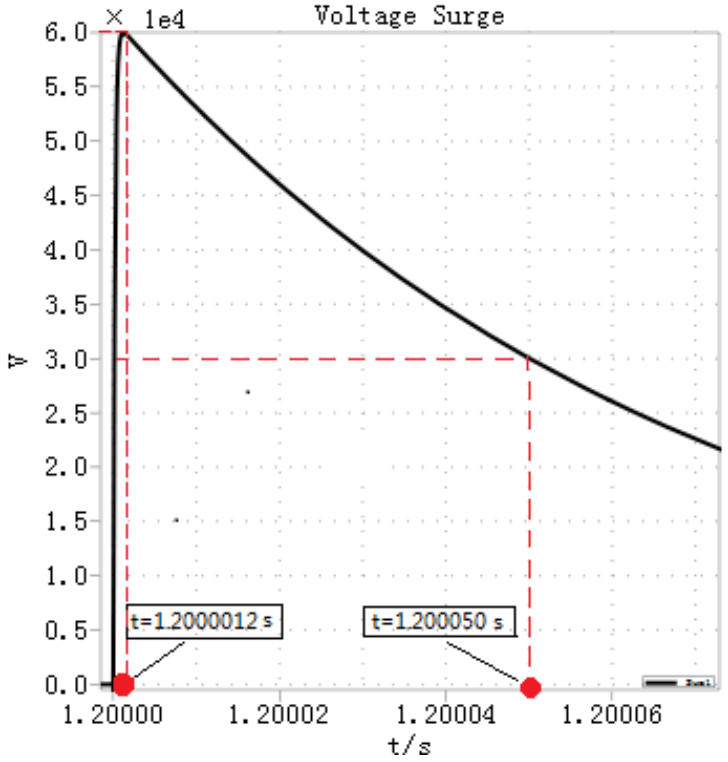
The 1.2/50 μs 60 kV voltage surge due to transmission line direct lightning is simulated according to standard IEC-60071

Voltage Surge

The wave shape is implemented as a ***double exponential***.

The parameters used for impulse wave are: T_1=1.2μs, T_2=50μs, V_{peak}=60kV.

This voltage impulse is ***directly applied at the SST filter front end*** at t = 1.2s.



Over-voltage response of each electrical element in the FREEDM SST

- Voltage and current on L_g
- Voltage and current on L_f
- Voltage and current on C_f
- Voltage and current on semiconductors in rectifier
- Voltage and current on C_h

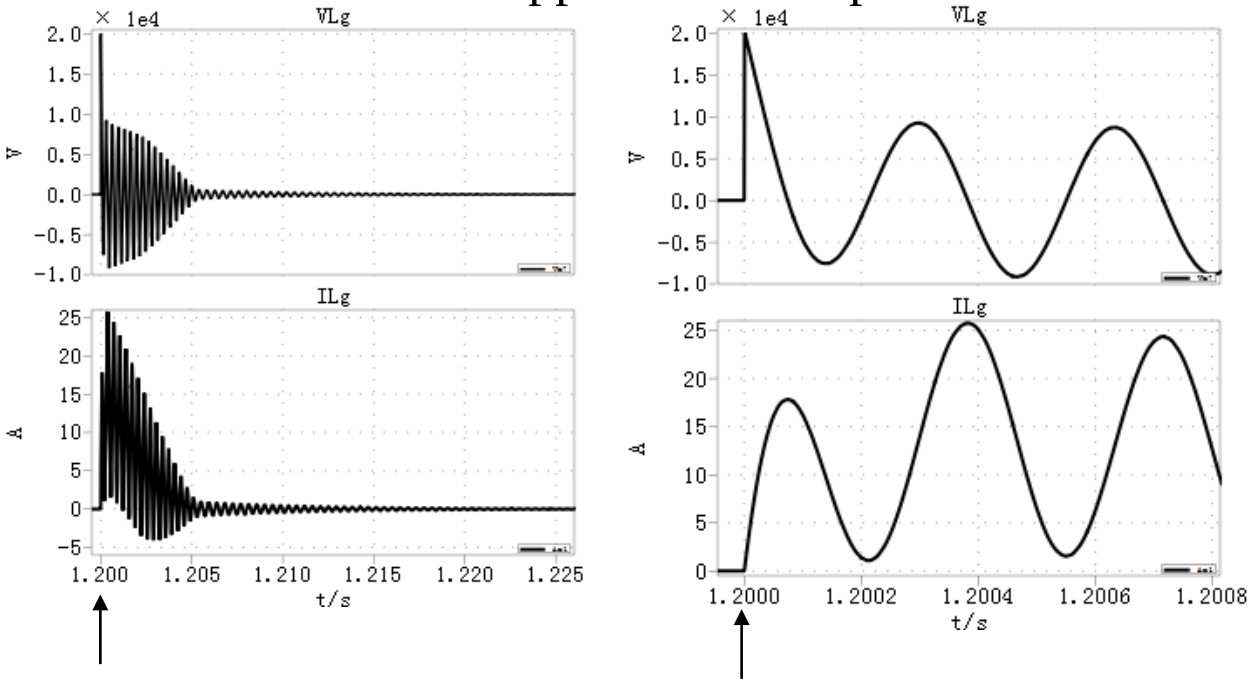
Voltage and current on L_g

Condition:

Source voltage zero, controller not operating

Voltage impulse: 60kV 1.2/50μs impulse

Applied to the input at 1.2s



V_{Lg_pk} = 19.98 kV

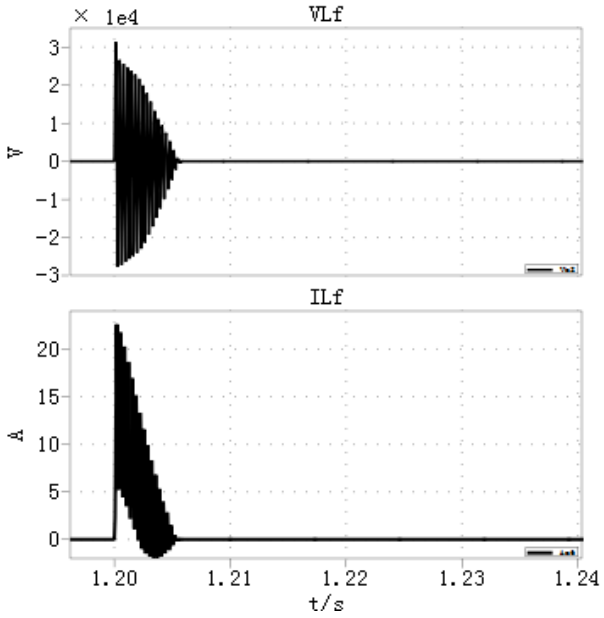
$\frac{dV_{Lg}}{dt}$ = 191.40 k$V/\mu s$

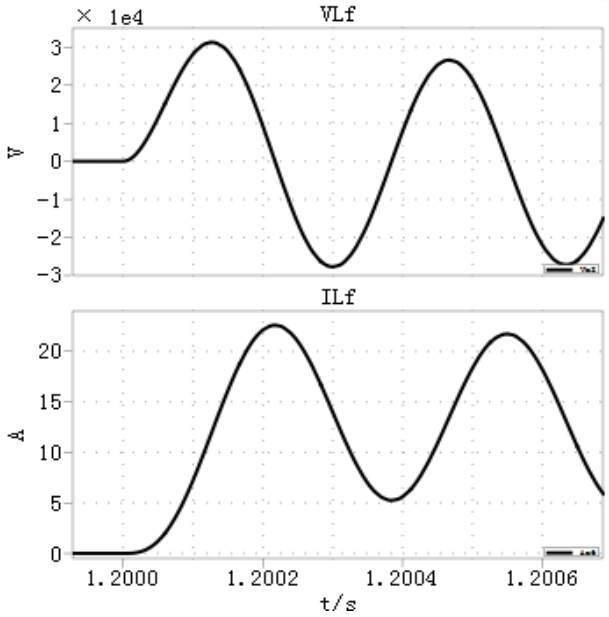
I_{Lg_pk} = 25.72 A

$\frac{dILg}{dt}$ = 4.91 $A/\mu s$

Measures should be taken to protect L_g in the front filter.

Voltage and current on L_f





$V_{Lf\_pk} = 31.30$ kV

$\frac{dV_{Lf}}{dt} = 1.54\ \mathrm{kV}/\mu s$

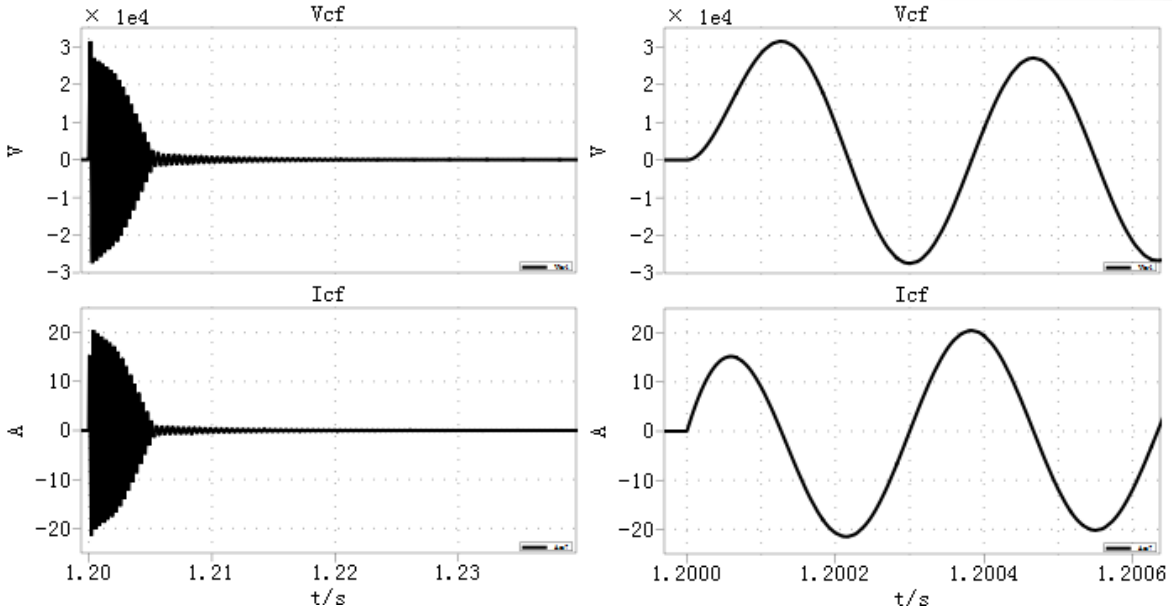
$I_{Lf\_pk} = 22.57$ A

$\frac{dILf}{dt} = 1.84\ A/\mu s$

Summary:

- The increasing rates for the surges are tolerable.
- The magnitudes of the voltage and current impulses on L_f are excessive, measures should be taken to protect L_f in the front filter.

Voltage and current on C_f



$V_{cf\_pk} = 31.45$ kV

$\frac{dV_{cf}}{dt} = 5.15\ \mathrm{kV}/\mu s$

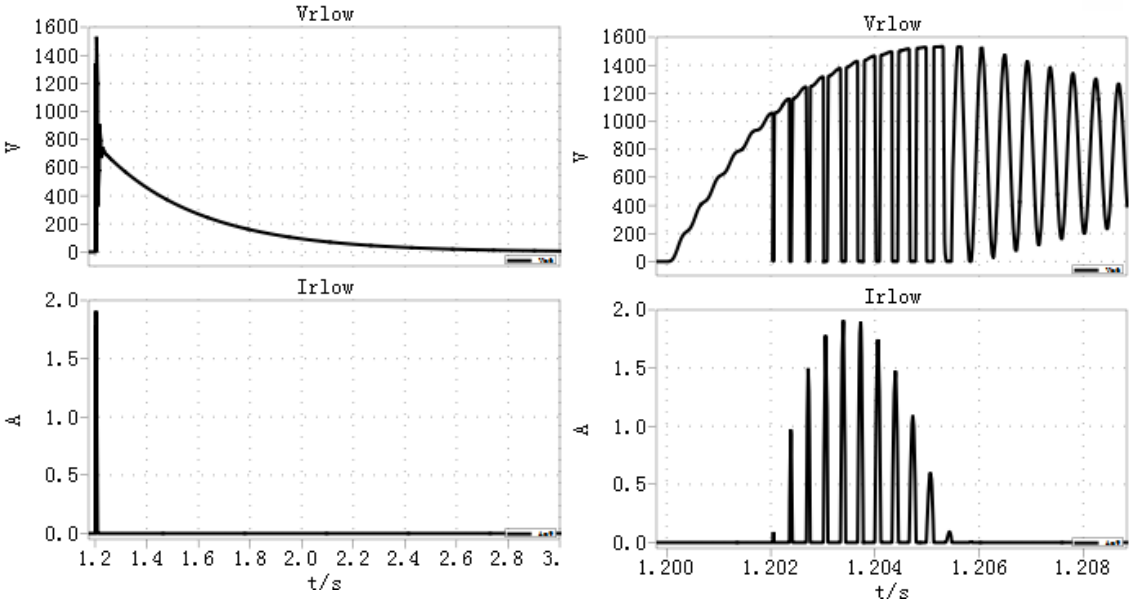
$I_{cf\_pk} = 20.61$ A

$\frac{dIcf}{dt} = 4.91\ A/\mu s$

Summary:

- The increasing rates for the surges are tolerable.
- The magnitudes of the voltage and current surge on C_f are again excessive, measures should be taken to protect C_f in the front filter.

Voltage and current on semiconductors in rectifier



$V_{rlow\_pk} = 1.54$ kV

$\frac{dV_{rlow}}{dt} = 15.26\ V/\mu s$

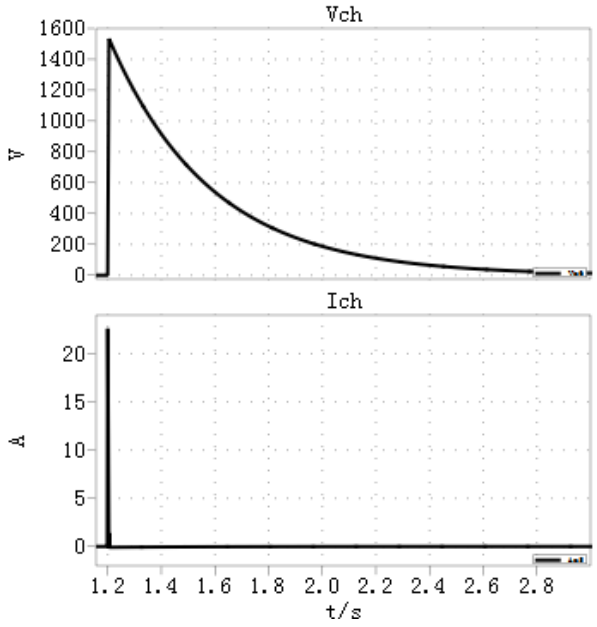
$I_{rlow\_pk} = 1.92$ A

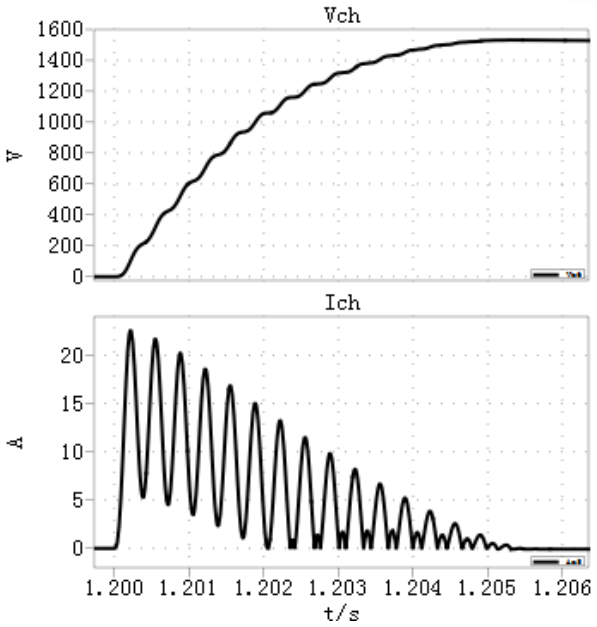
$\frac{dIrlow}{dt} = 0.76\ A/\mu s$

Summary:

The over voltage and over current on semiconductors in rectifier are tolerable in this design.

Voltage and current on C_h





$V_{ch\_pk} = 1.54$ kV

$\frac{dV_{ch}}{dt} = 10.75\ V/\mu s$

$I_{ch\_pk} = 22.57$ A

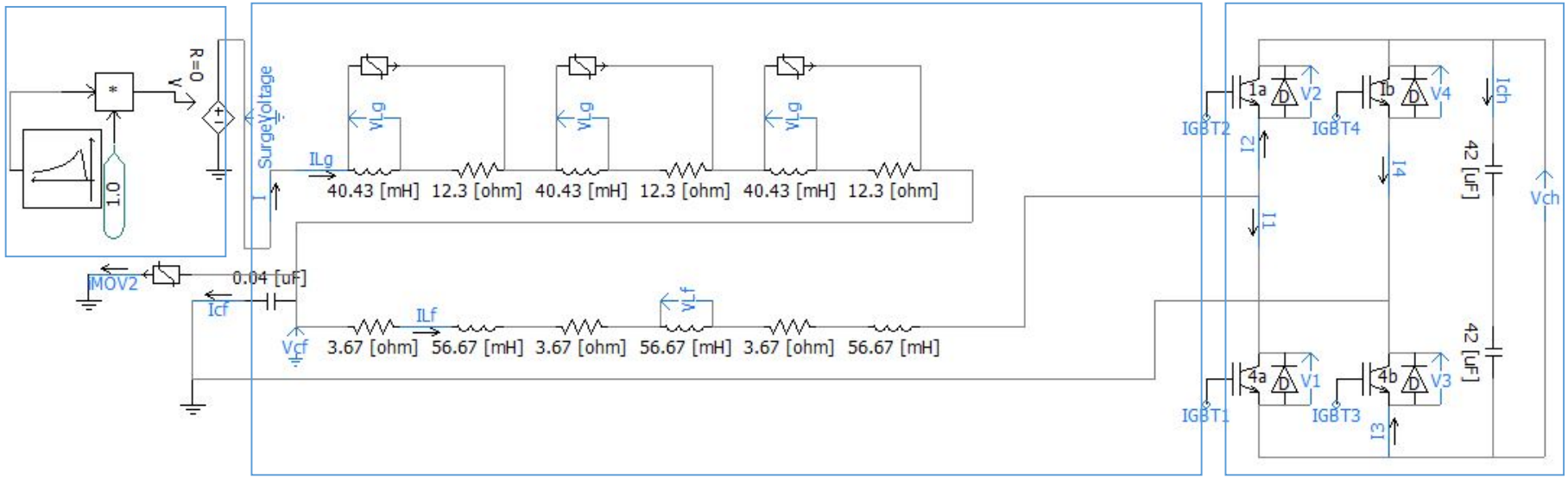
$\frac{dIch}{dt} = 1.84\ A/\mu s$

Summary:

The over voltage and over current on capacitor C_h in rectifier are tolerable in this design.

MOA Protection Analysis

Circuit Diagram in PSCAD



Lightning strike source

SST front filter

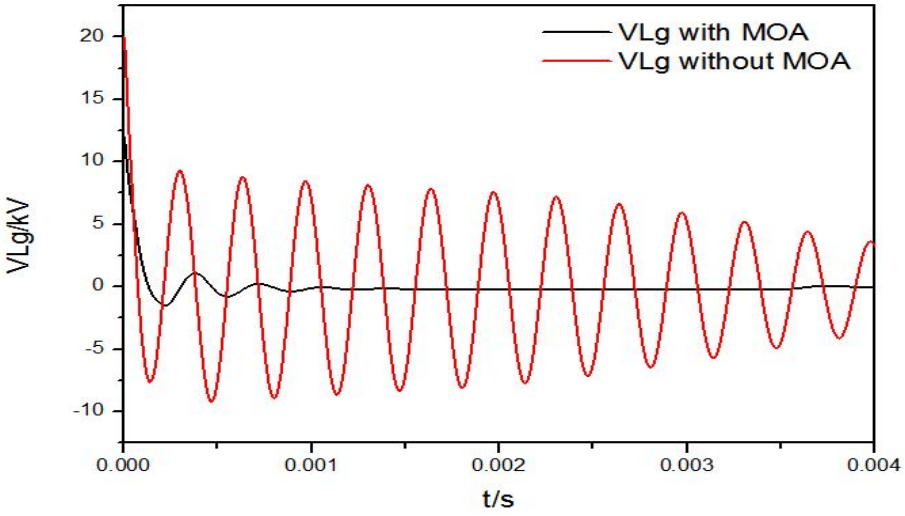
SST rectifier bridge

Performance of SST before and after the installation of MOA

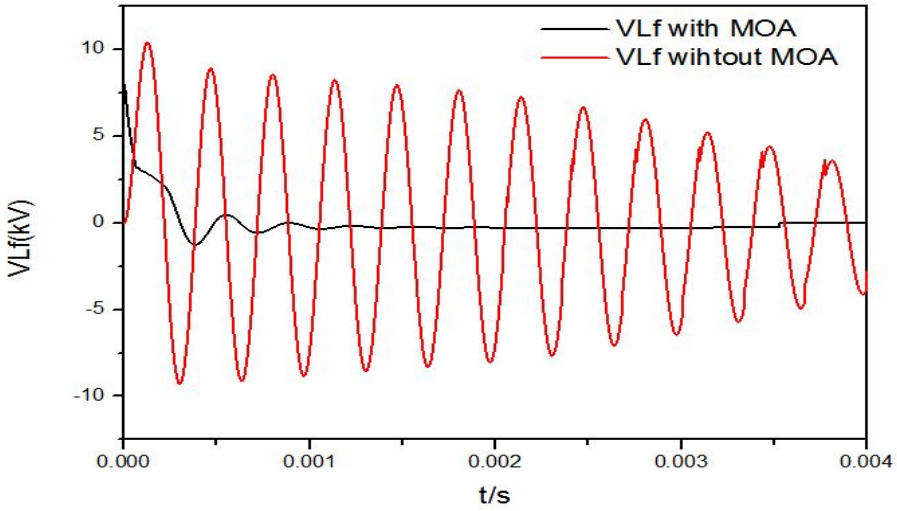
Model Property		Without MOA	With MOAs		Model Property		Without MOA	With MOAs	
			Value	Reduction Ratio σ(%)				Value	Reduction Ratio σ(%)
L_g	V_{Lg}	19.98 kV	11.99 kV	***39.99%***	R_{up}	V_{rup}	1.54 kV	0.46 kV	70.13%
	I_{lg}	25.72 A	7.73 A	69.95%		I_{rup}	22.57 A	9.28 A	58.88%
L_f	V_{Lf}	10.43 kV	8.99 kV	***13.81%***	R_{low}	V_{rlow}	1.54 kV	0.78 kV	49.35%
	I_{Lf}	22.57 A	9.28 A	58.88%		I_{rlow}	1.92 A	1.56 A	18.75%
C_f	V_{cf}	31.45 kV	23.99 kV	***23.72%***	C_h	V_{ch}	1.54 kV	0.78 kV	49.35%
	I_{cf}	20.61 A	915.49 A			I_{ch}	22.57 A	9.28 A	58.88%

σ(%) = (Value with two MOA – Value with one MOA) /(Value with one MOA) * 100%

Typical Results



Voltage surge on front filter inductor L_g before and after installation of MOA



Voltage surge on front filter inductor L_f before and after installation of MOA

Conclusion and Future Work

Conclusion

- The protection of SST from lightning is discussed
- The overvoltage response of each electrical element in the FREEDM SST is concluded
- An MOA is placed in parallel with the front filter capacitor and additional MOAs are implemented in parallel with the front filter inductor to protect the SST front filter components and semiconductors inside the SST.

Future Work

- The lightning pulse effects on the operating SST will be identified using the same simulation method
- A physical lightning test on the FREEDM SST would be carried out to validate the simulation results and provide more specific data as well

Thank you!