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Insulation Coordination of FREEDM Solid State Transformer

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SUMMARY

With the development of semiconductors, power electronics systems could act as one of the effective methods to integrate distributed renewable energy resources (DRERs) into power systems. However, when directly connected to transmission lines, those solid state devices might be subjected to a voltage impulse caused by lightning strikes or circuit switching. The Solid State Transformer (SST) in the Future Renewable Electric Energy Delivery and Management (FREEDM) system [1] is used to manage DRERs, loads and power flow. In these types of applications, since the SST is connected to the primary distribution supply line, a voltage surge caused by lightning strikes on the distribution line may damage the SST front filter components or the semiconductor elements in the SST. The protection of the SST under lightning strikes could be a good example of the insulation coordination of solid state devices. This case could also be applied to other similar electric equipment.

In this paper, the insulation coordination, dynamic performance and protection of typical components in the SST are analyzed. The simulation of a single-phase non-operating SST in FREEDM system under 60 kV, 1.2/50 μs lightning impulse is conducted based on standard IEC-60071. The simulation is done in both Piece-wise Linear Electrical Circuit Simulation (PLECS) [2] and Power Systems Computer Aided Design (PSCAD) software to get more objective results.

According to the simulation results, the lightning strike could cause voltage surge on electrical components inside the FREEDM SST. Placing an applied metal oxide surge arrester (MOA, also known as a metal oxide varistor, MOV) in parallel with the front filter capacitor and additional MOAs in parallel with the front filter inductor could provide effective protection. This configuration reduces the overvoltage by as much as 70.13%.

KEYWORDS

Insulation Coordination, Solid State Transformer, Semiconductor, Lightning Protection, Metal Oxide Surge Arrester, FREEDM System, Over-Voltage

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I. INTRODUCTION

An SST acts as an integral and important asset in the FREEDM System [3]. Compared with traditional distribution transformers, the functions of the SST are not limited to voltage conversion. An SST can also achieve power flow control, power factor correction and energy storage management [1] [4]. The design and control of the SST have been widely discussed [5] [6], and fast acting devices to isolate faults have been designed [7]. A related asset proposed for the FREEDM system is a fault current limiter. The topology of a fault current limiter has been proposed [8], but the protection of the SST under lightning strikes remains an open topic.

As depicted in Fig. 1, the SST model consists of three parts. The circuit segment following the filter is a rectifier which converts 3.6 kVrms AC to 6 kV DC. The rectifier controls both the high voltage dc-link voltage and the grid current. The second part is a Dual-Half-Bridge (DHB) which converts 6 kV DC to 400 V DC. Galvanic isolation between high and low voltage circuits is provided by the DHB with a high frequency transformer. The third part is an inverter which inverts 400 V DC to 120 Vrms AC, regulating voltage on the load side.

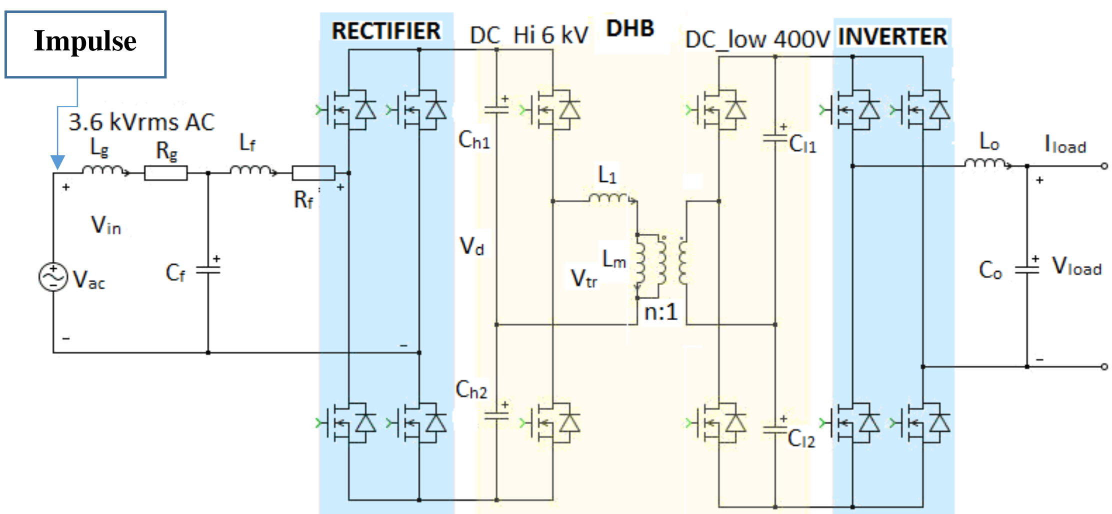

Fig. 1 SST connection diagram

Table 1 states SST basic specifications.

Table 1 GEN II SST parameters

Rectifier Parameters			
Grid voltage RMS	3.6 kV	HV dc voltage	6 kV
L_g	121.3 mH	R_g	36.87 Ω
L_f	170 mH	R_f	11 Ω
C_f	0.04 µF	Switching frequency	6 kHz
C_{h1}, C_{h2}	42 µF	Sampling frequency	12 kHz

A lightning strike is regarded as one of the main reasons for transformer failure [9]. Many researches on large oil transformer lightning surge response performance have been done so far, where most of the simulated models were made up of distributed RLC circuit [10]. In those studies, it is indicated that Zinc oxide arresters can be commonly used to protect the typical transformer operation from lightning surge [11].

Unlike traditional oil transformer, SST is much more complicated in circuit structure and contains power electronic devices. But currently little work has been done in the lightning surge response and its corresponding protection of the SST in the grid. In this paper, the simulation of a single-phase non-operating SST under a 60 kV, 1.2/50 µs lightning impulse is conducted based on standard IEC-60071.

II. SIMULATION METHOD

In this paper, the simulation is based on the switching model of FREEDM SST. The grid voltage is set as zero. The SST is under non-operating condition, the control of rectifier, DHB and inverter is shut down. The simulation is done in both PLECS and PSCAD platforms. Since a physical front filter for SST is going to be built, according to data sheet, three inductors rated 3 kV are connected in series as L_g.

According to IEC-60071, the voltage surge due to transmission line direct lightning is simulated in the waveform in Fig. 2, the parameters used for impulse wave are: $T1$=1.2 µs, $T2$=50 µs, $Vpeak$=60 kV. The wave shape is implemented as a double exponential. This 1.2/50 µs 60 kV voltage impulse is directly applied at the SST filter front end at t = 1.2s.

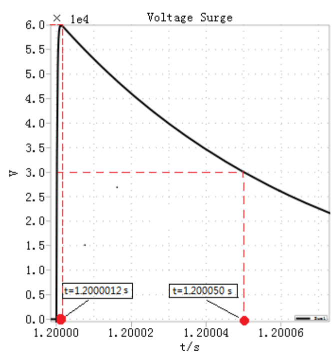

Fig. 2 1.2/50µs Lightning impulse

A voltage impulse caused by lightning strike on the grid side mainly affects the front filter and rectifier in the SST because of the galvanic isolation provided by the high frequency transformer. Therefore, the voltage and current across inductors and the capacitor in the front filter and semiconductors in the rectifier are simulated and analysed in this paper.

III. OVER-VOLTAGE RESPONSE OF EACH ELECTRICAL ELEMENT IN THE FREEDM SST

As shown in Fig. 3, the value and increasing rate of V_{Lg} (voltage across each front filter inductor L_g) and I_{Lg} (current through front filter inductor L_g) can be calculated as,

- Voltage across L_g: V_{Lg_pk} = 19.98 kV, increasing rate for voltage: dV_{Lg}/dt = 191.40 kV/µs,
- current through L_g: I_{Lg_pk} = 25.72 A, increasing rate for current: dI_{Lg}/dt = 4.91 A/µs

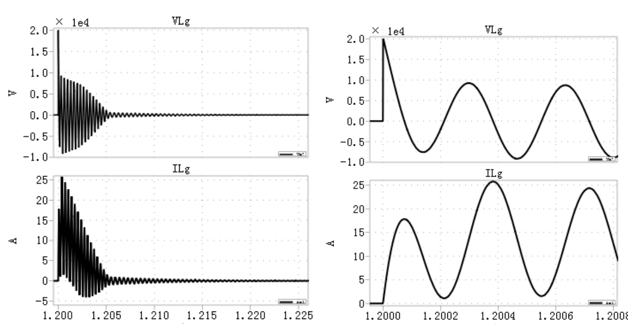

Fig. 3 V_{Lg} I_{Lg} when impulse was applied

(a) Overall trend for voltage and current surge on L_g (b) Enlarged picture of voltage and current surge on L_g

The magnitudes of the voltage and current surge on L_g are excessive as seen in this case. The increasing rates for the surges are tolerable, measures should be taken to protect L_g in the front filter. As shown in Fig. 4, the value and increasing rate of V_{Lf} (voltage across front filter inductor L_f) and I_{Lf} (current through front filter inductor L_f) can be calculated by,

- Voltage across L_f: V_{Lf_pk} = 31.30 kV, increasing rate for voltage: dV_{Lf}/dt = 1.54 kV/μs,
- current through L_f: I_{Lf_pk} = 22.57 A, increasing rate for current: dI_{Lf}/dt = 1.84 A/μs

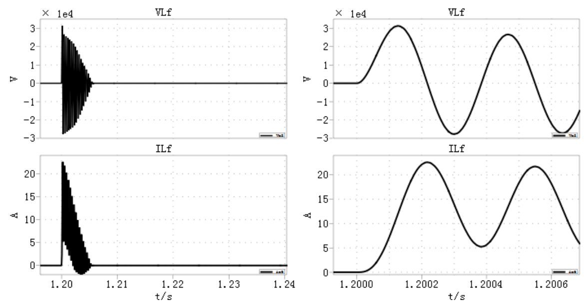

Fig. 4 V_{Lf} I_{Lf} when impulse was applied

(a) Overall trend for voltage and current surge on L_f (b) Enlarged picture of voltage and current surge on L_f

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

As shown in Fig. 5, the value and increasing rate of V_{cf} (voltage across front filter capacitor C_f) and I_{cf} (current through front filter inductor C_f) can be calculated by the equation below:

- Voltage across C_f: V_{cf_pk} = 31.45 kV, increasing rate for voltage: dV_{cf}/dt = 5.15 kV/μs,
- Current through C_f: I_{cf_pk} = 20.61 A, increasing rate for current: dI_{cf}/dt = 4.91 A/μs

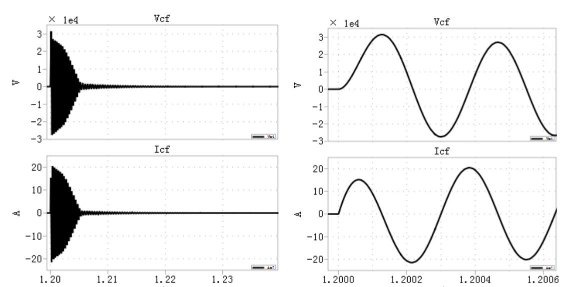

Fig. 5 V_{cf} I_{cf} when impulse was applied

(a) Overall trend for voltage and current surge on C_f (b) Enlarged picture of voltage and current surge on C_f

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

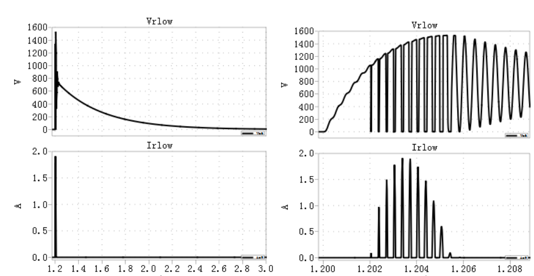

Fig. 6 V_{rlow} I_{rlow} when impulse was applied

(a)Overall trend for voltage and current surge on *Rlow* (b) Enlarged picture of voltage and current surge on *Rlow*

Fig. 6 is an example of voltage and current surges on semiconductors in rectifier, the value and increasing rate of V_{rlow} (voltage across lower semiconductor in rectifier) and I_{rlow} (current through lower semiconductor in rectifier) can be calculated by the equation below:

- Voltage across *Rlow*: V_{rlow} = 1.54 kV, increasing rate for voltage: dV_{rlow}/dt = 15.26 V/μs,
- Current through *Rlow*: I_{rlow} = 1.92 A, increasing rate for current: dI_{rlow}/dt = 0.76 A/μs

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

As shown in Fig. 7, the value and increasing rate of V_{ch} (voltage across capacitor C_h) and I_{ch} (current through front filter inductor C_h) can be calculated by,

- Voltage across C_h: V_{ch_pk} = 1.54 kV, increasing rate for voltage: dV_{ch}/dt = 10.75 V/μs,
- Current through C_h: I_{ch_pk} = 22.57 A, increasing rate for current: dI_{ch}/dt = 1.84 A/μs

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

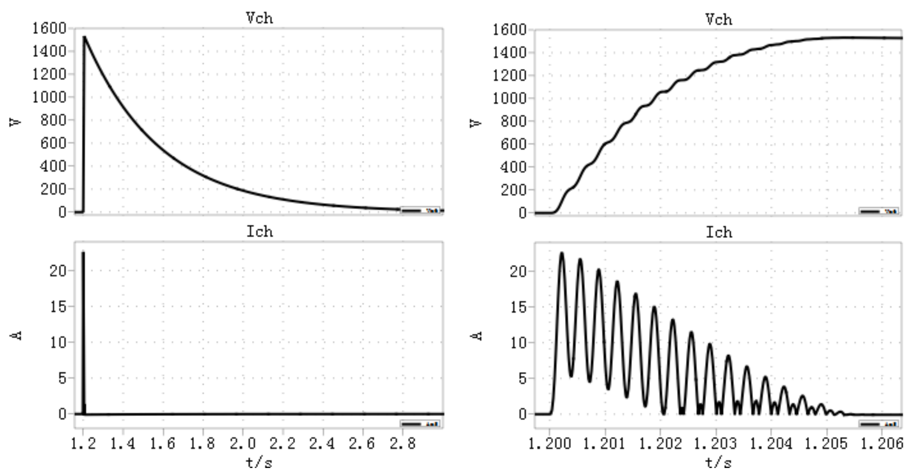

Fig. 7 V_{ch} I_{ch} when impulse was applied

(a)Overall trend for voltage and current surge on C_h (b) Enlarged picture of voltage and current surge on C_h

IV. MOA PROTECTION ANALYSIS

According to the simulation results, the lightning impulse has certain undesirable effects on the FREEDM SST. As shown in Fig. 9, the application of a MOA is discussed to protect the SST. The system is simulated in PSCAD. A surge arresters was placed in parallel with the capacitor C_f in the front filter to protect L_f and semiconductors from the voltage surge. The filter inductances are designed as three inductors connected in series rated at 3 kV AC voltage. Surge arresters rated 3 kV are chosen and placed in parallel with each front filter inductor L_g to protect L_g from over-voltage [12]. Therefore, three additional MOAs rated 3 kV are placed in parallel with front filter inductor L_g to protect L_g from over-voltage.

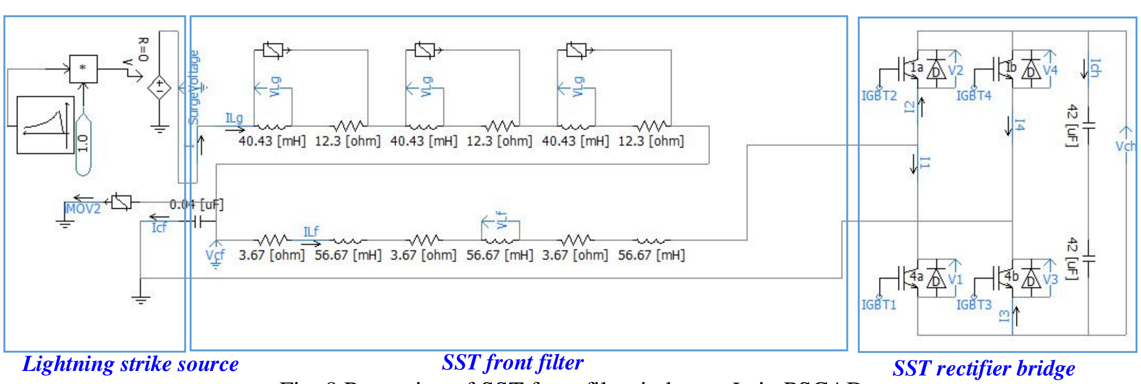

Fig. 8 Protection of SST front filter inductor L_g in PSCAD

Table 2 compares the performance of SST before and after the implementation of MOA.

Table 2. 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	[redacted]		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 are shown in Fig. 9.

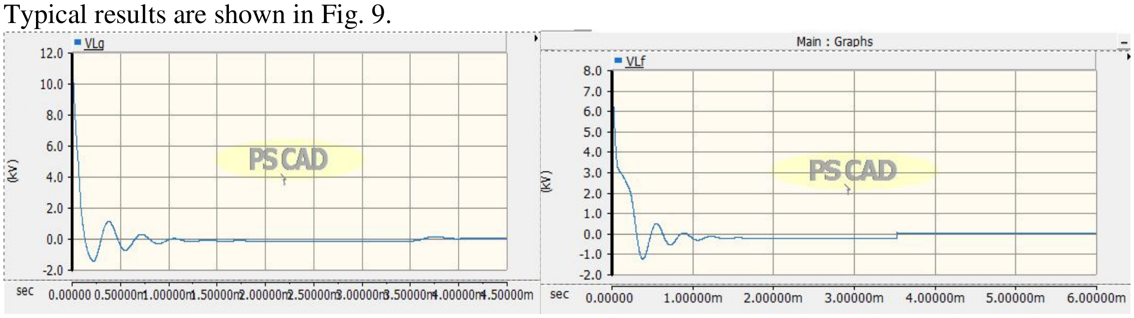

Fig. 9 V_{Lg} V_{Lf} after installation of MOA

(a) Voltage surge on L_g after installation of MOA (b) Voltage surge on L_f after installation of MOA

It is shown in Table 2 that lightning impulse could cause an unacceptably high voltage surge on across filter inductors in the SST. The overvoltage level across inductor L_g is high. Under 60 kV lightning voltage, the maximum voltage on L_g reaches 19.98 kV. The over-voltage across L_f and C_f is also large. Accordingly, the components in the front filter need to be protected.

Installing an MOA in parallel with the front filter capacitor C_f has positive effects in restricting the maximum overvoltage values across C_f and L_f, reducing the voltage surge by 23.72% and 13.81% respectively. Applying additional MOAs in parallel with L_g reduces the voltage surge by 39.99% on L_g.

The increase of current through front filter capacitor C_f (I_{cf}) after the installation of MOAs is tolerable. Currents through other components all decreases when MOAs are applied. Basically the voltage reduction was achieved by the surge arresters shunted the inductances (L_g), the inductances not shunted by the surge arresters (L_f) reduced the current.

CONCLUSIONS and FUTURE WORK

Lightning strikes could cause transformer failure and affect power system stability. Zinc oxide arresters are used to protect traditional distribution transformers from lightning; however, the protection of an SST under a lightning strike is rarely discussed in the literature. When connected directly to the transmission lines, power electronic devices might be damaged by the lightning voltage impulse. The protection of a FREEDM SST under lightning strike could be a good example of the insulation coordination of solid state devices.

In this paper, 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.

In the future, the lightening 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.

BIBLIOGRAPHY

[1] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, S. J. Dale, "Energy Delivery and Management (FREEDM) System: The Energy Internet," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 133-148, 2011.

[2] J. H. Allmeling, and W. P. Hammer, "PLECS Piece-wise Linear Electrical Circuit Simulation for Simulink," Proceedings of the IEEE, vol. 1, pp. 355-360, 1999.

[3] X. Zhou, Y. Liu, S. Bhattacharya, and A. Huang, "New inductor current feedback control with active harmonics injection for inverter stage of solid state transformer," *Industrial Electronics Conference*, 2010, pp. 593–598.

[4] O. Vodyakho, M. Steurer, D. Neumayr, C. S. Edrington, G. Karady, and S. Bhattacharya, "Solid-state fault isolation devices: application to future power electronics-based distribution systems," *IET Electric Power Applications*, vol. 5, no. 6, pp. 521-528, 2011.

[5] Z. Yu, R. Ayyanar, and I. Husain "A detailed analytical model of a solid state transformer," in *IEEE 2015 Energy Conversion Congress and Exposition*, pp. 723–729.

[6] S. Bhattacharya, T. Zhao, G. Wang, S. Dutta, S. Baek, Y. Du, B. Parkhideh, X. Zhou, and A. Q. Huang, "Design and development of Generation-I Silicon based solid state transformer," in *IEEE 2010 Applied Power Electronics Conference and Exposition,* pp. 1666–1673.

[7] O. Vodyakho, M. Steurer, C. Edrington, G. Karady, B. Chowdhury, and S. Bhattacharya, "Design of a solid state fault isolation device for implementation in power electronics based distribution systems," in *North American Power Symposium*, 2009, pp. 1-6.

[8] J. Prigmore, and G. Karady, "A Novel 7.2 kV fault current limiter for use in the FREEDM project," in *IEEE Transmission and Distribution Conference and Exposition*, 2012, pp. 1–7.

[9] T. Zhao, G. Wang, J. Zeng, S. Dutta, S. Bhattacharya, and A. Q. Huang, "Voltage and power balance control for a cascaded multilevel solid state transformer," in *IEEE 2010 Applied Power Electronics Conference and Exposition*, pp. 761–767.

[10] Shigemitsu Okabe, Masanori Koto, Genyo Ueta, Toshiyuki Saida, Shin Yamada, "Development of high frequency circuit model for oil-immersed power transformers and its application for lightning surge analysis," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 18, no. 2, pp. 541-552, 2011.

[11] P. N. Mikropoulos, T. E. Tsovilis, and S. G. Koutoula, "Lightning performance of distribution transformer feeding GSM base station," *IEEE Transactions on Power Delivery*, vol. 29, no. 6, pp. 2570–2579, 2014.

[12] Siemens, "Siemens Catalogue LV 60," 2005, Germany.