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ETAP simulation of short circuit currents in on board HV power plants

Leon Pana, Eduard Dragomir, Marius Eni

Mircea cel Batran Naval Academy
leon.pana@anmb.ro

Abstract. This paper addresses the topic of short-circuit current evaluation in on board HV power plants, focusing on the evaluation and interpretation of the calculations of these currents in ships electrical engineering. The main purpose of this research is to analyze and understand the electrical parameters involved in the event of a short circuit in on board HV power plants and to present the procedure for choosing the appropriate protective devices. We have focused on the complex calculation of these currents and on compliance with the regulations governing this procedure. The paper presents both the theoretical basis and the general structure of marine high voltage power plants, as well as a topical approach to the chosen field represented by compliance with the latest regulations on the evaluation of short-circuit currents.

1. Introduction

This paper provides fault level analysis simulations and results for 6.6 kV power plants of container ship project. This study uses the formulae, approximations and methods described in IEC 61363/1998-02 “Electrical Installations of Ships and Mobile and Fixed Offshore Units - Part 1: Procedures for Calculating Short-circuit Currents in Three Phase AC”.

The software used for this analysis is ETAP. The data used for this study and the tolerance values considered are provided at section 3.

The fault level analysis simulations are run for power plant and “with HV cable impedance”. The simulation scenarios are shown at section 3. The fault levels obtained are tabulated at section 6. This provides an assessment of the maximum potential fault currents that could be present, enabling the engineer to ensure that the making and breaking capacities of the switchgear are adequate, and providing a basis for the rating of switchboards, HV cables and other connected electrical equipment.

2. Evaluation the fault currents in on board HV power plants

For evaluation the fault currents is necessary you known the configuration of the shipboard power systems show in figure 1.

In this regard, the following calculation assumptions are made to determine the short-circuit currents [1]:

- Three-phase short-circuit current assessment is carried out to obtain fault level values at certain fault points of a shipboard power plant to ensure that the system components have adequate short-circuit current and short-circuit power capability, and to allow an appropriate choice of circuit protection equipment.
- Evaluation of short-circuit currents is carried out in accordance with the International Standard IEC 61363-1(1998-02).

- All impedances and armature resistance of the generators are given in percentage units or relative units (p.u) and for this purpose all the constants must be converted into SI units.
- If for the calculations that take into account the effects of the automatic voltage regulator and the impedance of the main bus bar systems, disconnecting switches and circuit breakers are not taken into account.
- At the same time, the time constants must be recalculated due to the impedances of the high voltage cables
- The calculation of short-circuit currents is carried out under conditions of maximum electrical loads
- Others such as assumptions and etc. which are not mentioned above shall be followed to the Standard

For the calculation of three-phase short-circuit currents based on the standard, an HV shipboard power system with the configuration shown in figure 1 will be taken into account. The calculation will be done taking into account only the on board power plant, which consists of four synchronous generators connected by means of high voltage cables to the main switchboard.

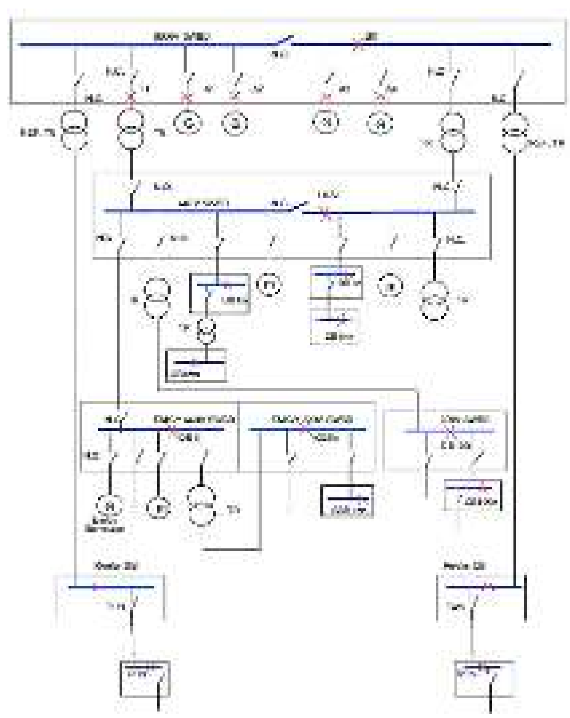

Figure 1. One-line diagram of fault level analysis

The nominal data of synchronous generators and high-voltage cables are summarized in table 1, respectively table 2.

Table 1. Synchronous generators input data

Generator data	U.M	DG1	DG2	DG3	DG4
Rated capacity S_{nG}	kVA	5800	5800	5146.7	5146.7
Rated voltage U_n	V	6600	6600	6600	6600
Frequency f	Hz	50	50	50	50

Rated current	A	507.4	507.4	450.2	450.2
Power factor cosφ		0.75	0.75	0.75	0.75
Armature resistance R_a	%	0.88	0.88	0.76	0.76
d-axis sub-transient reactance $x_d^{''}$	%	16.1	16.1	14.2	14.2
d-axis transient reactance $x_d^{'}$	%	26.5	26.5	23.9	23.9
d-axis synchronous reactance x_d	%	230	230	200	200
direct-axis sub-transient short-circuit time constant $T_d^{''}$	ms	5.4	5.4	5.7	5.7
direct-axis transient short-circuit time constant $T_d^{'}$	ms	28.2	28.2	26.56	26.56
d.c time constant T_{dc}	ms	46.7	46.7	47.7	47.7

Table 2 Input data for HV cables

Cable type		HTPYC-95	HTPYC-95	HTPYC-95	HTPYC-95
R	Ω/km	0.27	0.27	0.27	0.27
X	Ω/km	0.114	0.114	0.114	0.114
L	m	35	35	45	45
N		3	3	3	3

Since generator 1 and 2 have the same nominal data and cables, their short-circuit currents will therefore be equal. Likewise in the case of generators 3 and 4. Thus, we will divide the study of the four generators into two groups: generators 1 and 2 respectively generators 3 and 4.

- *Generators 1 and 2*

First, the reactance values and armature resistance are converted, which are given in percentage values or p.u values in absolute units:

$$\begin{aligned} R_a(p.u) &= R_a(\%)\cdot 10^{-2} = 0.0088 \\ X^{''}_d(p.u) &= X^{''}_d(\%)\cdot 10^{-2} = 10.161 \\ X^{'}_d(p.u) &= X^{'}_d(\%)\cdot 10^{-2} = 0.265 \\ X_d(p.u) &= X_d(\%)\cdot 10^{-2} = 2.3 \end{aligned} \tag{1}$$

The base impedance is calculated with the relation (2):

$$Z_b = \frac{U_n^2}{S_n} = \frac{6600^2}{5800\cdot 10^3} = 7.51\ \Omega \tag{2}$$

In the end, the values in absolute units with relations (3) result:

$$\begin{aligned} R_a(\Omega) &= R_a(p.u)\cdot Z_b = 0.066088\ \Omega \\ X^{''}_d(\Omega) &= X^{''}_d(p.u)\cdot Z_b = 1.20911\ \Omega \\ X^{'}_d(\Omega) &= X^{'}_d(p.u)\cdot Z_b = 1.99015\ \Omega \\ X_d(\Omega) &= X_d(p.u)\cdot Z_b = 17.273\ \Omega \end{aligned} \tag{3}$$

The calculation of the corrections due to the HV cables is made with relations (4)

$$
\begin{aligned}
&R=0.27\ \frac{\Omega}{km}=0.00027\ \frac{\Omega}{m}\\
&X=0.114\ \frac{\Omega}{km}=0.000114\ \frac{\Omega}{m}\\
&L=35 \rightarrow R_c=0.00027\cdot 35=0.00945\ \Omega\\
&L=35 \rightarrow X_c=0.000114\cdot 35=0.00399\ \Omega\\
&N=3 \rightarrow R=\frac{R_c}{3}=0.00315\ \Omega\\
&N=3 \rightarrow X=\frac{X_c}{3}=0.00133\ \Omega
\end{aligned}
\tag{4}
$$

- Armature resistance correction $R_{ca}=R_a+R=0.069238\ \Omega$
- Sub-transient reactance corrected $X^{"}_{cd}=X^{"}_{d}+X=1.21044\ \Omega$
- Transient reactance corrected $X^{'}_{cd}=X^{'}_{d}+X=1.99148\ \Omega$
- Synchronous reactance corrected $X_{cd}=X_d+X=17.27433\ \Omega$

The sub-transient and transient impedance of alternators including the non-active components (HV cable impedances) are given by relations (5) [1, 4]:

$$
\begin{aligned}
&Z^{"}_{e}=\sqrt{R_{ca}^{\ 2}+X^{"}_{cd}{}^{2}}=1.212418\ \Omega\\
&Z^{'}_{e}=\sqrt{R_{ca}^{\ 2}+X^{'}_{cd}{}^{2}}=1.992683\ \Omega
\end{aligned}
\tag{5}
$$

The sub-transient, transient and direct current or aperiodic time constant of alternators including the non-active components is given by the following relations (6) [1, 2]:

$$
\begin{aligned}
&T^{"}_{e}=\frac{X^{'}_{d}\cdot T^{"}_{d}\cdot (R_{ca}^{\ 2}+X^{"}_{cd}{}^{2})}{X^{"}_{d}\cdot \left[R_{ca}^{\ 2}+(X^{"}_{cd}\cdot X^{'}_{cd})\right]}=0.00540925\ s\\
&T^{'}_{e}=\frac{X_{d}\cdot T^{'}_{d}\cdot (R_{ca}^{\ 2}+X^{'}_{cd}{}^{2})}{X^{'}_{d}\cdot (R_{ca}^{\ 2}+X^{'}_{cd}\cdot X_{cd})}=0.02824682\ s\\
&T_{dce}=\frac{X^{"}_{cd}}{2\cdot \pi\cdot f\cdot R_{ca}}=0.0463733\ s
\end{aligned}
\tag{6}
$$

- *Evaluation of alternative current (symmetrical) component $I_{ac}(t)$*

  The sub-transient $E^{"}_{q0}$ and transient q-axis voltage $E^{'}_{q0}$ (r.m.s.) of a synchronous generator are given by relations (7) [2]:

$$
\begin{aligned}
&E^{"}_{q0}=\frac{U_n}{\sqrt{3}}+I_n\cdot Z^{"}_{e}=4\ 425.80445\ V\\
&E^{'}_{q0}=\frac{U_n}{\sqrt{3}}+I_n\cdot Z^{'}_{e}=4\ 821.71091\ V
\end{aligned}
\tag{7}
$$

With this values of the active voltages can evaluate the initial sub-transient, transient and steady-state short-circuit currents in the direct axis of two identical generators 1 and 2, with relations (8) [1, 2, 5]:

$$I''_{kd}=\frac{E''_{q0}}{Z''_{e}}=3\ 650.39487\ A$$
$$I'_{kd}=\frac{E'_{q0}}{Z'_{e}}=2\ 419.70796\ A \qquad (8)$$
$$I_{kd}=3\cdot I_{n}=1\ 522.2\ A$$

In finally the expression of the alternative current component of the three phase short circuit current is given by relation (9) [1, 2, 4]:

$$I_{ac}(t)=(I''_{kd}-I'_{kd})\cdot e^{\frac{-t}{T''_{e}}}+(I'_{kd}-I_{kd})\cdot e^{\frac{-t}{T'_{e}}}+I_{kd}\rightarrow I_{ac}(0)=I''_{kd}=3\ 650.39487\ A \qquad (9)$$

To find out the breaking capacity (breaking current) we have to calculate $I_{ac}(5T)$:

$$I_{ac}(0.5T)=I_{ac}(0.00833)=2454.1752\ A$$
$$I_{ac}(5T)=I_{ac}(0.083335)=1562.38\ A \qquad (10)$$

- *Calculation the direct current (unidirectional) component $i_{dc}(t)$*

$$i_{dc}(t)=\sqrt{2}\cdot(I''_{kd}-I_{n}\cdot\sin\varphi)\cdot e^{\frac{-t}{T_{dce}}}$$
$$i_{dc}(0)=4\ 688.11106\ A \qquad (11)$$
$$i_{dc}(0.5T)=3\ 917.29184\ A$$
$$i_{dc}(5T)=777.227868\ A$$

- *Calculation the peak value of a three phase short circuit current $i_p(t)$*

$$i_{p}(0)=\sqrt{2}\cdot I_{ac}(0)+I_{dc}(0)=9\ 850.53599\ A \qquad (12)$$

For evaluation the breaking capacity we need the peak short-circuit current for t=0.5T:

$$i_{p}(0.5T)=\sqrt{2}\cdot I_{ac}(0.5T)+I_{dc}(0.5T)=7\ 388.01095\ A\ \text{(making current)}$$
$$i_{p}(5T)=\sqrt{2}\cdot I_{ac}(5T)+I_{dc}(5T)=2\ 986.76129\ A \qquad (13)$$

- *Generators 3 and 4*

The reactance values and armature resistance are converted, which are given in percentage values or p.u (per units) values in absolute units (14):

$$R_{a}(p.u)=R_{a}(\%)\cdot 10^{-2}=0.0076$$
$$X''_{d}(p.u)=X''_{d}(\%)\cdot 10^{-2}=0.142$$
$$X'_{d}(p.u)=X'_{d}(\%)\cdot 10^{-2}=0.239 \qquad (14)$$
$$X_{d}(p.u)=X_{d}(\%)\cdot 10^{-2}=2$$

In this case the base impedance is given by relation (15):

$$Z_b=\frac{U_n{}^2}{S_n}=\frac{6600^2}{5146.7\cdot 10^3}=8.46367\ \Omega \tag{15}$$

The values in absolute units with relations (16) result:

$$\begin{aligned}
&R_a(\Omega)=R_a(p.u)\cdot Z_b=0.0643239\ \Omega\\
&X''_d(\Omega)=X''_d(p.u)\cdot Z_b=1.20184114\ \Omega\\
&X'_d(\Omega)=X'_d(p.u)\cdot Z_b=2.02281713\ \Omega\\
&X_d(\Omega)=X_d(p.u)\cdot Z_b=16.92734\ \Omega
\end{aligned} \tag{16}$$

The new correction of the high voltage cables are given by relations (17):

$$\begin{aligned}
&R=0.27\ \frac{\Omega}{km}=0.00027\ \frac{\Omega}{m}\\
&X=0.114\ \frac{\Omega}{km}=0.000114\ \frac{\Omega}{m}\\
&L=45\rightarrow R_c=0.00027\cdot 45=0.01215\ \Omega\\
&L=45\rightarrow X_c=0.000114\cdot 45=0.00513\ \Omega\\
&N=3\rightarrow R=\frac{R_c}{3}=0.00405\ \Omega\\
&N=3\rightarrow X=\frac{X_c}{3}=0.00171\ \Omega
\end{aligned} \tag{17}$$

- Armature resistance correction $R_{ca}=R_a+R=0.0683739\ \Omega$
- Sub-transient reactance corrected $X''_{cd}=X''_d+X=1.20195514\ \Omega$
- Transient reactance corrected $X'_{cd}=X'_d+X=2.02293113\ \Omega$
- Synchronous reactance corrected $X_{cd}=X_d+X=16.927454\ \Omega$

In this case the sub-transient Z''_e and transient impedance Z'_e of synchronous generators including the non-active components (high voltage cable impedances) are given by the relations (18):

$$\begin{aligned}
&Z''_e=\sqrt{R_{ca}{}^2+X''_{cd}{}^2}=1.20389831\ \Omega\\
&Z'_e=\sqrt{R_{ca}{}^2+X'_{cd}{}^2}=2.0240863\ \Omega
\end{aligned} \tag{18}$$

According to IEC 61363/1998-02, the following three reactance and their corresponding time constants for synchronous generators are defined as follows: direct sub-transient reactance X''_d and direct sub-transient time constant T''_d, direct transient reactance X'_d and direct transient time constant T'_d respective synchronous reactance X_d and direct current time constant.

The sub-transient, transient and direct current time constant of synchronous generators including the non-active components is given by the following relations (19):

$$T''_e = \frac{X'_d \cdot T''_d \cdot (R_{ca}^2 + X''^2_{cd})}{X''_d \cdot \left[R_{ca}^2 + (X''_{cd} \cdot X'_{cd})\right]} = 0.00539553 \text{ s}$$

$$T'_e = \frac{X_d \cdot T'_d \cdot (R_{ca}^2 + X'^2_{cd})}{X'_d \cdot (R_{ca}^2 + X'_{cd} \cdot X_{cd})} = 0.02658891 \text{ s} \quad (19)$$

$$T_{dce} = \frac{X''_{cd}}{2 \cdot \pi \cdot f \cdot R_{ca}} = 0.04663019 \text{ s}$$

Once these are recalculated taking into account the contributions of the cables, we can move on to the components that contribute directly to the peak short-circuit current:

- *Calculation of the alternative current (symmetrical) component $I_{ac}(t)$*

The active voltages E''_{q0}, E'_{q0} depend upon the nominal or rated current of synchronous generator and can be calculated using the analytical expression (20).

$$E''_{q0} = \frac{U_n}{\sqrt{3}} + I_n \cdot Z''_e = 4\,352.6185 \text{ V}$$

$$E'_{q0} = \frac{U_n}{\sqrt{3}} + I_n \cdot Z'_e = E'_{q0} = 4\,721.86721 \text{ V} \quad (20)$$

Using the values of the active voltages we can proceed to the calculation of transient, sub-transient and stationary short-circuit currents as follows (21):

$$I''_{kd} = \frac{E''_{q0}}{Z''_e} = 3\,615.437 \text{ A}$$

$$I'_{kd} = \frac{E'_{q0}}{Z'_e} = 2\,332.83888 \text{ A} \quad (21)$$

$$I_{kd} = 3 \cdot I_n = 450.2 \cdot 3 = 1\,350.6 \text{ A}$$

Knowing the values of the currents I''_{kd}, I'_{kd} and I_{kd} we can find the alternating current component using equation (22):

$$I_{ac}(t) = (I''_{kd} - I'_{kd}) \cdot e^{\frac{-t}{T''_e}} + (I'_{kd} - I_{kd}) \cdot e^{\frac{-t}{T'_e}} + I_{kd}$$

$$I_{ac}(0) = 3\,615.437 \text{ A}$$

$$I_{ac}(0.5T) = 2\,342.55747 \text{ A} \quad (22)$$

$$I_{ac}(5T) = 1\,393.36152 \text{ A } (\textit{breaking current})$$

- *Calculation the direct current (unidirectional) component $i_{dc}(t)$*

The analytical expression of a $i_{dc}(t)$ is given by (23)

$$i_{dc}(t) = \sqrt{2} \cdot (I''_{kd} - I_n \cdot \sin\varphi) \cdot e^{\frac{-t}{T_{dce}}} = 4\,692.14344 \cdot e^{\frac{-t}{0.04663019}}$$

$$i_{dc}(0) = 4\,692.14344 \text{ A}$$

$$i_{dc}(0.5T) = 4\,692.14344 \cdot 0.83640726117 = 3\,924.54284 \text{ A} \quad (23)$$

$$i_{dc}(5T) = 785.63936 \text{ A}$$

- *Calculation the peak short-circuit level $i_p(t)$*

In this case the analytical expression for $i_p(t)$ is (24):

$$i_p(0)=\sqrt{2}\cdot I_{ac}(0)+I_{dc}(0)=9\ 805.1306\ \text{A} \tag{24}$$

To evaluate the breaking characteristic we need the peak short circuit current at t=0.5T (25).

$$\begin{aligned} &i_p(0.5)=\sqrt{2}\cdot I_{ac}(0.5)+I_{dc}(0.5)=7\ 237.28592\ \text{A (making current)} \\ &i_p(5T)=\sqrt{2}\cdot I_{ac}(5T)+I_{dc}(5T)=2\ 756.14516\ \text{A} \end{aligned} \tag{25}$$

The calculation results are presented in table 3.

Table 3. Calculation results

	U.M	Generators 1 and 2 S_n=5800 kVA	Generators 3 and 4 S_n=5146.7 kVA
E''_{q0}	V	4 425.80445	4 352.6185
E'_{q0}	V	4 821.71091	4 721.86721
R_a	Ω	0.066088	0.0643239
x''_d	Ω	1.20911	1.20184114
x'_d	Ω	1.99015	2.02281713
x_d	Ω	17.273	16.92734
R	Ω	0.00315	0.00405
X	Ω	0.00133	0.00171
Z''_e	Ω	1.212418	1.20389831
Z'_e	Ω	1.992683	2.0240863
T''_e	s	0.00540925	0.00539553
T'_e	s	0.02824682	0.02658891
T_{dce}	s	0.0463733	0.04663019
I''_{kd}	A	3 650.39487	3 615.437
I'_{kd}	A	2 419.70796	2 332.83888
I_{kd}	A	1 522.2	1 350.6
$I_{ac}(0.5T)$	A	2 454.1752	2 342.55747
$i_{dc}(0.5T)$	A	3 917.29184	3 924.54284
$i_p(0.5T)$	A	7 388.01095	7 237.28592
$I_{ac}(5T)$	A	1 562.38 A	1 393.36152
$i_{dc}(5T)$	A	777.227868	785.63936
$i_p(5T)$	A	2 986.76129	2 756.14516

The most accurate assessment of the short-circuit currents is of particular importance in the correct selection of the switching equipment in the present case of the circuit breakers of the four generators. In case of circuit breakers the making capacity $I_{cm}>i_p$ and the breaking capacity $I_{cu}>I''_{kd}$.

The peak values of the short-circuit currents for all 4 generators are summarized in table 3.

Table 4. The peak values i_p of the three phase short-circuit current

Peak value	Generators 1 and 2	Generators 3 and 4	All 4 gen-sets
$i_p(0)$	9 850.53599 A	9 805.1306 A	39 311.333 A
$i_p(0.5T)$	7 388.01095 A	7 237.28592 A	29 250.5938 A
$i_p(5T)$	2 986.76129 A	2 756.14516 A	11 485.8129

3. ETAP three phase fault currents simulation

"Electrical Transient Analyzer Program" (ETAP) is an electrical network modeling and simulation software used by electrical system engineers to create an "electrical digital twin" and to analyze the dynamic regime, transient and protection of electrical distribution systems.
With the help of this program we will graphically represent the variation of the short-circuit current over time. For the exact calculation of the HV power plant, the nominal values of the generators and cables are entered, the system being represented as follows:

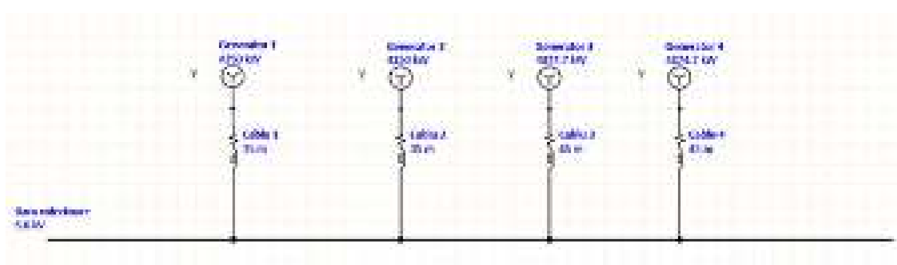

Figure 2. ETAP one-line diagram of 6.6 kV power plant

Using the "Short-circuit Analysis Module", it computationally calculates the variation of the short circuit current with the help of the software and displays its current value at the bus-bars on the right side with red color directly on the diagram as follows:

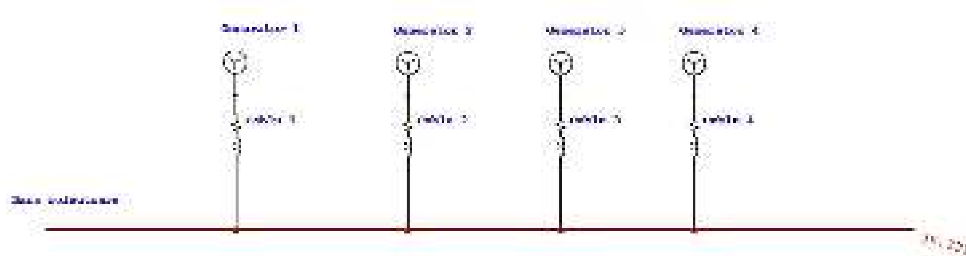

Figure 3. ETAP one-line diagram of short circuit calculation

The ETAP also plots the time variation diagrams of A.C and D.C components, total short-circuit current, and peak short-circuit current as follows:

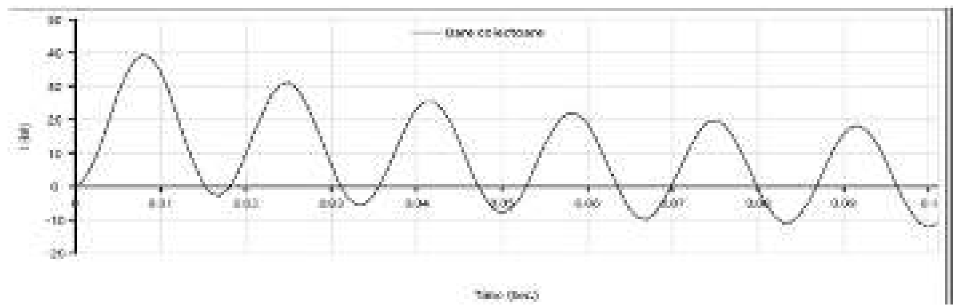

Figure 4. One-line diagram of the total short circuit current

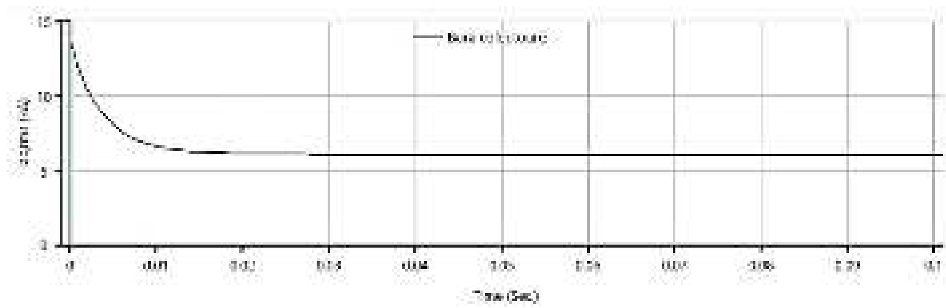

Figure 5. One-line diagram of A.C component of fault current

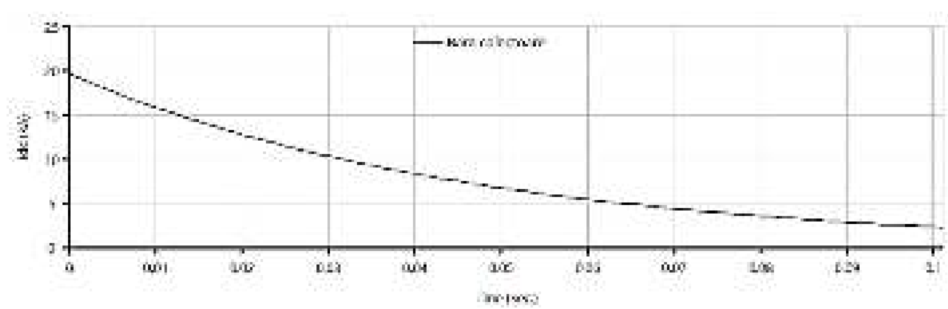

Figure 6. D.C component of fault current

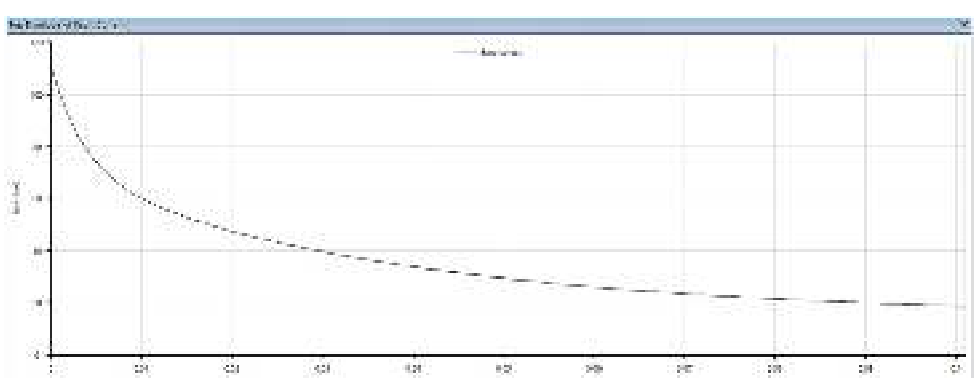

Figure 7. One-line diagram of a peak short circuit current

With the help of this graph it is possible to see how the total short-circuit current varies with time and how it stabilizes after the duration of about 5 periods. We also observe the decrease and stabilization of the alternating current component over time, the variation of the direct current component towards zero, as well as the variation of the peak short-circuit current value (top envelope).

- *Choosing the appropriate protective devices*

To choose the appropriate protective devices we need the values of the peak short-circuit current i_p at time t=0.5T for the breaking capacity and the alternating current component I_{ac} for the making capacity. Thus the circuit breakers will have the following characteristics:

For generators 1 and 2, the switches must meet the following conditions:

- making capacity $I_{cm} > 7.38$ kA
- breaking capacity $I_{cu} > 1.56$ kA

For generators 3 and 4, the switches must meet the following conditions:

- making capacity $I_{cm} > 7.23$ kA
- breaking capacity $I_{cu} > 1.39$ kA

4. Conclusions

The main purpose of the current work is the evaluation and simulation of short-circuit currents in power plants on board ships

In this sense, a 6.6 kV power plant from a container ship was considered. The power plant has in its component 4 synchronous generators of different powers located two by two on a bus-bar system sectioned by means of a circuit breaker.

The main purpose of the current work is the evaluation and simulation of short-circuit currents in power plants on board ships

In this sense, a 6.6 kV power plant from a container ship was considered. The power plant has in its component 4 synchronous generators of different powers located two by two on a bus-bar system sectioned by means of a switch.

The analysis of short circuit currents was done in two stages:

- in the first phase, the short-circuit currents were calculated manually based on the standard IEC 61363 Electrical installations of ships and mobile and fixed offshore units- Part 1: Procedures for calculating short-circuit currents in three-phase alternative current systems.
- and finally these currents were calculated with the help of the ETAP software, obtaining the same values.

The calculation was carried out taking into account the impedance of the HV cables that make the connection between the terminal terminals of the generators and the main distribution board.

The calculation was carried out taking into account the impedance of the HV cables that make the connection between the terminal of the generators and the main distribution board.

Determining the three-phase short-circuit current is of particular importance in choosing the circuit breakers of the 4 generators and obviously for the bus-tie circuit breaker.

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