CIRCUIT BREAKER PERFORMANCES SELECTION FOR NEAR-TO-GENERATOR FAULT CURRENT INTERRUPTION

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Abstract - Several installations include synchronous generators and, in some cases, synchronous motors. Under short-circuit conditions, the fault currents generated from the synchronous machine are characterized by a high level of asymmetry that requires suitable circuit breaker performances to ensure safe interruption of fault current.
To calculate such interrupting performances, which are important for effective circuit breaker selection (IEC Standard discussed in this paper), it is necessary to properly consider: short-circuit current calculation Standards that vary depending on installation type (onshore and offshore), network topology and IEC circuit breaker Standards.
A systematic steps approach is discussed referring to a real case study, investigating the symmetrical and asymmetrical components of the fault current and delayed zero crossing phenomena. Additionally, a set of sensitivity analysis is proposed to give the reader an overall feeling about potential critical conditions.

Index Terms — Synchronous machine, circuit breaker, short-circuit breaking capacity, delayed current zero crossing.

I. INTRODUCTION

It is well known from technical literature that in proximity of a medium voltage synchronous machine, the short-circuit current is characterized by a high degree of asymmetry and potential delayed current zero crossing.

Therefore, special care is required in “near-to-generator circuit breaker” selection process, to ensure suitable performances to effectively and safely interrupt the short-circuit current.

Transient recovery voltage (TRV) and out-of-phase current are not discussed in this paper.

A. System architecture and Electrical topology

The common architecture of an electrical system that includes medium voltage synchronous machine is typically one or a combination of the followings:

- Generator/s connected to the National grid system through unit step-up transformer/s. This is the typical case of conventional power plant, synchronous compensator plants, and industrial complex with internal generation capacity.
- Generator/s directly connected to a medium-voltage switchgear (e.g. at 11 kV level) where at the same voltage level are connected: the incomer from high-voltage grid (via step-down transformer), the distribution transformers (for load supply) and the users (e.g. medium voltage induction motors). This is the typical case of a mid-size industry.
- Island power system where generator/s is directly connected to a medium voltage switchgear (e.g. at 11 kV level) where are derived the distribution transformers (for load supply) and the users (e.g. medium voltage induction motors). This is the typical case of a mid-size industry not linked to the National grid, and is also the typical case of large offshore installations, FPSOs, cruise & operating vessels, etc…
- Large synchronous motor/s connected to a medium voltage switchgear, where commonly other feeders (distribution transformers and/or motors) are connected. This is the typical case of a large industrial complex such as LNG plants, etc…

All the above-listed types of installations, characterized by the proximity to the synchronous machine/s, are potentially exposed to short-circuit currents with a high degree of asymmetry and delayed current zero crossing phenomenon. Therefore, the investigation discussed in this report is required.

B. Analysis objective

The aim of the analysis is to accurately predict the short-circuit current that the circuit breaker is required to interrupt, to qualify its performances adequacy in respect of:

- Rated short-circuit breaking current (I_{sc}).
- DC time constant of the rated short-circuit breaking current.
- Rated short-circuit making current.
- Delayed current zero crossing phenomenon.

C. Theoretical background of a synchronous machine under short-circuit condition

A widely established fact from technical literature is that the equation below defines the natural asymmetrical short-circuit current behaviour of a synchronous machine at no-load (here specifically for a turbo generator):

$$I_{asym} = \frac{\sqrt{2}\cdot V_{mg}\cdot S_n}{\sqrt{3}\cdot {V_n}^3}\left\{\left[\left(\frac{1}{x"_d}-\frac{1}{x'_d}\right)e^{-\frac{t}{T"_d}}+\left(\frac{1}{x'_d}-\frac{1}{x_d}\right)e^{-\frac{t}{T'_d}} + \frac{1}{x_d}\right]\cos(\omega t)-\left(\frac{1}{x"_d}\right)e^{-\frac{t}{T_a}}\right\}$$

Where:

S_n	rated generator apparent power.
V_{mg} / V_n	maximum and rated generator line-to-

line voltage.

x''_d, x'_d, x_d saturated direct axis subtransient, transient and synchronous reactance's.

T''_d, T'_d short-circuit subtransient and transient time constants.

T_a armature time constant.

The equation describes the behaviour of both the symmetrical and the DC components, which together define the asymmetrical fault current that varies for each of the three phases as illustrated in the next figure (Fig. 1).

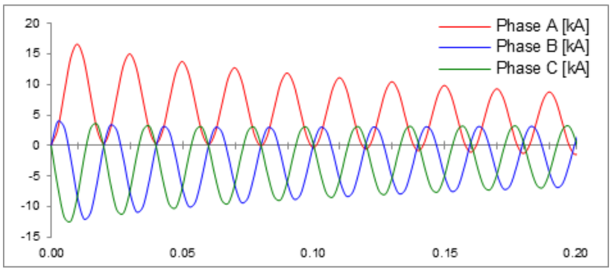

Fig. 1: asymmetrical fault current of the three phases

The main factor that causes the high degree of asymmetry in proximity of a synchronous machine is displayed in the following figure (Fig. 2). From the envelop of the upper / lower waveform, the combined effect of the DC current component and the current amplitude reduction can be observed. The first is the point of wave condition, which is essentially the voltage phase angle at the fault occurrence (in real-life it's a random and uncontrollable phenomenon) while the second is determined by the subtransient and transient (and after a long time by the synchronous) behaviour of the machine.

Those two factors lead to high peak short-circuit current values and possible delayed current zero crossing (as shown in example of below Fig. 2 not earlier than 5 cycles) by shifting away from the zero value the current waveform.

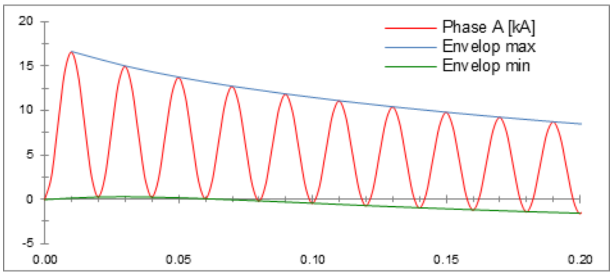

Fig. 2: max/min envelop of the worst-case phase

The resulting degree of asymmetry of the fault current can easily exceeds 100% value as shown in Fig. 3.

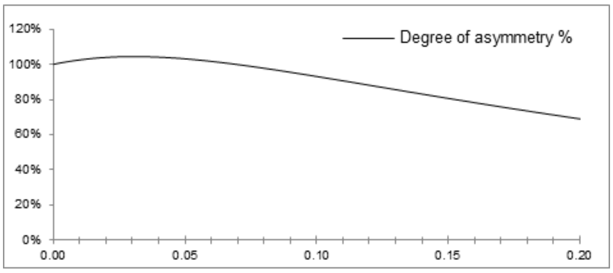

Fig. 3: % degree of the fault current

D. Reference IEC Standards

The following IEC Standards define the short-circuit current calculation procedure and the circuit breaker performances.

- IEC 60909-0 defines the procedure for calculating the short-circuit currents in high-voltage and low-voltage three-phase a.c. systems with a rated frequency of 50 Hz or 60 Hz, excluding the installations on board ships and aeroplanes [1].
- IEC 61363-1 defines a procedure for calculating the three-phase short-circuit currents of a.c. electrical installations of ships and mobile and fixed offshore units with a rated frequency of 50 Hz or 60 Hz [2].
- IEC 62271-100 defines the requirements applicable to three-phase a.c. circuit-breakers designed for indoor or outdoor installation and for operation at frequencies of 50 Hz and/or 60 Hz on systems having voltages above 1 kV [3].
- IEC/IEEE 62271-37-013 defines the requirements applicable to three-phase a.c. generator circuit-breakers (defined as a circuit-breaker installed between generator and associated step-up transformer) designed for indoor or outdoor installation and for operation at frequencies of 50 Hz and 60 Hz on systems having voltages above 1 kV and up to 38 kV. It is applicable to generator circuit-breakers that are installed between the generator and the transformer terminals with rating equal to or greater than 10 MVA [4]. This Standard defines both the short-circuit current calculation procedure and the circuit breaker performances.

Summarizing the above, two main types of high-voltage circuit breakers are defined: "circuit breaker" (in the following named "CB") and "generator circuit breaker" (in the following named "GCB") that comply with different Standards, respectively [3] and [4].

At the same time, three short-circuit current calculation methods are available. IEC 60909-0 specific for fixed onshore installations, IEC 61363-1 specific for ships and offshore installations, IEC/IEEE 62271-37-013 specific for circuit breaker installed between generator and transformer. Those methods, even if the physics are the same and the electrotechnical concepts are invariable, apply different mathematical equation and process.

II. SHORT-CIRCUIT CURRENT ANALYSIS

This paper presents a detailed case study, from the whole process of calculating the short-circuit current to the comparison of the circuit breaker performance and the examination of a possible delayed current zero crossing condition.

The objective is to qualify the required performances of the circuit breaker with potential alternative solutions.

ETAP power software is used for modelling and simulations, which enables a detailed representation of the system and relevant computations.

A. Studied case & topology

The architecture of the electrical system of this case study is represented in the Fig. 4. It is composed by a 11 kV switchgear at which are directly connected: the National grid network, though a 132/11 kV transformer, one synchronous generator, one synchronous motor and two distribution transformers for the plant auxiliaries. The data reflect a real-case project and some of them are shown in the following Fig. 4.

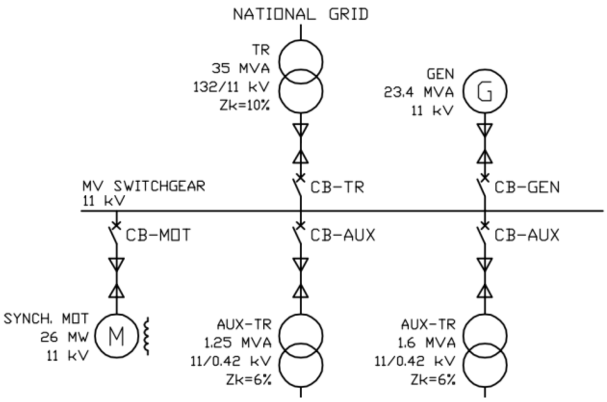

Fig. 4: simplified single line diagram of the electrical system

This analysis covers on all the 11 kV circuit breakers, which are named in this paper as detailed in TABLE I:

TABLE I
INVESTIGATED 11 kV CIRCUIT BREAKERS

Name	Description
CB-TR	Transformer incomer circuit breaker
CB-GEN	Generator incomer circuit breaker
CB-AUX	Auxiliary transformer feeder circuit breakers
CB-MOT	Synchronous motor feeder circuit breaker

B. Methodology for calculation

This case study does not correspond to IEC 61363 applications (onshore installation) and to IEC 62271-C37-13 (generator coupled to the network without a dedicated step-up transformer and with a synchronous motor at same voltage level).

Consequently, the only applicable IEC Standard for short-circuit current calculation methodology is the IEC 60909-0. However, this Standard uses simplified equations to describe the fault current behaviour that don't take into account some significant transient aspects.

For such reason, the predictability of the symmetrical (and consequently asymmetrical) short-circuit current at the fault clearing time is not optimal for the purpose of the case study.

Even if IEC 61363 and IEC/IEEE 62271-37-013 procedures should theoretically both not applicable, those two methods (that are almost identical from synchronous machine modelling point of view) provide more suitable and accurate representation of the effective transient fault current phenomenon. Consequently, in this case study was decided to apply the equations provided by IEC 61363 to determine the symmetrical and asymmetrical current behaviour, along with zero crossing condition.

C. Overall short-circuit results

The TABLE II summarizes the rated and calculation results of the total bus short-circuit current, which determine the thermal and peak ratings of the switchgear [5].

TABLE II
RATINGS AND OVERALL SHORT-CIRCUIT RESULTS

Rated short-time withstand current	Rated peak withstand current	Calculated initial symmetrical short-circuit current	Calculated peak short-circuit current
40 kA	100 kA	36.6 kA	94.7 kA

D. Current breaking capacity

The system has a short-circuit rating of 40 kA, and the target is to verify if a circuit breaker "CB" (not specifically a generator circuit breaker "GCB") with a rated short-circuit breaking current of 40 kA can suit one or more of the circuit breakers listed in TABLE I. Alternatively, for one or some of them, the next standard ratings or a generator circuit breaker "GCB" with special interrupting performances may be required, which would have cost and engineering implications.

The following TABLE III summarize the performances of the circuit breaker "CB" that will be compared with the next calculated fault currents, with the aim to confirm where possible, its adequacy.

Since the making current is higher than the total maximum peak current indicated in TABLE II (over-conservative result), it is validated.

TABLE III
CIRCUIT BREAKER PERFORMANCES

Symmetrical breaking current	Asymmetrical breaking current	Making current	Time constant	Minimum operating time
40 kA	46.3 kA	100 kA	45 ms	40 ms

The first step is to qualify the potential operating condition of the plant:

TABLE IV
REQUIRED OPERATING CONDITIONS

Name	Description
Normal	Normal scenario. Generator and synchronous motor running in parallel with National grid.
No-gen	Generator out of service. System supplied by National grid.
Island	Not allowed scenario. The system cannot operate in island from the National grid and therefore is not considered for verification purpose.

The assessment of current breaking capacity requires a different approach than the usual short-circuit current calculation used to determine the component sizing (e.g. switchgear). Here, it is essential distinguish the effective fault current to be interrupted, depending on the fault location and considering exclusively the fault current that each circuit breaker is required to interrupt.

The second step, then, is to determine the required case studies for each circuit breaker (see the Tables V, VI, VII and VIII below) based on the fault locations shown in the next Fig. 5.

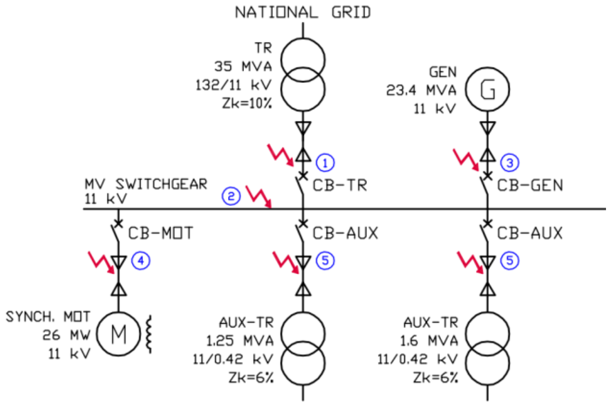

Fig. 5: fault locations identification

TABLE V
CASE STUDY FOR "CB-TR"

Fault position	Scenario	Fault current sources
Point 1, secondary side 11 kV transformer terminals	Normal	- Generator - Synch. motor - Aux. (negligible)
	No-gen	- Synch. motor - Aux. (negligible)
Point 2, 11 kV switchgear	All	- National grid

TABLE VI
CASE STUDY FOR "CB-GEN"

Fault position	Scenario	Fault current sources
Point 2, 11 kV switchgear	Normal	- Generator
Point 3, generator terminals	Normal	- National grid - Synch. motor - Aux. (negligible)

TABLE VII
CASE STUDY FOR "CB-MOT"

Fault position	Scenario	Fault current sources
Point 2, 11 kV switchgear	All	- Synch. motor
Point 4, motor terminals	Normal	- National grid - Generator - Aux. (negligible)
	No-gen	- National grid - Aux. (negligible)

TABLE VIII
CASE STUDY FOR "CB-AUX"

Fault position	Scenario	Fault current sources
Point 2, 11 kV switchgear	All	- Aux. (negligible)
Point 5, aux. transformer terminals	Normal	- National grid - Generator - synch. motor - aux. (negligible)
	No-gen	- National grid - Synch. motor - Aux. (negligible)

Increasing the level of complexity (but it's necessary), additional subcases are examined by considering how the fault current results are affected by the generator pre-loading condition. The three subcases are: no-load and full load with either rated power factor lead or lag. The used method is suitable for represent all those conditions.

In the following tables, and this we can name third step, are reported the calculated symmetrical and asymmetrical short-circuit currents, and the degree of asymmetry that each circuit breaker is required to interrupt.

These results are considered at 40 ms, the minimum time at which the circuit breaker may be initiate to open. Longer times would lead to less critical results.

Practically, the following tables summarize the results of case studies described in Table V, VI, VII and VIII which are compared with circuit breaker performances shown in TABLE III.

For the cases where generator contribution is considered as "Fault current source", three extra subcases are investigated to consider different generator pre-loading conditions: "no-load", "PF lead" and "PF lag". The results highlight that the highest value of asymmetry occurs when, prior to the fault, the generator is operating in underexcited mode, with a leading power factor. Under such a condition, the AC component of short-circuit current is lower than the assigned AC component of the rated generator-source short-circuit breaking current. In the case where the generator is carrying load with a lagging power factor prior to the fault, the degree of asymmetry will be lower, but the AC component will be higher.

TABLE IX
RESULTS FOR "CB-TR"

Fault pos.	Scenario	Gen.	I_{sym} [kA]	I_{asym} [kA]	% deg. asym.	
Point 1	Normal	no-load	15.2	30.6	124%	OK
		PF lead	14.9	30.4	125%	OK
		PF lag	15.8	30.8	119%	OK
	No-gen	n/a	9.50	20.0	131%	OK
Point 2	All	n/a	14.2	17.8	53%	OK

TABLE X
RESULTS FOR "CB-GEN"

Fault pos.	Scenario	Gen.	I_{sym} [kA]	I_{asym} [kA]	% deg. Asym.	
Point 2	All	no-load	5.59	10.6	114%	OK
		PF lead	5.36	10.4	118%	OK
		PF lag	6.20	10.9	102%	OK
Point 3	Normal	n/a	23.7	36.85	84%	OK

TABLE XI
RESULTS FOR "CB-MOT"

Fault pos.	Scenario	Gen.	I_{sym} [kA]	I_{asym} [kA]	% deg. Asym.	
Point 2	All	n/a	9.40	19.9	132%	OK
Point 4	Normal	no-load	19.9	28.0	70%	OK
		PF lead	19.7	27.7	70%	OK
		PF lag	20.5	28.4	68%	OK

TABLE XII
RESULTS FOR "CB-AUX"

Fault pos.	Scenario	Gen.	I_{sym} [kA]	I_{asym} [kA]	% deg. Asym.	
Point 2	All	n/a	~0	~0	n/a	OK
Point 5	Normal	no-load	29.2	47.3	90%	NO
		PF lead	29.3	47.4	90%	NO
		PF lag	29.1	47.2	90%	NO

The first result is that the degree of asymmetry is greater than 100% for all the cases where the fault current only includes the synchronous machines contribution, while the combination with National grid short-circuit contribution decreases this value to a maximum of 90%.

The second result is that the "CB-AUX" shows the highest value of the short-circuit current as related to the total of all the three main fault current sources (synchronous machines and National grid).

The consecutive next step, in term of mitigation and optimization, is to move to the next rating level if feasible (or to a circuit breaker with higher performance) or else, find the latest possible minimum time for the circuit breaker contacts separation initiation, to wait the lowering of the short-circuit current within the desired performances of TABLE III.

The following TABLE XIII, investigated the same results of above TABLE XII at 50 ms (instead of 40 ms).

TABLE XIII
RESULTS FOR “CB-AUX” with CPT = 50 ms

Fault pos.	Scenario	Gen.	I_{sym} [kA]	I_{asym} [kA]	% deg. Asym.	
Point 5	Normal	no-load	28.6	44.7	85%	OK
		PF lead	28.7	44.7	85%	OK
		PF lag	28.5	44.5	85%	OK

The results show that applying an additional 10 ms delay to the CB-AUX minimum opening time is enough to achieve satisfactory results. Therefore, for all cases, the circuit breaker “CB” with the performances described in TABLE III are validated, in terms of breaking current (symmetrical and asymmetrical). In other words, in term of magnitude of fault current values, there are not restrictions under short-circuit condition to use a standard circuit breaker “CB” instead of a specific generator circuit breaker “CGB”.

E. Delayed current zero crossing

The fourth step is the delayed current zero crossing assessment.

As well-known from the technical literature, the generator circuit breaker “GCB” is designed with the capability to interrupt short-circuit current with delayed zero by forcing it to cross the zero. On the contrary, a circuit breaker “CB” is not designed for that and is essential to ensure that, at the opening initiation, the short-circuit current naturally crosses the zero.

Therefore, the actual natural zero crossing for each circuit breaker (shown in TABLE I) will be calculated for faults on both source side and load side, based on the potential combination of fault current sources and system configurations: results are summarized on TABLE V to TABLE VIII.

In next TABLE XIV are summarized all the plotted current waveforms investigated for this assessment.

TABLE XIV
INVESTIGATED DELAYED CURRENT ZERO CROSSING

Figure	Description of short-circuit current sources
Fig. 6	National grid only
Fig. 7	Generator only
Fig. 8	Synchronous motor only
Fig. 9	National grid + Generator
Fig. 10	National grid + Synchronous motor
Fig. 11	Generator + Synchronous motor
Fig. 12	National grid + Generator + Synchronous motor

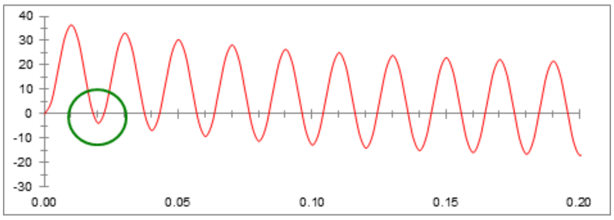

Fig. 6: National grid only

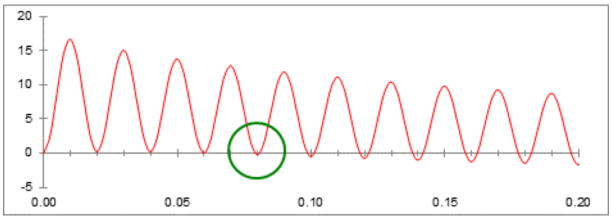

Fig. 7: Generator only

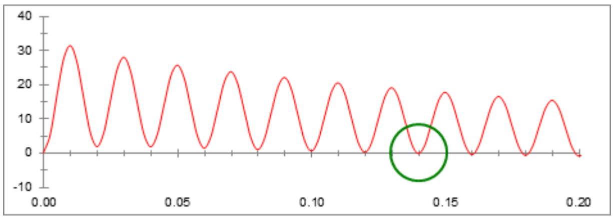

Fig. 8: Synchronous motor only

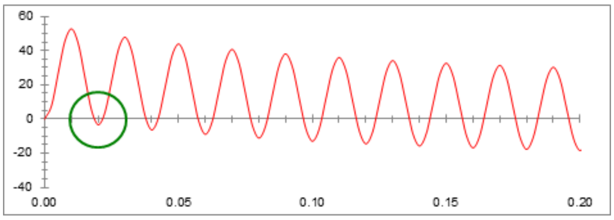

Fig. 9: National grid + Generator

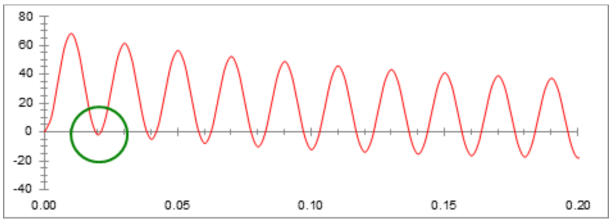

Fig. 10: National grid + Synchronous motor

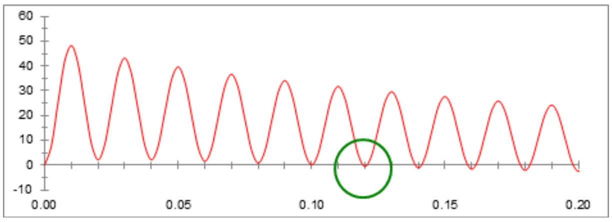

Fig. 11: Generator + Synchronous motor

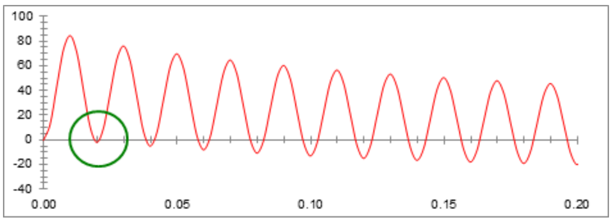

Fig. 12: National grid + Generator + Synchronous motor

The results of the above plots are translated in individual case studies result (from TABLE XV to TABLE XVIII).

TABLE XV
ZERO CROSSING TIME FOR "CB-TR"

Fault position	Scenario	Zero crossing
Point 1, 11 kV transformer terminals	Normal	120 ms
	No-gen	140 ms
Point 2, 11 kV switchgear	All	<20 ms

TABLE XVI
ZERO CROSSING TIME FOR "CB-GEN"

Fault position	Scenario	Zero crossing
Point 2, 11 kV switchgear	Normal	80 ms
Point 3, generator terminals	Normal	<20 ms

TABLE XVII
ZERO CROSSING TIME FOR "CB-MOT"

Fault position	Scenario	Zero crossing
Point 2, 11 kV switchgear	Normal	140 ms
Point 4, motor terminals	All	<20 ms

TABLE XVIII
ZERO CROSSING TIME FOR "CB-AUX"

Fault position	Scenario	Zero crossing
Point 2, 11 kV switchgear	Normal	n/a
Point 5, aux. transformer terminals	All	<20 ms

The first important result is that, in all the cases where the fault current includes the short-circuit contribution of the National grid, the current crosses zero within the first cycle.

With a conservative approach, further analysis is performed by considering the maximum reduction of the short-circuit power of the National grid (20% lower than the provided value). The results, shown in the following figure (Fig. 13), consider the worst-case scenario (generator + motor + National grid). The observed conclusion is that the zero crossing moves from 20 ms to 40 ms: not a big impact considering the effective expected trip time of the "CB-AUX" (50 ms) that's the one for which this case study apply.

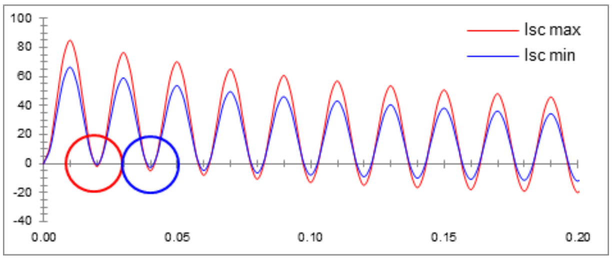

Fig. 13: National grid + Generator + Synchronous motor, sensitivity analysis

Vice versa, in all the cases where the fault current is composed by the synchronous machines only (generator or the synchronous motor or the combination of the two), the short-circuit current zero crossing occurs in a range from 80 ms to 140 ms. For delayed current zero crossing, the "CB-AUX" is the less critical one as there are no restrictions to use a standard circuit breaker "CB" while, for all the others, needs to be verified the effective opening time by adding the protection trip time: if it will be lower than the calculated 80-140 ms, the installation of a generator circuit breaker "GCB" may be required.

As a general note, the calculated delayed current zero crossing refers to the worst-case for one phase only based on point of wave. Therefore, is a "random" phenomenon that may occurs or not, on the same installation, in the same configuration, for the same fault type, depending on the voltage waveform at the instant of fault occurrence.

F. *Impact of protective philosophy*

The assessment of the circuit breaker performance cannot be disregarded from the deep understanding of the protective system and philosophy.

The achievement of fast acting protection system (short fault clearing time) combined with a proper selectivity (coordination) is a desirable condition for a series of reasons (minimize the damages, increase human safety, mitigate arc-flash effects, reduce system disturbances, increase rotor angle stability, etc…).

The moder protection technology allows to achieve satisfactory both fast fault clearance and coordination in medium voltage system, using zone differential protection and logical selectivity (independently or combined).

These techniques typically allow to get fault clearance in less than 150-200 ms with logical selectivity, and less than 100 ms with differential (zone) protections.

The protection scheme of this case study is displayed in the following Fig. 14 where are exclusively shown the protective function relevant to phase faults. The main equipment (transformer, generator and synchronous motor) are equipped with a differential protection (respectively ANSI code 87T, 87G, 87M). The auxiliary outgoing feeders are equipped with phase overcurrent (ANSI code 50). Generator and incomer from National grid, are moreover equipped with phase overcurrent (50) for busbar fault clearance (and for coordination back-up).

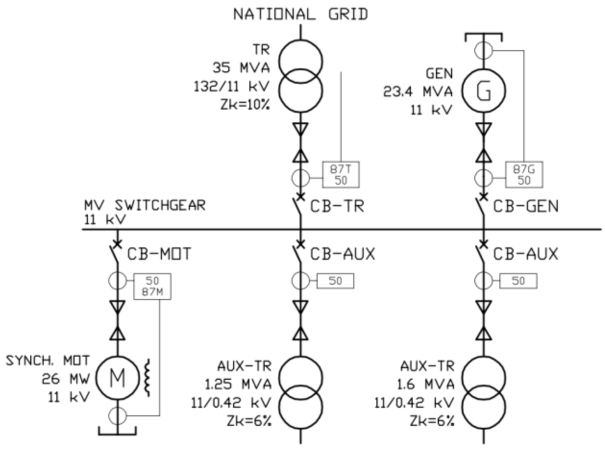

Fig. 14: simplified protection single line diagram

Summarizing, for this specific case, the following fault clearance times are expected:

TABLE XIX
PROTECTION TRIP COMMAND TIME

Fault position	Trip by	Trip command
Point 1, 11 kV transf. terminals	87T	30 ms
Point 2, 11 kV switchgear	50	300 ms
Point 3, generator terminals	87G	30 ms
Point 4, motor terminal	87M	30 ms
Point 5, aux. transformer terminals	50	20 ms

For Point 2, 11 kV switchgear, the considered trip command time of 300 ms for the operation of transformer incomer and generator phase overcurrent protection (50) ensure coordination with the other protections.

On breaker performance evaluation, is not intentionally listed above the arc-detection system (that's effectively installed on busbar compartment of the switchgear) even if are even faster than a differential protection. However, since the trip command results where arc is released in air, being the arc-plasma is characterized by high-resistivity component, the level of asymmetry and delayed zero crossing are naturally mitigated.

G. Final results

In this case study, are investigated the current breaking capacity and the delayed current zero crossing condition for the four circuit breakers investigated, with following results:

"CB-TR": Symmetrical, asymmetrical, and making currents are within the circuit breaker ratings in all the cases, at time 40 ms. Delayed current zero crossing exists for source side fault (Point 1, TR terminal 11 kV), where the current crosses zero in approx. 140 ms (worst-case). Differential protection 87T is expected to operate in this case and send the trip command in 30 ms. The following two alternative solutions can be applied:

1. select a circuit breaker "CB" type with performance as per TABLE II and impose to the protection setting a minimum intentional delay time of 120 ms.
2. select a generator circuit breaker "GCB" type, without any extra delay requirement.

"CB-GEN": Symmetrical, asymmetrical, and making currents are within the circuit breaker ratings in all the cases, at 40 ms. Delayed current zero crossing exists for a system side fault (Point 2, 11 kV switchgear), where the current crosses zero in approx. 80 ms. In this case, the protection system will not act before 300 ms and thus, a circuit breaker "CB" type with performance as per TABLE II is adequate and there is no need to install a generator circuit breaker "GCB".

"CB-MOT": Symmetrical, asymmetrical, and making currents are within the circuit breaker ratings in all the cases, at 40 ms. Delayed current zero crossing exists for a source side fault (Point 2, 11 kV switchgear), where the current crosses zero in approx. 140 ms but in this case, the protection relay of the synchronous motor will not directly operate on it (eventual intertrip in long time ≥300 ms). Consequently, also in this case, a circuit breaker "CB" type with performance as per TABLE II is adequate and there is no need to install a generator circuit breaker "GCB".

"CB-AUX": Symmetrical, asymmetrical, and making currents are within the circuit breaker ratings in all the cases, at 50 ms (for 40 ms the requirements are not satisfied). No delayed zero crossing condition subsists, and thus, a circuit breaker "CB" type with performance as per TABLE II is adequate with a minimum trip time of 50 ms.

III. SENSITIVITY ANALYSIS

The following additional technical consideration and sensitivity analysis are discussed.

A. Impact of armature resistance

One of the key factors determining the degree of asymmetry and delayed current zero crossing is the armature time constant of a synchronous machine.

With the target to provide a sensitivity analysis on this parameter, sets of results (plots) are provided for a range of values of armature time constant from 50 ms to 300 ms, by considering the same electrical parameters of the generator.

The first plot provides the DC short-circuit current profiles that determine the increase of both the peak value of the short-circuit current and the related zero crossing.

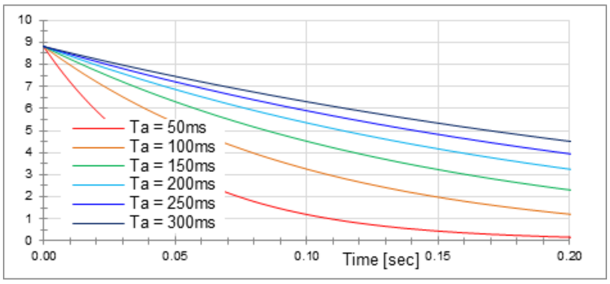

Fig. 15: DC short-circuit current [kA]

The following plot shows the profile of the degree of asymmetry (as a percentage) where is evident that a higher values of armature time constants determine a level of asymmetry above 100%.

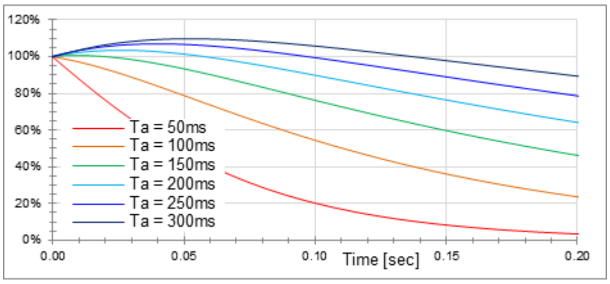

Fig. 16: Degree of asymmetry of short-circuit current [%]

The last plot describes the instantaneous current profile on the worst-case phase, with relevant impact in term of delayed zero crossing. Higher values of armature time constant postpone the zero crossing: 20 ms (1 cycle) for a T_a = 50/100 ms, 40 ms (2 cycle) for a T_a = 150 ms, 60 ms (3 cycle) for a T_a = 200 ms, 100 ms (5 cycle) for a T_a = 250 ms, 140 ms (7 cycle) for a T_a = 300 ms.

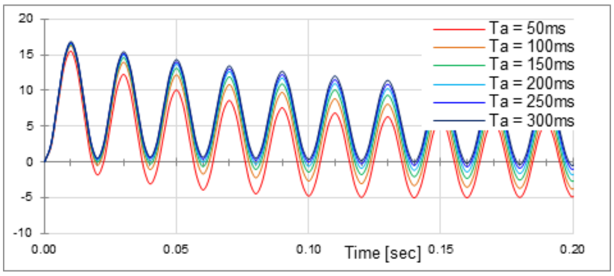

Fig. 17: Instantaneous short-circuit current [kA]

The above results show also that the impact of the armature time constant is not linear and generally recommends attention selecting the circuit breaker in proximity of a synchronous machine with a high value of armature time constant.

For statistical data, the typical values of the armature time constant, based on more than 75 synchronous generator datasheet of 50/60 Hz are in a range from 1 to 70 MVA, are here below displayed. The value of armature time constant is not linear with the generator rating, however it tends to increase for larger rating, as well known from technical literature.

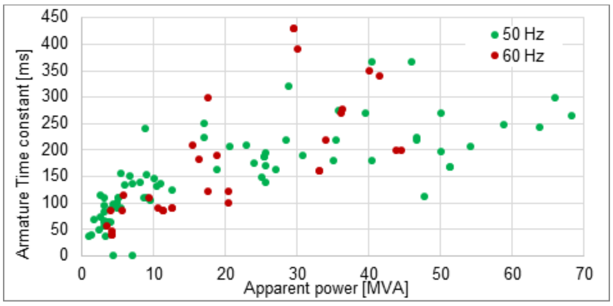

Fig. 18: armature time constant for various generator rating

B. Synchronous machine pre-loading condition

As shown in this paper, the pre-loading condition of the generator significantly affects the calculation results.

Since the generator's short-circuit current contribution is a direct consequence of its electromotive force, directly correlated to both the excitation condition and the machine reactance's, any operating point, that determines a higher excitation condition, causes a higher magnitude of the short-circuit current. The following Fig. 19 describes the symmetrical short-circuit current of a generator at two different pre-loading conditions (extreme cases) at no-load and at full-load with 0.80 lag power factor.

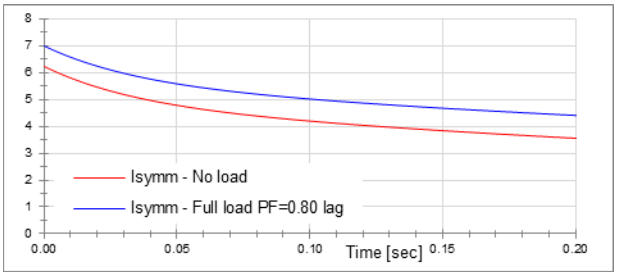

Fig. 19: impact of the pre-loading condition on the generator symmetrical short-circuit current

Therefore, a reduced magnitude of the short-circuit current, even with almost the same degree of asymmetry, conditions also the delayed current zero crossing. The following Fig. 20 confirms that the no-load case (zero crossing at 80 ms) is a worst-case respect to the full load with lead power factor (zero crossing in first cycle).

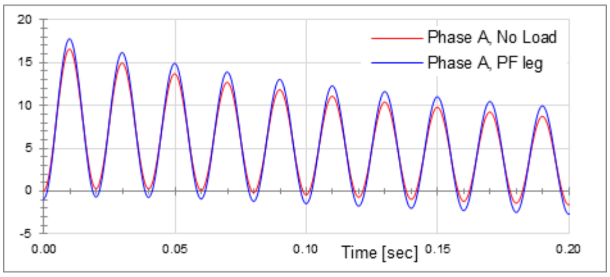

Fig. 20: impact of the pre-loading condition on the generator delayed current zero crossing

C. Problem propagation through a transformer

The near-to-generator problem, embed in the wording a non-scientific boundary. The meaning and the numerical value of the word "near" is not of obvious interpretation and arises the natural questioning, if all the above problems can (and how much) propagated from the generator terminals to the various parts of the plant.

The typical case of interest for potential propagation of the near-to-generator concern is through a transformer (e.g. a generator step-up transformer).

As intuitive, normally a power transformer is enough to mitigate the problem. The two reasons in behind are: the X/R ratio (that in a transformer is commonly lower than in a generator) speed-up the DC current decay, and the series impedance circuit (that reduces the ratio between the equivalent subtransient, transient and synchronous reactance's) mitigation effect is discussed in initial Fig. *2*.

The following two plots, obtained with a step-up transformer with a size 10% greater than the generator one, qualify both phenomena combined. Apart the numeric value itself, that's obviously lower with the series between generator and transformer, the concept to be read is the trend and the qualitative effect. Also important, the fault current zero crossing move from 80 ms (4 cycle) to 20 ms (1 cycle).

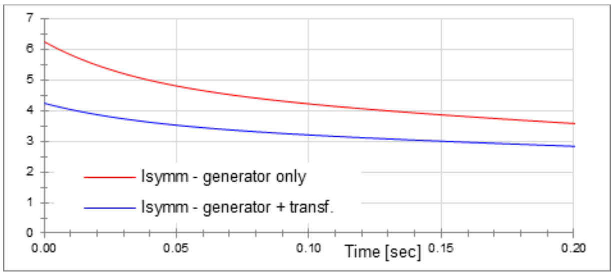

Fig. 21: impact of the unit-transformer on the generator symmetrical short-circuit current

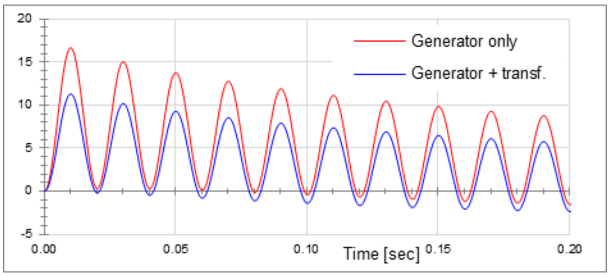

Fig. 22: impact of unit-transformer on delayed zero crossing from a generator

IV. CONCLUSIONS

The proximity (near-to) of a synchronous machine requires careful selection of the circuit breaker performances.

Such verification requires several analyses discussed step-by-step in this paper, where the electrical system was modelled and studied in ETAP software.

The investigation of the short-circuit current magnitude compared with the target circuit breaker performances, the delayed current zero crossing phenomena and the required circuit breaker opening time for the various locations of a fault, leads to a non-intuitive result.

In the studied network (Fig. 4 on page 3), for the circuit breakers located at the generator incomer and at the synchronous motor feeder, a circuit breaker "CB" responding to the requirement of IEC 62271-100 is adequate. On the contrary, the outgoing feeder to the auxiliary transformer is the one with the highest short-circuit current breaking performance request and is recommended to apply an extra delay time to the protection settings to prevent the needs of increase the circuit breaker rating. However, also in this case and with this additional delay (minor) a circuit breaker "CB" responding to the requirement of IEC 62271-100 is adequate. The incomer from the transformer (from National grid) requires more performances in term of delayed zero crossing, up to require a minimum delay to be applied to the transformer differential protection of 120 ms (to allow the use of circuit breaker "CB" responding to the requirement of IEC 62271-100), or to select a generator circuit breaker "GCB" responding to the requirement of IEC 62271-C37-13.

Under this specific case study, the presence of the National grid connection (for which a sensitivity analysis has been done) and the not-allowed island operation, significantly simplify the calculation process and provide many benefits in term of results. In this sense, it is obvious that any system operating in electrical island, is normally more subjected to this phenomenon, and for example in a case like this one, will require special performances and potentially the requirement of a "GCB" an all the circuit breakers, with a potential exception of the generator incomer circuit breaker "CB_GEN" only.

This paper also includes a sensitivity analysis of the main parameters affecting the circuit breaker selection, along with the discussion of the concept of "near-to-generator" with a more scientific approach.

V. REFERENCES

[1] IEC 60909-0 "*Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents*", 2016.

[2] IEC 61363-1 "*Electrical installations of ships and mobile and fixed offshore unit – Part 1: Procedures for calculating short-circuit currents in three-phase a.c.*", 1998.

[3] IEC 62271-100 "*High-voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers*", 2021.

[4] IEC/IEEE 62271-37-013 "*High-voltage switchgear and controlgear – Part 37-013: Alternating current generator circuit-breakers*", 2021.

[5] IEC 62271-1 "*High-voltage switchgear and controlgear – Part 1: Common specifications for alternating current switchgear and controlgear*", 2017.

II. VITA

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