Simulation of switching overvoltages of 400 kV shunt reactor

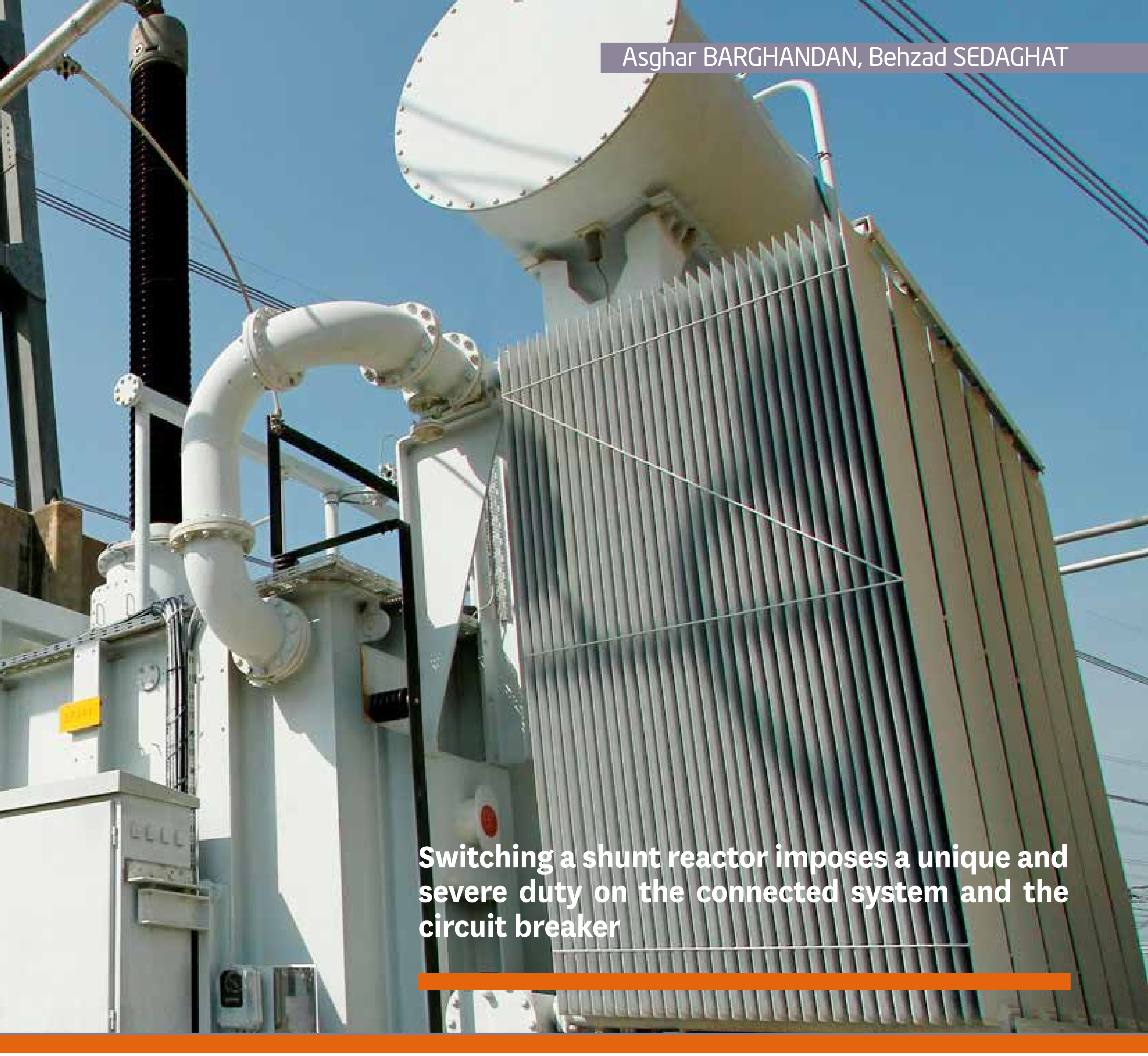
Shunt reactor grounded through a neutral reactor in 400/132 kV high-voltage substation

ABSTRACT

Bam 400/132 kV substation in Kerman region, Iran, has a 50 MVAR shunt reactor on 400 kV busbar which is grounded through a 128 kVAR neutral reactor. The neutral earthing reactor assists in interrupting line to ground arcing current when switching for clearing a line to ground arcing fault, but the switching of shunt reactor which is grounded through a neutral reactor can impose a more severe duty on the circuit breakers than switching a solidly grounded shunt reactor. While opening shunt reactor, transient phenomena, such as chopping overvoltages and reignition overvoltage/overcurrents can occur. These overvoltages/currents can put circuit breakers, reactors and other equipment in danger. In this paper, the Bam substation's equipment such as electrical circuits and associated equipment will be modelled in transient mode using EMTDC/PSCAD software. The arc behaviour and excessive voltage caused by the switching will be analysed. Finally, three methods including controlled switching, using surge arrester and a disconnecting switch across the neutral earthing reactor for mitigating these overvoltages will be compared.

KEYWORDS

shunt reactor, neutral reactor, chopping current, switching overvoltage, controlled switching



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Switching a shunt reactor imposes a unique and severe duty on the connected system and the circuit breaker

1. Introduction

In power systems, shunt reactors are applied to control the reactive power and voltage profile on the transmission lines. Shunt reactors which are grounded through neutral reactors are unique to extra high voltage (EHV) systems (generally, systems with voltage level above 345 kV can be called EHV systems). Such schemes are applied to achieve better single pole fault clearing of line to ground faults and therefore assist in successful reclosing. The switching of such reactor schemes is a combination of the directly grounded and ungrounded reactor cases [1].

Shunt reactor switching imposes a unique and severe duty on the connected system and the circuit breaker. Particularly, switching shunt reactors grounded through neutral reactor are more severe than solidly grounded shunt reactors [2]. In these cases, the current to be interrupted is generally less than 300 A, but the interruption of these currents can result in significant overvoltages [1]. Inspection of the circuit breakers after field service has shown that interrupters have been subjected to excessive transient recovery (even higher than type test values) and damaged [3].

1.1 Chopping current overvoltages

During opening of the circuit breaker (CB) at the instant of chopping current, an amount of energy is trapped in the load side. This trapped energy will oscillate between inductance and stray capacitance of the load (reactor) and create overvoltage as (1). The frequency of oscillating voltage is between 1 to 5 kHz and evenly distributed across the winding of the reactor [1].

$$\left(\frac{V_m}{V_0}\right) = \sqrt{1 + \frac{I_{ch}^2}{V_0^2} \times \frac{L}{C}} \qquad (1)$$

Where, L is inductance of reactor in Henry, C is load side capacitance in Farad, I_{ch} is amplitude of current chopping in amperes, V_o is the reactor voltage at the moment of current chopping, and V_m is the magnitude of chopping current voltage in volts [1].

To limit and control overvoltages several methods are used, like connecting surge arresters to shunt reactor terminals, disconnecting switches across to neutral reactor and synchronous opening control devices

1.2 Reignition overvoltages

The recovery voltage across the circuit breaker terminals is created after the current interruption. The peak of this recovery voltage is equal to the peak of chopping current overvoltage plus the peak of source side voltage. If the circuit breaker has had sufficient dielectric strength, it does not reignite at this point, then arc is extinguished successfully. But, if the instant of contact parting is such that the contact gap does not yet have sufficient dielectric strength to withstand the voltage appearing across the breaker contacts, then a reignition will occur [1]. When a reignition occurs, the load side voltage rapidly tends towards the source side voltage and produces an overshoot - in other words, a reignition overvoltage. Such voltage breakdowns (at the reignition instant) create steep transient voltages that are imposed on reactors. The front time of waves varies from less than one microsecond to several microseconds and may be unevenly distributed across the reactor winding. So these steep fronted transient voltages are stressing the entrance turns in particular with high inter-turn overvoltages [1].

1.3 Limiting of overvoltages

The above mentioned overvoltages cannot be eliminated completely but can be limited to acceptable values [1]. There are several ways, such as surge arresters on shunt reactor terminals, disconnecting switches across to neutral reactor and synchronous opening control devices, to limit and control these overvoltages [1]. In this study, three methods including controlled switching, using of surge arrester and usage of disconnecting switch across natural reactor for mitigation of these overvoltages will be compared.

2. System components

This section includes a brief description of the system components, modelling and implementation of these components in PSCAD/EMTDC software.

2.1 Circuit breaker model

2.1.1 Arc model

Conventional ideal circuit breakers have only two open and close positions and do not model arcs that occur within them. So, they are not suitable for reactor switching studies.

The approach taken in this study, as in Fig. 1, is a block diagram of the arc model. This model is based on energy balance theory during an arc to simulate the thermal interactions within the circuit breaker. Also, this block diagram simulates the voltage race that occurs inside and outside the circuit breaker. The voltage race means a race between system recovery voltage and circuit breaker dielectric withstanding recovery voltage. Arc model is mathematically expressed as formula for the time-varying resistance or conductance as a function of arc current, arc voltage and several time-varying parameters representing arc properties [4]. The arc model is based on Mayer model as shown in (2).

$$\left(\frac{1}{g_{m}}\right)\times\left(\frac{dg_{m}}{dt}\right)=\left(\frac{1}{T_{m}}\right)\times\left(\frac{i^{2}}{(P_{m}\times g_{m})}-1\right) \quad (2)$$

Where g_m is arc conductivity in Siemens, T_m is arc time constant in seconds, P_m is arc loss in Watts and i is arc current in Amperes [4].

This model assumes that changes of arc temperature are dominant and size and profile of the arc column are constant. In this model, thermal conduction is the main mechanism of energy removal [4]. The model with constant parameters (i.e., T_m and P_m) describes the arc with strictly defined mathematical functions that cannot be fitted to measured curves of current and voltage with sufficient accuracy. In order to overcome this deficiency the Mayer model was modified in following manner with Avdonin in (3) and (4).

$$T_{m}=T_{0}\times g^{\alpha} \quad (3)$$

$$P_{m}=P_{0}\times g^{\beta} \quad (4)$$

Where g is arc instantaneous conductivity in Siemens, α and β arc constant parameter, T_0 is arc initial time constant in Seconds, P_0 is arc initial loss in Watts. Here, parameters P_m in Watts and T_m in seconds are assumed to be function of arc conductance [3].

Similar to [3], due to the unavailability of accurate arc parameters for associated circuit breaker, typical parameters from others studies are used as arc parameters which are shown in Table 1 and Fig. 1. The initial value of variable resistance (before arc starting) is equal to circuit breaker contact resistance and during the arc, its value is controlled by equation (2). Also in circuit breaker model, during occurrence of a reignition, the arc resistance resets to its initial value.

This study has involved simulating circuit breakers with the arc model based on energy balance theory during an arc, and simulating the voltage race that occurs inside and outside the circuit breaker

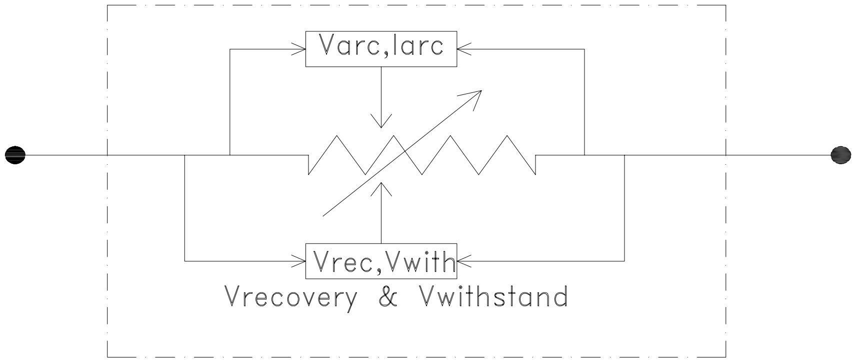

Figure 1: Circuit breaker model block diagram

2.1.2 Dielectric recovery characteristic

The dielectric characteristic between contacts when the circuit breaker is opened under no load or interrupted, a small current is different from that for short-circuits current switching. During small current switching the dielectric strength recovery characteristic relates to the inherent characteristic of the circuit breaker and this is normally referred to as a cold recovery characteristic.

A typical dielectric recovery characteristic of a SF6 interrupter is shown in Fig. 2. It can be seen that as the contact gap increases, the dielectric strength increases linearly at first and then levels off [3]. The circuit breaker dielectric recovery voltage capability is shown in Fig. 2. In this study, dielectric recovery curve is modelled by a line with a slope of 400 kV/ms, which will be constant after reaching standard switching withstanding level (1050 kV).

In voltage race across circuit breaker contacts, if the circuit breaker internal dielectric recovery voltage is lower than the system recovery voltage, the reignition will take place, else the arc will be extinguished.

Table 1: ARC constant parameters

Parameters	Value
T_0	0.85 (microsecond)
P_0	400 (kilowatt)
α	0.09
β	0.49

2.1.3 Stray capacitance

Stray capacitance of interrupting chamber and between terminals and earth are also considered in circuit breaker modelling [5].

2.2 Reactor model

The reactor is modelled by three phase self-inductances, mutual inductances between phases, equivalent capacitances (stray and insulation capacitance), winding resistance and insulation resistance [5], [6]. Self-inductance, equivalent capacitance and winding resistance are obtained from the routine factory tests. Insulation resistance can be measured by dielectric tests and its typical value is about several hundred kiloohms similar to [5] values. In 5-limbed reactors, the ratio of self-inductance to mutual inductance is high and mutual inductance is negligible. For example according to [6] the ratio is a value between 250 and 1000. The shunt and neutral reactor parameters are proposed in Table 2 and 3 as factory tests, respectively.

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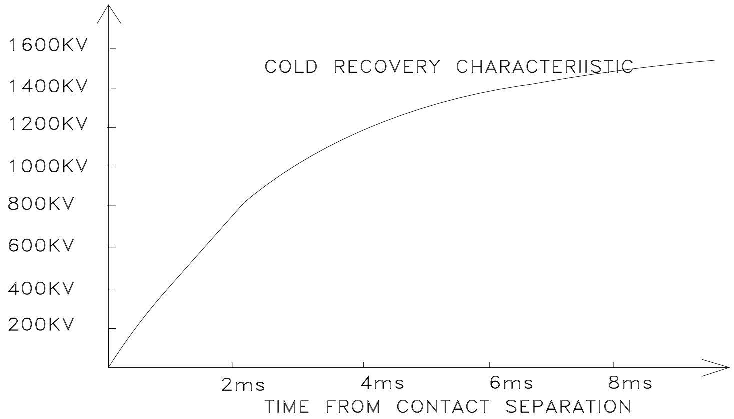

Figure 2: Typical dielectric recovery characteristic of a SF6 puffer interrupter

Table 2: Shunt reactor parameters (per phase)

Parameters	Value
L	9.92 (henry)
C	8.2 (nanofarad)
R (winding)	8.6 (ohm)
R (insulation)	400 (kiloohm)

Table 3: Neutral reactor parameters (single phase)

Parameters	Value
L	4.85 (henry)
C	0.97 (nanofarad)
R (winding)	16.11 (ohm)
R (insulation)	200 (kiloohm)

2.3 Other equipment models

In this study, surge arresters with non-linear voltage current characteristic are modelled. The parameters are extracted from manufacturer data sheets, specifications and documents. Conductors which are connected to the reactor are modelled using the Pi-Section model (π model is a lumped model to simulate conductors of transmission lines) in PSCAD/EMTDC applying values recommended in [1]. Current transformers and capacitive voltage transformers are modelled using equivalent capacitance and resistance as in routine factory test results of each one. Finally, the voltage source is modelled with Thevenin theorem. Single line diagram of the Bam substation 400 kV switchgear is shown in Fig. 3.

3. Simulation

It can be observed from Fig. 3 that the shunt reactor and associated neutral reactor have a dedicated circuit breaker which is connected to busbar. So if there is a line to ground fault on any transmission line, only the associated line circuit breaker will be opened but the shunt and neutral reactor will be in service (during line to ground fault on any transmission line) and help the line circuit breaker to clear the fault better. But there are some conditions where it is required to switch off only the reactors such as seasonal requirements due to load variations on transmission line, maintenance, etc. In the other words, there are no faults on transmission line but it is only required to switch off shunt reactor itself separately.

Surge arresters with non-linear voltage current characteristic are modelled extracting parameters from manufacturer data sheets, specifications and documents

In this paper, transient phenomenon of *such* reactor switching will be simulated and three methods to overcome or reduce this harmful phenomenon will be investigated.

The following three strategies are considered and evaluated:

1. controlled switching
2. applying surge arresters at shunt reactor terminals
3. application of earth disconnecting switch in parallel with neutral reactor

Based on the above mentioned strategies, the following scenarios were investigated:

When none of controlling devices is used chopping overvoltage in all 3 phases occurs and in one phase system recovery voltage reaches circuit breaker withstanding voltage consequently leading to a reignition

Scenario 1: In this scenario, none of the controlling devices (surge arrester, disconnecting switch and control switching relays) were applied. Fig. 4 shows that chopping overvoltage in all 3 phases occurs but according to Fig. 5, in one phase system recovery voltage reaches circuit breaker withstanding voltage and consequently reignition occurs. According to Figs. 4 and 5, reignition overvoltage at the reactor terminal is 2.4 per unit (the

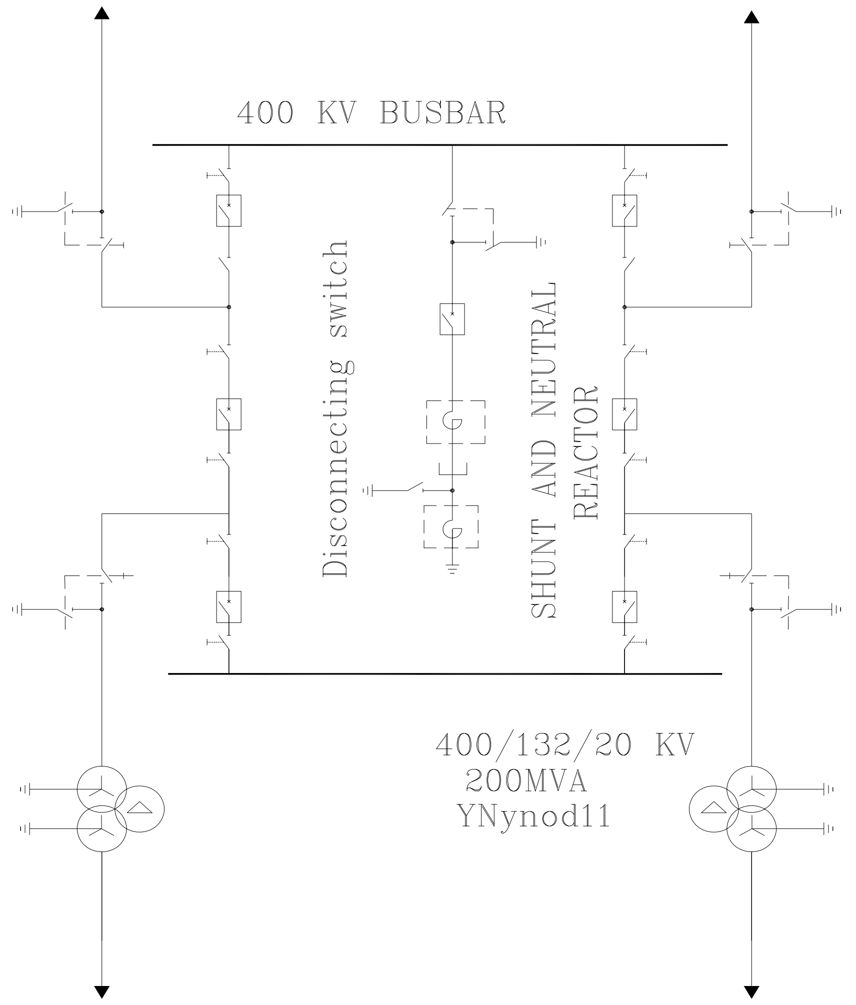

Figure 3: Bam 400 kV switchgear single line diagram

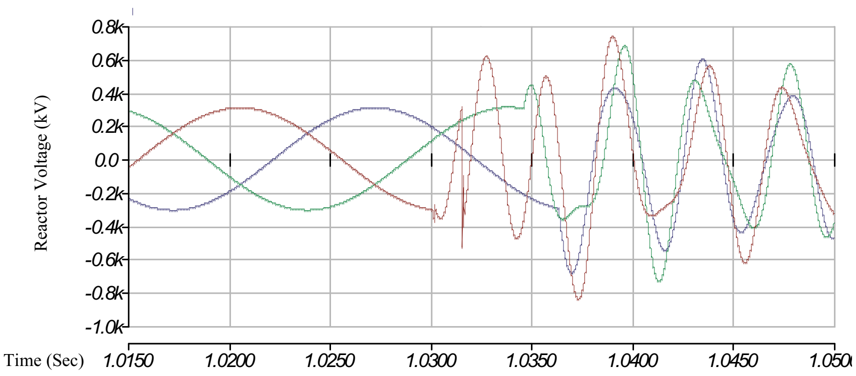

Figure 4: Chopping current and reignition overvoltages in shunt reactor terminals in the first scenario

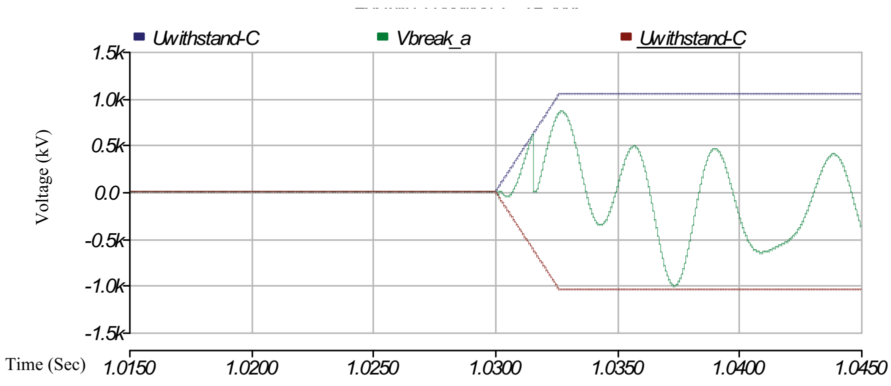

Figure 5: The race between system recovery voltage and circuit breaker withstanding voltage in the first scenario

When controlled switching is used it can shift and delay system recovery voltage peak and prevent reignition from occurring

base value assumes peak of phase voltage to ground) and reignition overvoltage across circuit breaker terminals reaches to the switching withstand level which is 1050 kV. It means that reactor and circuit breaker are under stress and likely to fail.

Scenario 2: In this scenario, controlled switching has been evaluated. This method, as Fig. 6 shows, applies to circuit breaker to ensure a minimum arcing time and successful interruption at the first current zero after contact parting [1]. According to Fig. 7, reignition does not occur but recovery voltage across circuit breaker terminals is still high and close to tolerable level. So, any changes in system parameters such as reactors stray capacitance may cause reignition at the circuit breaker.

In other words, due to controlled switching reignition does not happen. But recovery voltage still stresses equipment particularly the circuit breaker and reactor and that may lead to failure. By comparing Fig. 5 with Fig. 7 it is illustrated that controlled switching can shift and delay system recovery voltage peak and prevent reignition from occurring. In fact, this shifting/delaying provides necessary time for circuit breaker contacts to separate completely for applying the system recovery voltage across them. But this method cannot change system recovery voltage amplitude. It only changes system recovery voltage time not its amplitude. In fact, the peak of system recovery voltage depends on chopping current value, load side capacitance and reactor inductance [1].

The voltage at neutral reactor terminal is presented at Fig. 8 that reaches 1.2 per unit. (The base value assumes peak of phase voltage to ground). Such voltages on neutral reactor terminals are added to shunt reactor voltage (phase to ground) and also added to recovery voltage across the circuit breaker. Therefore, neutral reactor increases shunt reactor voltage (and circuit breakers recovery voltage) in comparison with directly grounded shunt reactor.

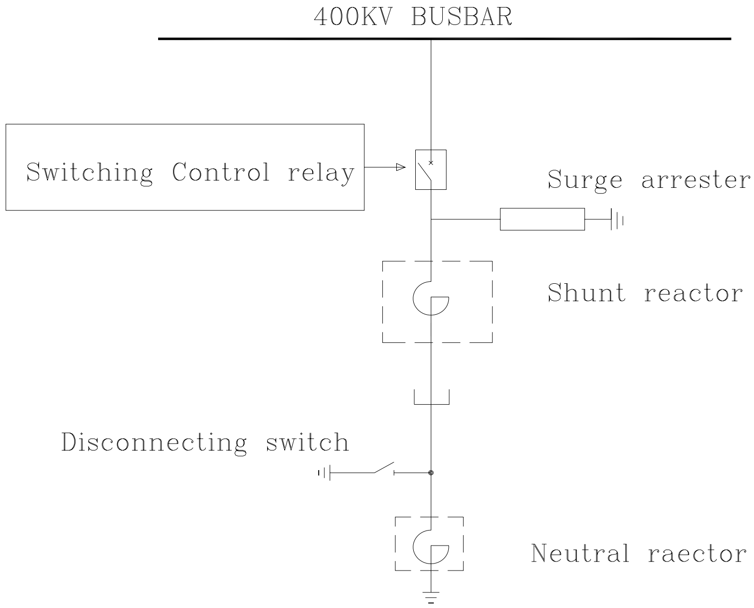

Figure6. Single line diagram of reactor feeder

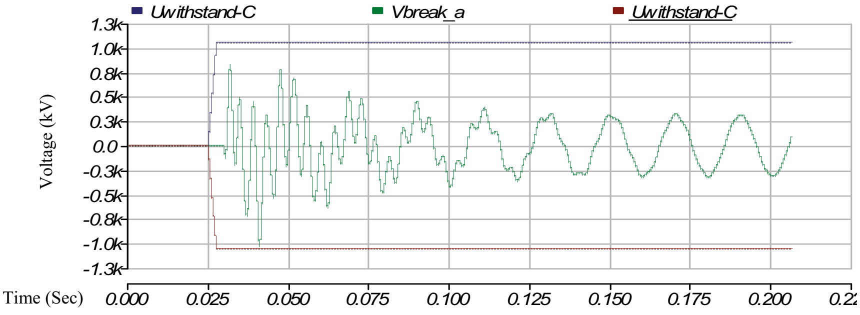

Figure 7: The race between system recovery overvoltage and circuit breaker withstanding voltage in the second scenario, the horizontal axis is time (sec)

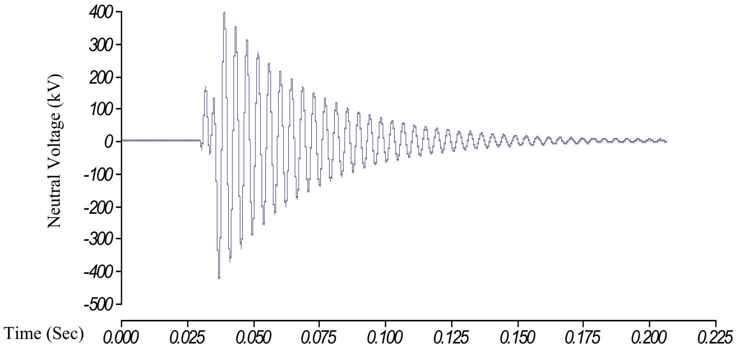

Figure 8: Voltage in neutral reactor terminal in the second scenario, the horizontal axis is time (sec)

When controlled switching and surge arresters are used, controlled switching avoids reignition and the surge arrester reduces the amplitude of system recovery voltage

Scenario 3: In addition to controlled switching, a three phase surge arrester is installed near the shunt reactor. Controlled switching method avoids reignition and the surge arrester reduces the amplitude of system recovery voltage. Overvoltage at shunt reactor terminals and recovery voltage across circuit breaker contacts are presented in Figs. 9 and 10. Comparing Fig. 10 with Fig. 7 indicates that vol-

When a disconnecting switch is used, it connects the neutral point of the shunt reactor to the ground directly prior to switching out the shunt reactor, resulting in limited switching overvoltage

tage across circuit breaker terminals has decreased only 0.6 per unit.

Also, the surge arrester decreases neutral reactor voltage about 100 kV as shown in Fig. 11. Due to this reduction, circuit breaker and reactor are exposed to less stresses. In addition, Fig. 12 indicates that the energy absorbed by the surge arrester is low too. And according to IEC 60099, surge arresters with class 1, 2 are sufficient for this purpose [7].

Scenario 4: Another way to limit switching overvoltage is connecting the neutral point of the shunt reactor to the ground directly prior to switching out the shunt reactor. It can be done by a single pole disconnect switch connected across the neutral reactor as in Fig. 6 [1]. By means of this disconnected switch, the "shunt reactor grounded through a neutral reactor scheme" converts to "directly earthed shunt reactor scheme". In addition to the disconnecting switch, a control switching device is used. Voltages at shunt reactor terminals and across circuit breaker contacts are presented in Figs. 13 and 14. Results in Figs. 13 and 14 show voltages at shunt reactor terminal and recovery voltage at circuit breaker terminals have reached to 1.35 p.u and 600 kV respectively which have a sufficient margin to switching withstand levels. These voltages are much smaller than in previous scenarios and it means that this method is more effective than previous methods to reduce switching overvoltages.

The summary of investigations and the results according to four scenarios can be found in Table 4.

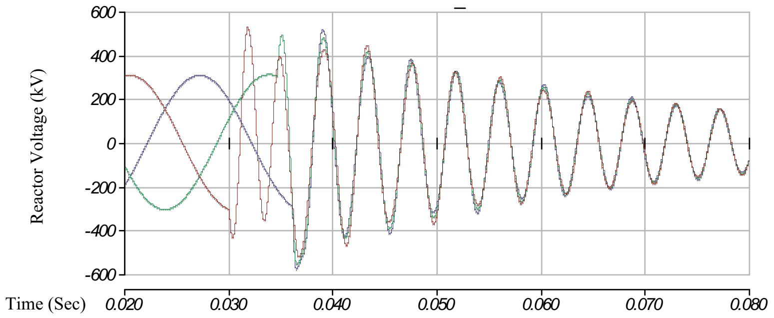

Figure 9: Overvoltage in shunt reactor terminal in the third scenario, the horizontal axis is time (sec)

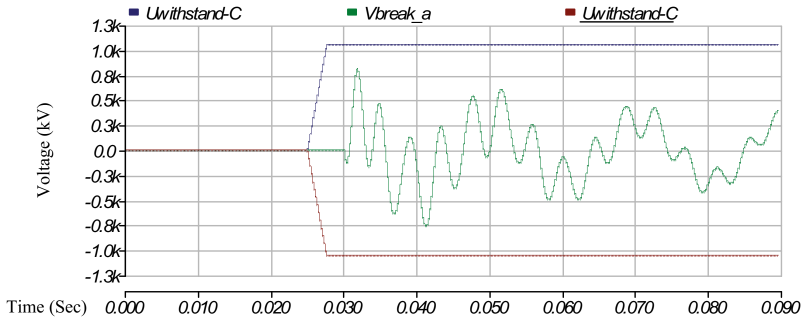

Figure 10: The race between system recovery overvoltage and circuit breaker withstanding voltage in the third scenario, the horizontal axis is time (sec)

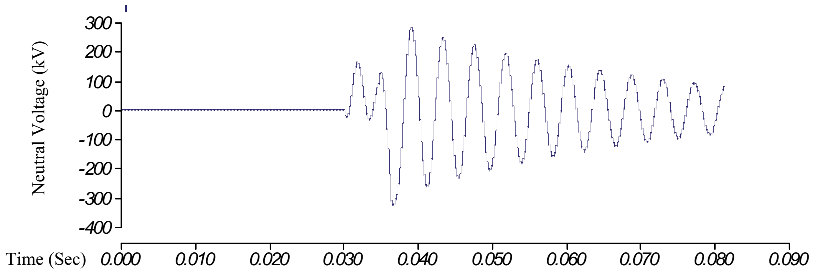

Figure 11: Voltage in neutral reactor terminal in the third scenario, the horizontal axis is time (sec)

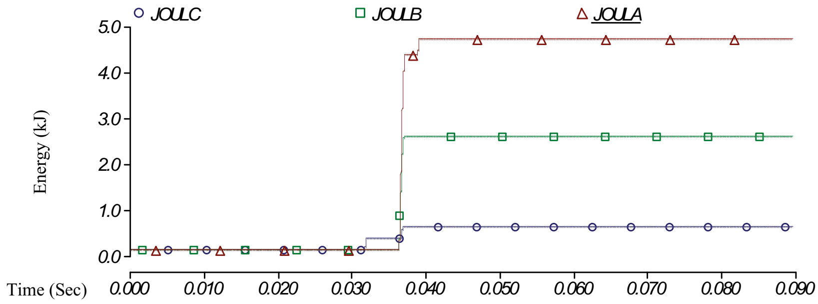

Figure 12: Energy absorbed by surge arresters in all phases in the third scenario, the horizontal axis is time (sec)

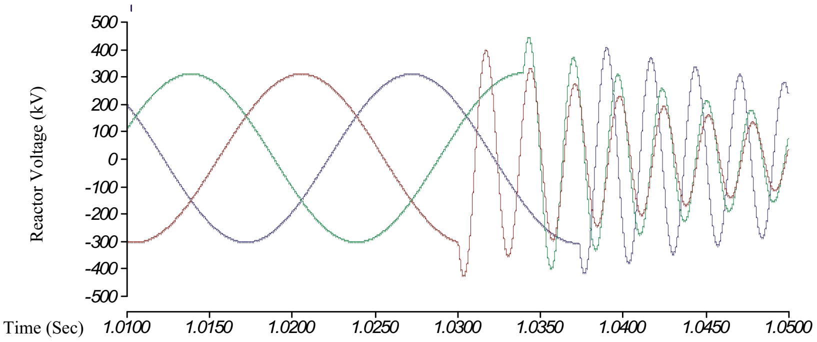

Figure 13: Voltage at shunt reactor terminal in the forth scenario, the horizontal axis is time (sec)

Studies and simulations indicated that the controlled switching method can shift and delay system recovery voltage peak and prevent reignition from occurring

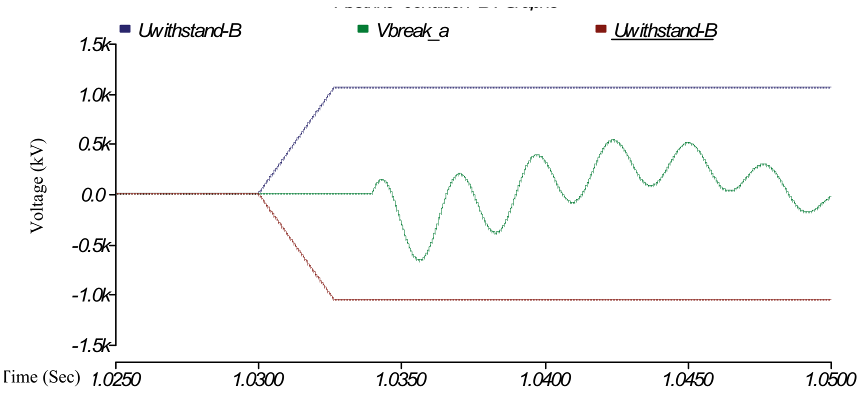

Figure 14. The race between system recovery overvoltage and circuit breaker withstanding voltage in the forth, the vertical axis is voltage (volts) and the horizontal axis is time (sec)

Conclusion

Switching shunt reactor which is grounded through a neutral reactor may generate overvoltages that damage the equipment. In the Bam 400/132 kV substation a shunt reactor is grounded through a neutral reactor. The substation equipment in transient mode was modelled and implemented in EMTDC/PSCAD software to investigate the associated switching overvoltages. Then three methods to overcome or reduce these overvoltages were proposed.

Studies and simulations indicated that the controlled switching method can shift and delay system recovery voltage peak and prevent reignition from occurring. In fact, this shifting/delaying provides necessary time for circuit breaker contacts to separate completely for applying the system recovery voltage across them. But this method does not protect the equipment from high recovery overvoltages. Second method or combining controlled switching method with surge arrester protection yields better results. They control both chopping current and reignition overvoltages time and amplitude. In the second method lower over-

Table 4: Summary of results

Scenarios	Controlling devices			Results	
	Control switching relay	**Surge arrester**	**Dis-connector**	**Reignition happens or not?**	**Overvoltage at reactor terminal or across circuit breaker terminals**
Scenario 1	x	x	x	Yes	The reignition overvoltage at reactor terminal is 2.4 per unit and reignition overvoltage across circuit breaker terminals is very close to switching withstand level.
Scenario 2		x	x	No	The reignition does not happen, but high recovery voltage still stresses the equipment particularly circuit breakers and reactor.
Scenario 3			x	No	Controlled switching method avoids reignition and the surge arrester somewhat reduces the amplitude of system recovery voltage.
Scenario 4				No	The voltage at shunt reactor terminal and recovery voltage at circuit breaker terminals have a sufficient margin to switching withstand levels. These voltages are much smaller than in previous scenarios.

The best results were obtained from simultaneous usage of controlled switching method and disconnecting switch across neutral reactor

voltages are applied to the equipment. In this method, the energy absorbed by surge arrester was low too and even surge arresters with class 1, 2 absorption capacities were sufficient. The best results were obtained from simultaneous using of controlled switching method and disconnecting switch across neutral reactor. The main idea of the proposed method is closing of the disconnecting switch and earthing the neutral point of shunt reactor first, then opening of the shunt reactor by controlled switching method. By this method, both chopping current and reignition overvoltages time and magnitude are controlled. In comparison with previous methods, voltages at shunt reactor terminal and system recovery voltage across circuit breaker terminals have adequate margin to switching withstand level.

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Reader‘s reaction

In Volume 1, Issue 1, on page 15, there is an error that is potentially dangerous to personnel and catastrophic to transformer equipment. The statement that a DETC can change taps when the transformer is not loaded is incorrect. The DETC can only be operated when the transformer is de-energized.
If the DETC is operated when the transformer is energized, this leads to arcing in the switch and most likely to the failure of the transformer. The misunderstanding about so-called „no-load tap changers“ has led to numerous operating mistakes and failures of transformers, requiring factory rebuild. Operating personnel are also in peril if this mistake is made.

Dick Amos, Consultant, TXMR US LLC