DIFFERENCE BETWEEN SWITCHING OF MOTORS & GENERATORS WITH VACUUM TECHNOLOGY

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ABSTRACT

Vacuum Circuit Breakers (VCBs) have been used for switching all kind of loads in industrial and distribution networks for more than 40 years. Due to their technological advancements and excellent advantages, the VCBs found their way into generator switching applications since 1994 and currently they are available for switching the generators rated up to 450 MVA.

However it is observed that the switching phenomenon of the motors & generators are slightly different when VCBs are used. Especially in terms of switching motors with VCBs, in certain range of inductive currents, overvoltages might occur. These overvoltages can be mitigated using surge protection equipment like surge arresters & surge capacitors.

On the other hand it has been widely asked if the same situation occurs during the switching of generators with VCBs. Do they also require surge arrester or surge capacitor for safe switching? The aim of this paper is to evaluate the switching phenomenon of motors that may cause overvoltages and analyze if the same phenomenon can be applied for generator switching. It is observed that the Vacuum Generator Circuit Breakers (VGCBs) don't require the surge protection to protect the generator since the VGCBs in this application will not generator any switching overvoltages.

INTRODUCTION

Many advantages like low maintenance, compact size and very high reliability make the vacuum technology to replace all the former arc quenching technologies in the medium voltage networks. About 85% of today's new installations employ vacuum switching technologies.

With an intense research activities and technological developments, the applications of the vacuum technology are extended to the more demanding generator circuits and are currently available for 100 kA of short-circuit current and 12500 A of rated current. Both power plant owners and the vacuum research engineers believe that the vacuum technology will replace the other existing technologies in generator networks as it did in the past in the distribution networks.

However, very often the public's opinion is that the VCBs are critical in terms of the switching overvoltages in the networks although the similar phenomenon can happen with other switching devices as well. A lot of research has been made in order to analyze the switching transients created by VCBs in order to design an adequate surge protection in combination. It has been found that in case of switching motors especially the situations of motor during starting or machine with locked rotor are considered to be critical. The starting currents that can go up to 5 to 7 times the rated current of motor, which is in the similar range to short-circuit currents. They are purely inductive in nature ($\cos\varphi \approx 0.2$ to 0.3). Switching of these starting currents, especially when the values are $\leq$ 600 A, can cause overvoltages as a result of multiple re-ignitions and virtual current chopping. In such cases, overvoltage protection such as surge arresters must be installed at the motor in order to protect the motor from the mentioned overvoltages.

On the other hand, one can ask if the same statement i.e. "overvoltages if switching currents < 600A" is also applicable for the generators. Most of the generator circuit breakers (GCBs) are equipped with a surge arrester and a surge capacitor in order to protect the generator from the overvoltages. But how necessary they are while switching the generators is still an open question. This paper is an attempt to educate the current market that VGCBs in particular don't require any overvoltage protection since the generator application is different in comparison with motor application. The generators we are talking in this situation are rated at least above 10 MVA. The VGCBs at this range will not cause any critical overvoltages while switching these generators and the only reason for using surge arresters & surge capacitors in VGCBs is for the protection against the travelling waves transferred from the primary side to secondary side of the transformer. This paper will firstly give an overview of the switching transients that could occur by motor switching and secondly about the generator switching and why they are not critical in terms of switching over voltages.

SWITCHING PHENOMENON OF MOTORS WITH VCBS

Every switching operation can generate transients. The characteristics of these transients like frequency, amplitude & the shape differ from inductive circuit to capacitive circuit. This paper is mainly focused on inductive loads. The VCBs when switching inductive loads like motors under certain conditions can produce over voltages due to the phenomena originating from current chopping, multiple re-ignitions and virtual current chopping [1].

In the following sections, basic theory of the above mentioned phenomena are given and the possibility of their occurrence due to vacuum switch is explained.

Current chopping

Current chopping normally refers to the possible over voltages which can occur due to the premature suppression of the power frequency current before normal current-zero in the vacuum circuit breaker. When the current is interrupted suddenly before the natural current zero, the magnetic energy depending on the chopping current remains trapped inside the load circuit ($\frac{1}{2}Li_{ch}^2$) . This energy will be discharged through the capacitance which is in most cases the cable capacitance (C) of the circuit and thus leads to the maximum possible chopping overvoltage (u_{max}). The typical behaviour in this case is shown in Fig. 1.

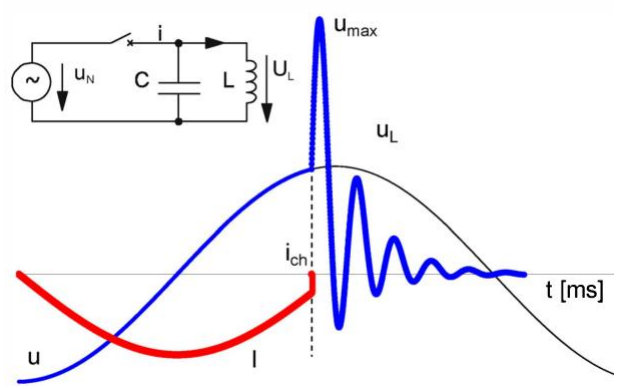

Fig. 1 General behavior of chopping phenomenon when switching inductive loads

$$\frac{1}{2}Li_{ch}^2 = \frac{1}{2}Cu^2 \quad => \quad u_{max} = \sqrt{\frac{L}{C}}\, i_{ch}$$

In VCBs the chopping current is only dependent on the interrupter contact material. The modern contact materials ensure the chopping current values $i_{ch} < 5$ A. Due to such low current values, the overvoltages at current chopping are not critical for the withstand voltages of the motors. So a surge protection is not necessary for this phenomenon.

Multiple re-ignitions

When the contact separation takes place close to the current zero, the contact gap is too small to withstand the Transient Recovery Voltage (TRV) that appears immediately after switching off the arc and thus leads to a re-ignition. This normally occurs while switching small inductive currents in the range of 20 A to several hundred amps. During the re-ignition, the capacitances on the both sides of the breaker discharge through the inductance results in a high frequency oscillating currents (some hundreds of kHz) that are superimposed on power frequency currents. The vacuum interrupters, being excellent in terms of dielectric strength, have an ability to interrupt such high frequency currents which leads to a new TRV that is steeper and higher than the previous one. This leads to another re-ignition as shown in Fig. 2 and this process will continue and higher voltages can be generated until the full contact gap is achieved.

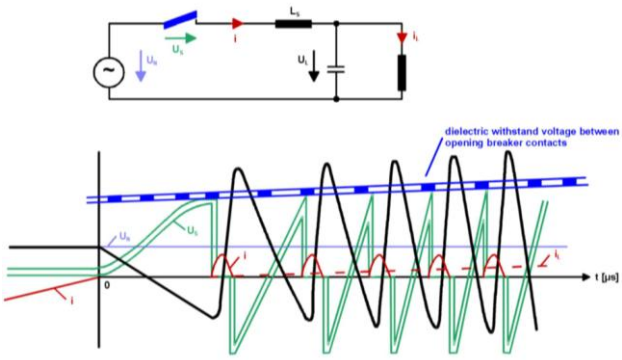

Fig. 2 Multiple re-ignitions during inductive switching

Virtual current chopping

The virtual chopping current is only considered as a 3-phase phenomenon in contrast to the current chopping and re-ignitions which can also occur in a single-phase circuit.

During the process of re-ignition, the high frequency currents created from the discharge of network capacitances will interact with other two phases through the capacitive coupling between the two phases as shown in Fig.5.

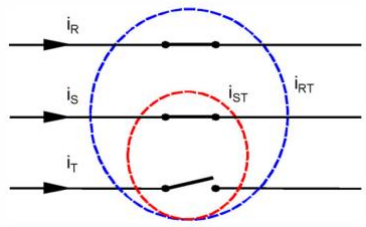

Fig. 3 Capacitive coupling of phases R & S due to the re-ignition in phase T

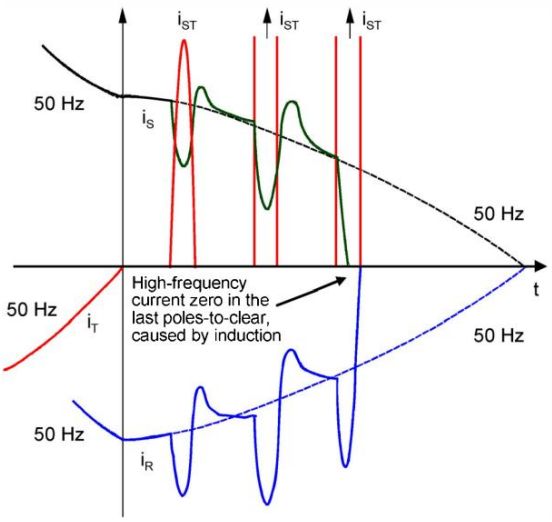

Fig. 4 Virtual current chopping in phase R & phase S when interrupting inductive currents

When the transient currents in phase T interact with other two phases carrying power frequency currents, high frequency current zeros will also appear in phases R & S. When the VCB interrupts at these current zeros, the process of multiple re-ignitions will start and leads to an increasing sequence of voltage peaks which is depicted in Fig. 4.

Based on numerous investigations carried out in our labs as well as collecting experiences from the customers, the following conclusions have been made in terms of switching motor loads with VCBs.

1) The overvoltages caused due to simple current chopping are below the BIL voltage levels of the motors. No overvoltage protection is necessary in these situations.
2) On the other hand, the overvoltages created by multiple re-ignitions and virtual current chopping could be critical and above the BIL levels of the motors. However certain pre conditions must be fulfilled for the overvoltages above BIL level to occur.
   a) Switching off the motors running in pure inductive modes i.e. during motor starting and during locked rotor situation
   b) The opening of the contacts at the instant that is close to current zero i.e. the first pole to clear < 0.5 ms before current zero.
   c) The TRV rise is faster than the rise of dielectric strength of the gap.
   d) The combination of capacitances & inductances at the both sides of the breaker must be in such a way that they lead to high frequency current zero.
   e) The current to be interrupted must be high inductive in nature and must be < 600 A. The current values above 600 A cannot produce virtual current chopping.

Pre-strikes / Pre-ignitions

While switching on the inductive loads like motor with VCB, several pre-strikes can occur when the contact gap breaks down before the galvanic contact is established. The process is more or less similar to re-ignition phenomenon. The first-pole-to-close induces an oscillatory voltage in other two phases due to the interaction of capacitance & load inductance. However, the pre-ignitions are less severe in comparison with re-ignitions since the transient voltage steepness will reduce with time as the contacts approach. In very rare events, the voltage surges with magnitudes up to 4 p.u. with steep rise times can be observed [2].

With respect to the frequency of the occurrence of above events and likelihood of damage they create, it has to be stated that these are very rare events in electrical plants. Installing a surge arrester is sufficient in most cases to protect the motors against the possible overvoltages. In case the RC suppressors are considered to be necessary or requested, an in-depth analysis of the individual constellation should be made in order to find an optimum solution. The outcome of this solution can also be that no protection elements are necessary at all.

SWITCHING PHENOMENON OF GENERATORS WITH VGCBS

All the generators rated above 10 MVA are recommended to be protected with generator circuit breakers that are specially designed as per the standards IEEE C37.013 & IEC 62271-37-013. The requirements of such large machines are generally more demanding in terms of rated currents, short circuit currents, high DC components and steeper TRVs which cannot be fulfilled by a normal distribution breaker.

The only suitable switching technology used for generator switching until end of 90's was using SF_6 as arc quenching medium. It was not possible to utilize the full potential of well proven vacuum technology for the large generator switching applications at that time. However the technological developments in the field of vacuum physics made it possible to use vacuum technology for generator switching applications and currently they are available for switching the generators rated up to 450 MVA.

Since the VGCBs are applied to switch the machines that are rated at least above 10 MVA, the possibility of the breakers switching a short circuit current I_k" < 600 A is not possible. This ensures that the VGCBs will not produce overvoltages due to current chopping or re-ignitions phenomenon that will endanger the insulation of a generator. For this reason, a surge protection is generally not required for VGCBs.

On the other hand we have been constantly asked by many customers to provide surge protection for VGCBs too. This comes from the historical reasons that the earlier dominant switching technologies for generator switching like SF_6 needed a surge capacitor in order to damp the Rate of Rise of Recovery Voltage (RRRV) which will be normally higher than the dielectric strength recovery rate of SF_6 gas.

It is important for the customers to understand that the TRV and the RRRV are system inherent parameters which are determined by the generator and the transformer characteristics. These parameters are by no means a result of the generator circuit breaker or the switching principle employed, e.g. vacuum or SF6.

Table 1 TRV parameters of generator circuit

Type of fault	Device	Rating (MVA)	TRV Peak (kV)	RRRV (kV/µs)
System – source fault	Step-up Transformer	< 100	$1.84U_r$	3.5
		101 – 200	$1.84U_r$	4
		201 – 400	$1.84U_r$	4.5
		401 – 600	$1.84U_r$	5
Generator – source fault	Generator	< 100	$1.84U_r$	1.6
		101 – 400	$1.84U_r$	1.8
		401 – 800	$1.84U_r$	2.0
Out-of-phase switching	Generator	< 100	$2.6U_r$	3.3
		101 – 400	$2.6U_r$	4.1
		401 – 800	$2.6U_r$	4.7

U_r = Rated maximum voltage in kV

The above table show the RRRV values to be tested for the generator circuits as defined by the new standard

IEC/IEEE 62271-37-013 [6].
A typical generator circuit in Fig.5 will provide an overview of the locations of the system source fault current and the generator source fault current.

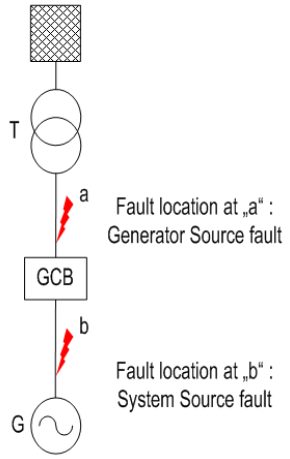

Fig.5 Typical generator circuit

The TRV magnitudes and the RRRV values for the above two fault scenarios are normally higher for three phase grounded faults when compared with single phase fault and two phase fault. This is mainly due to the reason the star point of the generator is usually grounded with a very high resistance and the transformer windings connected to the generator are delta connected. For this reason, the test values mentioned in Table 1 are for first-pole-to-clear during three-phase grounded faults in case of both generator source and system source fault currents. The RRRV values here are relatively smaller in generator source faults due to a larger equivalent capacitance of the generator when compared with transformer.
In addition, the stress imposed across the contacts of a GCB is much higher in case of interrupting the fault currents resulting from out-of-phase conditions due to the fact that the both sides of the GCB remains energised. Immediately after the fault current interruption, the voltages on the both sides of the GCB oscillates based on the generator and step-up transformer parameters. Due to this duel frequency oscillation, the first-pole-to-clear can experience a TRV up to 2.6 times the rated voltage with rise rates up to 4.7 kV/µs.
As it can be seen from the above values, the GCBs must withstand a RRRV up to 5 kV/µs in order to handle the TRVs and successfully interrupt the fault current. The dielectric recovery rate of SF_6 GCBs on other hand is only up to 2kV/µs [3]. Therefore an additional surge capacitor is mandatory for the SF_6 technology on the both generator side and the transformer side of the switchgear in order to reduce the steepness of the TRVs to the permissible level. In contrast, the VGCBs with vacuum as an interrupting medium have an extraordinarily fast dielectric recovery rate up to 10kV/µs [4] [5]. This ensures that a surge capacitor is not required for VGCBs on the generator side and the transformer side to withstand the steep TRV rates. The vacuum itself can handle them.
The prospective TRV appears across the VGCB immediately after the interruption of generator source faults and system source faults are shown in Fig.6 & Fig.7 respectively and compared with standard values and SF_6 without capacitor. The curves are derived based on the TRV equations from [7]. By observing both figures it is clearly evident that an additional surge capacitor is not necessary for VGCBs to withstand the steep TRVs and to interrupt the fault current successfully.

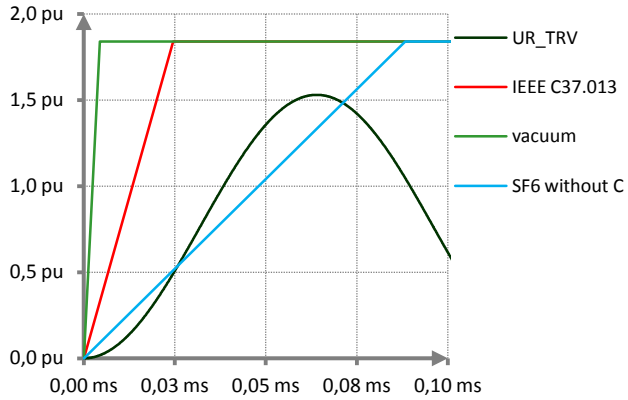

Fig. 6 TRV of the FPC – generator-source fault

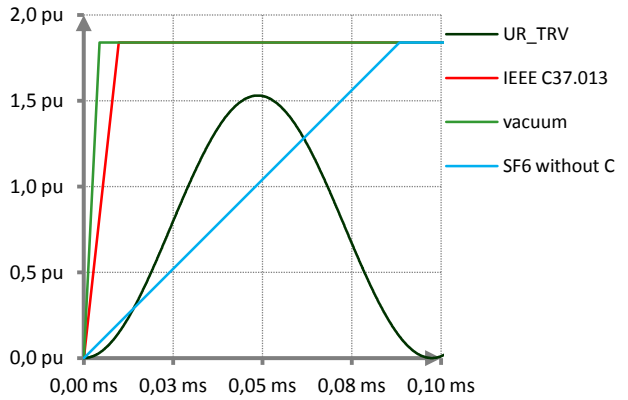

Fig. 7 TRV of the FPC – system-source fault

The only possible reason that a VGCB might need a surge capacitor on the transformer side is to protect the switchgear equipment from the travelling waves that are transferred from the HV side of the step up transformer to MV side of the transformer.
In general, over voltages due to lightning surges cannot directly occur on the generator voltage level but such surges can be transferred via the step-up transformer due to capacitive coupling of the HV and LV windings approaching the generator circuit breaker. Normally, the capacitances of the cables or bus bar systems between the transformer and the generator will reduce the amplitude of such surges to permitted values. But it can be confirmed only if the transformer manufacturer indicates the minimum line-to ground capacitance that is required to ensure that such stresses are limited to the permitted value. In addition to the lightning surges, the zero sequence voltages can also be transferred capacitively from the step up transformer. As long as the generator is constantly connected to the network, the line-to ground capacitance which includes the generator capacitance will be high enough to limit the stresses created by transferred

overvoltages. But in case of the VGCB being open, the capacitance of the short bus bar connections between the transformer and breaker terminals are low. In order to compensate the missing generator capacitance in such situations, additional capacitors are installed on the transformer side of the VGCB. Since the minimum line-to ground capacitance requires is not always available given by the transformer manufacturer, a capacitance of 250 nF or 300 nF is normally recommended to ensure the safe limitation of the stresses.

CONCLUSION

In this paper an attempt has been made to differentiate the influence of vacuum technology in switching motors and Generators. While switching motors with VCBs, special attention is required when switching purely inductive currents. As long as the current values to be interrupted are less than 600 A, surge protection is necessary due to the voltage escalation created from virtual current chopping and multiple re-ignitions. The overvoltages due to current chopping are no longer critical during motor switching as the chopping current values are reduced up to 5A with modern interrupter contacts.
Switching generators with VGCBs, on other hand, will not produce any switching overvoltages since the Ik" values are always higher than 600 A. However, in order to limit the stresses created by the overvoltages transferred from high voltage side of step up transformer to the medium voltage side due to capacitive coupling, additional surge capacitor in the range of 250nF to 300nF is generally recommended. In addition, unlike SF_6 GCBs, no surge protection is necessary on the generator side of the VGCBs due to the very fast dielectric recovery strength rates of vacuum ranging up to 10 kV/µs.

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