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Switching phenomena and requirements of the capacitor bank circuit at the tertiary side of 1000kV transformer

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SUMMARY

High voltage long distance transmission systems have been introduced in some countries recently. Specifically for UHV class such as 1000kV, the capacity of power transformer of these systems tends to be large. Static capacitor (SC) banks are designed and installed in a lot of higher voltage substations at the power transformer tertiary side to supply reactive power according to the power system operation requirement. In the case that SC banks are connected in unearthed circuit, special attentions should be paid to the requirements for the tertiary side switching devices because of large capacity of the transformer and SC banks.

We focus on the switching phenomena in the tertiary side of UHV class power transformer connecting to SC banks, and conduct parametric study of switching duty requirements over 50 cases using EMTP-ATP to find the practical requirements for switching devices at the tertiary side of the transformer.

From the results of study, the maximum required duties could exceed those of 170kV rating circuit breaker in the present IEC 62271-100 in spite of the system voltage of tertiary side is 154kV. In some cases, the voltage waveform across contacts during capacitive current breaking is not so-called (1- cosθ) shape but the shape which superimposes low frequency component on , and maximum voltage appears more than one cycle later comparing to (1- cosθ) shape that appears during capacitive current breaking. Therefore, it is difficult to evaluate the suitable switching device whether a circuit breaker covers that requirement or not. Special capacitive switching test to evaluate those duties may be necessary, even in applying higher rating circuit breaker, such as 245kV or 300kV.

KEYWORDS:

UHV, Static capacitor bank, Tertiary of transformer, Non-grounded circuit

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1．Introduction

Static capacitor (acronym SC) banks are designed and installed in a lot of higher voltage substations at the power transformer tertiary side to generate reactive power according to the power system operation requirement. In case of UHV systems, breaking duty covering large current and/or high recovery voltage may be required for switching devices at the tertiary side of the main transformer, since the capacity of the transformer and SC is often large and system neutral of the tertiary side is unearthed[1] [2]. Switching requirements of the SC bank circuit at the tertiary side of the transformer under normal and single-phase or three-phase grounded fault (1LG or 3LG) are studied.

2．Parametric studies for switching duty

Generally, in the tertiary side of the power transformer relatively higher recovery voltage of switching devices may occur because of voltage shift at neutral point. Specially, the tertiary voltage of UHV class is higher than that of EHV class and large capacity SC banks at their tertiary side are installed to supply reactive power according to the power system operation requirement. Therefore we focus on the switching phenomena in the tertiary side of UHV class power transformer connecting to SC banks. Parametric studies for switching duty at a main circuit breaker (M-CB) on the transformer tertiary terminal and a load switch (SW) on individual SC are conducted by using EMTP-ATP. In this study, all the M-CB and SW are with 3 phase gang operation.

Figure 1 shows the circuit configuration for this parametric study. Ratings of UHV transformer are shown in Table 1 and Table 2.
The parametric study over 50 cases are conducted as follows,

- Number of SC banks: From zero (0) to four (4) * 240MVA bank with 6% series reactor to suppress inrush current and reduce the harmonic components. SC banks are connected to the tertiary circuit of the transformer via power cable. 6% series reactor is the commonly used in Japan.
- Voltage transformer (acronym VT) installation at tertiary circuit: With or without
- Fault conditions: Normal condition, 1LG or 3LG
- Switching device: M-CB or SW
- Breaking conditions:
  Switching device: M-CB or SW
  The first phase for breaking: Sound phase, Fault phase
  Number of SCs before and after breaking: 1 bank to 0 bank, 4 banks to 3 banks, etc
- Making conditions:
  Switching device: SW
  Instant of making phase: voltage peak, voltage zero
  Number of SCs before and after making: 0 bank to 1 bank, 3 banks to 4 banks
- Neutral grounded resister (NGR) installation at neutral of SC: With and without

Table 1 Voltage of equipment

	System voltage	Rated Voltage for Transformer	Rated voltage for Switchgear
Primary	1000 kV	1050 kV	1100 kV
Secondary	500 kV	525 kV	550 kV
Tertiary	154 kV	147 kV	168 kV

Table 2 Ratings and parameter of UHV Transformer

Rated Capacity[MVA]	Primary	3000MVA
	Secondary	3000MVA
	Tertiary	1200MVA
%IZ (Primary-Secondary)		18 %
Vector group		Y-y-d
Rated frequency		50Hz
Connections	Primary,/ Secondary	Direct connection to GIS with GIB
	Tertiary	Cable connection (XLPE 1200mm^2 - 200m) Z=25.637ohm, v=144.5m/us,

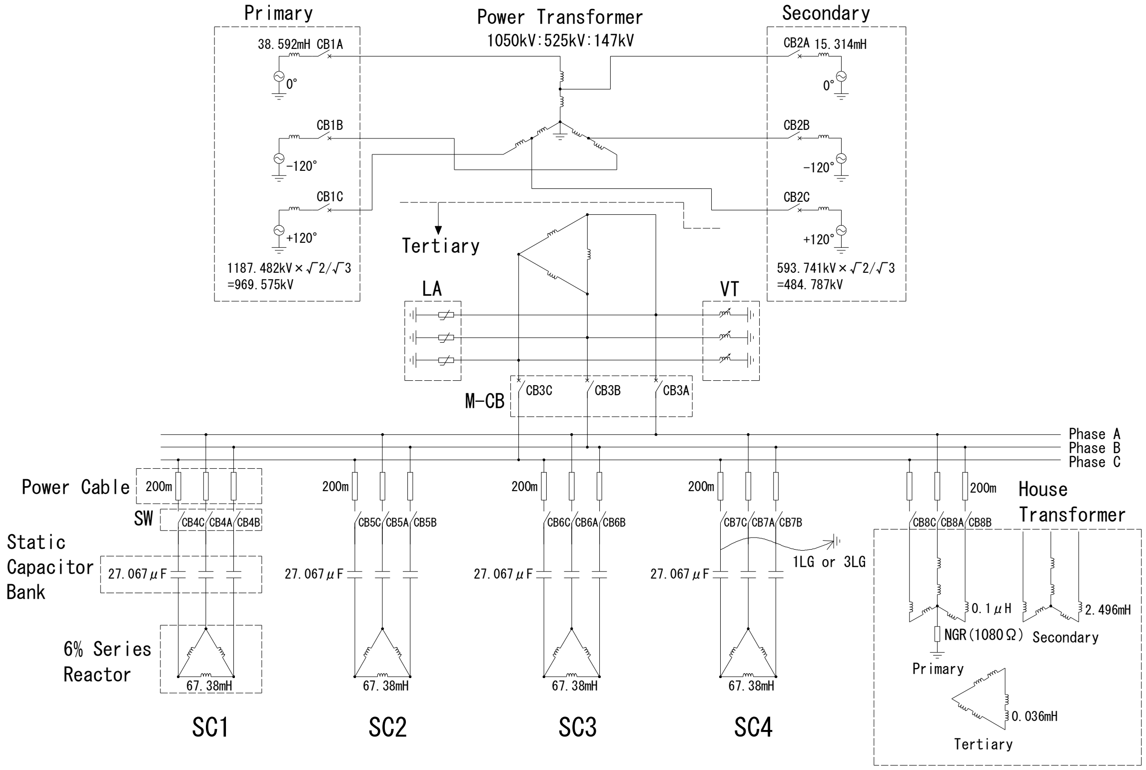


Fig. 1 Circuit configuration for EMTP analysis

3. Analysis result

Typical cases for study are shown in Table 3.

3.1 SW operation for making and breaking in normal condition

Table 4 shows the result of study on typical examples of making operation in normal condition. Typical waveform is shown in Fig.2 when the 4th SC bank is energized (case I). In a making operation, inrush current of about 200Hz appears, and its peak reaches 6.0 kA, which is significantly larger than that of steady state current of 1.3 kA.

Table 5 shows the result of study on typical examples of breaking operation in normal condition. Typical waveform of breaking last one SC in normal condition is shown in Fig. 3 (case II) in which the maximum voltage across contacts is 362kV. The voltage waveform is so called (1-cosθ) shape.

Table 3 Typical cases for study

	Case I	Case II	Case III	Case IV
Operation	Making by SW *	Breaking by SW	Breaking by M-CB	Breaking by M-CB
Number of SCs before switching	3 (720MVA)	1 (240MVA)	4 (960 MVA)	4 (960 MVA)
Number of SCs after switching	4 (960MVA)	0 (0 MVA)	0 (0 MVA)	0 (0 MVA)
Fault condition	No fault	No fault	1 LG (phase A)	1 LG (phase A)
First pole to clear	NA	not specified	Fault phase	Fault phase
VT	With	With	Without	With
NGR	Without	Without	Without	Without

Note *: At peak voltage of phase A

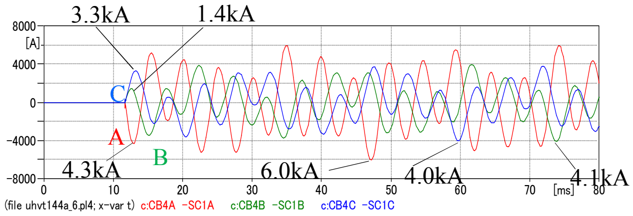
Table 4 Typical examples of making operation in normal condition

Case	No of SCs during operation	Source side voltage before making	Making current		Maximum source side voltage after making	Zero sequence voltage
			Initial peak value	Maximum value		
I	3 banks => 4 banks	144 kV	A: 4.3 kA B: 1.4 kA C: 3.3 kA	A: 6.0 kA B: 4.0 kA C: 4.1 kA	190 kV 1.24pu	1.0 V

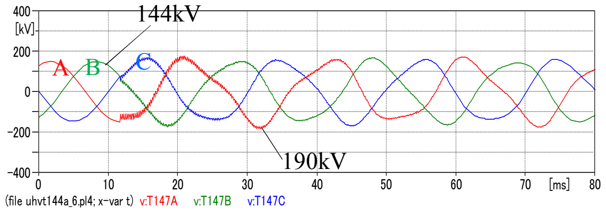
Table 5 Typical examples of breaking operation in normal condition

Case	No of SCs during operation	Voltage before breaking	Breaking current	Maximum Voltage across SW after breaking	Zero sequence voltage
II	1 bank => 0 bank	140 kV *	1.26 kA	362 kV	6.3 kV

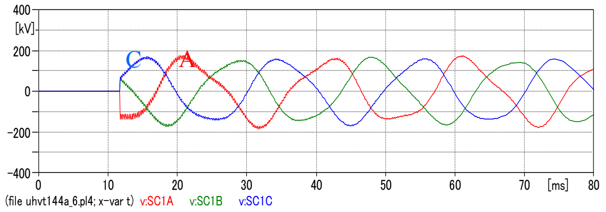
Note *: The rated voltage of tertiary side is 154 kV; however, calculations are conducted based on 187 kV which is actual system operating conditions.



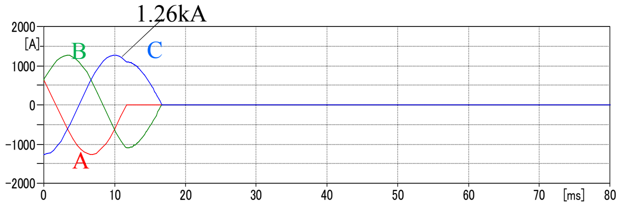
(a) Making Current



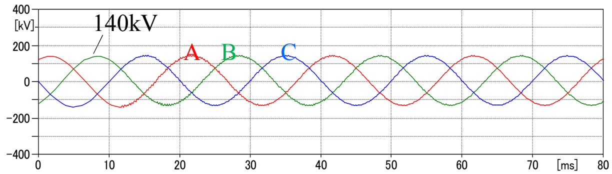
(b) Source side voltage



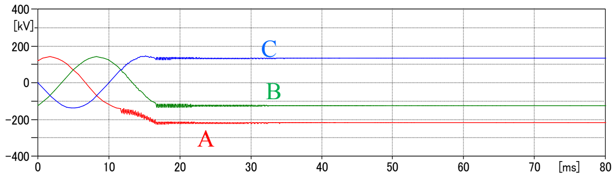
(c) SC side voltage



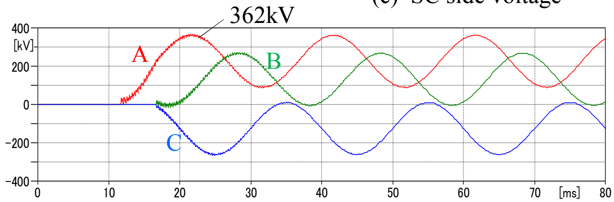
(a) Current through SW



(b) Source side voltage



(c) SC side voltage



(d) Voltage across SW

Fig. 2 Obtained waveform of making 1 SC in by SW in normal condition (case I)

Fig. 3 Obtained Waveform of breaking 1 SC by SW in normal condition (case II)

3.2 M-CB operation for breaking in 1LG

Table 6, Fig. 4 and Fig. 5 shows the analysis conditions and results for typical cases. They include waveforms of M-CB currents, voltages on source side and SC side, voltage across the M-CB and zero sequence voltage.

Table 6 Typical examples of breaking operation in 1LG

Case	Operating switch	VT installation	breaking current	Maximum voltage across contacts	Zero sequence voltage
III	M-CB	With	5.6 kA	730 kV (at 2^{nd} peak)*	244 kV
IV	M-CB	Without	5.6 kA	353 kV (at 1^{st} peak)**	244 kV

Note Earth fault phase is the first phase to clear, and it is phase A in the study.

*: Maximum voltage appears in the second phase to clear.

**: Maximum voltage appears in the first phase to clear.

(1) Analysis results of case III (With VT)

In this case, M-CB breaks 5.6kA, total current of four SC banks. Even in 1LG, short circuit path is not composed in unearthed system, almost the same as load current flowing after 1LG occurrence as shown in Fig.4. At the SC side, DC component remains after current breaking. Source side voltage includes DC and 50Hz AC component with about 15 Hz oscillations. 730kV appears across contacts of the second phase to clear, and it is higher than the voltage obtained in the cases without VT (Case IV). The maximum voltage appears at the second peak, not at the first one. On the other hand, zero sequence circuit voltage waveform also includes oscillating component of about 15 Hz.

(2) Analysis results of case IV (without VT)

As shown in Fig.5, current waveform and SC side voltage are similar to those in case III. Because waveform of the source side voltage is drastically different from case III which does not include about 15Hz AC oscillation. Consequently the maximum voltage across contacts is 353kV that occurs at first peak of the first phase to clear, which is lower than that of case III.

3.3 Summary of breaking phenomena

In normal condition, maximum recovery voltage is 362kV, and the value is approximately 2.5pu. But at 1LG with VT, the maximum voltage across contacts of M-CB is 730kV (4.7pu). And DC voltage to earth remains at the source side after clearing the fault, due to voltage shift of neutral point.

4. The influence of circuit configuration and conditions to capacitive current switching duty

The breaking current is mainly determined by the number of SC banks and not so much influenced by the other parameters. The breaking current is around 5.6kA for M-CB. The influence of circuit configuration and conditions to capacitive current switching duty are as follows.

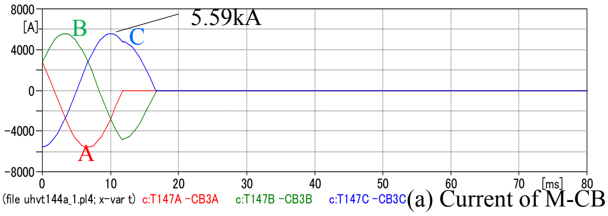
4.1 Influence of 1LG

In the case of 1LG, the voltage of sound phase jumps up to √3 times of system voltage. The recovery voltage of 1LG is higher than normal condition.

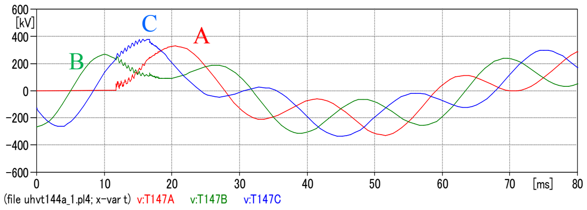
4.2 Influence of VT in 1LG

Case III in Fig.4 (with VT) clearly shows the source side voltages oscillate which superimpose lower frequency component on power frequency. Consequently the recovery voltage of the M-CB is higher than that of case IV in Fig.5 (without VT).

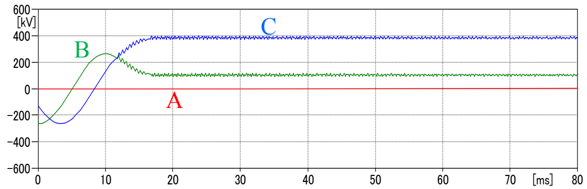
Firstly, voltage rise in sound phases is caused by voltage shift of neutral point by 1LG in unearthed circuit. When this voltage discharges via VT excitation inductance, the source side voltages start to oscillate at lower frequency with DC component because of large capacitance of tertiary circuit of the transformer. It brings higher voltages across contacts. In other words, VT causes higher recovery voltage in 1LG. Fig.6 shows the phenomena schematically. The SC side voltages are same in spite of VT installation, but the source side voltages with VT are at the peak of negative polarity approximately 27ms after breaking in phase C.



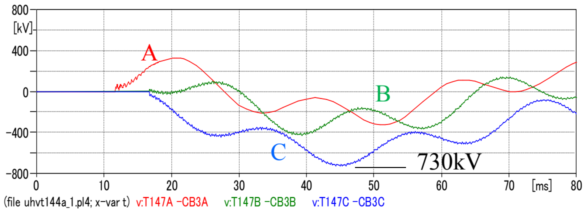
(a) Current of M-CB



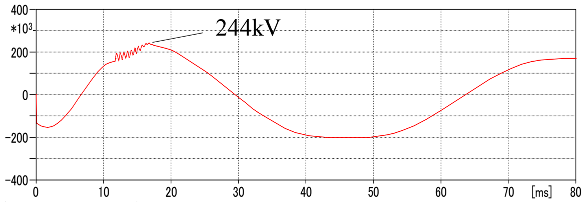
(b) Source side voltage



(c) SC side voltage

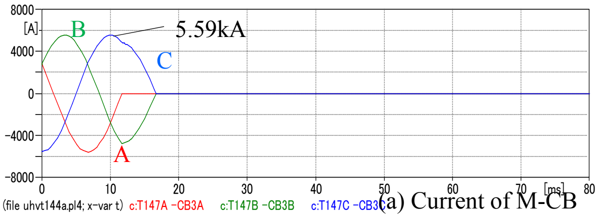


(d) Voltage across contacts

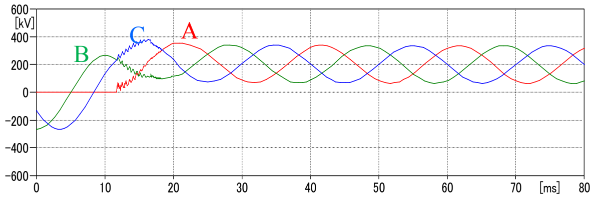


(e) Zero sequence voltage

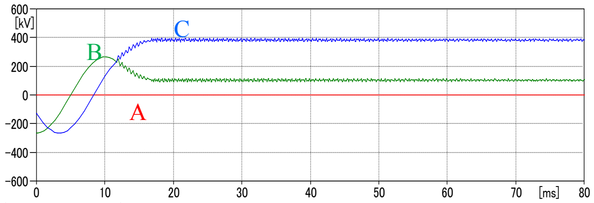
Fig.4 Obtained waveform of breaking (Case III)



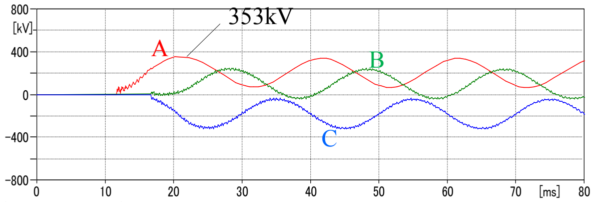
(a) Current of M-CB



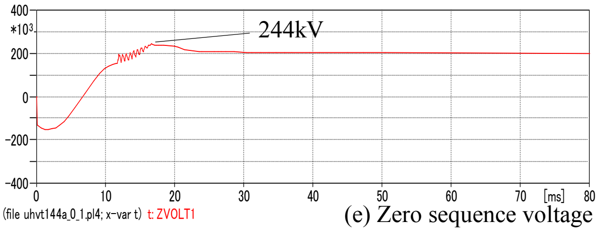
(b) Source side voltage



(c) SC side voltage

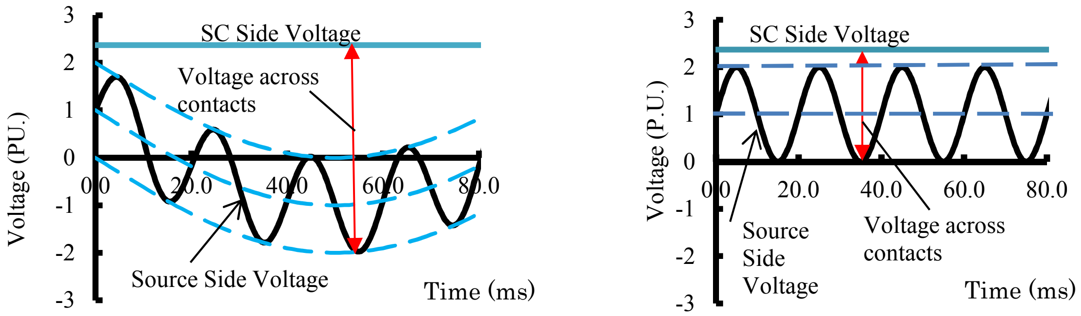


(d) Voltage across contacts



(e) Zero sequence voltage

Fig.5 Obtained waveform of breaking (Case IV)



(a) Case with VT

(b) Case without VT

Fig.6 Schematic drawing that shows change of voltage oscillation after breaking current

5. Switching duty in tertiary side SC bank of UHV power transformer.

Table 7 summarizes more than 50 cases results of parametric study including the typical examples case I to case V.

5.1 Summary of required performance

(1) Making duty of SW

After making, inrush current of about 200Hz appears, and it reached 6.0kA in a few cycles as shown in Fig.2. The current is rather higher than that of steady state, but the damage to the contact is not assumed to be so critical, because maximum current occurs after being mechanically closed.

(2) Breaking duty of M-CB and SW

Breaking duties for M-CB and SW are proposed as Table 7. The system voltage of tertiary side is 154kV, but these duties could not be covered by 170kV rating circuit breaker in the present IEC 62271-100[3]. The breaking current is higher than that of standard value of back-to-back capacitive switching current of 400A. This may reduce the contact lifetime, thus requiring frequent maintenance.

6. Conclusion

Maximum voltages across contacts are much higher than that of standard value of 170kV class breaker described in IEC 62271-100. But for with VT case, the voltage waveform is not (1 - cosθ) shape but the shape which superimposes low frequency component on, and peak voltages appear more than one cycle later comparing to normal capacitive breaking duty. Therefore, it is difficult to evaluate the suitable switching device whether a circuit breaker covers the requirement shown in table 7, based on type test reports of the standard capacitive current switching. Special capacitive switching test to consider those duties may be necessary, even in applying higher rating circuit breaker, such as 245kV. According to IEC 62271-100 [3], the peak recovery voltage of capacitive current switching for 245kV is 555kV (See Table 8). This value is lower than the maximum voltage in Table 7.

Table 7 Summary of capacitive switching duty for M-CB and SW

Switching device	Fault condition	VT installation	NGR installation	Current	Maximum voltage across contacts
M-CB	1LG	With	Without	4000 Arms	730 kV* (Case III)
		Without	Without	4000 Arms	353 kV** (Case IV)
SW	1LG	With	Without	1000 Arms	649 kV*
		Without	Without	1000 Arms	373 kV**
	No fault	With	Without	1000 Arms	393kV**

Note *: Maximum voltage may appear at the second or later AC component peak.
**: Standard capacitive current switching recovery voltage; (1- cosθ) type waveform

Table 8 Capacitive current switching test condition according to IEC62271-100

Rated voltage	Rated capacitive current for single capacitor bank	Peak Recovery voltage*
170 kV	400 Arms	384 kV
245 kV	400 Arms	555 kV
420 kV	400 Arms	950 kV

Note *:Voltage factor Kc=1.4 is supposed for all cases.

Besides switching performance, attentions must be paid to insulations. Source side voltage in case of 1LG is higher than that of normal condition. Insulation level to earth required in tertiary circuit should be high. Therefore special consideration should be taken to evaluate the equipment connecting to the tertiary side of the transformer.

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