The International Conference on Electronics
& Oil: From Theory to Applications
March 05-06, 2013, Ouargla, Algeria

Back-up Protection to Enhance Operation of HVDC System

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***Abstract*— the most important part of HVDC transmission project is DC control and protection system which decides DC system operation and equipment safety directly. If DC control and protection system modules fail, system safety will be threatened heavily.**

DC line short circuit is different from AC short circuit, because once DC fault starts it will not be extinguished by itself until the current is reduced to zero and the arc is deionised. Thus, there has to be some control function that brings the current down to zero when a fault occurs on a DC line.

This paper presents a detailed analysis and simulation of HVDC line protection under the single pole to ground fault of CIGRE HVDC benchmark model. In order to prevent the fall of the operation reliability due to DC protection system failure, back-up protection is adopted.

Key- HVDC; back-up protection; VDCL

I. Introduction

HVDC transmission control and protection system is very important. It can decide the DC system operation mode and power and can reflect various operation conditions real-time and ensures the AC/DC system safety [1].

HVDC protection is a complex system with a hierarchical structure where all equipment is protected by various measures and principles. It is sometimes difficult to clearly distinguish between a protective and a control function as they are performed by the same or similar devices.

With the development of electric technology, modem DC system protections have become computerized and integrated highly by means of micro-processor technology. Protections for fault that can make DC system stop operate should be centralized in one protection system which should include stronger protective functions. In order to prevent the fall of the operation reliability due to DC protection system failure, duplication of protection is adopted [1]. DC system control can be realized through changing the converter firing angle. And DC protection system stars different sequential control programmes according to different faults [2]. The main step of protective operation is changing and blocking firing pulses. So there's intimate relationship between DC control system and protective function. The cooperation of them can restrain fault development and clear fault and restore the transmitted power. [1]

Statistics of Tian-Guang HVDC power transmission system (China) in 2001-2007 show that 50% of DC system faults are line faults within which the proportion of right operations of line protection is only 60%. The remaining 40% of line faults cause unnecessary DC outages. [2]

Ge-Nan HVDC transmission (China) was closed down because of control and protection system failure made up 29.4% of the total number in 1998. In 2003 because control system couldn't adapt to system changes and control function was in disorder, DC system was closed down three times. And DC system was compelled to close down to have a check because DC protection module failed. However the most important part of HVDC transmission project is DC control and protection system which decides DC system operation and equipment safety directly. If DC control and protection system modules fail, system safety will be threatened heavily. [1]

This paper presents a detailed study of HVDC line protection under the single pole to ground fault of CIGRE HVDC benchmark model. In order to prevent the fall of the operation reliability due to DC protection system failure, back-up protection is adopted.

Simulation study on SimPowerSystems toolbox in the MATLAB is carried out to validate the concept.

II. Model Description

The HVDC considered in this paper (fig. 1) is of conventional type based on the CIGRE benchmark system [4]–[5].

The rectifier and the inverter are 12-pulse converters using two 6-pulse thyristor bridges connected in series. The transformer tap changers are not simulated and fixed taps are assumed. Reactive power required by the converters is provided by a set of capacitor banks plus 11th, 13th and high pass filters on each side. A series reactor is also included between the two HVDC stations to make the DC current smooth. The controls used are primarily those of the CIGRE Benchmark model. [3]–[4]

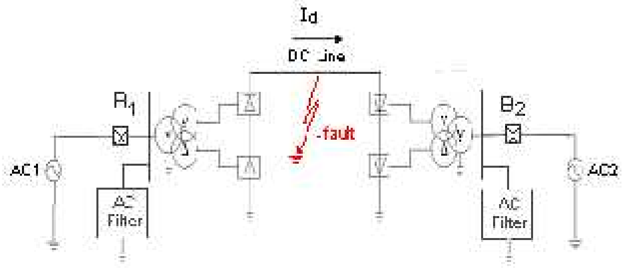


Fig.1. HVDC system

The details of CIGRE benchmark model for HVDC are given in Appendix A.

The current controller is shown in Fig. 2. The limited current $I_{ref\text{-}lim}$ reference is generated using the Voltage Dependent Current Limit (VDCL) unit [3]–[4]. These units provide current reference values during steady and transient-state conditions respectively. In order to maintain the operation of the AC system, VDCL limits the current in the DC line, if the DC voltage V_d decreases, e.g. due to an AC or DC system disturbance. When normal operation has returned and the DC voltage recovered, current returns to its steady-state level I_{ref} (1 pu) [3]–[4].

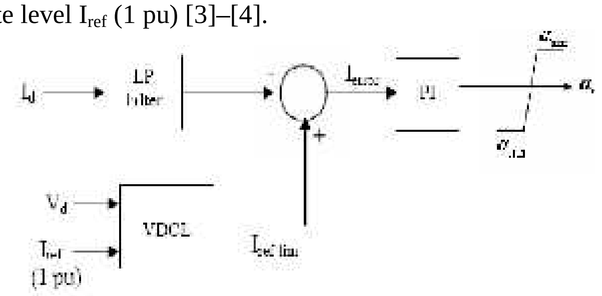


Fig.2. Current controller

The VDCL characteristic is illustrated in Fig.3 by the line ABC. It determines that when V_d falls below 0.18 pu, the $I_{ref\text{-}lim}$ is limited to 0.2 pu. When V_d is higher than 0.6 pu, the $I_{ref\text{-}lim}$ is set up by the characteristic between the points A and B. When the V_d drop is between 0.18 and 0.6 pu, the $I_{ref\text{-}lim}$ is determined by the characteristic between the points B and C.

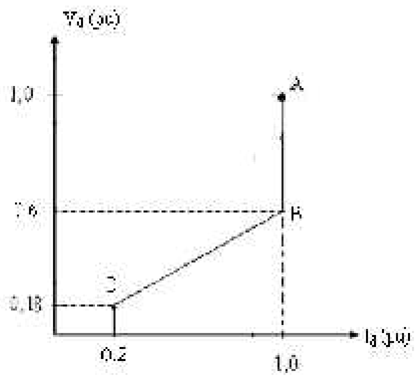


Fig.3. VDCL characteristic

$I_{ref\text{-}lim}$ is compared with the measured DC current I_d and the error Ierror is fed to the PI controller. The rectifier firing angle is the output of the PI controller, which is limited between 5º and 145º.

A low-pass filter to eliminate higher order harmonics. Limitation of the maximum DC current between minimum I_{MIN} and maximum I_{MAX} current limits to protect the thyristor valves.

III. HVDC Line Protection

A. DC Line Fault

DC line short circuit is different from AC short circuit, because once DC fault starts it will not be extinguished by itself until the current is reduced to zero and the arc is deionizer. A DC line fault is applied from 0.2 s to 0.3 s at the DC line side of the rectifier (fig. 1). Observe in fig.4 the changes of the voltage and current without protection system.

Rectifier keeps in constant current mode if line protection fails to start. In this case rectifier firing angle will ascend (fig.4.e). Then VDCL function operates. According to VDCL (fig.3) DC current will keep on 0.2 pu (fig.4.d) because DC voltage is 0.18 pu below (fig.4.c). The relation between converter bridge's AC current and DC current is described as below:

$$I_a \approx 0.816\, I_d$$

Where I_a is AC current of converter bridge, I_d is the mean value of DC current. Judging from the above equation, DC current after fault occurs is the same, so AC current of converter on the side of network is the same.

In normal operation condition, reactive power needed accounts for 40%~60% of active power transported [1]. Therefore adequate static VAR compensators should be equipped in the HVDC installation. Active power transported decreases because of DC line earth-fault, so reactive power needed decreases too. Then AC bus voltage ascends (fig.4.a) result from redundant reactive power.

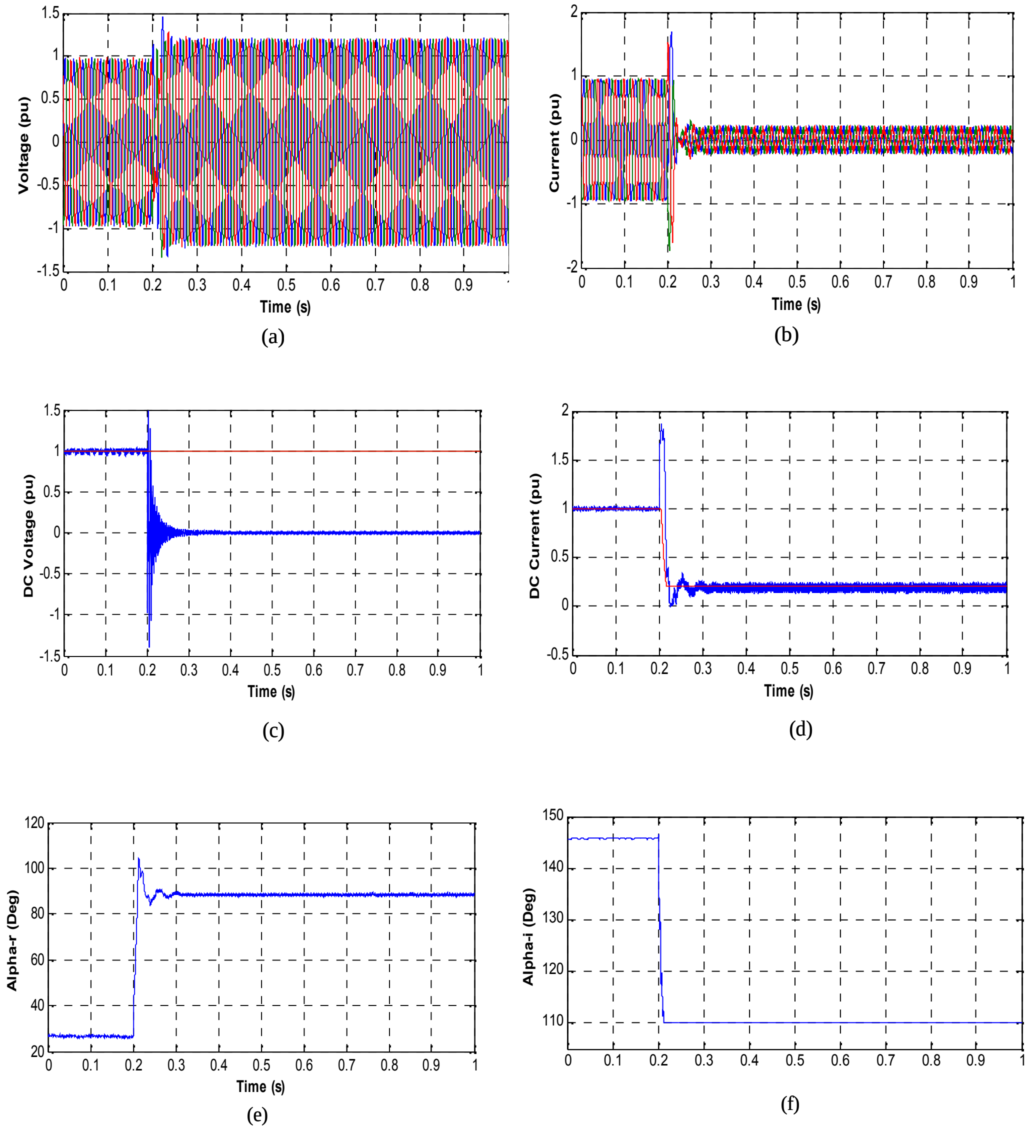


Fig.4. (a) AC Voltage, (b) AC current of converter transformer on the side of network, (c) DC voltage, (d) DC current, (e) rectifier firing angle order and (f) inverter firing angle order, when earth-fault occurs at the sending end of DC line without protection system

B. Auto-restart control function

The objective of the DC-line protection is to detect ground faults on the DC line and extinguish the fault current by control action. In case the fault is not permanent, pre-fault power transmission should be restored by control action after sufficient time delay for arc deionisation [3].

After the fault detection, the rectifier is forced to full inversion operation and does not supply any current to the fault. This is done by increasing the firing angle α over 90º into inverting region and it is kept at that value until the arc extinction and deionisation is likely to be completed.

The inverter voltage already has the correct polarity, thus the two converters are temporarily inverting at the same time and transferring the energy stored in the DC circuit electric and magnetic fields into the two AC systems [3, 4]. The inverter firing delay is advanced at the same time, but a limitation is set to 110º to prevent the inverter from going into the rectifying region. By this control action the fault arc can be deionised and the fault cleared very rapidly when compared with AC protection.

DC line protection detects fault and starts auto-restart control. The following is the process of the control:

1. Protection detects earth-fault on the DC line.
2. Tetrads the rectifier firing control into full inverter operation mode. In this way both the rectifier and the inverter will act to discharge the DC line.
3. Keeps rectifier state inverter operation mode for about 50~500ms so as to extinct arc.

4. Cuts down the rectifier firing angle and operates in rectifier mode again. Then DC voltage and current starts building up and thus restoring the transmitted power after the fault has been cleared.

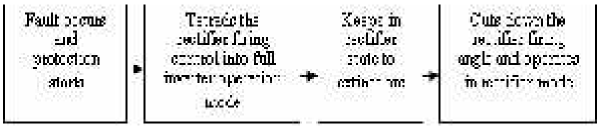
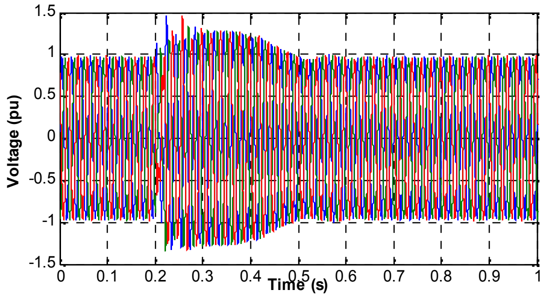
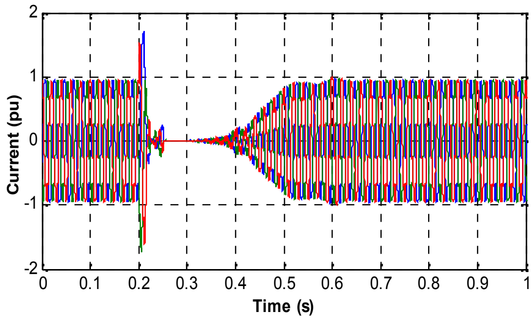


Fig.5. Logic of auto-restart

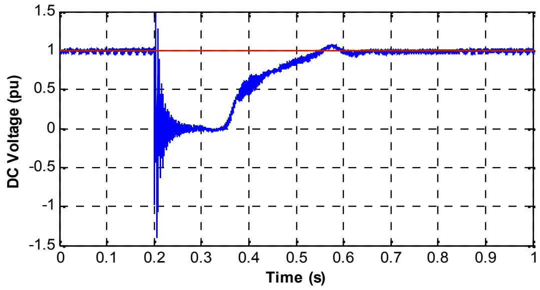
A DC line fault is applied from 0.2 s to 0.3 s at the DC line side of the rectifier (fig. 1). Observe in fig.6 the changes of the voltage and current with auto-restart. From the period 0.25 s to 0.3 s, a protection signal is applied to force the rectifier alpha to 145 degrees (fig.6.e) i.e. into inverter region to extinguish the fault current and deionize the fault arc.



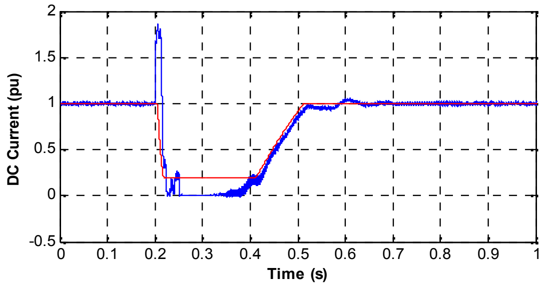
(a)



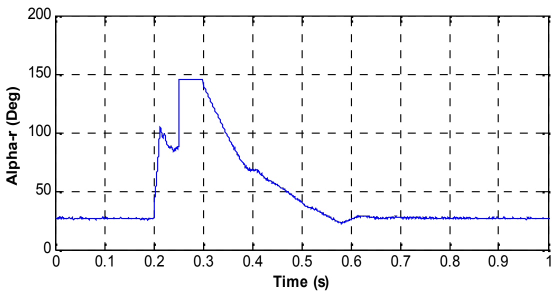
(b)



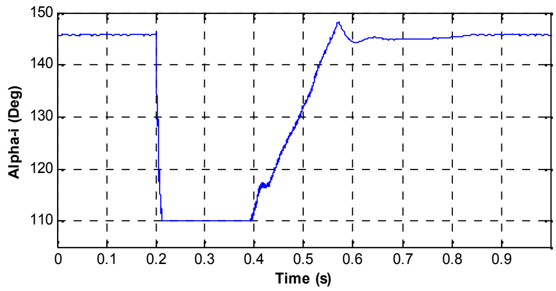
(c)



(d)



(e)



(f)

Fig.6. AC Voltage, (b) AC current of converter transformer on the side of network, (c) DC voltage, (d) DC current (e) rectifier firing angle order and (f) inverter firing angle order, when large grounded resistance earth-fault occurs at the sending end of DC line with auto-restart.

C. Back-up protection system

In order to prevent the fall of the operation reliability due to DC protection system failure, duplication of protection is adopted. It is hoped that AC system and DC system can act as back-up protection for each other if the control process of DC line auto-restart fails.

A DC line fault is applied from 0.2 s to 0.3 s at the DC line side of the rectifier (fig. 1). Observe in fig.7 the changes of the voltage and current if auto-restart fails and with back-up protection. After a period of 80 ms (at 0.28 s), trip signals are given simultaneously to circuit breakers $B_1$and B_2 at both ends of the line to clear the fault. Thereafter, circuit breakers are reclosed after a delay of 20 ms (at 0.3 s).

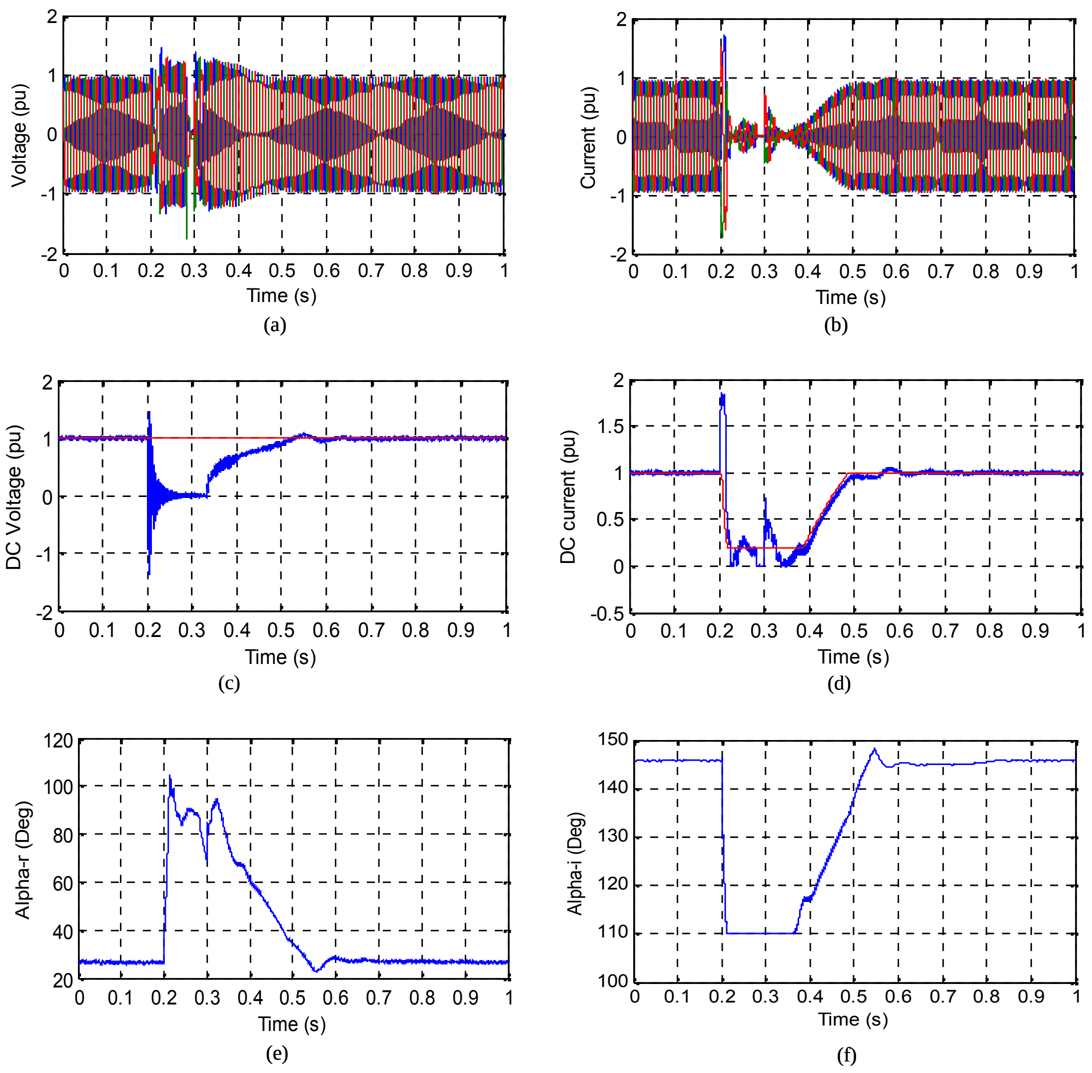


Fig.7. AC Voltage, (b) AC current of converter transformer on the side of network, (c) DC voltage, (d) DC current (e) rectifier firing angle order, (f) inverter firing angle order and (g) Ifault, when large grounded resistance earth-fault occurs at the sending end of DC line if auto-restart fails to work and with back-up protection.

IV. Conclusion

Simulate the DC line fault by means of CIGRE HVDC benchmark model, and discuss the changes of voltage and current with and without protection system. AC bus voltage ascends because of redundant reactive power. The most important part of HVDC transmission project is DC control and protection system which decides DC system operation and equipment safety directly. If DC control and protection system modules fail, system safety will be threatened heavily.

In order to prevent the fall of the operation reliability due to DC protection system failure, back-up protection is adopted, if the main protection fails.

So there's intimate relationship between DC control system and protective function. The cooperation of them can restrain fault development and clear fault and restore the transmitted power.

APPENDIX

Appendix A

Figure A.1 shows the CIGRE HVDC benchmark test system:
(All components in Ω, H and µF).

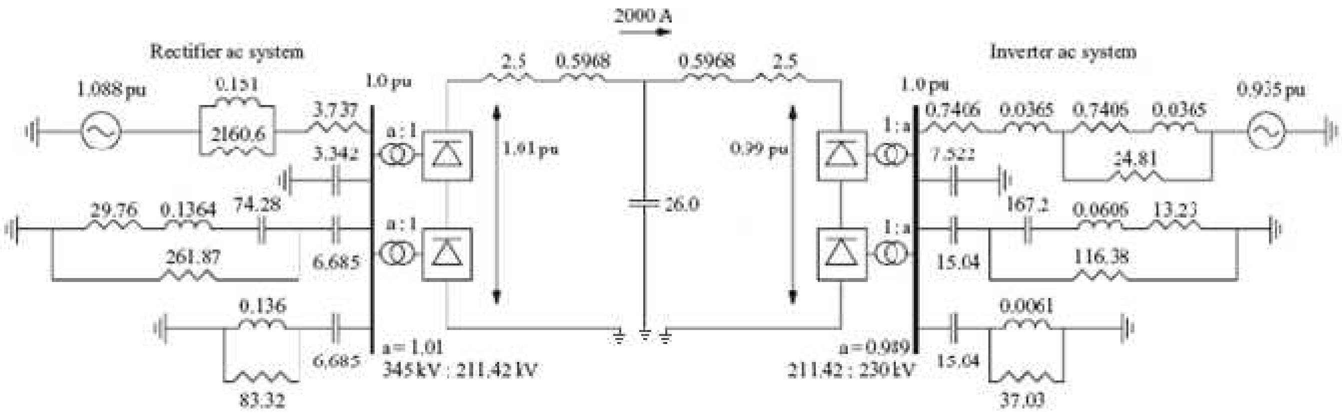


Fig.A.1 CIGRE HVDC benchmark test system

Table.A.1 CIGRE model main parameters

Parameter	Rectifier	Inverter
AC. system voltage	345 kV	230 kV
AC. system impedance magnitude	119.03 Ω	52.9 Ω
Equivalent commutation reactance	27 Ω	27 Ω
DC. voltage	505 kV	495 kV
DC. current	2000 A	2000 A
DC. power	1010 MW	990 MW
Rectifier AC. voltage base	345 kV	230 k V
Rectifier voltage source	1.088 ∟22.18°	0.93∟-23.1°
Transformer leakage reactance	0.18 pu	0.18 pu
Thyristor forward voltage drop	0.001 kV	0.001 kV
Thyristor onstate resistance	0.01 Ω	0.01 Ω
Snubber resistance	5000 Ω	5000 Ω
Snubber capacitance	0.05 µf	0.05 µf

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