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Development of a Pre-Insertion Resistor for an 800 kV EHV GIS Circuit-Breaker

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SUMMARY

EHV/UHV power transmission systems are widely used for bulk power transmission from remote power plants to densely populated load centres. As EHV/UHV substations are connected by overhead transmission line with a distance longer than 300 km, the switching surges might exceed the insulation level of the transmission line. Controlled switching or pre-insertion resistors (closing resistors) are used to limit switching surges and provide the necessary margins. This paper briefly discusses pre-insertion resistor (PIR) and pre-insertion switch (PIS) for circuit-breakers (CB) in EHV/UHV power system and its design and realization for GIS.

An 800kV CB with parallel PIR is developed, which is compact in footprint and with better life-cycle performance. PIS is linked mechanically to the CB's drive, and a head-head contact system ensures reliable coordination of their mechanical movement and the effective electrical pre-insertion time. Simulations are performed to investigate on pre-insertion time. And a PIS making test shows its good making ability. The separated resistor tank can accommodate resistors with large thermal capacity to meet demanding duty cycle as well as a wide selection range of resistance.

The thermal capacity of PIR is deeply investigated. Non-linear performance of resistor material, different insertion instant and different resistance are considered. Dynamic resistance and energy injection in one duty cycle are presented, which helps to better understand PIR work process and essential influence factors. Also thermal capacity test is conducted to verify the design. Based on test data, the most severe voltage stress and instant are investigated. Calculation and test result show that PIR is able to withstand the severe duty cycle Close-Open operation (CO)-30min- Close-Open operation (CO) at 2 p.u..

Test approach in PIS making test and PIR thermal capacity test which is developed in cooperation with the test laboratory can be applied in other product development.

KEYWORDS

Circuit-Breaker (CB), Pre-Insertion Resistor (PIR), Pre-Insertion Switch (PIS), Thermal Capacity, Making Test

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1 Introduction

EHV/UHV line breakers energize transmission lines or reclose after a fault. In the worst case, the re-closure may occur when the trapped charge on the line is at opposite polarity [1] of the source voltage, generating a higher transient switching overvoltage. The switching overvoltage (SOV) could cause flashovers between the conductors and the towers of the transmission line and may damage the insulation systems of other attached equipment such as transformers and switchgears. The cost for the insulation systems would increase without limiting devices such as closing resistors and surge arresters [2].

A pre-insertion resistor (PIR), integrated in a CB, is a typical method to reduce switching surges. Circuit breakers with PIR are occasionally used at rated voltages of 362-420 kV and more often at voltages of 550-1100(1200) kV [1]. Approximately 50% of CB applications installed are directly connected to a transmission line [1]. Reducing the switching overvoltage will minimize design and overall costs of a transmission system [2].

The pre-insertion resistor reduces voltage transients when a no-load transmission line is energized or re-energized after a line fault. In addition to closing resistors, metal-oxide surge arresters (MOSAs) are recommended. A combination of closing resistors and MOSAs would lead to a further decrease of the SOV's maximum amplitude [2]. The PIR's resistance value is selected to provide an optimum compromise between reduction of switching surges and high thermal capacity of the resistor. Typically, pre-insertion resistors limit switching surges to 1.8 p.u. A typical 750 kV substation design shows that the overvoltage can be lowered from 2.5 p.u. to 1.26 p.u. by combining MOSAs and a 600 Ω PIR [3, 5].

2 PIR and PIS Design

2.1 PIR Scheme Design

PIRs are used in two different circuits [4]. The resistor can be connected to the interrupter electrically in parallel or in series, requiring different closing and opening sequences. Figure.1 shows the circuits and Table 1 compares the features of circuit differences.

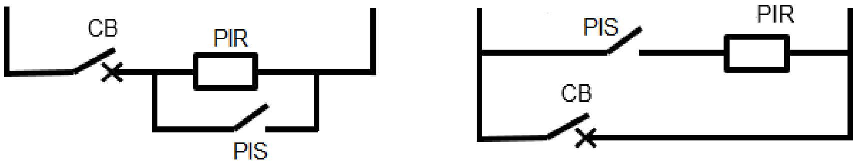


Figure 1 Resistor connected to CB in series (left) and in parallel (right)

In series resistor design, the PIS is operated by the same operating mechanism as the CB and is mechanically connected in series to the CB's interrupter(s). Before closing of the main CB contacts, the PIS shortens the PIR after the pre-insertion time, typically 8-11ms. In parallel resistor design, the PIR stack is connected in parallel to the CB interrupter. The PIS closes first, followed by the CB main contacts after the pre-insertion time. The PIS can be opened as soon as the CB is closed. The PIS can be operated by the CB's or by a separate operating mechanism.

In both designs, the PIR needs to be dimensioned according to the system voltage and the required switching duties.

Table 1 Comparison of series and parallel circuits

No.	Item	Series Connection of PIR and CB	Parallel Connection of PIR and CB
1	Layout with CB	Larger single enclosure to accommodate PIR and interrupter; cost lower; but capacity limited	Smaller but may needs a separate enclosure; larger capacity for all application when enclosure separated.
2	Current flow	PIS carries rated current and short circuit current	PIS does not carry current after closing operation
3	Thermal capacity	Limited by enclosure dimensions (length). Only applicable for high	Allows large variation of thermal

No.	Item	Series Connection of PIR and CB	Parallel Connection of PIR and CB
		resistance values.	capacity.
4	Dielectric insulation level of PIS contact gap	Comparable to disconnector gap, withstand BIL, Out of Phase level	Comparable to disconnector gap, withstand BIL, Out of Phase level
5	PIS function	switch full short circuit current	switch several thousand A depending on PIR resistance value
6	PIS mech. linkage	Mechanical linkage connected with CB's drive during closing & opening.	Mechanical linkage connected with CB's drive for closing; Disconnected after CB closed
7	Safety	Small particles from PIR could impact on dielectric stress	Individual tank avoids the interference between CB and PIR

When connected in series, the PIS short-circuits the resistor and must be able to carry the rated current and the short-time current. Thermal capacity and insulation distances to the tank are limited by available space. Switching by-products and exhaust gases might influence PIR and PIS. When connected in parallel, the PIS contact only needs to be able to carry a few kA during the pre-insertion time.

Considering the above, the team developed a parallel PIR for an 800 kV GIS CB. As in previous designs, the resistor stack is contained in a separate tank in parallel to the CB. The PIR tank can accommodate more resistor disc, and promises good thermal performance with 300 Ω at lowest. Figure 2 shows a complete circuit breaker with PIS and PIR. Based on modular design, PIR and CB tanks are detachable which results in smaller and easier-to-handle assembly and shipping units. Both CB and PIS are operated by the same operating mechanism.

Figure 2 A complete view of 800kV GIS Circuit Breaker with PIR and PIS

2.2 PIR Thermal Capacity Design

The thermal capacity of PIR is determined by the most demanding duty cycle, its resistance, the pre-insertion time and the thermal behaviour of the resistor elements. The most demanding duty cycle is a CO-30min-CO sequence at phase opposition (180° phase shift between source and line side).

The duty cycle and the PIR's resistance determine the amount of thermal energy that needs to be absorbed by the resistor elements without exceeding their permissible operating temperature. The required number of resistor elements (discs) can be arranged in parallel and series connected stacks. An optimum combination of parallel circuits stacked in series provides the compact dimensions to fit the tank and the insulation to the enclosure, while keeping the voltage peak across each element within a permissible level. The circuit is determined by several iterations to meet the disc's requirement and to achieve a compact structure of the PIR and the PIS.

The disc's performance is defined by following characteristics:

1) Thermal capacity
2) Voltage withstand ability
3) Mechanical withstand ability
4) Dimension tolerance

To meet characteristic 1), a set of calculations and simulations are applied. The temperature rise of the resistor's bulk material is determined by number of discs in the stack, heat capacity per disc and the cooling system comprising heat sinks and SF6 gas convection in the tank. The temperature rise must be limited in all cases to the permissible operating temperature of the discs.
Characteristic 2) determines the number of serially connected discs and consequently the circuit stack. Stray capacitances may contribute to an uneven voltage distribution along the stack and should be considered.
Characteristic 3) and 4) relate to the mechanical stress imposed on an individual disc as they must not be damaged while being compressed or bent.
Table 2 gives an example for a PIR with 450 Ω for an 800kV CB. In this case, the maximum calculated temperature is 128℃. Similar calculations for resistance values from 300Ω to 1500Ω show that voltage withstand level and thermal capacity limits of the discs are satisfied.

Table 2 PIR Thermal Capacity Design

PIR data		
Total resistance	Ω	450
Number of resistor discs		450
Resistance per disc	Ω	25
Line voltage	kV rms	800
Insertion time	ms	10
Specific heat capacity of the active material	$J.cm^{-3}.°C^{-1}$	2
Ambient temperature	°C	80
Cooling time	s	1800
Thermal time constant	s	4622
Disc characteristics		
Maximum voltage withstand rms	kV/disc	19.3
Maximum temperature	°C	250
Voltage withstand ability		
Working voltage rms	KV/disc	10.26
Safety factor rms， >40%	%	46.87
Thermal Capacity		
Maximum energy per operation	MJ	20.86
Maximum energy per cm^3	$J.cm^{-3}$	107.35
CO-CO with 30 min cooling	°C	110.61
CO-CO without cooling	°C	128.03

The resistance of the PIR disc has a non-linear dependency on the applied voltage inject and the bulk material temperature. The absorbed energy depends also on the instant of closing in relation to the power cycle. The calculation of the temperature rise requires solving a set of differential equations governed by:

Injected energy: $$E(t) = \int \frac{U(t)^2}{R(t)} dt$$

Temperature rise: $$dT(t) = \frac{E(t)}{V \cdot n \cdot C_m}$$

R(t) denotes the instantaneous value of the PIR resistance which depends on the disc's temperature and the applied voltage. C_m denotes the specific heat capacity of the resistor bulk material; *V* denotes the volume per disc and *n* the number of discs in the entire stack.
Figure 3 shows the results at a pre-insertion time of 11 ms and a resistance of 400 Ω for two closing instants, one closes at maximum voltage peak, the other is at zero point of applied voltage.

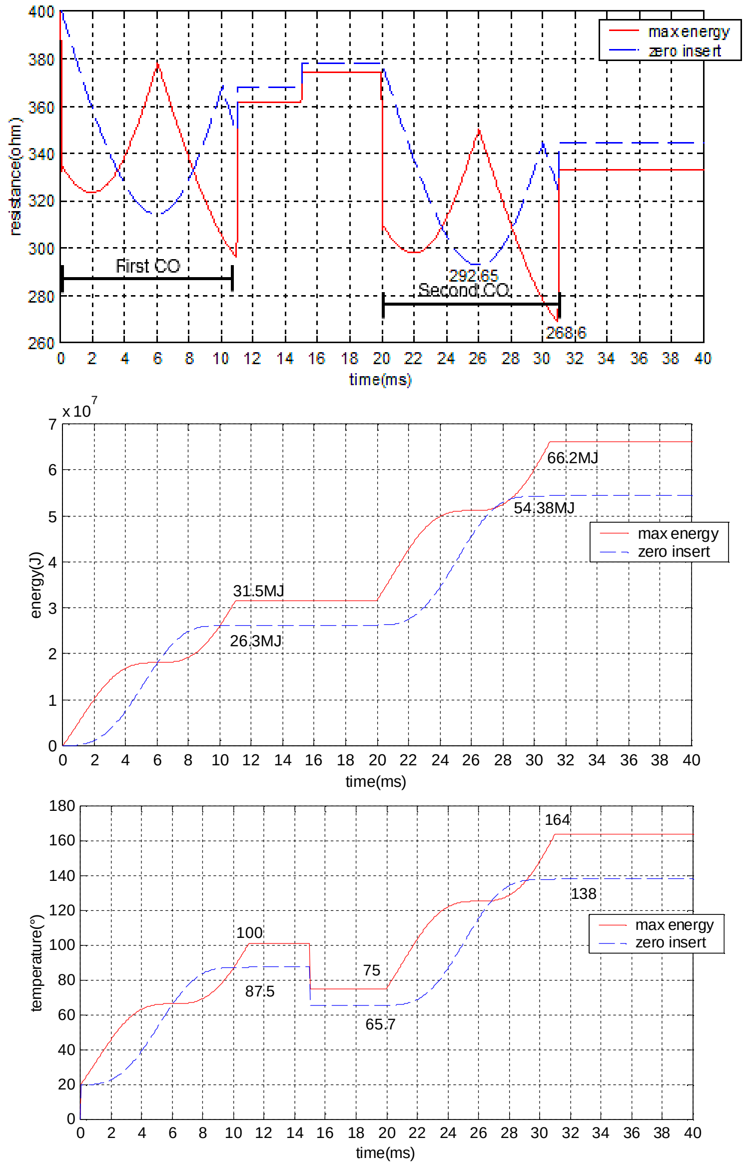


Figure 3 Resistor disc thermal and temperature simulation result

In case of maximum energy injection, the resistance drops to 268.6 Ω (33% less than the nominal 400 Ω). The reduced resistance increases the energy injection and the temperature rise. The final stack temperature is 164°C, which is 28% higher than a calculation disregarding the non-linear behaviour of the discs. The disc's resistance is more sensitive to the applied voltage than the temperature rise. Typical resistance coefficients are -0.05% ~-0.15%/°C and -0.5% ~0.75%/kV/cm for the selected discs. The final data for different insertion timings are shown in Table 3.

Table 3 PIR temperature and energy injection

	Max energy inserting instant	Voltage zero inserting instant	
Energy /MJ	66.2	54.38	18% less
Min resistance /Ω	268.6	292.7	9% larger
Final temperature /°	164	138	16% less

The final temperature varies with the closing instant by 16% due to the variations of the injected energy. Insertion near the voltage peak results in higher energy injection and lower resistance due to the non-linear behaviour of the disc.

2.3 PIS Design

As discussed in section 2.1, electric stress and mechanical operation are the main factors in designing the PIS. The PIS is linked mechanically to the CB, and makes contact during the pre-insertion time and stays in close position until the CB closes. A head-head contact system is developed to ensure reliable coordination of their mechanical movement and the effective electrical pre-insertion time. Mechanical pre-insertion time is 8-11ms, but PIS and interrupter has pre-arcing during close. Electric Pre-insertion time changes along with pre-arcing time which depends on the voltage between gaps, and closing instant of phase angle. During PIS closing, the rate of decrease of dielectric strength (RDDS) changes dynamically. The CB's and PIS's RDDS and their mutual mechanical synchronization determine an electrical pre-insertion time which includes the arcing time before mechanical making of the contact systems. Figure 4 shows the absorbed energy for different closing instants at electric pre-insertion times of 8ms, 10ms, 11ms for a 300 Ω resistor.

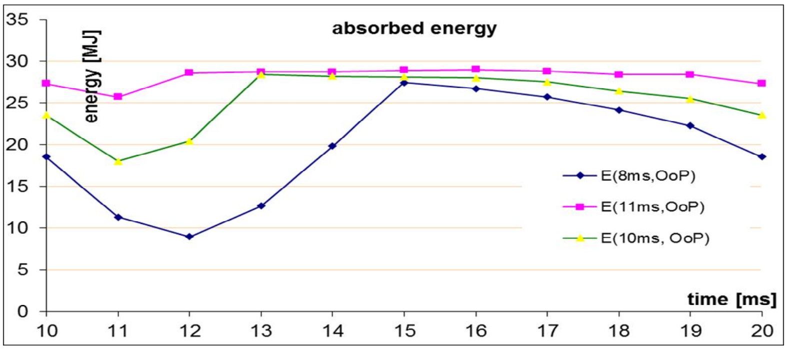


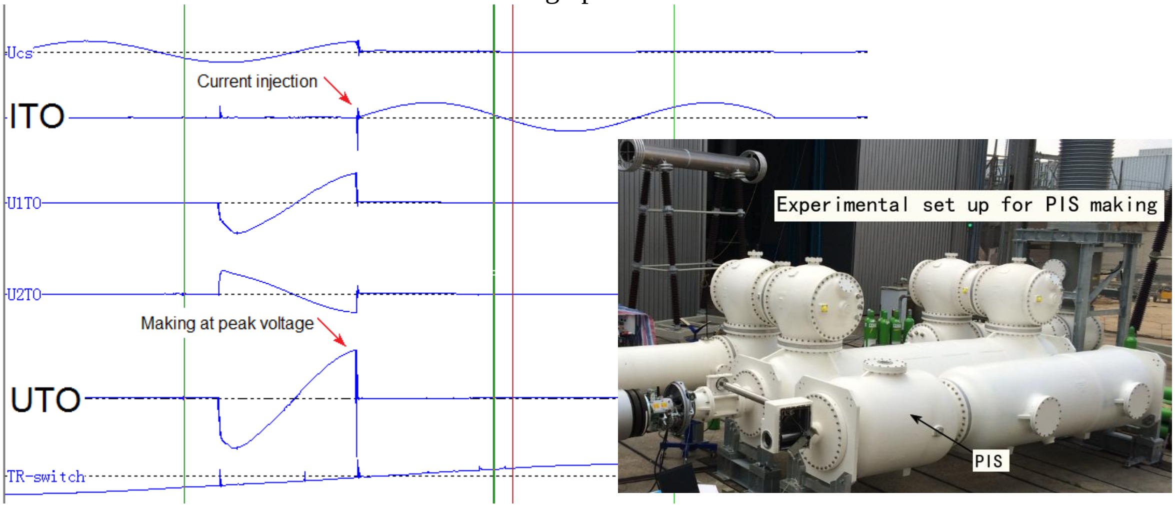
Figure 4 PIR absorbed energy

3 Design Verification

Most type tests requirement about 800 kV CB are covered by IEC standards, e.g. dielectric tests and mechanical endurance tests [7, 8, 9]. However PIS making test and PIR thermal capacity test are not specified in published standards. These tests are developed in cooperation with the test laboratory.

3.1 PIS Making Test

For PIS, the technical specification on making test under severe condition of out of phase was verified during 800 kV CB development. Making test performed at complete CB pole is shown in Figure 5 with 1306 kV_{peak} and corresponding current at minimum PIR resistance. The results of making test show that the PIS can fulfil 800 kV CB making operation.



(a) *(b)*

Figure 5 (a) one typical PIS making test and (b) test object for making test

3.2 PIR Thermal Capacity Test

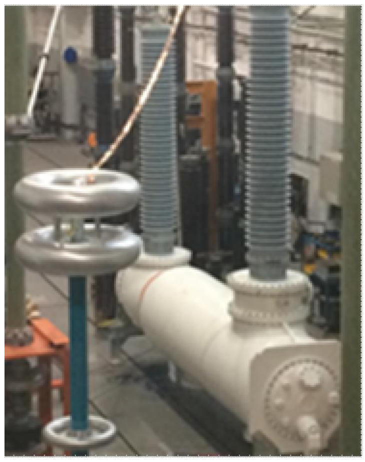


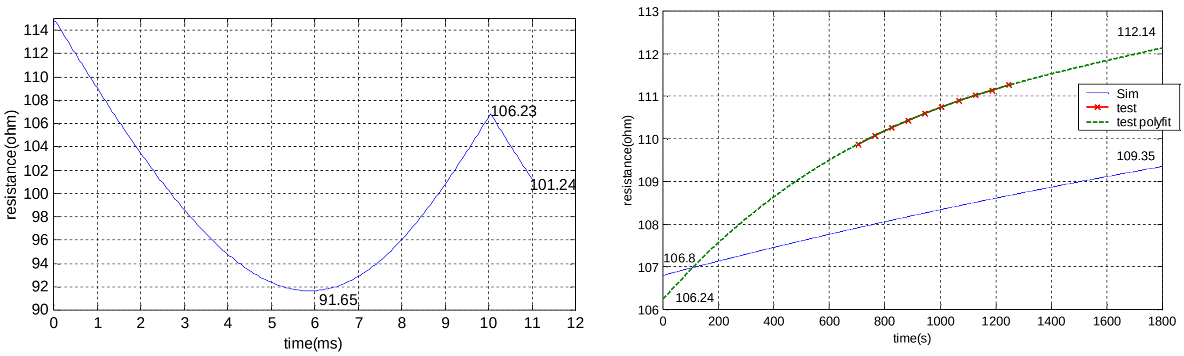
Figure 6 PIR Thermal Test at lab

Demanding test duty cycle CO-30 min-CO at 2 p.u. is applied on test object with electrical insertion time 11ms. To test whole PIR is very difficult due to the limitation of the generator capacity and maximum voltage in the lab. As shown in Figure 3 and Table 3 for 400 Ω PIR, the injected energy under the test duty cycle would reach abbr. 70 MJ and power supply could reach 3.2 GVA, which far exceeds the capacity of lab generator. Therefore, to test part of resistor discs under proportional decreased voltage but same current is recommended. This test approach could be equivalent to full energy test from technical point, and has been verified its effectiveness in China 1100 kV PIR thermal capacity test [4].
Regarding lab test facility's capacity, a typical test pole with 111.1 Ω under 256.6 kV and 2310 A instead of complete 400 Ω PIR is tested. To keep test effective, PIR structure remains unchanged and only part of PIR discs are short-circuited. These PIR discs are replaced by the same dimension conducting components with same specific heat capacity. In this way, the dielectric stress on each disc could be same as real product. The test pole parameter are listed in Table 4, and the testing object in lab is shown in Figure 6.
Resistance difference measured before and after PIR thermal capacity test ΔR is less than 5% [10], which means there is no damage in resistor discs and PIR can withstand specified thermal load.

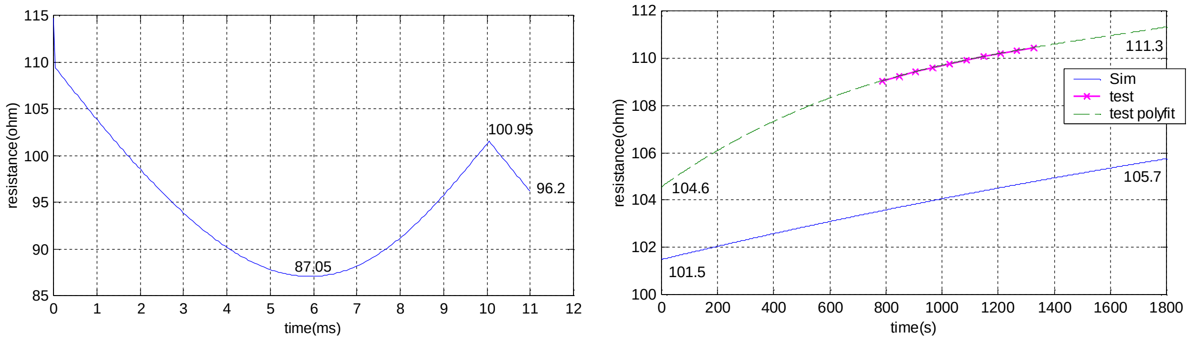
Table 4 Thermal capacity test input data

Rated voltage	Ur=256.6 kV
Number of resistor discs inserted	N=125
Resistance	111.1 Ω
Electrical pre-insertion time	t=11 ms
Ambient temperature	Ta=11 °C

The test was conducted at an ambient temperature of 11 °C and insertion at voltage zero. A simulation has been carried out to calculate dynamic resistance, injected energy, and temperature rise during and after test cycle. Maximum SF6 gas temperature of 70 °C and the most severe closing instant are considered.
Based on fitting curve of the resistance measured after each close operation as indicated by red cross, and simulation curve of resistance changes as indicated by blue line in Figure 7 and 8, the resistance at end of first CO is 106.24 Ω and 106.8 Ω respectively, and 104.6 Ω and 101.5 Ω at second CO respectively. The resistance are matched well between measurement and simulation.
The final total injected energy and temperature is 13.07 MJ and 113 °C respectively. Considering maximum energy insertion timing (about 16 % higher according to Table 3) and a safety margin 20%, the final temperature is ((113-11)x1.16)x1.2+70=212°C, which is still under the resistor disc limit 250°C.



(a) Resistance during first CO; (b) Simulated (blue line) or measured (red cross) resistance
Figure 7 PIR thermal capacity test - first close operation



(a) Resistance during second CO; (b) Simulated (blue line) or measured (red cross) resistance

Figure 8 PIR thermal capacity test - second close operation

High temperature and applied high voltage may cause resistor disc breakdown. By analysing voltage stress of each disc during test, most critical stress and instant during a duty cycle can be investigated. Simulation result is showed in Figure 9. The simulation input data is based on actual test data in each CO. The disc voltage withstand ability reaches lowest in 5-6 ms after closing, e.g., it can reach 17.39 kV at 6 ms in the first CO. When the resistance of the disc reaches the lowest value and the applied voltage remains high, the break-down of the resistor disc is most likely to happen. Comparing the dynamic disc withstand voltage and voltage distribution during CO (insert instant at voltage zero), there are still 20 % safety margin even at the most critical time point.

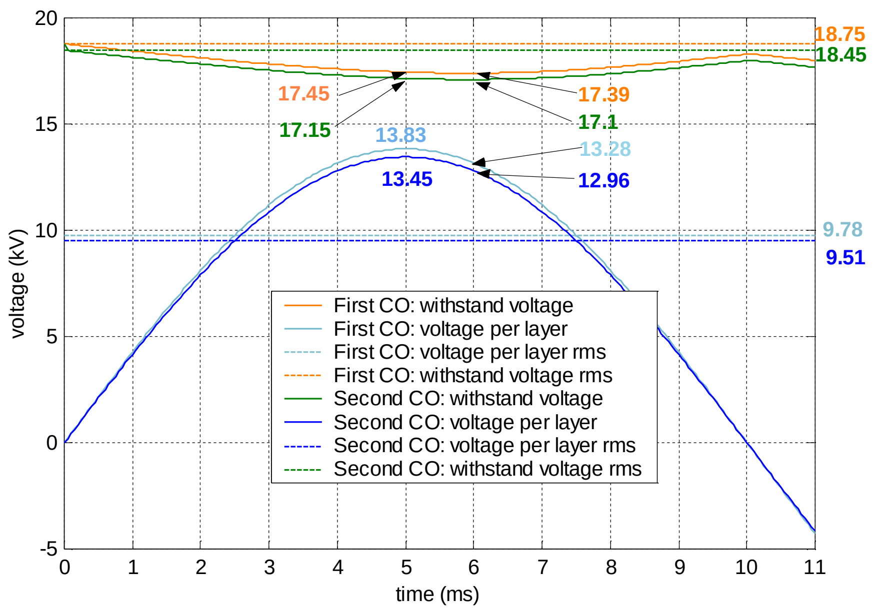


Figure 9 PIR Thermal Capacity Test – Voltage Stress

4 Conclusion

An 800kV CB with parallel PIR is developed, which shows great performance achieved in compact footprint, high thermal and making capacity.

Design elements of PIR are discussed, and thermal capacity as a most critical point is deeply investigated. The non-linear behaviour of resistor material is taken into consideration. And impacts of different insertion instant are compared, which shows max 18% difference in energy injection. Calculation demonstrates PIR high performance under severe duty cycle CO-30min-CO at 2p.u..

PIS determines the insertion instant and pre-insertion time. Simulations of RDDS in PIS and CB interrupter are performed to find the most critical electric pre-insertion time. Making test results shows that PIS has high making withstand ability.

A specific thermal capacity test approach is developed to test PIR thermal withstand ability and voltage withstand ability at the same time. The most demanding instant during above duty cycle to check the voltage stress is analysed. Test results shows that developed PIR is able to withstand the most severe thermal load.

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