Impact of grading capacitor on transient recovery voltage due to shunt reactor de-energization for different values of current chopping

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ABSTRACT

This paper investigates the impact of grading capacitors on transient recovery voltage (TRV) during shunt reactor switching in high voltage systems, considering different levels of current chopping. Shunt reactor de-energization can result in voltage surges and instability due to current chopping effects. The study utilizes simulation models using ATP-Draw software to assess the effectiveness of grading capacitors in mitigating TRV under various operating conditions as well as of using a proposed method to mitigate the excessive TRV across the circuit breaker. The findings provide valuable insights into managing TRV during shunt reactor switching, enhancing power system stability and reliability. The results obtained showed that the TRV across the circuit breaker decreased by 61.5% by using circuit modification as well as adding a grading capacitor.

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1. INTRODUCTION

A shunt reactor is a type of electrical device used in power systems to compensate for reactive power. Reactive power is the power that oscillates between the generation and consumption of electric energy due to the presence of inductive or capacitive elements in the system [1]–[4]. Shunt reactors are specifically designed to consume or produce reactive power, the reactor bank should be switched off during periods of high load on the transmission line, based on the power system's needs [5], [6]. One of the main problems related to the de-energization of a shunt reactor is the occurrence of transient overvoltages. Reactive power passing through a shunt reactor is abruptly interrupted when it is de-energized. This sudden change in the system refers to the phenomena of current chopping which can lead to voltage surges or overvoltages, which can pose risks to the power system and connected equipment.

The impact of current chopping on transient recovery voltage (TRV) is significant, as current chopping can influence the characteristics and behavior of the TRV waveform. The voltage observed across the contacts of a switching device right after current interruption is referred to as TRV [7], [8]. Current chopping can lead to higher magnitudes of TRV compared to smooth current interruptions. During current chopping, the rapid interruption of current can create high-frequency oscillations in the system, resulting in voltage transients. These transients contribute to higher peak values of the TRV waveform, increasing the magnitude of the voltage across the switching device's contacts [9], [10]. The voltage distribution across breaking chambers additionally serves as crucial for circuit breaker (CB) dielectric stresses during switching operations, besides the TRV peak value. When the CB has not been equipped with grading capacitors, the voltage distribution between the breaking chambers is mostly unequal, and this can occasionally result in the CB failing [11]. The grading capacitor plays a crucial role in controlling the TRV across a circuit breaker during its operation. Grading capacitors are strategically placed within the circuit breaker mechanism to ensure a gradual voltage distribution across the interrupting contacts during the current interruption process [12]. By carefully selecting the capacitance value and placement, the grading capacitors help divide the TRV into multiple stages, minimizing voltage concentration at any particular point and improving the overall voltage distribution across the breaker contacts.

In this study, the switching overvoltage for a high-voltage shunt reactor is determined together with the related equipment that will be placed in a 400 kV switchyard. Furthermore, computer simulations of a three-phase circuit were conducted to simulate the shunt reactor switching under several values of current chopping. The objective of the simulations aimed to produce insightful findings to examine the overvoltages across the breaking chambers and appear significance of adding a grading capacitor to ensure voltage distribution as well as using the proposed model represented by circuit modification for suppression overvoltage and to illustrate the variations in the results. The results were obtained using ATP-Draw software for computer simulation for validation purposes.

2. DE-ENERGIZATION PROCESS OF SHUNT REACTORS

The de-energization process of shunt reactors in power systems is often accompanied by the phenomenon of current chopping. Current chopping refers to the rapid interruption and re-establishment of current flow during switching operations, particularly in inductive circuits. The transient behavior can create various issues and hurdles that require attention to guarantee the secure and dependable functioning of shunt reactors and their corresponding circuit breakers. [13], [14]. Figure 1 illustrates the circuit corresponding to a single phase of the shunt reactor, where: L_S is the load side inductance; C_S is the source side capacitance; C_L is the shunt reactor stray capacitance; L is the shunt reactor inductance; CB is the circuit breaker; L_b is the connection series inductance; and L_P; C_P is the breaker stray inductance and capacitance.

De-energizing a shunt reactor involves opening circuit breakers or disconnectors, which are capable of causing transient overvoltages. The interruption of the current flow causes a rapid change in the magnetic field, inducing voltage transients. The magnitude of these transients depends on the switching characteristics of the equipment and the circuit configuration [15]–[17].

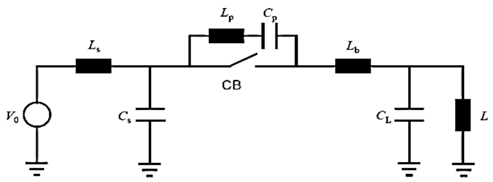

Figure 1. Shunt reactor switching analysis using a single-phase equivalent circuit

3. CURRENT CHOPPING

A phenomenon known as "current chopping" occurs when the current abruptly switches off in a circuit breaker before it reaches its natural zero [18]. When a circuit breaker opens, the current flowing through the breaker is interrupted, and the voltage across the breaker poles rapidly increases. The problem of current chopping can occur in shunt reactors during switching operations. Small inductive current interruption is significant in power systems, especially in high-voltage applications, as it can result in transient overvoltages that may exceed the system's insulation withstand capabilities. These overvoltages can potentially damage equipment, cause insulation breakdown, and compromise the reliability of the system [19]. The (1) indicates that as the chopped current level rises, both the stored energy and chopping voltage increase. Moreover, it's evident that current chopping significantly affects reactors with lower stray capacitance. The calculation of suppression peak overvoltage, also known as chopping overvoltage, can be determined using the energy balance equation provided below [20].

According to the energy balance in (1) current energy interruptions = energy at chopping peak voltage,

$$\frac{1}{2}CV^2 = \frac{1}{2}LI_{ch}^2 + \frac{1}{2}CV_O^2 \tag{1}$$

where: C is capacitance on the load side; I_{ch} is current chopped level; V is maximum chopping voltage; and Vo is the maximum voltage observed across the inductor during current interruption.

A new equation in (2) is derived by rearranging the previous formula, offering the value of the suppression peak overvoltage.

$$\frac{V}{V_O} = \sqrt{(1 + \frac{LI_{ch}^2}{CV_O^2}} \quad (2)$$

The (3) is computed assuming that the arc voltage of the CB before current chopping is negligible. Now, it's simple to determine the actual chopping current (I_{ch}) based on the measured overvoltage factor (Ka) using the given expression:

$$k_a = \sqrt{1 + \frac{3 \times i^2\ ch}{2 \times w \times Ct\ Q}}\ p.u \quad (3)$$

where Ct is shunt reactor capacitance; I_{ch} represents the chopping currents; and Q-reactive power.

When the current flowing through a shunt reactor is abruptly interrupted during current chopping, it can result in transient overvoltage. This overvoltage can occur due to the sudden collapse of the magnetic field in the reactor, causing voltage spikes that can stress the insulation of the equipment and potentially damage connected devices. The overvoltage across the shunt reactor due to current chopping is shown in Figure 2. The switching devices used for interrupting the current should be carefully selected and coordinated to minimize the effects of current chopping. Special attention should be given to their switching characteristics and the associated transient recovery voltage TRV requirements.

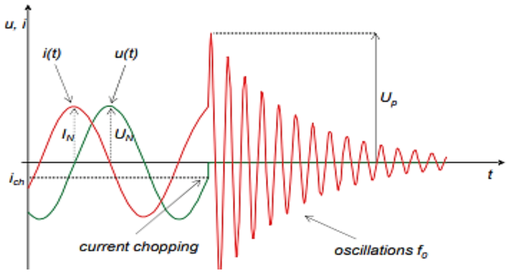

Figure 2. Inductive current interruption without arc re-ignition, i(t) – current, u(t) – voltage, i_{ch} – chopping current, I_N – nominal maximum current, U_N – nominal phase voltage, U_p – The highest voltage after de-energization, f_0 – represents the frequency of oscillations

4. TRANSIENT RECOVERY VOLTAGE

The voltage produced across the terminals of a circuit breaker after interrupting a current is referred to as TRV. It is an essential parameter of a high-voltage circuit breaker's fault interruption process. The TRV depends upon several elements, such as the system characteristics associated with both terminals of the circuit breaker as well as the kind of fault that the circuit breaker is required to interrupt [21]. Figure 3 shows the TRV circuit breaker terminals when interrupting the current. During current chopping, the arc extinguishes at a non-zero current level, which causes a transient current to continue flowing for a short duration after the main arc is gone. This transient current is known as the chopping current. The rapid dielectric recovery across the breaker contacts results in a brief reignition of the arc, leading to the chopping current. The effect of current chopping on TRV is significant, as current chopping can influence the characteristics and behaviors of the TRV waveform. TRV stands for the transient voltage that emerges across the contacts of a switching device following the interruption of current [22].

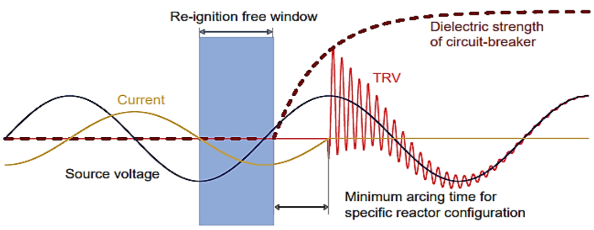

Figure 3. The overvoltage produced during shunt reactor switching

5. METHODOLOGY AND PROPOSED MODEL

The ATP-Draw application is used to model the switching shunt reactor (SR) and analyze the impact of switching. Figure 4 presents 400 KV as the case study. The characteristics of the reactor with a 150 MVAr rated power are provided in Table 1. Two breaking chambers constitute the 400 KV high-voltage circuit breaker. A potential grading capacitor with a C = 500 pF value is connected across each [23].

The circuit was first subjected to uncontrolled switching to provide a comprehensive understanding of the transient overvoltage, which is presented using the TRV value across the CB, which is believed to be the worst case. Therefore, mitigation techniques, such as controlled switching, have been used in different contexts. In a circuit breaker with two braking chambers, the chambers are typically connected in series. This means that the current flowing through one chamber must also flow through the other chamber [25]. By connecting the chambers in series, the circuit breaker can effectively interrupt the flow of current in the event of an overload or short circuit. This series connection ensures that both chambers work together to provide a higher level of protection and prevent any potential damage to the electrical system. The work will also show the effect of using a grading capacitor and its impact on controlling the distribution of voltage across the contacts of a circuit breaker. Consequently, this approach improves the overall interruption capability of the system.

In this context, the proposed model involves a circuit modification essential for preventing transient overvoltage during the SR switching. It also utilizes a grading capacitor to reduce the high TRV and prevent re-ignition. A modification in the circuit Figure 4 was made by incorporating circuit breaker (CB2) in series with resistance across the SR, as illustrated in Figure 5, as part of the study. The circuit's modification would allow it to absorb the transient overvoltage produced by both the SR and (CB_1). Grading capacitors, which provide regulated voltage distribution across the contacts of circuit breakers and other switching devices, will be essential in power systems.

Table 1. Parameters of the reactor [24]

Parameter	Value	Unit	Parameter	Value	Unit
Equivalent source resistance (R_S)	0.77	Ω/phase	Stray capacitance on the load side (C_L)	3.2	nF/phase
Equivalent source impedance (X_L)	6.19	Ω /phase	Corresponding reactor resistance (R_L)	1.2	Ω /phase
Stray capacitance on the source side (C_S)	4	nF/phase	Inductance of reactor (L)	3.395	H/phase
Bus inductance (L_B)	32	μH/phase			

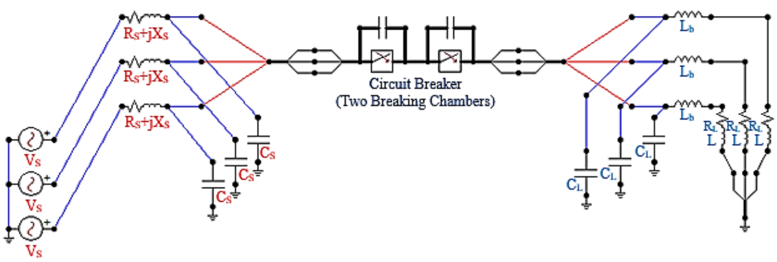

Figure 4. Shunt reactor's equivalent ATP-Draw model

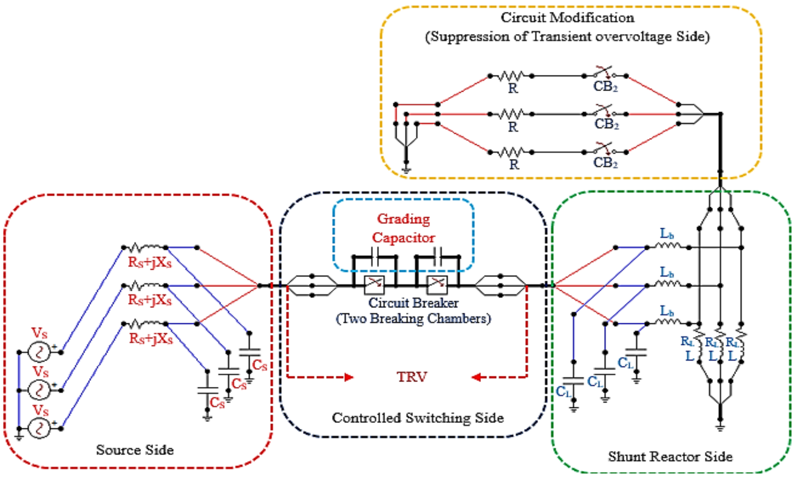

Figure 5. Circuit diagram after modification

6. RESULTS AND DISCUSSION

The ATP-Draw software was formerly used to create the circuit in this part. This study explores different shunt reactor switching scenarios, including uncontrolled switching, controlled switching, and a proposed circuit modification method to suppress transient overvoltage. This approach aims to gain a thorough understanding of de-energization, identifying both the worst-case and ideal scenarios during the interruption of a small inductive current, along with its associated transient overvoltage. All cases have been presented with and without grading capacitors. Figures 6 and 7 show the TRV across the breaking chambers during shunt reactor switching at (I_{ch}=20 A) in other words this case represents uncontrolled switching.

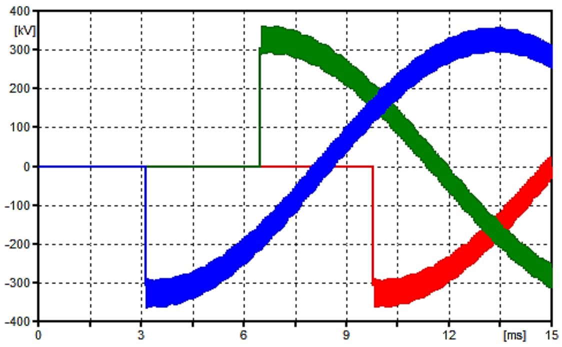

Figure 6. TRV (breaking chamber 1) at I_{ch}=20 A without grading capacitor

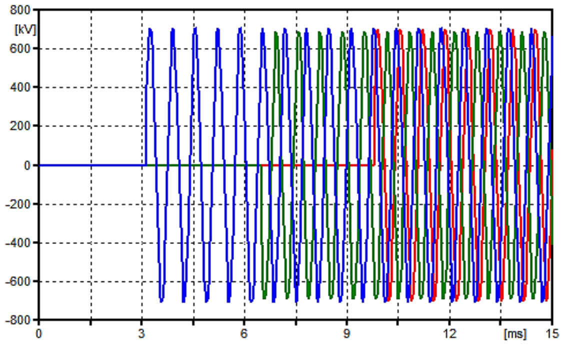

Figure 7. TRV (breaking chamber 2) at I_{ch}=20 A without grading capacitor

As noted from the figures above high transient overvoltage produced during shunt reactor switching across the circuit breaker chambers as well as unequal distribution of the voltage across the CB contacts, the case above represents the uncontrolled switching case with the absence of a grading capacitor. The following case will illustrate the case of using the circuit modification with the use of the grading capacitor at (I_{ch}=20 A) as shown in Figures 8 and 9.

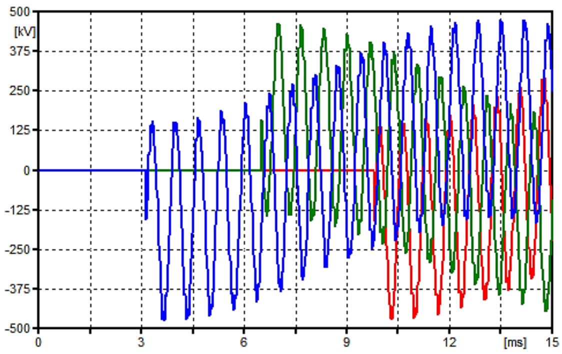

Figure 8. TRV (breaking chamber 1) at I_{ch}=20 A with circuit modification and grading capacitor

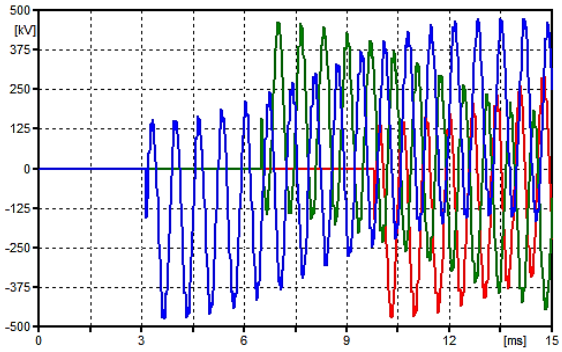

Figure 9. TRV (breaking chamber 2) at I_{ch}=20 A with circuit modification and grading capacitor

The figure noted the effect of using the circuit modification as a suppression method and the obvious effect of absorbing the transient overvoltage. Besides using the circuit modification, the grading capacitor has been used. Grading capacitors serve a crucial function in power systems by distributing voltage in a regulated manner over the contacts of circuit breakers and other switching equipment. The following example is considered to be the optimal scenario since it uses both the proposed method's circuit modification and grading capacitor at current chopping (I_{ch}=0 A), which results in the lowest TRV value possible. Figures 10 and 11 illustrate the ideal case which represents the controlled switching with circuit modification in addition to the use of grading capacitor.

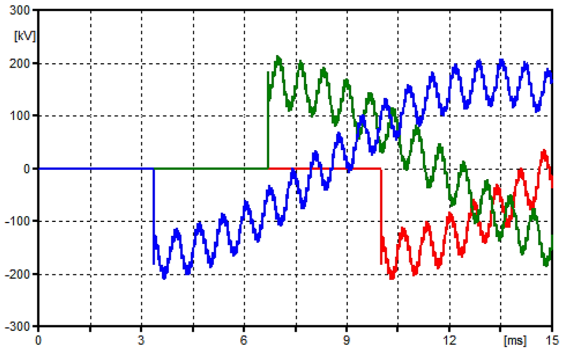

Figure 10. TRV (breaking chamber 1) at I_{ch}=0 A with circuit modification and grading capacitor

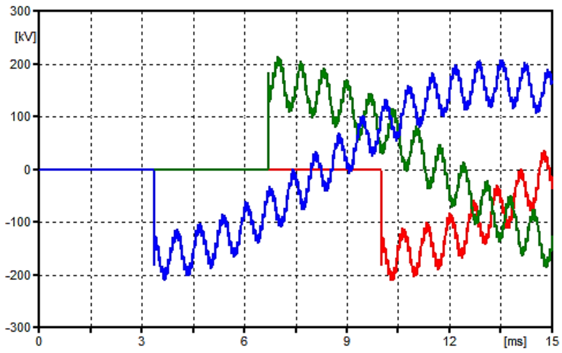

Figure 11. TRV (breaking chamber 2) at I_{ch}=0 A with circuit modification and grading capacitor

This paper focused on the impact of current chopping on TRV during shunt reactor switching, as depicted in Table 2. The table presents various scenarios, comparing the effects of circuit modification and its absence, along with the presence or absence of grading capacitors. The results provide insights into the different values of current chopping and their corresponding influence on TRV.

The analysis of simulated representations of the shunt reactor across various current chopping scenarios yielded significant findings. The results clearly indicate a direct correlation between higher current chopping values and elevated levels of TRV. Furthermore, the outcomes also demonstrate the pronounced impact of grading capacitors on the voltage distribution across the circuit breaker contacts, effectively regulating the voltage levels. Using a constant value for grading capacitors holds promise in making TRV consistent across different circuit breaker chambers during shunt reactor de-energization, even when dealing with different values of current chopping. The objective is to establish a dependable and controlled TRV environment by maintaining a uniform grading capacitor value, regardless of fluctuations in current chopping. This strategy aims to standardize TRV properties among various circuit breaker chambers, ultimately enhancing the stability and reliability of the power system during shunt reactor de-energization.

Table 2. TRV across the breaking chambers of the circuit breaker

	I_{ch}	TRV (without grading capacitor)						TRV (with grading capacitor)					
		Breaking chamber (1)			Breaking chamber (2)			Breaking chamber (1)			Breaking chamber (2)		
		A	B	C	A	B	C	A	B	C	A	B	C
Without applying circuit modification	20 A	363	360	362	695	685	707	502	500	511	502	500	511
	15 A	353	350	352	562	556	548	445	441	438	445	441	438
	10 A	343	344	340	445	440	433	389	385	382	389	385	382
	5 A	332	335	333	346	354	349	335	339	336	335	339	336
	0 A	324	325	326	324	325	323	324	325	326	324	325	323
With applying of circuit modification (proposed method)	20 A	359	361	362	618	609	629	470	465	474	470	465	474
	15 A	351	352	350	466	456	444	393	388	382	393	388	382
	10 A	343	343	342	315	305	295	320	316	311	320	316	311
	5 A	332	335	333	143	161	152	238	248	243	238	248	243
	0 A	324	326	325	88	93	85	208	210	206	208	210	206

7. CONCLUSION

In this study, overvoltage during shunt reactor de-energization simulation results are presented. The shunt reactor switching overvoltages at a functioning substation has been examined using simulations. Different levels of current chopping have been specifically examined after the shunt reactor was disconnected. High TRV is produced by the circuit breaker randomly opening. Switching at current zero, which corresponds to the point at which the reactor has the least amount of energy stored, as well as employing circuit modification as a suggested approach for overvoltage suppression, can both reduce these amplitudes. Additionally, the effects of chopped current on the TRV have been investigated. Increased TRV across the circuit breaker is caused by higher chopping levels. The results obtained showed that the TRV across the circuit breaker decreased by 61.5% by using circuit modification as well as adding a grading capacitor. Grading capacitors are employed to balance the electrical potential within the breaking chambers, as per calculations. This balancing reduces the likelihood of a restrike occurring inside the circuit breaker.

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