

## **EFFECT OF BRAKING RESISTOR AND FAULT CURRENT LIMITER ON CIRCUIT BREAKER OPERATION**

Amir Ghorbani and Allahverdi Azadru

Department of Electrical Engineering, Salmas Branch, Islamic Azad University, Salmas, Iran

### **ABSTRACT**

This paper presents a study of Transient Recovery Voltage (TRV) of a Circuit Breaker (CB) connected to transmission line with presence of Braking Resistor (BR). In order to effectively control the transient stability of the synchronous generator during the dynamic period, the BR unit is located at the generator terminal bus through the thyristor switching circuit and near the circuit breaker. It is shown in this paper that, when a fault occurs in the transmission line and circuit breaker acts, existence of braking resistor and its natural performance during instability eliminates TRV in the circuit breaker completely. The Fault Current Limiter (FCL) in series with a circuit breaker could be practically used in electrical distribution systems. In this paper, an Electromagnetic Transient Program (EMTP) model of diode-bridge-type non-superconductor fault current limiter (NSFCL) is proposed. The results show that improvement in FCL controller is essential for eliminating TRV. The simulations are implemented by using the Electromagnetic Transients Program (EMTP/ATP).

**Keywords:** Transient recovery voltage (TRV), circuit breaker (CB), braking resistor (BR), non-super conductor fault current limiter (NSFCL), EMTP/ATP.

### **1. INTRODUCTION**

Braking Resistor (BR) is known to be one of the very effective methods for transient stability improvement. Braking Resistor uses the concept of applying an artificial electrical load during a dynamic period to control the active power output of

generator and thereby control rotor oscillations. BR can be utilized for variety of functions: Prevent transient instability during the first power system swing cycle; damp sub-synchronous resonance (SSR) resulting from series capacitor

compensation; reduce and rapidly damp subsynchronous shaft torques. A BR can often be the lowest cost, and a simple, highly reliable FACTS Controller. The best location for a BR is near a generator that would need braking during transient instability conditions [1]. When a fault occurs on a system, variable rotor speed of the generator is measured and the firing-angle for the thyristor switch is determined from the BR controller. By controlling the firing-angle, BR can control the accelerating power in generator and thus improves the transient stability.

After interruption of a short-circuit current by a high-voltage fuse or a power circuit breaker, a transient recovery voltage (TRV) appears across the terminals of the interrupting device [2]. Circuit breakers can fail to interrupt fault currents when power systems have TRV characteristics which exceed the rating of the circuit breakers [3]. Fault current limiters (FCL) can limit the prospective short-circuit currents to lower levels, so that the underrated switchgears can be operated safely. The SFCL in series with a circuit breaker could be practically used in electrical distribution systems [3]. Different configurations such as Is-limiters, solid state fault current limiters (SSFCLs) and superconducting fault current limiters (SFCLs) were proposed in researches. In [4], [5] proposes a controllable simple structure and cost effective NSFCL to restrain the magnitude of fault current to a certain predefined value.

Some research has been done to evaluate the TRV of a circuit breaker with presence Flexible AC Transmission System (FACTS) controllers. In [3] and [6]–[8] impact of different types of FCLs on power switch TRV have been investigated. In [3], a case study of HTS resistive superconducting FCL in electrical distribution systems is investigated; the studies include the circuit breaker TRV analysis. The work in [6] looks at the mathematical expression of the rate of rise of recovery voltage (RRRV) across a circuit breaker connected with FCL as a function of the limiting impedance  $Z_{FCL}$  and the limited current when a fault occurs at a distance near the load-side terminals of the FCL. The investigation in [7], presents analytical basis and theoretical reference for optimal parameter design of inductive FCLs and reliable selection of the interrupting characteristics of HV circuit breakers. The work in [8] presents the impact of inductive Fault Current Limiter (FCL) on the interrupting characteristics of high-voltage CBs.

In this paper, BR is modeled in ATP environment. Then impact of BR on power switch TRV is investigated. The results show that, existence of BR when CB acts cause the elimination of TRV. Also simulation results show that the conventional controller for NSFCL is not capable in TRV elimination and so the controller of NSFCL must be modified for both elimination of TRV and limitation of fault current. ATP (Alternative Transients Program) is considered to be one of the most

widely used software for digital simulation of transient phenomena of electromagnetic, as well as electromechanical nature in electric power systems. The previous papers about the effect of FACT devices are just related to the old type of FCL that current limiting resistor doesn't exist in it. The novelty of this paper is studying the effect of BR and the new type of FCL or NSFCL on TRV of the circuit breaker.

## 2. MODELING OF SYSTEM, BR AND NSFCL

Two different test systems for modeling of BR and NSFCL are used. Conventionally BR employed in HV networks and also BR is located at the generator terminal bus, but NSFCL designed to work in distribution systems. For the simulation of transient stability and TRV with presence BR, the model system [9], as shown in Fig. 1, has

been used in this paper. The model system consists of a synchronous generator (SG) feeding an infinite bus through a transformer and double circuit transmission line. CB in the figure represents a circuit breaker. The CB1 is modeled as a time-controlled switch and a stray capacitance ( $C_p$ ) of the circuit breaker to the ground which is shown in the figure. In order to show TVR phenomena, re-strike phenomena which occurs after opening the switch is neglected in simulations.

In order to effectively control the power balance of the synchronous generator during a dynamic period, the BR unit is located at the generator terminal bus [1].

Automatic Voltage Regulator (AVR), Excitation System Stabilizer (ESS) and governor (GOV) control system have been included to make the system closer to practical systems.

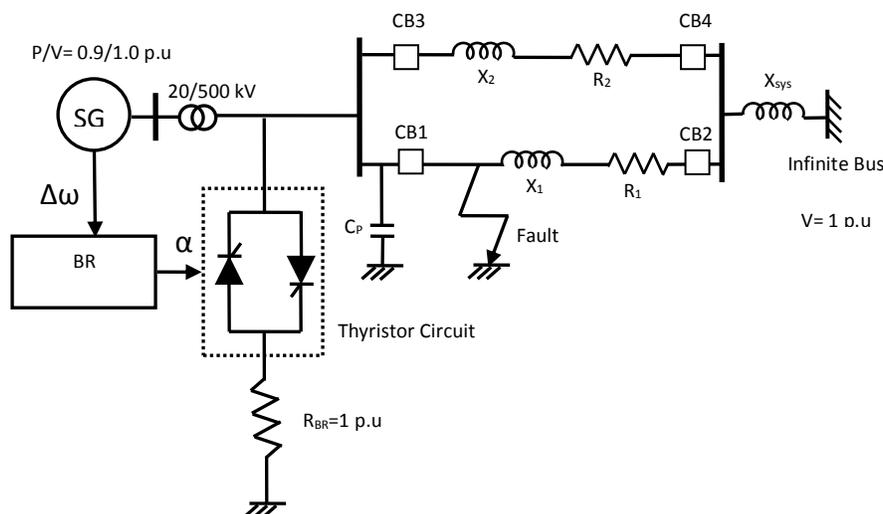


Figure 1. Sample system with BR.

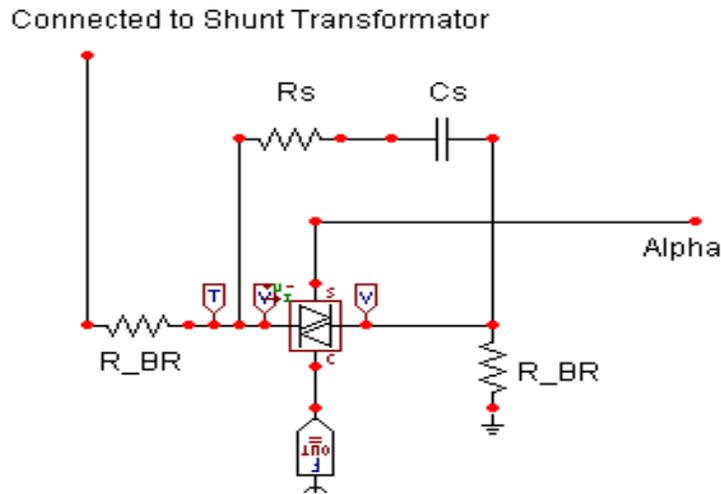


Figure 2. Phase 'a' related to BR which is modeled in EMTP/ATP.

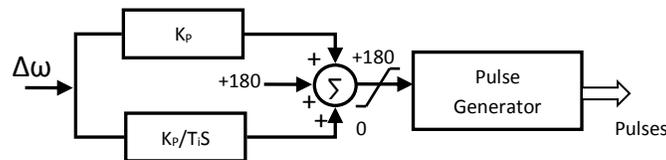


Figure 3. Block diagram of PI controller.

Parameters of the system are completely listed in appendix. The Braking Resistor (Fig. 1) is a shunt-connected thyristor-switched resistor (usually a linear resistor). Speed deviation of synchronous generator ( $\Delta\omega = \omega - \omega_0$ , in which  $\omega$  is the actual generator speed and  $\omega_0$  is the steady state generator speed) is the basic control parameter. The phase 'a' related to BR which is modeled in EMTP/ATP is shown in Fig. 2. The Thyristor block in Fig. 2 also contains a series  $R_s$ - $C_s$  snubber circuit that

can be connected in parallel with the thyristor device. The firing-angle  $\alpha$ , for the thyristor switching circuit is calculated from the output of the PI controller. PI controller for the BR is shown in Fig. 3. In normal operation the value of  $\Delta\omega$  in the generator is negligible and the output of the controller is 180 degrees. In other words both thyristors are out of circuit it means that the braking resistor is not operate. In presence of any possible fault in the transmission line, an unbalance will be created in the input

mechanical power and generator electrical power which lead to a  $\Delta\omega$  in the generator rotor and with this  $\Delta\omega$ , breaking resistor operates and improves the transient stability of the generator. Fig. 4 shows the power circuit topology of the proposed NSFCL. This circuit is composed of four main parts that are described as follows:

- 1) A three-phase transformer, used as voltage transformer, is connected to a three-phase diode-bridge rectifier. The three-phase diode-bridge rectifier provides power source for compensation of losses which take place in both DC reactor resistance and semiconductor devices. This rectifier is called "voltage transformer rectifier".
- 2) Three sets of single-phase transformers, utilized as power isolation transformer, is connected to

a three-phase diode-bridge rectifier. The three-phase diode bridge is called "isolation transformer rectifier".

- 3) A non-superconductor (copper coil) magnet which is modeled by an inductor ( $L_d$ ).
- 4) A parallel connection of a protection resistor and semiconductor switch which are connected in series with the DC reactor.

Similar to presence of BR in system CB is modeled as a time-controlled switch and a stray capacitance ( $C_p$ ) of the circuit breaker to the ground. Parameters of the system are completely listed in appendix. In [4], PSCADE software has been used for NSFCL modeling and TRV hasn't been studied. In this paper ATP is used for NSFCL modeling that its model is shown in Fig. 5.

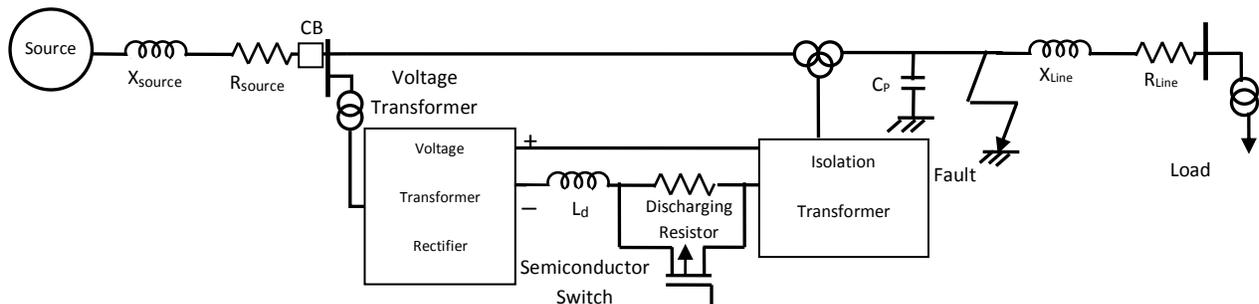
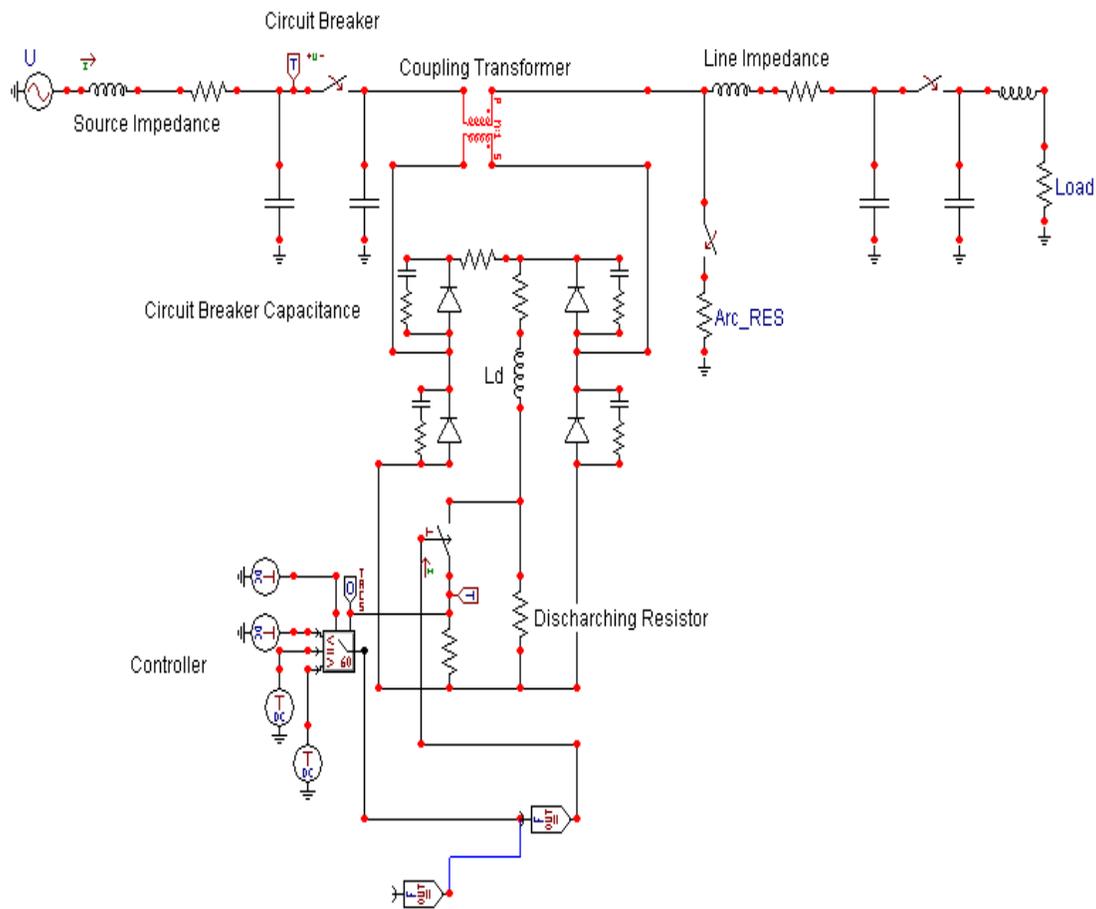


Figure 4. Power circuit topology of the proposed NSFCL.



**Figure 5.** Phase ‘a’ related to NSFCL and sample system which is modeled in EMTP/ATP.

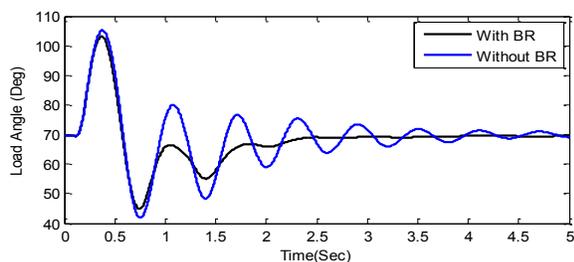
### 3. SIMULATION RESULTS

The simulation is implemented by using the electro- magnetic transients program (EMTP/ATP) [8]. Alternative Transient Program (ATP) is one of the EMTP versions and ATP Draw is a graphical pre-processor to ATP and is used to create and edit circuit files which are used in the simulations carried out in this paper. The severity of a circuit breaker duty is generally determined by the value of the short-circuit current

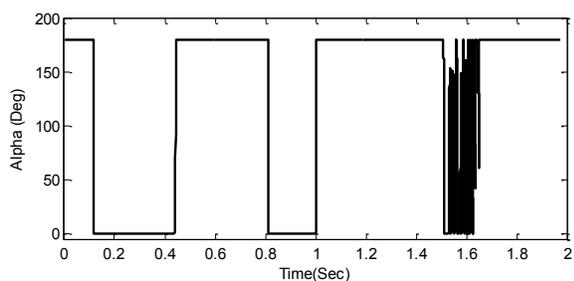
together with the shape and the recovery voltage. For the short-circuit current, a symmetrical three-phase-to-ground short circuit was assumed to occur because the estimation of the MVA required of a circuit breaker is usually made on the assumption that it must clear a three phase fault because, as that is almost the worst case, it is reasonable to assume that the circuit breaker can clear other fault.

### 3.1 System with BR

Simulations are performed considering 3LG (three-phase-to-ground) fault near the generator at line 2 as shown in the system model (Fig. 1). It is also considered that the fault occurs at 0.1 s, circuit breakers on the faulted line are opened at 0.21 s, and closed again at 1.2 s [9]. Simulation step is considered as  $1\mu\text{s}$  to capture the high frequency TVR phenomena. Fig. 6 show the load angle responses for both 3LG fault. It is clear from this response that BR effectively enhance the transient stability. Fig. 7 depicts the firing-angle response of the thyristor switch for phase 'a'. The firing-angle varies from 0 Deg to 180 Deg according to the value of controller output.



**Figure 6.** Load angle responses for 3LG fault.



**Figure 7.** Firing angle for phase 'a'.

When the firing angle of thyristor is zero Deg the complete resistor is in circuit and conversely, when firing angle is  $180^\circ$  the complete resistor is not in the circuit.

Considering the firing angle of thyristor two important points are obtained:

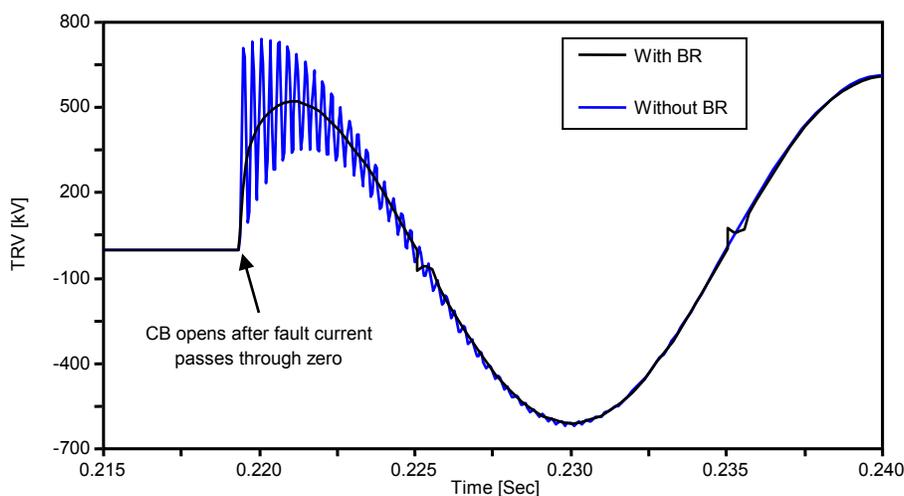
- 1) Before opening CB at 0.2 sec, breaking resistor is in the circuit because of the fault in the transmission line.
- 2) During investigation TVR (which starts from opening the CB and lasts at most two cycles), firing angle of thyristors are zero and in other words, BR is fully in the circuit.

The TRV has various parameters such as a Rate of Rise of Recovery Voltage (RRRV). The RRRV is an important parameter in the power system operation, specified in volts per microsecond ( $\text{V}/\mu\text{s}$ ) in IEEE C37.41 Standard [3]. Fig. 8 shows the CB's TRV with and without the BR. As can be achieved from this figure, the value of RRRV is about  $5.03 \text{ kV}/\mu\text{s}$  for the case without the BR. BR presence has caused to eliminate TRV and decreasing the value of RRRV to  $0.3 \text{ kV}/\mu\text{s}$ . The simulation results are shown only for phase 'a'. The results are similar for the other two phases. It is shown that BR presence improves TRV and RRRV. In all the different faults, BR and NSFCL are suppressing the effect of TRV so that in this paper, only a result for single phase fault (the most occurred and important fault) is considered for decreasing the number of figures.

### 3.2 System with NSFCL

In normal operation of utility the semiconductor switch is closed and the protection resistor is bypassed. By choosing appropriate value for  $L_d$ , it is possible to achieve an almost DC current through the DC reactor. Obviously, increasing the inductance of  $L_d$ , decreases the ripple of DC

current,  $I_d$ . This leads to short circuit of  $L_d$  during normal operation of utility. The "voltage transformer rectifier" output compensates power losses of diodes, resistance of DC reactor and semiconductor switch. In this way, the proposed NSFCL has no effect on utility voltage and load current waveform in normal operation [4], [5].



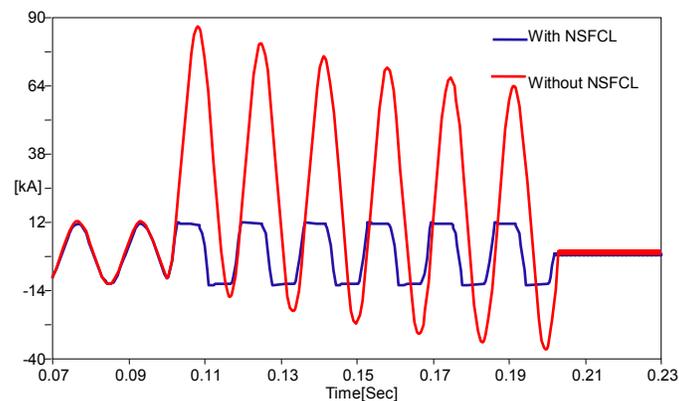
**Figure 8.** Circuit breaker's TRV with and without the BR.

During fault condition, the DC reactor current increases almost linearly. If the fault continues for long time, the current through the DC reactor continues to increase. There is a controller circuit that controls the turn-on and turn-off of semiconductor switch to maintain the DC reactor current below a specified level. It should be noticed that by turning off the semiconductor switch the protection resistor discharges the absorbed energy of NSFCL

inductance, thereby the current of DC reactor decreases. Obviously, as semiconductor switch turns on the DC reactor current increases. So, by using suitable turn-on and turn-off duration and protection resistor value, it is possible to maintain the DC reactor current below the specified level. It is clear that, the proposed NSFCL can gain both canceling out the superconductor cooling system and reduction of inductance and current rating of

DC reactor due to controlling the DC reactor current. In addition, it has no effect on utility voltage and load current due to compensation of all power losses.

Especially, it has no need to disconnecting switches that should be installed in series with basic circuit of FCL to cut-off the tie line at fault intervals.



**Figure 9.** Line Current for phase 'a'.

Consequently, the proposed NSFCL is more suitable and acceptable for limiting current in distribution grid as it provides more advantages compared to previous SFCLs.

The detailed model of diodes is used in NSFCL modeling for TRV investigation (e.g. each diode is parallel with a series capacitor- resistance). Fig. 9 shows the simulation results for 3LG (three-phase-to-ground) fault in presence of NSFCL and without it. It is also considered that the fault occurs at 0.1 s, circuit breakers are opened at 0.2 s. As shown in this figure NSFCL is enough capable to limitation of fault current in desired value. Fig. 10 shows the transient

voltage of CB. As shown in this figure in conventional control of NSFCL, TRV elimination is not possible. In other words, in conventional control of NSFCL, the switching resistor retreated by switch and no effect on TRV. For problem solving the controller of NSFCL and CB is coupled with together. By new control strategy when CB starts to open the switching resistor is placed in circuit at once. The simulation result of new control strategy is shown in Fig. 11. As shown in this figure the modified control strategy is able to elimination of TRV. Also the proposed control strategy has no effect on fault current limitation ability of NSFCL.

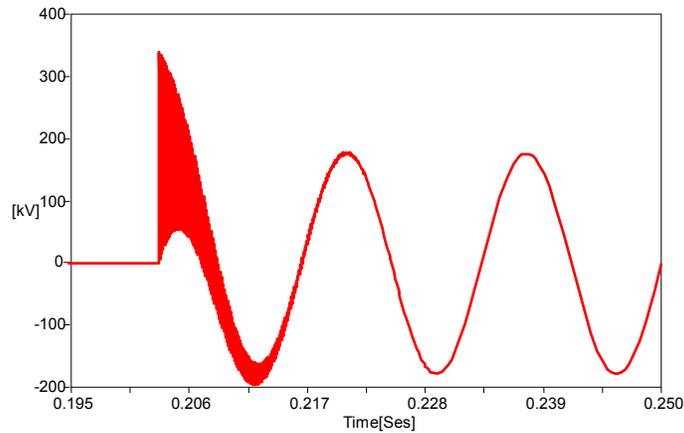


Figure 10. Circuit breaker's TRV with NSFCL and conventional controller.

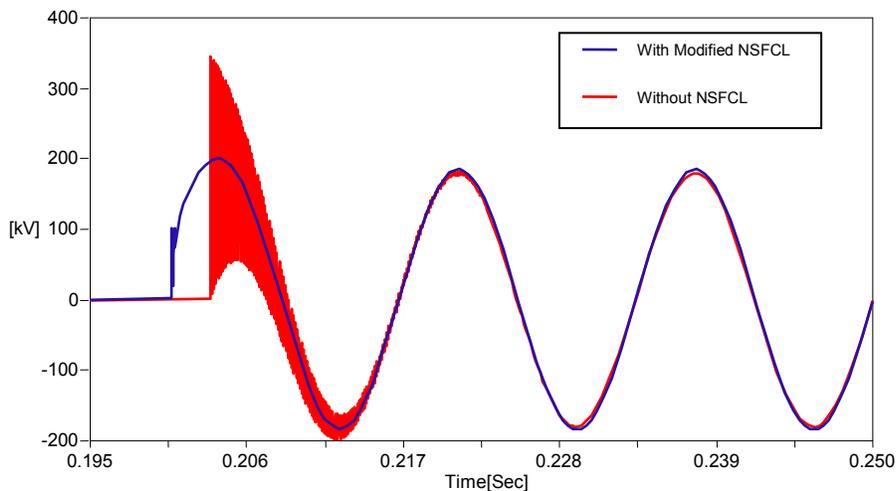


Figure 11. Circuit breaker's TRV with modified NSFCL and without NSFCL.

#### 4. CONCLUSION

The investigations in EMTP/ATP environment shows that using breaking resistor besides synchronous generator not only improves the transient stability of the generator but also eliminates TVR in CB

and decreases the RRRV value significantly. TVR phenomena is analyzed for different types of faults in different parts of the transmission lines. In all the cases BR eliminates the TVR across a Circuit Breaker. When a fault occurs in transmission line, the

output power of the generator decreases. BR operates to compensate for this decrease. When CB tries to clear the fault, BR is fully in the circuit and eliminates TVR. So, eliminating circuit breaker TVR is another advantages of using BR. Also simulation results show that the conventional controller for NSFCL is not capable in TRV elimination and so the controller of NSFCL must be modified for both elimination of TRV and limitation of fault current. For problem solving the controller of NSFCL and CB is coupled with together.

### Appendix

#### A) System with BR:

Parameters of system:

$X_1=X_2= 0.2$  p.u,  $X_{sys}= 0.1$  p.u,  $R_1=R_2= 0.04$  p.u, SG output active power= 0.9 p.u, SG terminal voltage= 1.0 p.u

Parameters of AVR excitation system:

$K_p= 25$ ,  $K_d= 0.2$

Parameters of GOV:

$K_p= 25$ ,  $K_d= 2.0$

Parameters of BR controller:

$K_p= 180$ ,  $T_i= 0.2$

#### B) System with NSFCL:

Parameters of system:

Source voltage= 180 kV (Amp), Frequency= 60 Hz,  $L_{source}= 10$  mH,  $R_{source}= 0.1$  ohm

Parameters of NSFCL:

$L_d= 200$  mH, Discharging Resistor= 65 ohm.

### REFERENCES

- [1] N. G. Hingorani and L. Gyugyi, *Understanding FACTS Concepts and Technology of Flexible AC Transmission Systems*, New York: IEEE Press, 2000.
- [2] Lou van der Sluis, *Transients in Power Systems*, John Wiley & Sons Ltd, ISBNs: 0-471-48639-6 (Hardback); 0-470-84618-6 (Electronic).
- [3] Lin Ye, A.M. Campbell, "Case study of HTS resistive superconducting fault current limiter in electrical distribution systems" *Electric Power Systems Research* 77 (2007) 534–539.
- [4] M. Tarafdar Hagh, and M. Abapour, "Nonsuperconducting Fault Current Limiter With Controlling the Magnitudes of Fault Currents" *IEEE TRANSACTIONS ON POWER ELECTRONICS*, VOL. 24, NO. 3, MARCH 2009, pp.613-619.
- [5] M. Tarafdar Hagh, and M. Abapour, "Non-superconducting fault current limiters" *EUROPEAN TRANSACTIONS ON ELECTRICAL POWER*, DOI: 10.1002/etep.247.
- [6] E. Calixte, Y. Yokomizu, H. Shimizu, T. Matsumura, "Theoretical expression of rate of rise of recovery voltage across a circuit breaker connected with fault current limiter" *Electric Power Systems Research* 75 (2005) 1–8.
- [7] Qingmin Li, Hongshun Liu, Jie Lou, and Liang Zou, "Impact Research of Inductive FCL on the Rate of Rise of Recovery Voltage With Circuit Breakers" *IEEE TRANSACTIONS ON*

- POWER DELIVERY*, VOL. 23, NO. 4, OCT 2008, pp. 1978–1985.
- [8] Hongshun Liu, Qingmin Li, Liang Zou, and Wah Hoon Siew, “Impact of the Inductive FCL on the Interrupting Characteristics of High-Voltage CBs During Out-of-Phase Faults” *IEEE TRANSACTIONS ON POWER DELIVERY*, VOL. 24, NO. 4, OCT 2009, pp. 2177–2185.
- [9] Mohd. Hasan Ali, Toshiaki Murata, and Junji Tamura, “A Fuzzy Logic-Controlled Superconducting Magnetic Energy Storage for Transient Stability Augmentation” *IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY*, VOL. 15, NO. 1, JAN 2007, pp. 144–150.