DELAYED CURRENT ZEROS IN FPSO OFFSHORE UNITS

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Abstract – It is well established that when short-circuit occurs close to generators' terminals, the instantaneous value of the fault current through the circuit-breaker may not reach zero amperes for some considerable time, so called delayed current zero phenomenon. Therefore circuit-breakers may not be suitable to clear the fault under this condition. Today's floating production, storage and offloading (FPSO) units are very large in terms of installed generation capacity, in the range of 100 MVA, and in terms of number of medium voltage motors, many of them connected directly to the generation voltage level. This leads to a very favorable condition for the occurrence of delayed currents zeros in FPSO's electrical power systems. This paper presents the results obtained in the analysis for a typical FPSO electrical power system. The main objective of this analysis is to verify the presence of delayed currents zeros, the non-zero times and how the system operational condition and type of event may influence the results.

Index terms — delayed current zeros, FPSO, circuit-breaker.

I. LIST OF SYMBOLS AND ABBREVIATIONS

FPSO floating production, storage and offloading unit
CB circuit-breaker
a.c. alternating current
d.c. direct current
X/R short-circuit reactance over resistance ratio
T"d short-circuit subtransient direct axis time constant

II. INTRODUCTION

A circuit-breaker is a mechanical switching device capable of making, carrying, and breaking currents under normal circuit conditions and also under specified abnormal circuit conditions such as those of a short-circuit. However, some types of applications can result in performance requirements for short-circuit current which exceed the limitations of the CB standards.

All high-voltage circuit-breakers manufactured today are of the alternating current type, i.e. circuit-breakers that need current zeros to interrupt [1]. Under certain conditions, faults occurring close to power plants may lead to a delay on the first zero-axis crossing of the generator short-circuit currents, resulting in arcing time prolongation which poses a potential hazard and can be a severe requirement [2]. This phenomenon is called delayed current zeros.

The phenomenon is associated with high X/R values, which result in a slow attenuation of the d.c. component of the fault current (long d.c. time constant), and with the decreasing values of the subtransient and transient short-circuit current contribution from generators (related to the small value of T"d of synchronous generators), responsible for the fast attenuation of the a.c. component. Both characteristics are present in the neighborhood of power plants.

If generators and high-power motors are located close to each other, the damping of the short-circuit current d.c. component is particularly low and the probability of occurrence of delayed current zeros is even higher. If there is a fault, the motors act as generators and feed back into the system a current with a high d.c. component and fast decaying a.c. component. As they are slowing down, they will gradually become out-of-phase with respect to the generators. The frequency of the current generated by the motors will drop below the generators' frequency. Even if the short-circuit current from the generators has current zeros, the superposition of the current generated by the motors results in a total short-circuit current with delayed current zeros [1][3]. Therefore, this leads to a very favorable condition for the occurrence of delayed current zeros in FPSO's electrical power systems.

Not only fault conditions, but also attempting to synchronize at an unsuitable differential angle may cause the current zeros to be delayed [1]. However, this case is not evaluated in this article.

When the short-circuit current does not cross the zero axis prior to opening of the circuit-breaker, it is equivalent to attempting to interrupt d.c. current, and high-voltage CBs have an extremely limited capability of interrupting d.c. current [2]. That means that such currents could not be interrupted immediately and according to [4] in such circumstances the duty of the circuit-breaker can be eased, for example, by delaying its opening.

III. METHODOLOGY

To determine the moment when a short-circuit current reaches zero amperes, it is important to evaluate how the a.c. and d.c. components behave during the short-circuit, considering that they decay with different time constants. So it is necessary to describe the short-circuit current as a function of time.

A detailed three-phase model of the system under analysis was prepared using a calculation software [5]. Several transient simulations were performed in order to meet the most severe conditions with respect to asymmetry and delayed zero crossing of the short-circuit currents.

All the simulations were carried out based on the assumption that in any practical circuit-breaker at least one phase will be able to clear the fault current, due to the fact that the d.c. component in one phase will be always small enough so that there will be current zeros. This gives the respective circuit-breaker pole a chance to interrupt as the first pole-to-clear [1][3]. Thus, a phase shift will take place in the other two phases, and the distribution of current in the other phases will be affected.

Then the goal is to evaluate the behavior of the current of the two phases that remain feeding short-circuit after the first pole clears, and verify the corresponding arcing times (non-zero times).

Scenarios with different situations are considered in order to verify the influence of system parameters, pre-fault conditions and types of faults on the severity of the phenomenon. The scenarios are obtained by the combination of the aspects described below.

A. Types of faults

1) Balanced (simultaneous) faults

To demonstrate the capability of the circuit-breakers to withstand and to clear the faults with delayed current zeros, three-phase short-circuit tests should cover the following conditions [1][3][6]:

a) with the maximum d.c. component in one phase, i.e. one phase fully offset, corresponding to a short-circuit occurring at voltage zero;

b) with practical no d.c. component in one phase, i.e. one phase fully symmetrical, corresponding to a short-circuit occurring at voltage crest.

Accordingly, the following simultaneous fault cases are evaluated:

- 3-phase fault (maximum voltage on phase A);
- 3-phase fault (minimum voltage on phase A).

2) Sequential (non-simultaneous) faults

Non-simultaneous fault closure on the phases can substantially extend the time to reach a current zero and then the circuit-breaker may attempt to clear the fault under more severe conditions [7]. The following progressive fault cases are evaluated:

- 1-phase fault (minimum voltage phase A) → 2-phase fault (minimum voltage phase B) → 3-phase fault (minimum voltage phase C);
- 1-phase fault (minimum voltage phase A) → 3-phase fault (minimum voltage between phases B and C);
- 2-phase fault (minimum voltage between phases A and B) → 3-phase fault (minimum voltage phase C).

B. Pre-fault operating conditions of the system

With respect to current asymmetry, the stress on the circuit-breakers are also influenced by the generator loading before the fault inception [1][6]. The operating conditions evaluated in this work are presented in Table I.

It is important to highlight that in FPSO systems the generators' power factor does not change significantly for the different load conditions, and it is approximately equal to 0,88.

TABLE I
OPERATING CONDITIONS

Operating condition	Number of generators in operation	Loading [% kVA Generator]
#1	3	90%
#2	4	67%
#3	1	0 (no load)

C. Fault locations and circuit-breakers

Not only the amplitude of the short-circuit current is important but also its composition with respect to the contribution of generators and motors. According to Fig. 1, the following fault locations and circuit-breakers were evaluated for a short-circuit on the 13.8 kV system:

- Busbar fault (F1) → Generator circuit-breaker (CB#1) opening;
- Outgoing CB terminals fault (F2) → Load circuit-breaker (CB#2) opening.

Only faults on 13.8kV system are performed in this study.

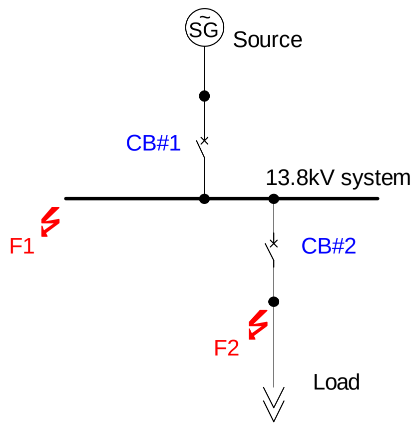

Fig. 1 – Fault locations and circuit-breakers

IV. SYSTEM DESCRIPTION

The FPSO electrical system is comprised by the following elements:

- 13,8, 4,16, 0,69 and 0,48 kV 60 Hz main busbars;
- Four 31,25 MVA, 13,8 kV main generators;
- Two 10 MVA / 13,8-4,16 kV two-winding transformers and corresponding loads;
- Two 5 MVA / 13,8-4,16 kV two-winding transformers;
- Two 4 MVA / 13,8-0,69-0,69 kV three-winding transformers and corresponding loads;
- Two 4,5 MVA / 13,8-0,48 kV three-winding transformers and corresponding loads;
- Two 3,15 MVA / 13,8-0,48 kV three-winding transformers and corresponding loads.

The main single line diagram of the model is shown in Fig. 2. Details about the modeling of network elements are presented in the next section.

V. POWER SYSTEM MODELING

A. Circuit-breakers

The circuit-breakers are represented by ideal switches, with instantaneous transition from short-circuit to open-circuit, that open each phase at the first current zero crossing after the contact separation. The effect of the arc voltage upon the decay of the d.c. components is neglected.

The following times are considered in the analysis:

- Minimum relay operating time: 20 ms;
- Opening time: 35 ms;
- Delay time (intentional): not considered.

Therefore, it is considered that the contact separation occurs 55 ms after the fault initiation.

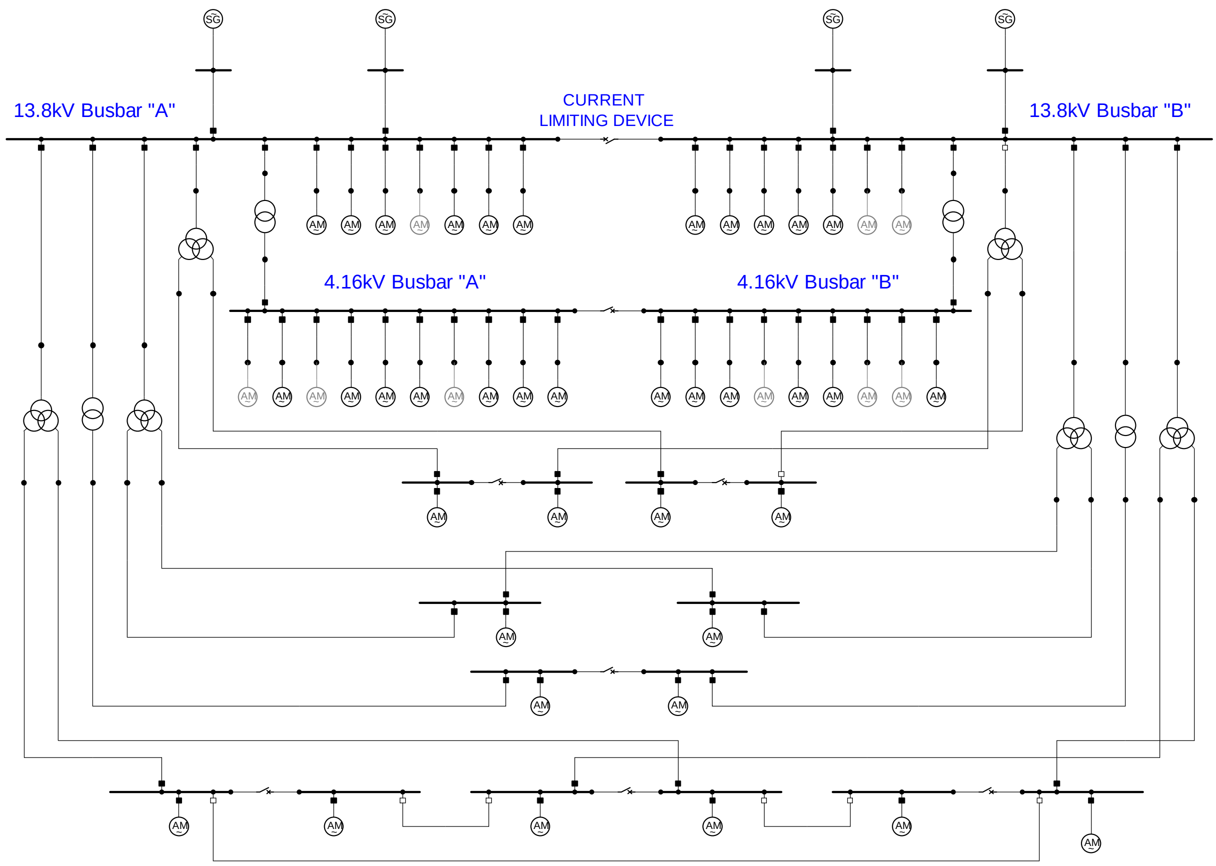

Fig. 2 – Main single-line diagram

B. Synchronous machines

For the electromagnetic model, the generators are modeled using the complete synchronous machine model, which is represented in a rotor-oriented system (Park coordinates, dq-reference frame). The equivalent circuit is shown in Fig. 3. The parameters of these machines are presented in Table II. The saturation is also taken into account in the model and is presented in Fig. 4.

According to [8] and as observed in preliminary simulations, the effect of the voltage regulator that increases the internal voltage of the machine during a short-circuit – which results in the increase of the a.c. component – may be neglected due to the small time constants involved. Then this control is neglected in the model.

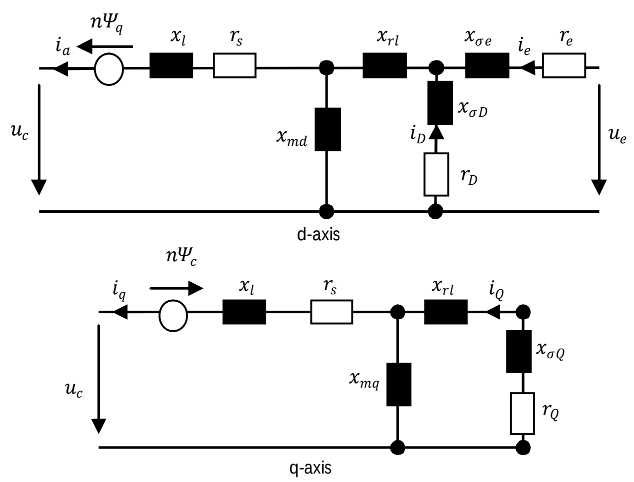

Fig. 3 – General synchronous machine equivalent circuit

TABLE II
GENERATOR DATA

Nominal Volt. [kV]	13,800
App.Pow. [MVA]	31,250
H [Sgn] [s]	1,920
rs [pu]	0,002
xl [pu]	0,110
xrl [pu]	0,000
xd'' [pu]	0,140
xq'' [pu]	0,170
xd' [pu]	0,260
xq' [pu]	N.A.
xd [pu]	1,630
xq [pu]	0,810
x0 [pu]	0,065
r0 [pu]	0,002
Td0' [s]	8,759
Tq0' [s]	N.A.
Td0'' [s]	0,013
Tq0'' [s]	0,033

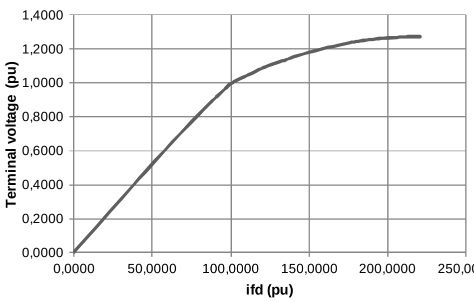

Fig. 4 – Generators' saturation curve

C. Asynchronous machines

The motors are represented by the squirrel cage induction machine model with a frequency (or slip) dependent rotor impedance. The equivalent circuit is shown in Fig. 5.

Squirrel cage rotors exhibit current displacement on starting and at low speeds (i.e. at high slip) due to the skin effect. The current displacement effect can be modeled by adding an additional R-L branch in parallel to the single cage rotor. The additional branch is modeled to represent the squirrel cage rotor on starting, where the rotor leakage reactance predominates. As the speed increases, the influence of the additional R-L branch decreases.

The 13,8 kV asynchronous motors were modeled by directly specifying the electrical parameters of the equivalent circuit diagrams. The parameters are presented in Table III. The mechanical loads of the 13.8 kV motors are also considered in the model. A typical load curve is presented in Fig. 6.

The 4,16kV motors are modeled by means of the slip-torque/current characteristic and the performance parameters using the software's built-in parameter estimation algorithm [9]. Low-voltage motors are grouped into equivalent induction motors.

Although all medium-voltage motors were individually represented in the model, it was found to be sufficient to consider only the 13.8kV motors to perform the analysis proposed in this article [3].

TABLE III
13.8 kV ASYNCHRONOUS MOTORS DATA

Data	Type 1	Type 2	Type 3	Type 4
Rated mech. power [kW]	6205	1350	2600	11000
Total number of motors	2	2	2	8
Motors on busbar "A"	1	1	1	4
Motors on busbar "B"	1	1	1	4
Inertia [kgm^2]	89,437	35,110	50,000	591,300
Stator res. [p.u.]	0,0060	0,0090	0,0080	0,0051
Stator reac. [p.u.]	0,1970	0,1210	0,1300	0,2087
Mag. reactance Xm [p.u.]	4,231	4,669	3,567	5,940
Slip indep. resist. RrA0 [p.u.]	0	0	0	0
Slip indep. react. XrA0 [p.u.]	0	0	0	0
Resistance RrA1 [p.u.]	0,0100	0,0062	0,0073	0,0095
Reactance XrA1 [p.u.]	0,1601	0,1568	0,1005	0,1531
Resistance RrA2 [p.u.]	0,1246	0,1099	0,0549	0,0728
Reactance XrA2 [p.u.]	0,1403	0,1562	0,0704	0,0913

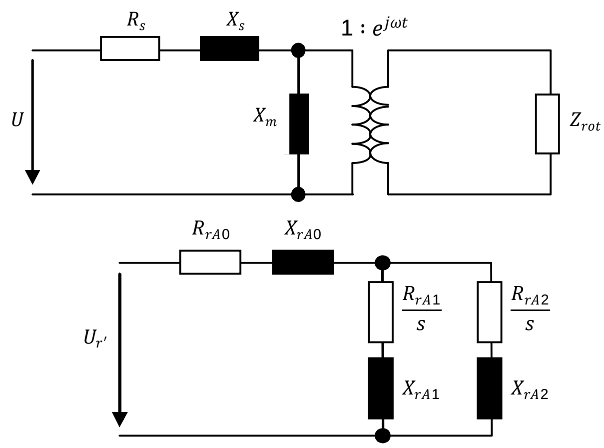

Fig. 5 – Squirrel cage (current displacement effect) rotor equivalent circuit

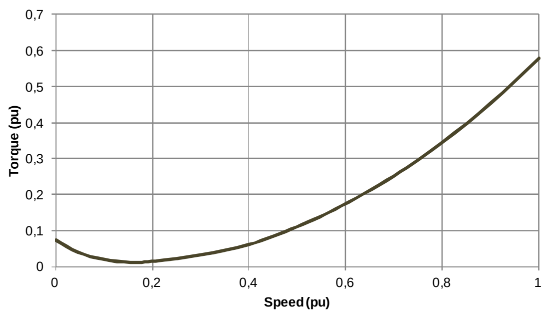

Fig. 6 – A typical load curve for the 13.8 kV motors

D. Cables

Cables may contribute to reduce the non-zero times, due to the fact that the additional cable resistance, in series with the armature resistance of the machines, forces the d.c. component of the short-circuit current to decay faster. Therefore, the cables are included in the model and the most important parameters are presented in Table IV.

TABLE IV
13.8 kV CABLES DATA

Circuit	R1	X1	R0	X0
	Ohm	Ohm	Ohm	Ohm
Generators	0,0039	0,0034	0,0156	0,0137
Motor 6205kW	0,0149	0,0090	0,0594	0,0360
Motor 1350kW	0,0372	0,0188	0,1488	0,0750
Motor 11000kW	0,0257	0,0156	0,1030	0,0624
Motor 2600kW	0,0645	0,0325	0,2579	0,1300

E. Current limiting device

In the typical FPSO there is a short-circuit current limiting device installed between busbars “A” and “B” of the 13,8kV switchgear. This device is triggered for phase-to-phase short-circuits at the 13.8kV system when three or four generators are connected to the system, to reduce the system short-circuit ratings. Since the opening time of this device is very low (less than 4 ms), this element is modeled as an ideal switch that is closed in the pre-fault operation and opens right after a two- or three-phase short-circuit at the 13.8kV level.

F. Transformers

The transformers are modeled as ideal transformers plus impedances. The main data are shown in Table V and Table VI.

TABLE V
TWO-WINDING TRANSFORMER DATA

Data	Type 1	Type 2
Rated power [MVA]	10	5
Number of equipments	2	2
Prim. rated voltage [kV]	13,8	13,8
Sec. rated voltage [kV]	4,16	4,16
Vector group	Dyn1	Dyn1
x1 [%]	8	7
X/R	16	12

TABLE VI
THREE-WINDING TRANSFORMER DATA

Data	Type 1	Type 2	Type 3
Number of equipments	2	2	2
Prim. rated power [MVA]	4	3,15	4,5
Prim. rated voltage [kV]	13,8	13,8	13,8
Sec. rated power [MVA]	2	1,575	2,25
Sec. rated voltage [kV]	0,69	0,48	0,48
Tert. rated power [MVA]	2	1,575	2,25
Tert. rated voltage [kV]	0,69	0,48	0,48
Vector group	D0y1d0	D0y1y1	D0y1y1
X/R	7,8	7	8,25
x1 prim-sec [%]	9	9	10
x1 sec-tert [%]	18	18	20
x1 tert-prim [%]	9	9	10

VI. RESULTS OF CALCULATIONS

The summary results of the delayed current zeros analysis are presented in Table VII, Table VIII and Table IX. It can be observed from the results that:

- Sequential faults (non-simultaneous) may present more severe conditions for the circuit breakers in terms of delayed current zeros;
- Short-circuit contributions from 13.8 kV motors into the system have high d.c. components and fast a.c. component decaying. Because of the superposition of these currents in case of a fault on the load side of a 13.8kV outgoing circuit-breaker, the total short-circuit current present a more severe condition in terms of delayed current zeros;
- Load circuit-breakers are subjected to more severe conditions in terms of short-circuit delayed current zeros. It can be noticed that for these equipments:
  - there are more cases that the phenomenon occurs in comparison with generator circuit-breakers (see Table IX);
  - maximum arcing times after contact separation are higher for these equipments.
- Generator circuit-breakers are subjected to more severe conditions in terms of short-circuit delayed zeros (higher arcing times) when the generators operate with no load before the fault inception than when they are feeding an inductive load.

TABLE VII
RESULTS FOR LOAD CIRCUIT-BREAKER

Sim.	Oper. cond.	Fault type	First phase to clear	Arcing time first pole to clear [ms]	Last phase to clear	Arcing time last poles to clear [ms]
01	#1	3F max volt.	A	3,60	B / C	27,60
02	#1	3F min volt.	C	0,83	A / B	8,93
03	#1	1F/2F/3F	A	7,94	B / C	84,34
04	#1	1F/3F	A	3,67	B / C	27,67
05	#1	2F/3F	B	7,96	A / C	84,36
06	#2	3F max volt.	A	3,80	B / C	27,80
07	#2	3F min volt.	C	1,03	A / B	9,13
08	#2	1F/2F/3F	A	8,14	B / C	84,44
09	#2	1F/3F	A	3,87	B / C	27,77
10	#2	2F/3F	B	8,16	A / C	84,56
11	#3	3F max volt.	A	4,50	B / C	11,90
12	#3	3F min volt.	C	1,83	A / B	9,13
13	#3	1F/2F/3F	A	8,94	B / C	68,04
14	#3	1F/3F	A	4,57	B / C	11,87
15	#3	2F/3F	B	8,96	A / C	68,06

TABLE VIII
RESULTS FOR GENERATOR CIRCUIT-BREAKER

Sim.	Oper. cond.	Fault type	First phase to clear	Arcing time first pole to clear [ms]	Last phase to clear	Arcing time last poles to clear [ms]
01	#1	3F max volt.	A	3,10	B / C	9,70
02	#1	3F min volt.	C	0,53	A / B	7,43
03	#1	1F/2F/3F	A	7,35	B / C	48,45
04	#1	1F/3F	A	3,07	B / C	9,67
05	#1	2F/3F	B	7,46	A / C	48,46
06	#2	3F max volt.	A	3,30	B / C	10,10
07	#2	3F min volt.	C	0,73	A / B	7,73
08	#2	1F/2F/3F	A	7,65	B / C	48,95
09	#2	1F/3F	A	3,37	B / C	10,07
10	#2	2F/3F	B	7,66	A / C	48,96
11	#3	3F max volt.	A	4,50	B / C	11,90
12	#3	3F min volt.	C	1,83	A / B	9,13
13	#3	1F/2F/3F	A	8,94	B / C	68,04
14	#3	1F/3F	A	4,57	B / C	11,87
15	#3	2F/3F	B	8,96	A / C	68,06

TABLE IX
QUALITATIVE COMPARISON OF RESULTS

Oper. cond.	Fault type	Delayed zeros presence after contact parting	
		Load CB	Gen CB
#1	3F max volt.	Yes	No
#1	3F min volt.	No	No
#1	1F/2F/3F	Yes	Yes
#1	1F/3F	Yes	No
#1	2F/3F	Yes	Yes
#2	3F max volt.	Yes	No
#2	3F min volt.	No	No
#2	1F/2F/3F	Yes	Yes
#2	1F/3F	Yes	No
#2	2F/3F	Yes	Yes
#3	3F max volt.	No	No
#3	3F min volt.	No	No
#3	1F/2F/3F	Yes	Yes
#3	1F/3F	No	No
#3	2F/3F	Yes	Yes

VII. COMMENTS ABOUT CIRCUIT-BREAKER APPLICATION

As discussed in the previous section, in the occurrence of non-simultaneous faults FPSO electrical systems may be subject to severe conditions in terms of short-circuit delayed zeros. Fig. 7 and Fig. 8 show that the arcing times may extend for several cycles.

The IEC 62271-100 standard [4] does not cover generator circuit-breakers and recommends mitigation actions in applications which the percentage of the d.c. component at the earliest possible current zero is higher than the prescribed values in the standard, e.g. when short-circuit current does not have a current zero for a number of cycles.

Therefore, circuit-breakers manufactured according to this standard shall be carefully evaluated before its application in FPSO systems. The manufacturer shall be involved in this evaluation, and the following aspects shall be taken into account:

- The effect of arc resistance after the contact separation and how it can contribute to reduce the non-zero times. The arc introduces resistive damping and it will contribute to lower the d.c. current offset, thereby accelerating the occurrence of a current zero crossing;
- The implications of using additional external delay for the breakers to avoid the opening of the circuit-breaker until it is highly probable that a zero-axis crossing is occurring;
- The use of special circuit-breakers.

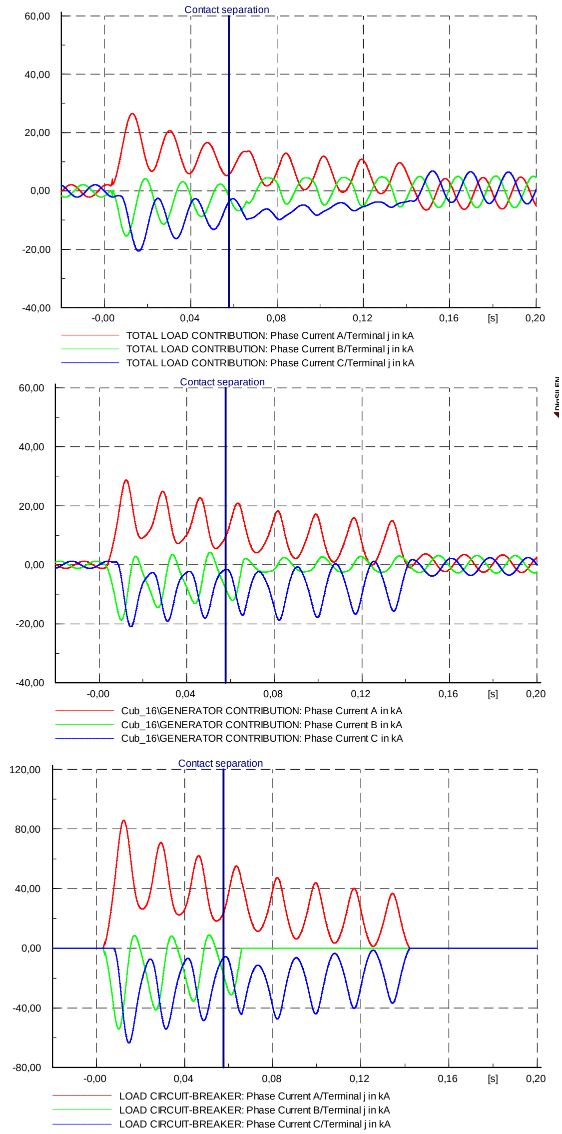

Fig. 7 – Results of simulation #10 (load CB opening)

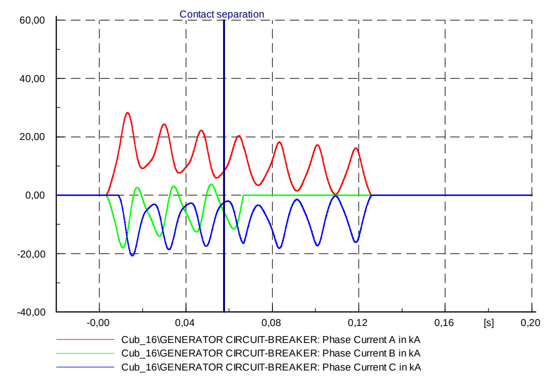

Fig. 8 – Results of simulation #15 (generator CB opening)

VIII. CONCLUSIONS

In modern FPSO power systems, short-circuits with delayed current zeros are likely to occur. This phenomenon may affect both generator and load circuit-breakers, and the worst conditions generally occur on the load circuit-breaker due the motors contribution.

Accordingly, the application of standard circuit-breakers shall be carefully evaluated and the manufacturer shall be involved in this discussion.

Special attention shall be given to both generators and motors modeling, since their electrical parameters have a significant impact in the simulation results.

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X. CURRICULA

Leonardo Hernandes was born in Neves Paulista, Brasil, in 1987. He received the B.S. degree in electrical engineering from Universidade de São Paulo, Escola de Engenharia de São Carlos, Brasil, in 2009. In 2010 he joined Figener Engenheiros Associados, Brasil, working in assessments, analyses, projects and development of studies with focus on power systems.

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