SPECIFIC SHORT-CIRCUIT CONDITIONS IN POWER PLANTS WITH SMALL GENERATOR UNITS

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ABSTRACT

This paper deals with the investigation of generator circuit-breaker applicability in power plants with low rating generator units. The IEEE Std. C37.013 covers round rotor machines only, whereas the generators of the smaller size are often of the salient pole type. The specific short-circuit conditions, such as the presence of delayed current zeros, as well as the transient recovery voltages in these installations are analysed and the results are compared with the performance requirements in the standard. The results show that the short-circuit current ratings of a generator circuit-breaker need to be carefully selected. Moreover, the overvoltages that are generated on fault current interruption require the installation of overvoltage protection means. The main reason for that is the saliency of the generators and considerations of tolerances on its subtransient impedances. However, the usage of conventional overvoltage protections, such as RC filters, allows to meet the requirements in the relevant IEEE standard and particularly of the ones in the new joint IEC 62271-37-013 standard. Therefore additional tests on the circuit-breaker intended for use in such network configurations are not required.

INTRODUCTION

The standard test duties for demonstration of the generator circuit-breaker (GCB) switching performances are defined to cover the most severe short-circuit conditions. These are mainly derived from requirements of power plants with GCBs installed between the generator and the step-up transformer terminals, e.g. at generators with rated power above 100 MVA. However, in power plants with low rating generator units, connected in parallel to one step-up transformer or behind a three winding transformer, specific short-circuit conditions can be observed. These are linked to thermal constraints, e.g. short-circuit currents with a higher degree of asymmetry and much delayed current zero crossings, or to dielectric constraints, e.g. the Transient Recovery Voltage (TRV) exceeding the standard values. Analysis of IEC breakers in generator applications have already been conducted in [3] and [4]. The purpose of this paper is to point out and demonstrate the switching performance of an IEEE C37.013 qualified generator circuit-breaker under these specific short-circuit conditions.

STANDARDS AND MANDATORY SWITCHING TEST DUTIES

The IEEE Std. C37.013 [1] was introduced in 1993 and is currently the only applicable standard for generator circuit-breakers in installations with a rated power over 10 MVA and up to more than 1000 MVA. In this standard the mandatory type testing as well as constructional and operational requirements are defined.

Following a decision from IEC and IEEE boards a new working group WG52 was established in 2009, in order to create a joint standard under IEC 62271-37-013 [2] . The document is currently under a CD2 status and is expected to be implemented in 2014. Although there will be no significant changes in the requirements for short-circuit switching test duties, it will formalise new voltage rated levels that are already used to test generator circuit-breakers. As it will be seen this introduction makes sense since it will formally reduce the over-sizing of generator circuit-breakers.

From the GCB point of view, there are two short-circuit situations, which both have a different physical background:

- A short-circuit on the generator side (called system-fed fault). The fault current is characterized by a high degree of asymmetry (standard value of 133 ms) and a steep rate-of-rise of recovery voltage (e.g. 3,5 kV/µs for a 100 MVA step-up transformer)
- A short-circuit on the step-up transformer side (called generator-fed fault). The character of the fault current is determined by the type of the generator and can lead to delayed current zero crossings. The standard test duty for generator fed-faults is defined by dc components of 110% and 130%.

SHORT-CIRCUIT ANALYSIS IN PLANTS WITH THREE WINDING TRANSFORMERS

Typically in hydro power plants, low rating generators are connected to the utility network through a three winding transformer. In the following analysis the calculation of the short-circuit currents is conducted for such a network configuration. The single line diagram is shown in Figure 1:

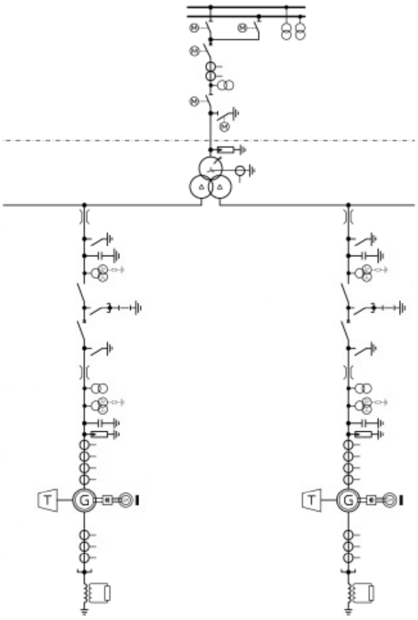

Figure 1 Power plant with a 3-winding transformer

The important technical data are described in TABLE 1:

TABLE 1 Technical data

Data	*Value*
Generator data	
Sr (MVA)	81.2
Ur (kV)	10.5
Xd (pu)	1.97
Xd´ (pu)	0.238
Xd´´ (pu)	0.175
Xq (pu)	1.1
Xq´ (pu)	1
Xq´´ (pu)	0.259
Ra (pu)	0.00195
Td´ (s)	1.349
Td´´ (s)	0.025
Utility	
Rated voltage, (kV)	120
Rated short-circuit power, (MVA)	5000
Step-up transformer rated power, (MVA)	160/80/80
Step-up transformer ratio LV / LV / HV (kV / kV / kV)	10.5 / 10.5 / 120
Step-up transformer sc voltage, LV/LV/HV (% /% / %)	17 / 17 / 25

System-fed fault

In the case of a 2-winding transformer, the system-fed fault has only one source. This is the utility network, neglecting a possible auxiliary transformer.

In the case of a 3-winding transformer, the system-fed fault has two parts. One, corresponding to the contribution of the utility network and another, corresponding to the contribution of the remaining generator, G2 on Figure 2, coming through the tertiary winding of the step-up transformer. A three phase short-circuit without consideration of an arc voltage at fault location A, interrupted by the GCB1 is illustrated in Figure 2.

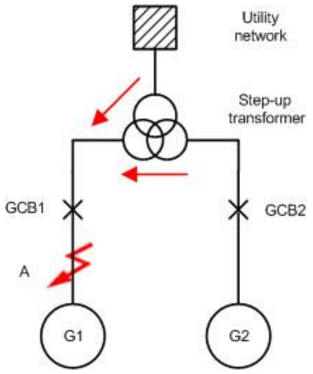

Figure 2 System-fed fault

The situation, when G2 is not in operation and GCB2 is opened can be compared with the case of a 2-winding transformer. However, when G2 is in operation and GCB2 is closed the short-circuit conditions are changed. The comparison of the short-circuit current with and without the contribution of the second generator through the tertiary winding is shown in Figure 3. Only the phase with the highest asymmetry is represented. The fault initiation is assumed to occur at the voltage zero and the generators are set in no-load operation prior to the fault.

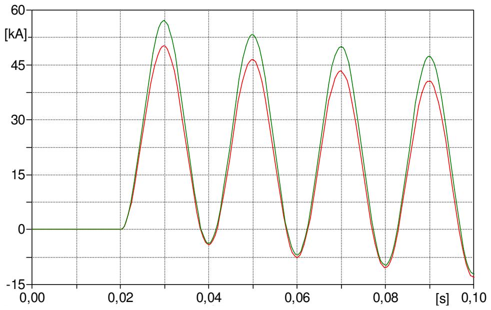

Figure 3 G2 contribution to system-fed fault at GCB1 green (higher) curve: G2 connected, red: G2 disconnected

The numerical results, given in TABLE 2 are obtained for a GCB1 contact parting time of 45 ms after fault occurrence. This time is a sum of the circuit-breaker minimum opening time of 35 ms and the relay time of 10 ms (one half cycle of 50 Hz).

TABLE 2 Comparison of short-circuit currents

	G2 disconnected	**G2 connected**
Asymmetrical peak current	50.2 kA	57.1 kA
Short-circuit current, rms value	18.5 kA	20.7 kA
dc component	71.1 %	75.3 %
Time constant	132 ms	159 ms

The contribution of the second generator increases the asymmetrical peak current as well as the rms value of the short-circuit current and the dc component. The arc energy, I x t on the circuit-breaker contacts is also increased.

Generator-fed fault

For the same fault location, the short-circuit current seen by the GCB2 exhibits another specific condition. The short-circuit current is limited by the impedance of the transformer winding, so that its value is relatively low. However, the current curve can feature prolonged delayed current zeros. This happens due to the superposition of the step-up transformer impedance and the generator transient and subtransient ones. The increase in the equivalent inductance from the generator to the fault will modify the time constants of the fault currents, in particular the time constant for the dc component can increase. The value may exceed the limits compared to the IEEE required test duties and therefore there might be several cycles without current zero crossings.

The situation is illustrated in Figure 4 in the case of an ideal circuit-breaker, without consideration of its arc voltage. The fault initiation is assumed to occur at the voltage maximum of the first phase to clear and the generators are set in no-load operation prior to the fault.

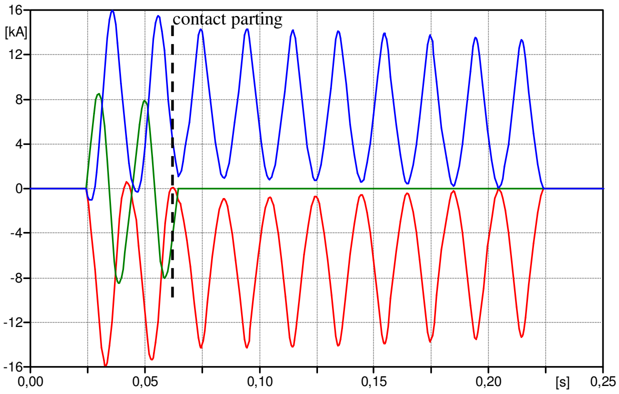

Figure 4 Extremely delayed current zeros

There are no current crossings for about 185 ms, which is unacceptably long. The GCB2 can be thermally overloaded when interrupting this fault.

Mitigation of thermal constraints

As it was described, the specific short-circuit conditions at power plants with 3-winding transformers may exceed the testing requirements of IEEE C37.013. The main constraints are linked to increased arc energy due to higher short-circuit currents with higher dc components. This needs to be carefully considered when defining the protection relay times (delaying the GCB opening time) or when selecting the proper GCB ratings. As to the latter, one has to consider the arc voltage between the contacts of the GCB in the case of a short-circuit with extremely delayed current zero crossings.

The effect of the arc voltage is shown in Figure 5 and corresponds to the case of a vacuum circuit-breaker. Based on the rms value of the short-circuit current, the resulting arc resistance amounts to 10 mΩ. This "additional" resistance in series with a generator winding resistance of about 4 mΩ decreases the time constant of the short-circuit current. Consequently, the current zero crossings are forced to occur earlier.

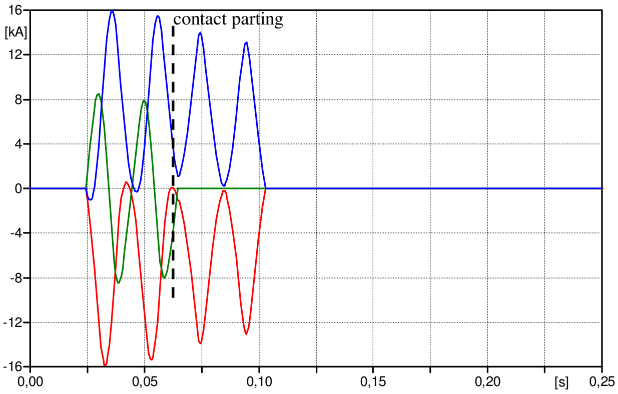

Figure 5 Influence of circuit-breaker arc voltage

The arcing time is decreased to 40 ms, compared to 185 ms (Figure 4), which prevents the GCB2 from being thermally overstressed.

TRANSIENT RECOVERY VOLTAGE ANALYSIS

For the purpose of TRV analysis an example network containing 6 generators and one utility transformer will be considered. The electrical diagram of the network is shown in Figure 6:

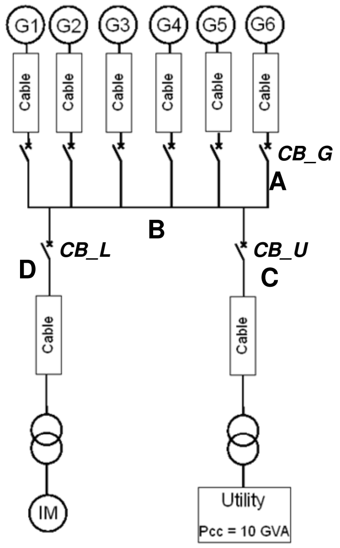

Figure 6 Electrical diagram for TRV analyses

For the sake of simplicity the generators are identical as well as their connecting cables.

The data for the network is summarized in TABLE 3:

TABLE 3 Data of network for TRV analyses

Data	*Value*
Generator data	
Sr (MVA)	12.125
Ur (kV)	15
Pole Pairs	4
Xd” (pu)	0.12±10%
Xq” (pu)	0.137±10%
Capacitance to earth, per phase, (µF)	0.11
Utility	
Rated voltage, (kV)	347
Rated short-circuit power, (MVA)	10 000
Step-up transformer rated power, (MVA)	75
Step-up transformer ratio (kV/kV)	15 / 347
Step-up transformer scc voltage (%)	15
Capacitance to earth on LV side, (µF)	0.00455
Loads	
Aux. transformer rated power, (MVA)	2.5
Aux. transformer ratio (kV/kV)	15 / 0.4
Aux. transformer scc voltage (%)	5
Capacitance to earth on HV side, (µF)	0.00187
Cables	
Cross-section (mm^2)	300
Length (km)	0.05
Cables per phase generator / aux transformer / utility	2 / 1 / 6
Capacitance to earth (µF/km)	0.366

Since the system has a rated voltage of 15 kV, the appropriate GCB for that application should have been tested at a higher rated voltage. This will ensure its compliance with the transient increase in the voltage of the generators. A variation of ±10% has to be considered. According to IEEE rated values, a breaker of 27 kV rated voltage has to be chosen for this application, since there is no other convenient voltage level higher than 15 kV. In order to optimize GCB sizing, manufacturers often perform tests at intermediate voltage levels, such as 17.5 kV. This has been formalized in the new joint standard, IEC 62271-37-013, [2], which will introduce additional rated voltage levels, and particularly the 17.5kV.

The GCB in this study will be therefore rated at 17.5 kV with a short-circuit current of 50 kA. The TRV analyses are performed for faults occurring at four locations: on the generator side, on the busbar, on the utility side and on the load side.

In terms of fault current seen by the GCB, for each fault location one can distinguish:

- Utility and generators fed fault; fault on the terminals of one generator, point A. The fault is cleared by the generator’s GCB.
- Single Generator fed fault when the fault is on the busbar, point B, cleared by the generator GCB.
- System, utility fed fault when the fault is on the busbar, point B, cleared by the utility GCB.
- Generators fed fault when the fault is located on utility side, point C, fault cleared by the utility GCB.
- Utility and generators fed fault when the fault is located on the load outcome, point D, cleared by the load GCB.

Each of these cases will produce a TRV on the current interruption, which shall remain lower than the dielectric capabilities of the GCB. Based on [1], the worst case will be obtained for the following conditions:

- Fault at maximum voltage in one phase, in which the fault current will not contain a dc component.
- First-pole-to-clear at the minimum clearing time of the GCB on the same phase.

The minimum opening time is composed of:

- Minimum protection relay trip time – considered as 10 ms, such as for differential protections.
- Opening of the CB – dependent on the GCB, 35 ms is used.

For a fault downstream towards the load, however, the protection relay is considered to have a tripping delay of 200 ms, necessary to meet the appropriate level of protection.

In [3], the tolerances on the generator impedances are considered. These tolerances apply mainly in the case of salient poles machines. For these machines, there exists a second harmonic fault current together with a corresponding respective internal voltage source. The difference between the subtransient impedances increases the impact of the second harmonic component on the current and on the TRV that follows its interruption. Moreover, depending on the moment of current interruption, the impact can have positive or negative sign. An interruption at a full cycle (40, 60 ms…) after the fault appearance will give reduced TRV values, and an interruption at a half cycle (50, 70 ms…) will give the highest values. The values are much modified when tolerances are considered.

The results of TRV calculations will therefore include values with tolerances, -10% on Xd” and +10% on Xq”.

TABLE 4 Results of TRV calculations

Fault location	CB to open	Fault current, kA	TRV peak, kV	TRV rate of rise, kV/µs	Maximum withstand [2] kV; kV/µs
A	CB_G	48.2	34.9	0.34	32.2; 1.6
B	CB_G	4.6	33.9	0.22	45.5; 1.6
B	CB_U	28.6	36.1	0.57	32.2; 1.6
C	CB_U	22.2	34.1	0.29	32.2; 1.6
D	CB_L	36.6	31.5	0.32	32.2; 1.6

The analyses of TRV show that the GCB will require the installation of overvoltage protection solutions, in order to meet all of the TRV constraints. The connection of an RC snubber (60 Ω + 500 nF) on the busbar and upstream the utility GCB would efficiently damp the overvoltages, below the limit values from TABLE 4.

CONCLUSION

In this paper the specific short-circuit conditions in power plants with low rating generators were analysed with the use of transient calculations in EMTP-ATP. Simulation results were compared to the switching test requirements of IEEE C37.013. The short-circuit conditions, which can occur in the power plants utilizing 3-winding transformers or having generators in parallel may exceed the standard test parameters. However, the proper combination of network protection and appropriately dimensioned overvoltage protection limit the switching constraints. This fact makes the simulation a key element to select the right circuit-breaker.

REFERENCES

[1] IEEE C37.013-2007, IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis

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