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Effects of Braking Resistor on Circuit Breaker Operations

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***Abstract*— This paper presents a study of Transient Recovery Voltage (TRV) of a Circuit Breaker (CB) connected to a transmission line in presence of Braking Resistor (BR). In order to effectively control the transient stability of a synchronous generator during the dynamic period, a BR unit through the thyristor switching circuit is located at the generator terminal bus and near the circuit breaker. Mathematical expressions for TRV are obtained for two different cases: a) when a BR is connected in the CB circuit during the fault, and b) when BR is not available in the faulty circuit. Also, Rate of rise of recovery voltage (RRRV) for different values of BR are obtained to show the effect of BR value on amount of the established TRVs. Furthermore, 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's TVR is another advantage of using BR. It is shown in this paper that when a fault occurs in the transmission line and circuit breaker operates, presence of braking resistor and its common operation during instability, completely eliminates TVR in the circuit breaker.**

Keywords—Transient recovery voltage (TRV), circuit breaker (CB), Rate of rise of recovery voltage (RRRV) , braking resistor (BR), EMTP/ATP.

1 INTRODUCTION

Braking Resistor (BR) is known as one of the very effective tools for transient stability improvement. Braking Resistor utilizes concept of applying an artificial electrical load during a dynamic period to control the active power output of a generator and thereby to control rotor oscillations. BR can be used for variety of applications such as to prevent transient instability during the first power system swing cycle, to damp subsynchronous resonance (SSR) resulting from series capacitor compensation and to 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 will 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 is able to control the accelerating power in generator and thus improves the transient stability. Here, a variety of BR applications in power systems is summarized. One type of electric brake process is called energy consuming brake, and its components are motor, brake resistor and its heat dissipation subsystem. In [2], the calculations and numerical simulation models of the brake resistor and its cooling subsystem of a heavy duty series-parallel hybrid electric vehicle is developed to investigate the heat transfer regulations in the electric brake process. North American (IEEE) and European (IEC) Standards are embarking on significant efforts to harmonize breaker specifications and testing requirements, including TRV tests. An electromagnetic transient program (EMTP) study has been performed to verify system TRV requirements under different conditions against Standard requirements and supplier's provided test data [3]. Current-limiting reactors are often used in applications where high fault currents encroach or exceed rated fault duties of downstream switchgear. Ref. [4] has examined transient program modeling techniques associated with reactor-limited fault current interruption and the subsequent TRV response that develops using electromagnetic transients program (EMTP) simulations. Severe transient recovery voltage (TRV) after current interruption may appear when a fault occurs in the immediate vicinity of a power transformer without any appreciable capacitance between the transformer and the circuit breaker. TRVs for transformer-limited faults (TLFs) conditions with large capacity and high-voltage shell-type power transformer were measured by the capacitor current injection method [5]. 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 [6]. Circuit breakers may fail to interrupt fault currents when power systems have TRV characteristics which exceed the rating of the circuit breakers [7]. The reactors are often dry-type with low inherent capacitance and, if no remedial measures are applied such as the addition of capacitance, will add a fast rising component to the transient recovery voltages (TRVs) seen by the station circuit breakers. Ref. [8] describes how the reactor-affected TRVs can

be calculated using a basic RLC circuit approach and the principle of superposition.
Ref. [9] is specifically concerned with a novel tool that uses a genetic algorithm for the calculation of the parameters of complex equivalent circuits in order to represent the specific transient recovery voltage required for a particular generator circuit-breaker application. The parameters of complex equivalent circuits can be chosen to accurately represent the behavior of actual machines. These circuits can be then used to calculate the transient recovery voltages modified by the capacitors of a generator circuit-breaker.
Moreover, mathematical formulas are obtained for describing the relationship between the current limit factor and the recovery voltage of a CB as well as the rate of rise of recovery voltage (RRRV) based on theoretical analysis. The research [10] in includes TRV after circuit breakers interrupt the short-circuit currents or the current in out of phase condition and TRV under different fault types. The investigation was carried out by digital simulation to analyze TRV waveforms. The objective of [11] is to simulate and analyze the transient recovery voltage on circuit breaker. It is to investigate the transient recovery voltage before and after the circuit breaker interrupts and also the transient recovery voltage under the fault. In this paper, BR is modeled in ATP environment. Then, impact of BR on power switch TRV is investigated. The results show that when CB operates, existence of BR results in elimination of TRV. ATP (Alternative Transients Program) is considered as 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 investigations in EMTP/ATP environment shows that using braking resistor besides synchronous generator, not only improves the transient stability of the generator, but also eliminates TVR in CB,
and significantly decreases the RRRV value. 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's TVR is another advantage of using BR.

2 Modeling of System and Braking Resistor

Traditionally, BR is employed in HV networks and also is located at the generator terminal bus. For the simulation of transient stability and TRV in the presence of BR, the model system [12] has been used in this paper, as shown in Fig. 1. 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. 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 the 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. Parameters of the system are completely listed in the 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 ω is the actual generator speed and ω_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

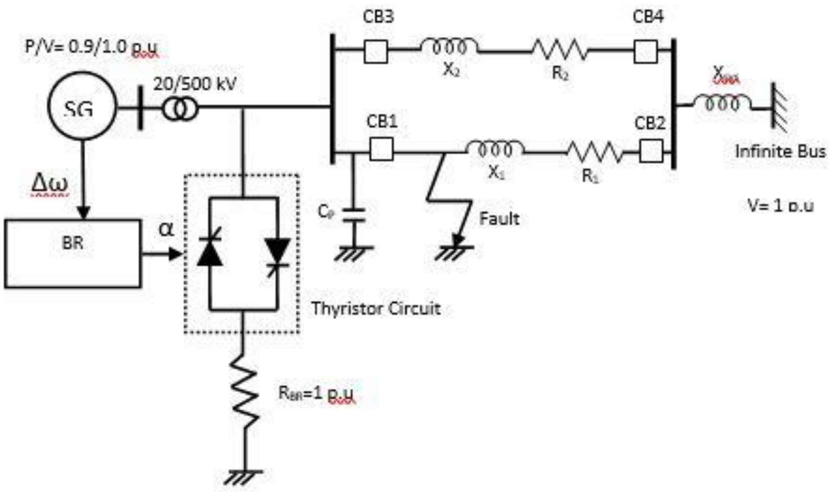

Figure 1. Sample system with BR

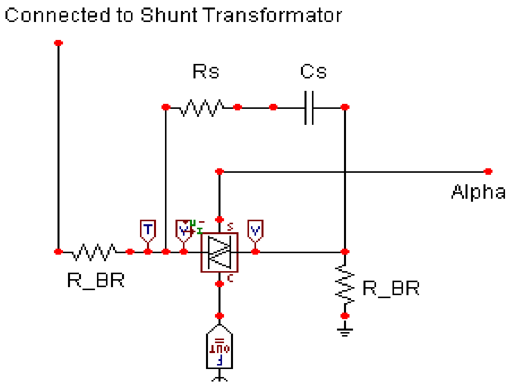

Figure 2. Phase 'a' related to BR, modeled in EMTP/ATP.

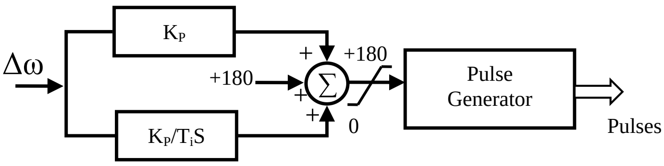

Figure 3. Block diagram of PI controller.

also contains a series R_s-C_s snubber circuit that can be connected in parallel with the thyristor device. The firing-angle α, 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 does 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 leads to a $\Delta\omega$ in the generator rotor and with this $\Delta\omega$, braking resistor operates and improves the transient stability of the generator.

3. Theoretical Analysis

3.1 Circuit without BR

In this section, theoretical analysis of the system with and without the braking resistor is presented. Simplified TRV circuit representation shown in Fig. 4 describes one phase of a three-phase power system with a source voltage, transformer, transformer winding capacitance, circuit breaker and a three-phase ungrounded fault. The shunt capacitance represents the total phase-to ground capacitances of the transformer winding and that of the secondary cables. A small resistor is also added next to the shunt capacitance, which represents internal resistance of the shunt capacitor [13].

Assuming: $V_s = V_m \sin(\omega t+\theta)$, where θ is the phase shift between source voltage and current passing through the circuit breaker before interrupting process and after the fault. In this situation, simply, θ is π/2. So, $V_s = V_m \cos(\omega t)$ [14]. Using a simple KVL for obtaining V_{TRV} or equally V_C, and also using Laplace transformation give:

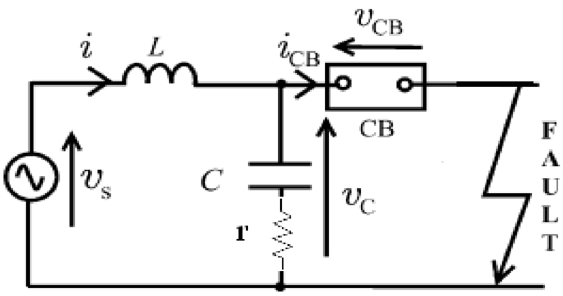

Fig 4. Simplified TRV circuit

Assuming: $V_s = V_m \sin(\omega t+\theta)$, where θ is the phase shift between source voltage and current passing through the circuit breaker before interrupting process and after the fault. In this situation, simply, θ is π/2. So, $V_s = V_m \cos(\omega t)$ [14]. Using a simple KVL for obtaining V_{TRV} or equally V_C, and also using Laplace transformation give:

$$V_C(s) = \frac{V_s(s)\cdot(1+r\cdot C\cdot s)}{L\cdot C\cdot\left(s^2+\frac{r}{L}\cdot s+\frac{1}{L\cdot C}\right)} \qquad (1)$$

assuming the below parameter values:

L = 10 mH, C = 1 uF, r = 0.1 Ω, ω = 60 Hz, V_m = 1 kv and

$$\omega_0 = \frac{1}{\sqrt{L\cdot C}}$$

by using inverse Laplace for eq.(1), replacing values of the above parameters and plotting V_C or equally V_{TRV}, the waveform shown in Fig. 5 is obtained. Magnified picture of Fig. 5 is presented in Fig. 6. Note that, in all figures below, vertical axis is voltage in kV and horizontal axis is time in seconds.

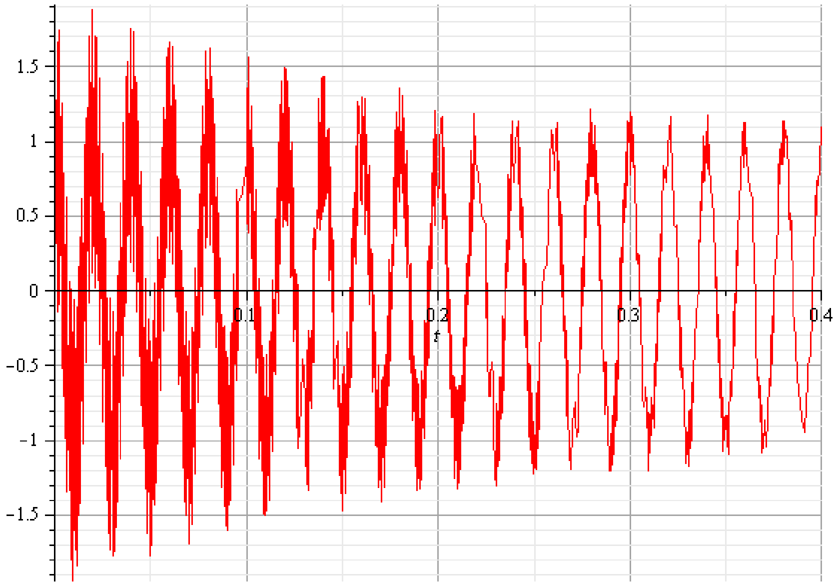

Fig 5. TRV voltage for a circuit without BR.

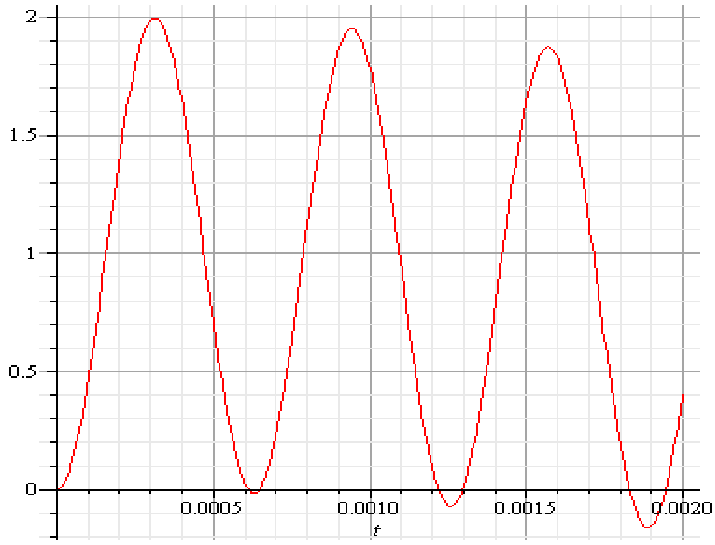

Fig 6. Magnified picture of Fig 7

For this case, RRRV value is RRRV= 2KV/300μs = 0.0067 KV/μs. Also, the TRV waveform is very distorted and it takes a long period of time for it to be settled down in a sinusoidal form. Now, we consider a case with BR in the circuit and calculate the new RRRV values and compare them with the obtained value for a case without BR in the circuit.

3.2 Circuit with BR

In this case, BR (shown with “R” in the Fig. 7) is located in the circuit and the same procedure is conducted to calculate RRRV for this situation. KVL and KCL equations for the circuit shown in Fig. 7, give V_{TRV} as (2):

$$V_{TRV}(s) = \frac{V_s(s) \cdot R \cdot (1 + r \cdot C \cdot s)}{(r+R) \cdot L \cdot C \cdot s^2 + s \cdot (r \cdot R \cdot C + L) + R} \qquad (2)$$

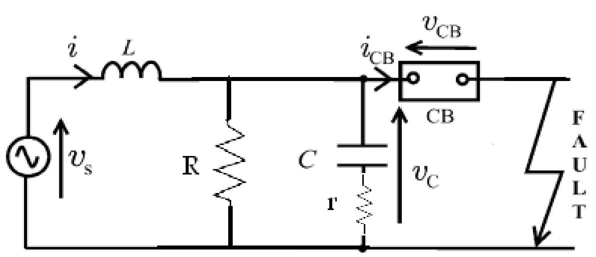

Fig 7. Circuit diagram with BR.

Assuming R = 100 Ω, and plotting VTRV in the time domain gives the waveform shown in Fig. 8.

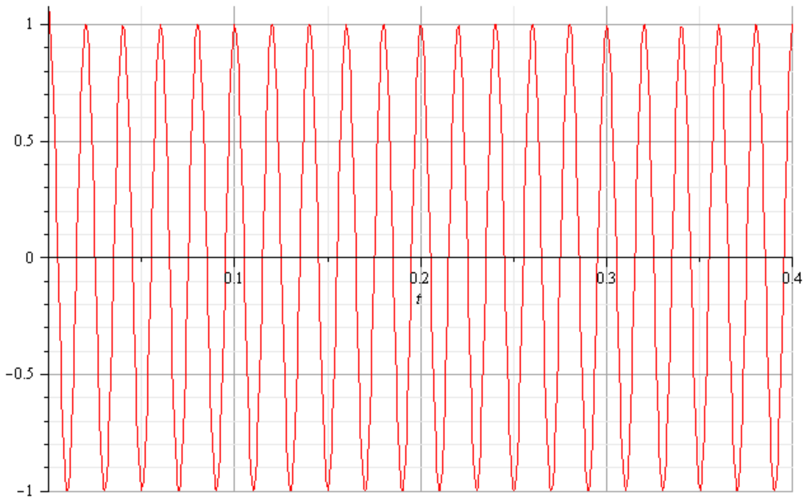

Fig 8. TRV curve for the case R=100 Ω.

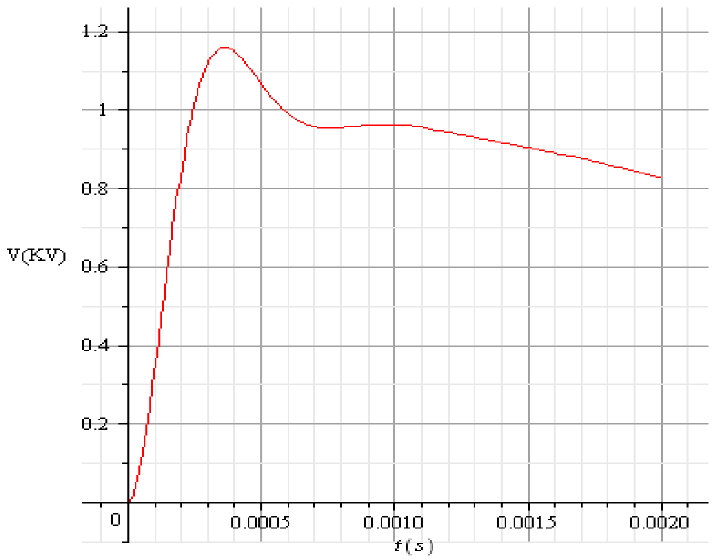

Fig 9. Magnified picture of Fig 10.

Table 1. RRRVs for different BR values.

Case	Without BR	With BR				
		R = 300 Ω	R = 200 Ω	R = 100 Ω	R = 50 Ω	R = 30 Ω
RRRV (KV/μs)	0.0067	0.005	0.0047	0.0039	0.0018	0.0016

RRRV value for this case is: RRRV = 1.18 KV/300μs = 0.00394 KV/μs. We note that with presence of BR=100 Ω, the value of RRRV has been decreased from 0.00670 KV/us to 0.00394 KV/μs. Also, magnitude of the VTRV has been decreased from 2KV to 1.18 KV. RRRV values for different values of BR are calculated and summarized in Table 1. It should be noted that the above results are obtained for the assumed values of parameters and may not be in accordance with the simulation results, which are given in the next section. So, the main aim

of the presented analysis was to show how the presence of braking resistor influences RRRV values and reduces TRV magnitudes. True and real values should be adopted for parameters to acquire exact and accurate results.

4 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 ATPDraw 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 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 for a circuit breaker is usually made based 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 faults.

4.1 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 [10]. Simulation step is considered 1μs to capture the high frequency TVR phenomena. Fig. 10 shows the load angle responses for both 3LG fault. It is clear from this response that, BR effectively enhances the transient stability. Fig. 11 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.

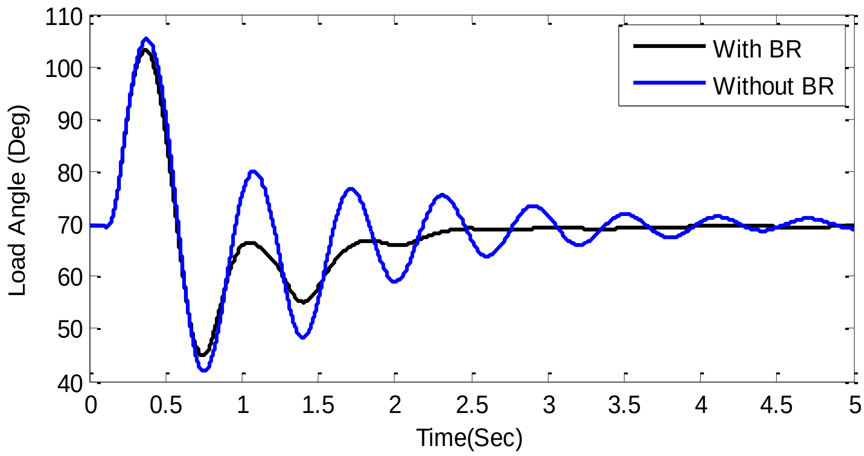

Figure 10. Load angle responses for 3LG fault**.**

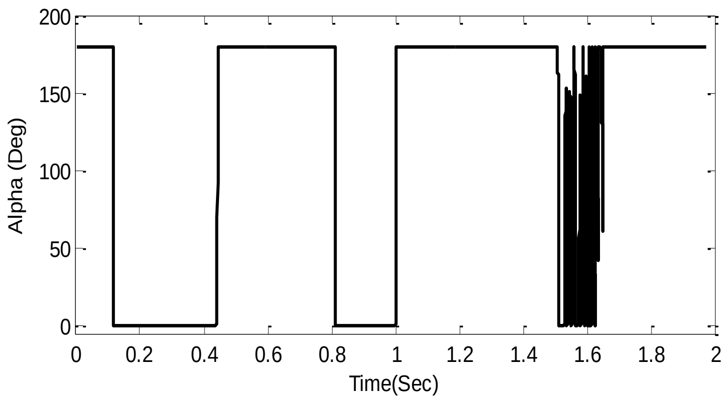

Figure 11. Firing angle for phase 'a'**.**

When the firing angle of thyristor is zero Deg, the whole resistor is in the circuit and conversely, when firing angle is 180°, the whole resistor is not in the circuit.

Considering the firing angle of thyristor, two important remarks are obtained:

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

The TRV has various parameters such as Rate of Rise of Recovery Voltage (RRRV). The RRRV is an important parameter in the power system operation, specified in volts per microsecond (V/µs) in IEEE C37.41 Standard [3]. Fig. 8 shows the CB's TRV with and without the BR. As can been achieved from this figure, the value of RRRV is about 5.03 kV/µs for the case without the BR. BR presence has led to elimination of TRV and decreased value of RRRV to 0.3 kV/µs. 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 the results of single phase fault (the most occurred and important fault) is considered, to reduce the number of figures.

5 Conclusion

The investigations in EMTP/ATP environment shows that using braking resistor besides synchronous generator, not only improves the transient stability of the generator, but also eliminates TVR in CB, and significantly decreases the RRRV value. Mathematical expressions for TRV are obtained for two different cases: a) when a BR is connected in the CB circuit during the fault, and b) when BR is not available in the faulty circuit. Also, Rate of rise of recovery voltage (RRRV) for different values of BR are obtained to show the effect of BR value on amount of the established TRVs. Furthermore, 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's TVR is another advantage of using BR.

Appendix

System parameters:

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

AVR excitation system parameters:

K_p= 25, K_d= 0.2

GOV parameters:

K_p= 25, K_d= 2.0

BR controller parameters:

K_p= 180, T_i= 0.2

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