ROLE OF VACUUM GENERATOR CIRCUIT BREAKER IN IMPROVING THE PLANT EFFICIENCY & PROTECTING THE GENERATORS UP TO 450 MVA

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ABSTRACT

Vacuum interruption technology is the leading technology for the medium voltage range up to 52 kV especially in the distribution circuits. Over the decades, the interrupting capability of the Vacuum Circuit Breakers (VCB) has increased significantly and their application range is extended even to generator circuits which are more demanding than the regular distribution breakers. With the recent developments, it is now possible to apply Vacuum Generator Circuit Breakers (VGCB) for the protection & synchronization of power plants rated up to 400 MW. The generator circuits are particularly more demanding due to their high short circuit currents, high rated currents, delayed current zeros and very fast Rate of Rise of Recovery Voltages (RRRVs) and the vacuum interrupters have been proven to handle such stresses reliably. All the VGCBs must be tested according to the standard IEEE C37.013 or IEC 62271-37-013 which are created specially to address the above mentioned conditions.

No emission of green house gases, easy to install, maintenance free, high number of short circuit interruptions and cost effectiveness are some of the distinctive advantages of the VGCB which are making it as a best alternative of another technologies for the generator circuit applications. Over the years, they are proved to be an economical and efficient solution in protecting the generators and step up transformers thus improving the plant efficiency and reliability.

Furthermore, in contrary to many arguments against vacuum circuit breakers as generator circuit breakers, the vacuum interrupters too have an arc voltage up to 150V depending on the type of the contact which helps in damping the dc component and reduces the arcing time at-least up to two cycles or more. This paper gives a brief overview of the switching characteristics of the VGCB along with a case study that shows the influence of arc voltage in advancing the current zeros of a generator fed fault and Out-of-phase fault currents. Commercial simulation software called PSS NETOMAC is used to analyze the effect of arc voltage and the results are presented.

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I. INTRODUCTION

Over the last 35 years, the VCBs are the most preferred switching devices in the medium voltage levels up to 52kV and today more than 80% of installed devices are VCBs. It is mainly because of their advantages in terms of installation, maintenance and operation over other technologies. When it comes to the generator switching applications, which are also considered as medium voltage applications, in the past it was not possible to utilize the vacuum interruption technology for the generator applications. But over the decades, the interrupting capability of the VCBs has increased significantly and the technological developments in the field of vacuum arc physics enabled them to interrupt higher short circuit currents and carry higher rated currents making them as an ideal solution for the generator applications up to 450 MVA.

In the following sections, some of the main challenges for the circuit breakers installed in the generator circuits are given. Irrespective of the switching medium, a generator breaker has to withstand severe switching conditions. They are briefly explained in section II.

In section III, a brief explanation about some of the main switching characteristics of VCBs like their excellent dielectric strength and various contact types are given. Especially in terms of arc voltage, VCBs are always projected as less efficient. For that reason, an arc voltage measurement is made on the latest developed vacuum interrupters with short circuit interrupting capacity of 100 kA, and a voltage in the range of 100 to 120 V was measured [2]. This voltage showed a non-negligible influence on the decay of DC component and aids to advance the current zeros

The section IV present the results of a case study which is carried out based on a typical generator and system parameters. The graphs showcase the influence of the arc voltage up to 100 V inside the vacuum interrupters in advancing the current zeros and reducing the arcing time significantly. The simulations showed here are carried out using PSS NETOMAC.

Last but not least, in addition to the above mentioned switching characteristics, the general advantages of VGCBs over the other technologies are presented in section V.

II. CHALLENGES FOR GENERATOR CIRCUIT BREAKERS (GCBs)

GCBs are always installed between the generator and the generator step up transformer (GSUT). In some cases the generator also feeds the auxiliary transformer for the station service which is connected to the main bus bar via another GCB. A simplified generator circuit arrangement is shown in the Fig 1.

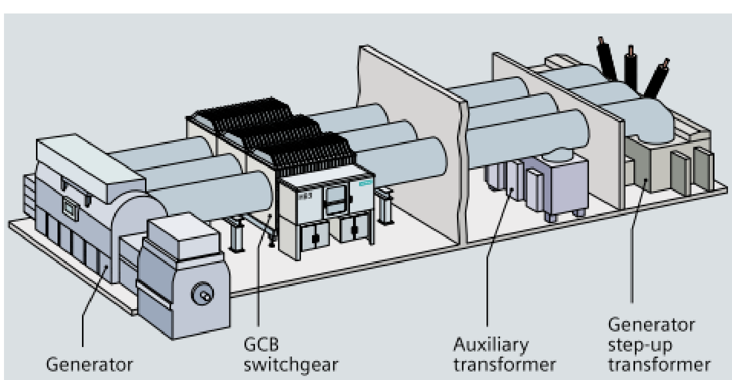

Fig. 1 A typical layout of a generator circuit

Irrespective to the type of the switching medium, the installed GCBs must be able to withstand severe switching conditions that are imposed due to the generator circuit parameters. For instance, depending on the fault location, the circuit breaker is stressed either thermally or mechanically.

In the following paragraphs, the type of the fault and its respective challenges are given.

(a) Generator Source Faults: when the fault occurrs between the GCB and GSUT, then the fault is termed as "generator source faults". As shown in the Fig. 2, the fault currents are fed by the generator. The magnitude of these fault currents are relatively smaller but still considered as critical due to their higher degree of asymmetry which leads to delayed current zeros as shown in Fig. 3. The possible reasons for such an asymmetry are high X/R ratio of the circuit due to shorter connections between the generator and GCBs and the faster decaying of AC component than the DC component due to the machine parameters like the generator reactances (Xd", Xd', Xd) and the time constants (Td", Td', Ta).

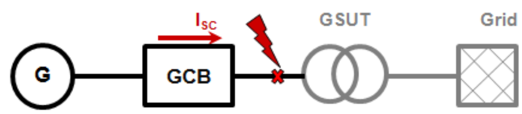

Fig. 2 Generator source fault

As stated in the standard [3], the DC component of a generator source fault can reach up to 130% and above at the time of contact separation depending on the type of fault occurred in the circuit which leads to delayed current zeros. This necessitates all the installed GCBs must be able to withstand the thermal stress created by such a long arcing times.

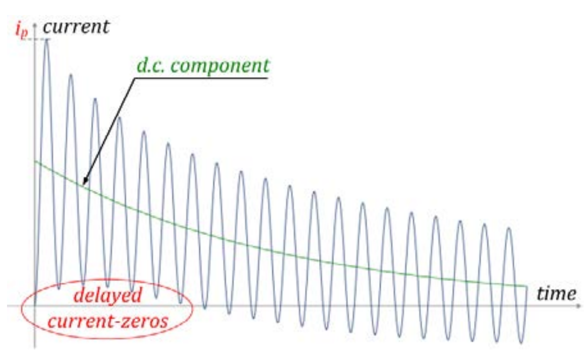

Fig. 3 Short circuit current with delayed current zeros

(b) System Source Faults: When the fault occurs between the generator and GCB, then the fault is termed as system source fault as the fault current is fed from the system via GSUT as shown in Fig. 4.

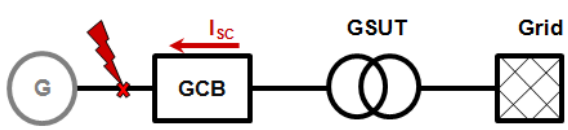

Fig. 4 System source fault

In contrast to the generator source faults, the DC components of system source faults are normally in the range of 75% due to the presence of the GSUT. However, the fault current here is almost double the generator source fault current. This is due to the energy from the whole system will feed the fault and the low transformer impedance will have less impact on reducing these fault currents. A typical system source fault current is shown in Fig. 5. These high currents stress the breakers mechanically.

(c) Out-of-phase switching: Out-of-phase synchronization occurs occasionally in the power plants due to the wiring errors during the commissioning and after the maintenance of the equipment. In this condition, a current up to 50% of the system source short circuit current will flow in the circuit. These fault currents may have delayed current zeros depending on the out-of-phase angle due to the reasons which different when compared with the traditional delayed current zeros of generator source faults [5].

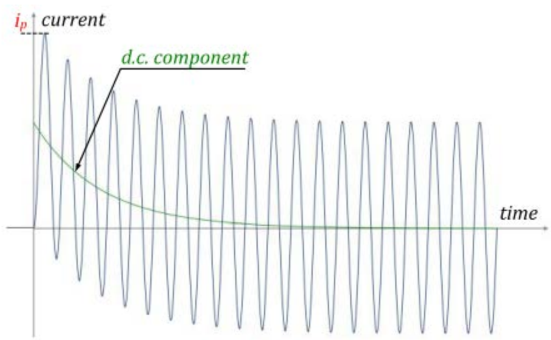

Fig. 5 Short circuit current with higher magnitude

In addition, the interruption of these kinds of fault currents leads to TRVs that are driven by the Out-of-phase voltage difference between the generator and the system with the values up to 2.6 p.u and with RRRVs up to 5 kV/µs [3].

(d) Other critical conditions: In addition to the above conditions, the other demanding requirements for the GCB are to withstand the extreme TRVs with very high Rate of Rise of Recovery Voltages (RRRV) and the Out-of-phase conditions. Due to having high inductive elements like generator & transformer and the low resistance and capacitance of the generator circuit results in the natural frequencies that are very high which leads to high TRVs with very fast RRRVs up to 5 kV/µs.

III. SWITCHING CHARACTERISTICS OF VGCBs

The VCBs have very distinctive advantages over other switching mediums as the switching process occurs in a complete different way due to its switching characteristics. During the generator source faults, the DC component is comparatively high and the interrupter contacts must be able to withstand the thermal stress due to long arcing times and be able to hold the high TRVs immediately after the interruption. The cathode spots which are created on the interrupter contacts and are responsible for the arc continuity between the contacts, disappear at current zero. Due to the very fast radial diffusion of ions and electrons in the contact space, the vacuum interrupters have a rate of rise of the dielectric strength of up to 10 kV/µs [6]. Therefore an additional surge capacitor is not required for the VGCBs and thus the vacuum switching technology is perfectly suited for the TRV requirements in generator applications. And since the arc energy inside the interrupter tube is less, the contact erosion is very minimal ensuring its very low contact resistance.

The suitability of VCBs for the generator applications with delayed current zeros was first investigated and proved by Schramm and Kulicke [7]. According to them, the type of the interrupter contacts plays a vital role in handling these delayed current zeros. The commonly used contact types are RMF (Radial Magnetic Field) and AMF (Axial Magnetic Field) contacts. When the fault current is more than 10kA, due to pinch-effect, the arc gets constricted. In order to avoid the local thermal contact overheating, this constricted arc should be either rotated over the contact surface using RMF contacts or diffused over the contact surface using AMF contacts. For very high currents, generally AMF contacts are preferred due to its even distribution of heat over the contact surface through arc diffusion. The typical design of the both types of the contacts is shown in Fig. 6.

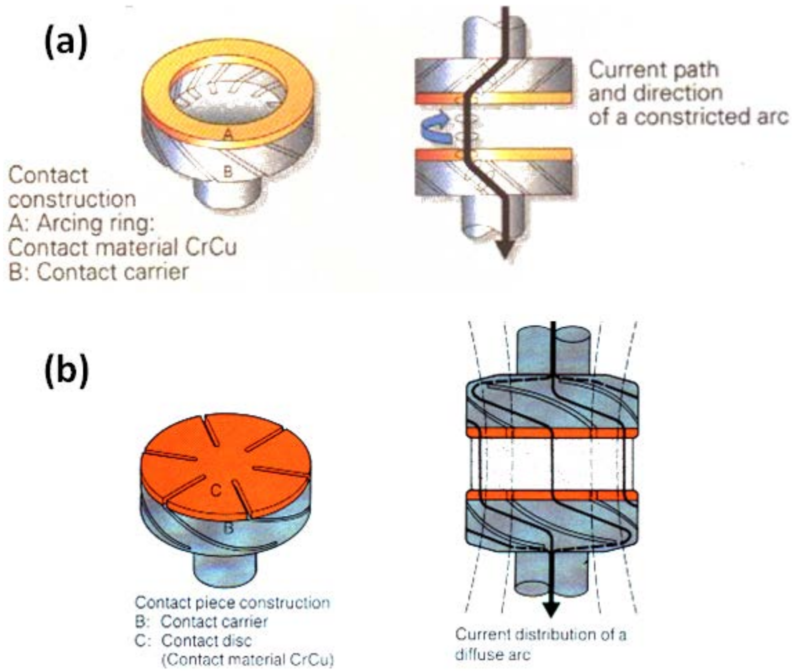

Fig. 6 Types of vacuum interrupter contacts (a) RMF contacts, (b) AMF contacts.

Vacuum arc voltage after contact parting:

The arc voltage of a typical vacuum circuit breaker - follows a non linear resistance - can reduce the DC time constant of the circuit and force the current zeros. The arc voltage basically depends on the short circuit current and the length of the arc. When compared with SF6 breakers, the arc voltage levels are smaller for vacuum but still show a non negligible influence on the delayed current zeros. The average arc voltage produced by an AMF vacuum interrupter contacts is in the range of 100-120 V as recorded by the switching performance tests at SIEMENS AG [2] and by a TMF vacuum interrupter contacts is in the range of 120-150 V [8]. Generally for high current applications i.e. for the short circuit currents of 80 kA and 100 kA, vacuum interrupters with AMF contacts are preferred.

In the coming sections, a case study with a typical machine data of steam turbine generator is presented. The situations of delayed current zeros due to generator source fault and out-of-phase conditions are simulated and the effect of arc voltage is observed. The conceptual explanation of the reasons behind the occurrence of delayed current zeros due to generator source short circuit conditions and Out-of-phase switching is given in the references [7] & [5] respectively.

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IV. CASE STUDY

A simplified configuration of a generator circuit as shown in Fig. 7 is used for the analysis of this study. The fault at location “a” is termed as a generator source fault. Table 1 shows a typical generator, transformer and system parameters. They impose severe fault conditions on the GCB especially during the generator source fault.

Table1: Typical system parameters with a Steam turbine generator

High-voltage system	
Rated voltage U_{rQ}	400 kV
Initial short-circuit current I_{sc}''	40 kA
Impedance ratio R/X	0.08 pu
System frequency f	60 Hz
Voltage regulation	10%
Step-up transformer	
Apparent power S_{rT}	350 MVA
% Impedance u_k	13.04%
Ohmic part of % Impedance u_r	0.35%
Rated voltage U_{rTHV}/U_{rTMV}	400/19 kV
Synchronous generator	
Apparent power S_{rG}	323 MVA
Rated voltage U_{rG}	19 kV
Rated current I_{rG}	9815 A
Leakage reactance x_L	18.6 %
Synchronous reactance, unsat x_d	146.5 %
Transient reactance, sat x_d'	26.92 %
Subtransient reactance, sat x_d''	20.36 %
Transient time constant T_d'	1.040 s
Subtransient time constant T_d''	0.035 s
Transient reactance, sat x_q'	41.66 %
Subtransient reactance, sat x_q''	20.14 %
Transient time constant T_q'	0.181 s
Subtransient time constant T_q''	0.035 s
Inertia constant T_A	12.34 s
Armature time constant T_a	0.68 s

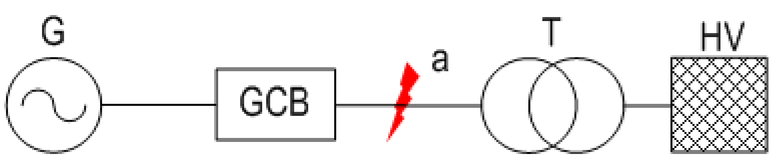

Fig. 7 Simplified single line diagram of a generator circuit.

(a) Condition of generator source fault:

By using the commercial software “PSS NETOMAC”, three phase short circuit calculations were carried out based on the above system parameters and the configuration. Here the worst case scenario is considered to simulate the most stress full conditions. A three phase short circuit at no load with the fault initiation at voltage maximum (first clearing pole is symmetric) is considered. With this condition, the possibility of having delayed current zeros for the last poles to clear is very high.

Table 2: Generator source short circuit currents

Results	Gen source
I_{sym}	43.8 kA
I_{dc}	70.3 kA
I_{asym}	82.8 kA
I_p	145.1 kA
DC%	114 %

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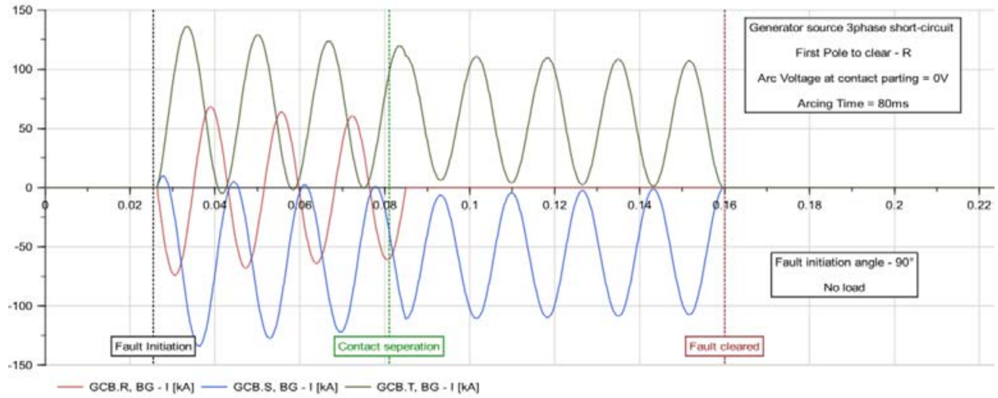
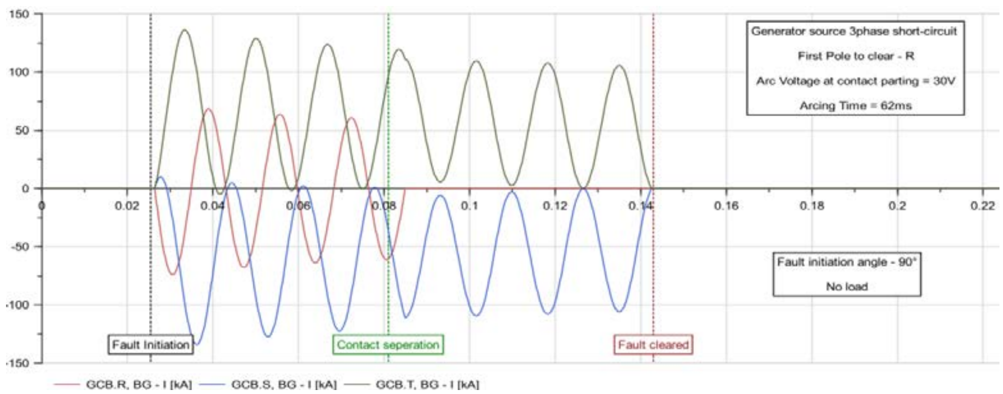
After the simulation, the short circuit currents from the generator fed faults are recorded in the table 2. The time between the fault initiation and the contact parting is considered as 53ms which include a relay operating time of ½ cycle and mechanical operating time of 45ms. In Fig. 8 the influence of four different arc voltages (peak) i.e 0V, 30V, 60V & 100V is observed.

(a)



(b)



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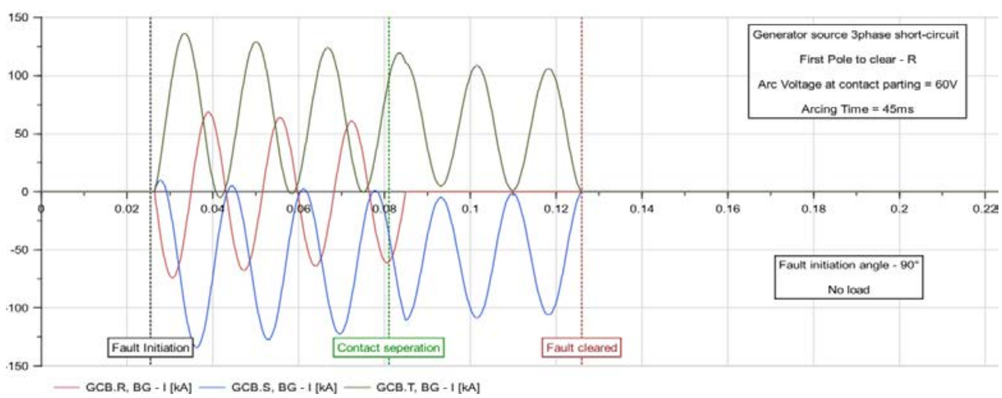

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(d)

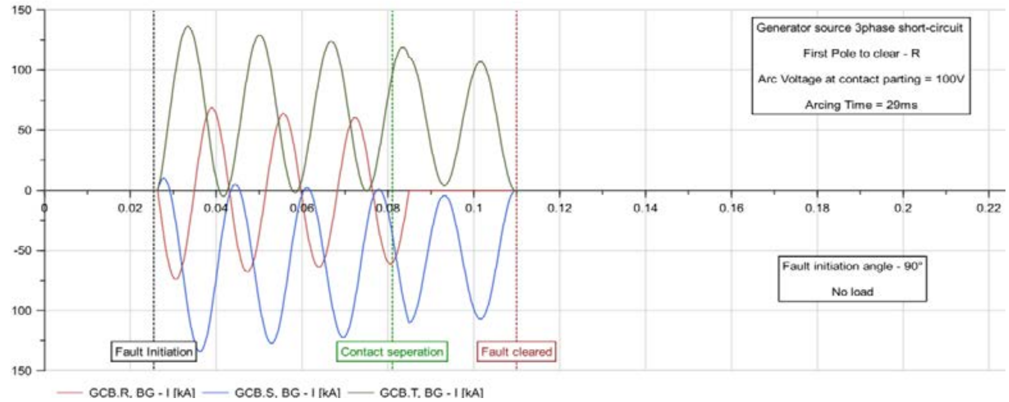


Fig.8 Three phase generator fed fault current with the arc voltages of (a) 0V, (b) 30V, (c) 60V and (d) 100V

These voltages seems very low when compared with the circuit voltage of 19 kV, but the simulation results shows that the additional resistance dueto the arc voltage does play a significant role in advancing the current zeros.

The part (a) of Fig. 8 shows the generator fed short circuit current without any arc voltage. It can be seen that the arcing time is lasted up to 80 ms. In the parts (b), (c) & (d), the arc voltages 30 V, 60 V and 100 V respectively are used and the arcing times are reduced to 62 ms, 45 ms & 29 ms respectively.

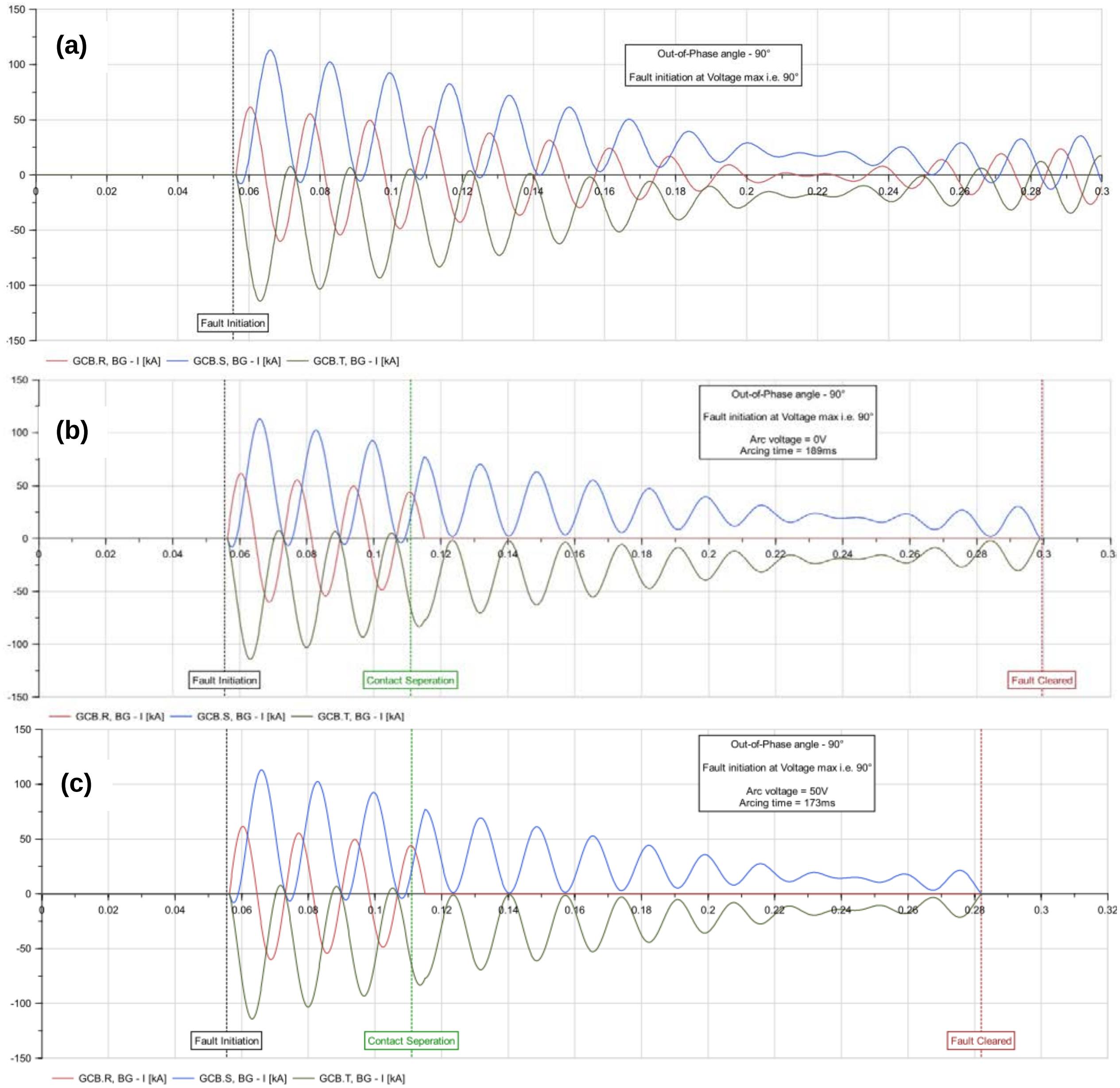
In some cases, an intentional delay up to 150 ms in the tripping circuit is used so that the DC component at the time of the contact separation reaches to a value that the circuit breaker will be able to interrupt the fault current quickly. But it is not recommended using the delayed tripping since any fault duration above 150 ms can leads to the damage of transformer’s internal insulation. So it is generally advisable to use the generator circuit breakers which have a sufficient arc voltage to force the current zeros.

(b) Condition of Out-of-phase switching

Out of phase synchronization occurs rarely in power plants resulting in fault currents that exhibit delayed current zeros. The Out-of-phase angles can be of any value and caused due to manual synchronization or wiring errors. Based on the type of the machine and the system parameters, any out of phase angle can be critical. The fast rotation of the rotor from the initial out of phase angle to the 0 angle leads to a small AC component and a very high DC component. This leads to very long delayed current zeros. When the machine has a high inertia constant, then the DC component during the contact separation is comparatively less. For the rotors with high mass, the inertia constant is smaller and the DC component during the contact separation will be higher. In both the cases, it is very important that the circuit breaker must be able to force the current zeros using its arc voltage. For the machine and system parameters in table 1 with higher inertia constant, the out-of-phase angle of 90° was more critical in terms of delayed current zeros.

Fig.9 shows the curves of (a) typical Out-of-phase currents when the Out-of-phase angle is 90°, (b) interruption of Out-of-phase current with 0V arc voltage, (c) interruption with 50V arc voltage and (d) interruption with 100V arc voltage. The arcing time without arc voltage is 189 ms which is very critical to the equipment involved in the circuit. But the presence of the 100 V of arc voltage due to the vacuum arc decays the DC component significantly and reduces the arcing time to 30 ms.

Based on the above case study one must observe that the arc voltage of the vacuum has an influence on short circuit interrupting capabilities of the breaker. In the following section, brief advantages of the VGCBs over other existing technologies are given in terms of cost efficiency as well as the technical benefits.



(d)

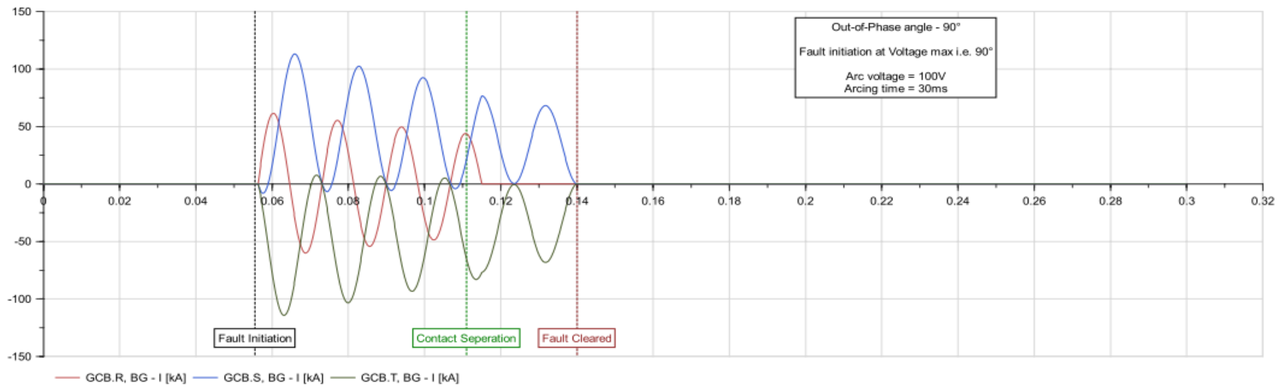


Fig.9 Out-of-phase synchronizing at 90° with (a) without interruption (b) interruption with 0V arc voltage, (c) with 50V arc voltage and (d) with 100V arc voltage.

V. ADVANTAGES OF VGCBS OVER EXISTING TECHNOLOGIES

VGCBs are already considered as a potential replacement of the existing technologies for the market up to the ratings of 100kA short circuit current with 24 kV rated voltage and up to 12500 A rated currents due to their distinctive advantages [4]. Some of them are listed below.

1) Easy to install: Vacuum generator switchgear is a factory assembled solution that undergoes factory acceptance testes before it leaves the factory which means the switchgear is ready to be installed in the power plant. For the SF_6 switchgear, the gas must be extracted before the transportation and then refilled at the site during the installation using special tools and safety regulations. This necessitates an additional expenses and testing on site.

2) Highly reliable: Due to its outstanding switching capabilities, the VGCBs are highly reliable for any kinds of faults occur in the generator circuits. In addition they guarantees a high level of personal and operational safety due to the less number of moving parts in the arcing chamber and in extremely unlikely case of loss of vacuum, the arc develops and stays inside the interrupter's envelope until the backup breaker interrupt the circuit.

3) Maintenance & cost efficient: VGCBs are maintenance free up to 10,000 electrical switching (up to 100% rated current) operations. This means, no re-lubrication and readjustment is required throughout the service life time. Additionally, no gas handling equipment is necessary which reduces the costs to a considerable amount.

4) Switching duties: The VGCBs are suitable for all switching duties because of its low chopping currents and can disconnect the loads safely without re-strikes. This eliminates the possible overvoltage issues. Having a dielectric recovery strength >10 kV/µs, VGCBs doesn't require an additional surge capacitor against high TRVs of generator circuit which is a very good advantage over other technologies.

5) Environmental impact: Of all the medium voltage switching technologies, the VCBs offer the lowest environmental impact over the entire product life cycle. In contrast, the SF_6, the other major technology in generator applications is considered as a potential green house gas. The Environmental Protection Agency of USA and Denmark have both recommended using the alternatives to SF_6, where ever it is possible. Denmark has gone a step ahead by enacting a set of green taxes on the consumption of industrial green house gases like SF_6 [9].

VI. CONCLUSIONS

The generator circuits are very demanding in terms of short circuit conditions. The installed breakers must perform well in conditions like high amplitude short circuit currents, delayed current zeros during both generator source fault and Out-of-phase switching, steeper TRVs.

Simulations using PSS NETOMAC are carried out with typical system parameters in order to observe the influence of vacuum arc voltages in decaying the DC component faster and reducing the arcing times considerably. Based on the simulation results, VGCBs with their typical arc voltages around 100-120 V are capable to clear the faults without delayed current zeros.

In addition, numerous advantages of VGCBs over existing technologies made it as a potential replacement. Today VGCBs are available up to short circuit current ratings of 100kA with 12500 A of rated current capacity with natural cooling. Thus, for the power plants rated up to 400MW irrespective of the type of turbine, VGCBs offer an ideal and reliable solution with a better cost position.

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