Volume XXIV 2021
ISSUE no.1
MBNA Publishing House Constanta 2021

Scientific Bulletin of Naval Academy

SBNA PAPER • OPEN ACCESS

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To cite this article: L. PANA and M. D. STOCHITOIU, Scientific Bulletin of Naval Academy, Vol. XXIV 2021, pg.157-166.

Submitted: 18.03.2021
Revised: 15.06.2021
Accepted: 22.07.2021

Available online at www.anmb.ro

ISSN: 2392-8956; ISSN-L: 1454-864X

doi: 10.21279/1454-864X-21-I1-019

The influence of the deforming regime on the losses of power and energy in the electrical transformers on board the cruise ships

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Abstract. Power transformers are the basic components of a naval power system at the same time as the equipment with the most significant losses. The deforming regime is introduced by the power electronics in the case of ships of static frequency converters, cycloconverters or syncroconverters (variable speed drives) for the control of propulsion motors, etc. The central theme of this paper is the impact of the deforming regime on power and energy losses in the case of electrical transformers on board cruise ships. For this purpose, the analytical model regarding the determination of losses in transformers when operating in deforming regime is presented. In addition to the winding losses, the magnetic and dielectric circuit also includes additional losses due to the deforming regime. At the same time, an analysis was performed regarding the optimal operation management of the power transformers affected by the deforming regime.

1. Introduction

In the electrical distribution systems on board cruise ships there are mainly two types of power transformers namely:

- distribution transformers
- propulsion transformers

The distribution transformers installed in the electrical power systems on board the ships are of two types:

- with solid insulation (dry-type distribution transformer)
- with liquid insulation (oil distribution transformer)

The difference between them is given by the temperature class of the windings:

- Oil distribution transformer — winding max. temp. 105°C (Class A)
- Dry-type distribution transformer — winding max. temp. 155°C (Class F), or winding max. temp. 130°C (Class B)

Propulsion transformers are especially designed for operation with variable speed drives (inverter, frequency converter, syncroconverters and cicloconverters). The role of propulsion transformers is to adapt the converter to the electrical network and provide a galvanic isolation between variable speed drive and supply network. Propulsion transformers are available for nearly all power and voltage ratings. Secondary voltages are optimized to match the converter and propulsion motor voltage. They can be oil or dry types for indoor or outdoor use [1], [13], [14].

2. Power losses in the component of the electrical transformer

During the operation of the electric transformers in deforming regime, additional active and reactive power losses occur in their component elements [2], [4], [7], [9]:

- Power losses in windings (electrical circuits) or short-circuit operating
- Power loss in magnetic circuits (core) or no-load operating
- Power losses in dielectric

2.1. Active power losses

In this respect, the following general expression is allowed for active power losses in windings of electrical transformers, or short circuit at a certain load S, in deforming regime [5], [10], [12].

$$\Delta P_k = (1 + k_{DI}^2) \cdot k^2 \cdot \Delta P_{kn} \tag{1}$$

where:

$k = \dfrac{S}{S_{nT}}$ load coefficient (relative apparent load)

S_{nT} the apparent rated power of the transformer, in kVA

ΔP_{kn} nominal losses of active power in windings, in kW

$k_{DI} = \sqrt{\sum_{p=2}^{\infty} \dfrac{I_p^2}{I_1^2}}$ total harmonic distortion of current (THD)

p harmonic order of magnitude

Note that the sum $\left(\sum_{p=2}^{\infty} I_p^2 \right)$ operates only on significant harmonics.

For the operational evaluation of active power losses (by hysteresis and eddy currents) in the circuit of electrical transformers, or no-load, two main analytical methods are used.

Mainly, the following expression of active power losses is used in the magnetic circuit of electrical transformers or no-load:

$$\Delta P_0 = k_1 \cdot f^{1.3} \cdot B^2 = \frac{k_2 \cdot U^2}{f^{0.7}} \quad ; \quad k_2 = k_1 \cdot k_T \tag{2}$$

where:

k_1 coefficient that takes into account specific losses (at f=50 Hz and B=1T)

k_T the constant of the electrical transformer, having the expression determined by the relation between the quantities (U, B, f)

U effective supply voltage, in kV

f the frequency of the supply voltage, in Hz

B magnetic induction, in T.

In deforming regime, the active power losses at the no-load operation of the electrical transformer, will be expressed as follows:

$$\Delta P_0 = k_2 \cdot \sum_{p \geq 1} \frac{U_p^2}{f_p^{0.7}} = k_2 \cdot \left(\frac{U_1^2}{f_1^{0.7}} + \sum_{p \geq 2} \frac{U_p^2}{f_p^{0.7}} \right) \tag{3}$$

or

$$\Delta P_0 = k_2 \cdot \frac{U_1^2}{f_1^{0.7}} \cdot \left(1 + \frac{f_1^{0.7}}{U_1^2} \cdot \sum_{p \geq 2} \frac{U_p^2}{f_p^{0.7}} \right) \tag{4}$$

In the above relations it is noted as follows:

$\Delta P_{01} = k_2 \cdot \frac{U_1^2}{f_1^{0.7}}$ active power losses in the magnetic circuit or in the no-load operation of the transformer, corresponding to the fundamental harmonics, in kW

$k_{D0} = \sum_{p \geq 2} \left(\frac{1}{p} \right)^{0.7} \cdot \left(\frac{U_p}{U_1} \right)^2$ factor of supplementation of the losses of active power in the magnetic circuit of the electrical transformer, when operating in deforming regime.

In the conditions in which $f_1 = f_n$ and $U_1 = U_n$ then $\Delta P_{01} = \Delta P_{0n}$ (active nominal power losses in the magnetic circuit of electrical transformers) and, therefore, in deforming regime, we have:

$$\Delta P_0 = \Delta P_{0n} \cdot (1 + k_{D0}) \tag{5}$$

In high voltage distribution transformers, active power losses in dielectric (solid insulation and transformer oil) can become significant.

Thus, the frequencies that characterize higher order harmonics have the effect of decreasing the value of capacitive reactance. This situation involves increasing the dielectric currents.

Next, the equivalent capacity for a phase (C_T [F/phase]) is determined, respectively the active power losses in the dielectric of the electrical transformers will be expressed in analogy with the active power losses in the dielectric of a capacitor, when operating in deforming regime:

$$\Delta P_d = 3 \cdot \pi \cdot f_1 \cdot C_T \cdot \sum_{p \geq 1} p \cdot U_p^2 \cdot \tan \delta_{ep} \tag{6}$$

respectively

$$\Delta P_d = 3 \cdot \pi \cdot f_1 \cdot C_T \cdot U_1^2 \cdot \tan \delta_{e1} \left[1 + \sum_{p \geq 1} p \cdot \left(\frac{U_1}{U_p} \right)^2 \cdot \frac{\tan \delta_{ep}}{\tan \delta_{e1}} \right] \tag{7}$$

In these relations it is noted with

$\Delta P_{d1} = 3 \cdot \pi \cdot f_1 \cdot C_T \cdot U_1^2 \cdot \tan\delta_{e1}$ active power losses in dielectric, corresponding to the fundamental harmonic

$k_{Dd} = \sum_{p \geq 1} p \cdot \left(\frac{U_1}{U_p} \right)^2 \cdot \frac{\tan \delta_{ep}}{\tan \delta_{e1}}$ the factor of supplementation of the active power losses in the dielectric of the electrical transformers when operating in deforming regime

$\tan \delta_{ep}$ the equivalent of the tangent of the angle of loss (solid insulation - transformer oil) for the "p" order harmonic.

If $f_1 = f_n$ and $U_1 = U_n$ it turns out that $\Delta P_{d1} = \Delta P_{dn}$ (active nominal power losses in the dielectric of electrical transformers) and when operating in deforming mode, we have:

$$\Delta P_d = (1 + k_{Dd}) \cdot \Delta P_{dn} \tag{8}$$

2.2. Reactive power losses

In particular, the following reactive power losses occur in distribution transformers [3], [6], [11]:

- ΔQ_0 magnetic field magnetization reactive power losses equal to reactive power losses when the transformer is no-load
- ΔQ_k reactive power losses corresponding to the magnetic release field equal to the reactive power losses during short-circuit operation of the transformer

In the case of high voltage electrical transformers, the losses of reactive power in the dielectric can become significant ΔQ_D.

The analytical expression of reactive power losses by magnetization or no-load, in permanent sinusoidal regime, is:

$$\Delta Q_0 = \frac{i_0 \cdot S_{nT}}{100} = \frac{U}{U_n} \cdot \frac{f_n}{f} \cdot i_{0n} \cdot \frac{S_{nT}}{100} = \frac{U}{U_n} \cdot \frac{f_n}{f} \cdot \Delta Q_{0n} \tag{9}$$

in which:

i_0, i_{0n} are the no-load currents in (%) at the actual values of voltage and frequency (i_0) and, respectively, at rated voltage and frequency (i_{0n}).

ΔQ_{0n} the nominal value of the reactive power losses in the no-load operation of the transformer.

In case of deformed regime, at $f_1 = f_n$ and $U_1 = U_n$, the following relation results:

$$\Delta Q_0 = \left(1 + \frac{f_1}{U_1} \cdot \sum_{p \geq 2} \frac{U_p}{f_p}\right) \cdot \Delta Q_{0n} \tag{10}$$

In relation (10) it is denoted by:

$k_{DQ0} = \sum_{p \geq 2} \frac{1}{p} \cdot \frac{U_p}{f_1}$ the factor of supplementation of the reactive power losses in the no-load of the distribution transformer during the operation in deforming regime.

Finally, the analytical expression for the component (ΔQ_0) of the reactive power losses in deforming regime results, as follows:

$$\Delta Q_0 = (1 + k_{DQ0}) \cdot \Delta Q_{0n} \tag{11}$$

For to determine the reactive power losses corresponding the short-circuit operation (ΔQ_k), the expression of the reactive power losses in the equivalent reactance of short-circuit (X_k) is taken into account:

$$\Delta Q_k = X_k \cdot I^2 = 2 \cdot \pi \cdot f \cdot L_k \cdot I^2 \tag{12}$$

Therefore, for electrical transformers that have nominal reactive power losses (at f_n and S_n) of value (ΔQ_{kn}) and operate in deforming mode at a certain apparent power (S), the relation can be written:

$$\Delta Q_k = (1 + k_{DQk}) \cdot k^2 \cdot \Delta Q_{kn} \tag{13}$$

where:

$k_{DQk} = \sum_{p \geq 2} p \cdot \left(\frac{I_p}{I_1}\right)^2$ the factor of supplementation of the reactive power losses at short-circuit to the operation of the distribution transformer in deforming regime.

Reactive power losses in dielectric are calculated with the relation:

$$\Delta Q_D = (1 + k_{DQd}) \cdot \Delta Q_{D1} \tag{14}$$

where:

ΔQ_{D1} reactive power losses in the dielectric of the electrical transformer corresponding to the fundamental harmonic

$k_{DQd} = \sum_{p \geq 2} p \cdot \left(\frac{U_p}{U_1}\right)^2$ the factor of supplementation of the reactive power losses in the dielectric of the electrical transformer to the operation in deforming regime.

In nominal conditions of operation, for $f_1 = f_n$ and $U_1 = U_n$ result:

$$\Delta Q_D = (1 + k_{DQd}) \cdot \Delta Q_{Dn} \tag{15}$$

where:

ΔQ_{Dn} are the reactive power losses in dielectric corresponding to the nominal value when operating in deforming mode

In order to determine whether a transformer meets the requirements of the naval electricity network, an analysis of consumption characteristics is required.

The measurement of only the active and reactive electricity usually existing in all 11/0.44 kV distribution transformer units respective 11/1.5 kV for propulsion transformer units on board cruise ships, does not allow an assessment of the operating conditions of the transformer.

As demonstrated in this paragraph, the evaluation of energy losses during the deforming operation of a transformer is not a simple problem.

As a result, the analysis that must be done to evaluate the offers in order to purchase the electrical transformers on board the cruise ships is not simple either.

2.3. Total and additional power and energy losses of electrical transformers in deforming regime

In case a distribution transformer operating in a deforming regime and $f_1 = f_n$ and $U_1 = U_n$ respectively, at an apparent power S (momentary value) the analytical expressions of the total active and reactive power losses are:

$$\begin{aligned} \Delta P &= (1+k_{Do})\cdot \Delta P_{0n} + (1+k_{Dd})\cdot \Delta P_{Dn} + (1+k_{DI}^2)\cdot k^2 \cdot \Delta P_{kn} \\ \Delta Q &= (1+k_{DQ0})\cdot \Delta Q_{0n} + (1+k_{DQd})\cdot \Delta Q_{Dn} + (1+k_{DQk})\cdot k^2 \cdot \Delta Q_{kn} \end{aligned} \tag{16}$$

respectively active and reactive energy losses:

$$\begin{aligned} \Delta W_a &= [(1+k_{DF})\cdot \Delta P_{0n} + (1+k_{Dd})\cdot \Delta P_{Dn}]\cdot T_f + (1+k_{DI}^2)\cdot k^2 \cdot \Delta P_{kn}\cdot \tau \\ \Delta W_r &= [(1+k_{DQ0})\cdot \Delta Q_{0n} + (1+k_{DQd})\cdot \Delta Q_{Dn}]\cdot T_f + (1+k_{DQk})\cdot k^2 \cdot \Delta Q_{kn}\cdot \tau \end{aligned} \tag{17}$$

where:

T_f the duration of connection of the transformer to the network, in [h]

τ the calculation duration of the annual technological energy losses, in h/year, the value of which is determined by the relation:

$$\tau = T_{SM}\frac{10000 + T_{SM}}{27520 - T_{SM}} \tag{18}$$

where:

T_{SM} represents the duration of use of the maximum annual apparent power, expressed in h/yr.

Energy losses in a time interval (T), in which (M) values of the matrix are recorded (K, U_p, f_p, I_p) are calculated with the relation:

$$\Delta W_T = \sum_{i=1}^{M} \Delta P_{ti}\cdot \Delta t_i \quad ; \quad T = \sum_{i=1}^{M} \Delta t_i \tag{19}$$

In the deforming regime, the own technological consumption of the electric transformers depends on the variables $(K, U_p, f_p, I_p; p \geq 1)$, which have a random character and are determined on the basis of statistical-probabilistic analyses.

Another essential aspect is the one related to the management of the optimal operation regime of the electrical transformers (distribution and propulsion respectively) to the operation in deforming regime.

In the case of an electrical transformer operating in a deforming mode, the value of the load factor or coefficient changes.

The influence of the deforming regime in the case of the electric transformers on board the ships is reflected first of all on the optimal load coefficient for which a maximum efficiency result.

In order to determine the optimal load coefficient of a transformer when operating in deforming mode, two criteria are used, namely:

- the criterion of minimum power losses

- the criterion of minimum energy losses.

In the first case, the analytical expression of the optimal load coefficient based on the criterion of minimum power losses in case it is abstracted from the dielectric and reactive power losses is:

$$k_{D.ec.T} = \sqrt{\frac{(1+k_{D0})\cdot \Delta P_{0n}}{(1+k_{DI}^2)\cdot \Delta P_{kn}}} = \sqrt{\frac{(1+k_{D0})}{(1+k_{DI}^2)}}\cdot\sqrt{\frac{\Delta P_{0n}}{\Delta P_{kn}}} = C_D \cdot k_{ec.T} \tag{20}$$

In the second sense, if the criterion of the minimum energy losses in deforming regime corresponding to a transformer is applied, the analytical expression of the optimal load coefficient is:

$$k_{D.max.ec.T} = \sqrt{\frac{(1+k_{D0})\cdot \Delta P_{0n}\cdot T_f}{(1+k_{DI}^2)\cdot \Delta P_{kn}\cdot \tau}} = \sqrt{\frac{(1+k_{D0})}{(1+k_{DI}^2)}}\cdot\sqrt{\frac{\Delta P_{0n}}{\Delta P_{kn}}\cdot\frac{T_f}{\tau}} = C_D \cdot k_{max.ec.T} \tag{21}$$

where:

$k_{ec.T} = \sqrt{\frac{\Delta P_{0n}}{\Delta P_{kn}}}$ the economic load factor (with reference to the minimum power losses criterion), when operating the electrical transformers in reference mode;

$k_{max.ec.T} = \sqrt{\frac{\Delta P_{0n}\cdot T_f}{\Delta P_{kn}\cdot \tau}}$ the maximum economic load coefficient (with reference to the minimum energy losses criterion)), to the operation of the electrical transformers in reference regime;

$C_D = \sqrt{\frac{(1+k_{D0})}{(1+k_{DI}^2)}}$ the amplification coefficient of the optimum load factor in deforming regime compared to the reference regime.

The following are the calculation relationships for the optimal inefficient coefficient from which the switching between the two states (state 1 with one transformer in operation and state 2 with both transformers in operation) is required based on the two optimization criteria. In practice, there is the problem of connecting or disconnecting a distribution or propulsion transformer.

In this case the optimal load coefficients corresponding to the two criteria are determined by the relations:

$$k_{D.ec.T12} = \sqrt{\frac{(1+k_{D0})}{(1+k_{DI}^2)}}\cdot\sqrt{\frac{2\cdot \Delta P_{0n}}{\Delta P_{kn}}} = C_D \cdot k_{ec.T12} \tag{22}$$

and

$$k_{D.max.ec.T12} = \sqrt{\frac{(1+k_{D0})}{(1+k_{DI}^2)}}\cdot\sqrt{\frac{2\cdot \Delta P_{0n}}{\Delta P_{kn}}\cdot\frac{T_f}{\tau}} = C_D \cdot k_{max.ec.T12} \tag{23}$$

where:

$k_{.ec.T12} = \sqrt{\frac{2\cdot \Delta P_{0n}}{\Delta P_{kn}}}$ the optimal load coefficient corresponding to the minimum power losses when operating two transformers in normal operation in parallel

$k_{max.ec.T12} = \sqrt{\frac{2\cdot \Delta P_{0n}}{\Delta P_{kn}}\cdot\frac{T_f}{\tau}}$ the optimal load coefficient corresponding to the minimum energy losses when operating two transformers in normal operation in parallel

This operating regime for which the efficiency reaches the maximum value is called optimal or economic regime.

3. Case studies analyzed

The algorithm proposed in this paper will be further exemplified in the electrical distribution and propulsion transformers in the structure of the electrical networks of cruise ships having the configurations presented in Figure 1 and Figure 2.

Figure 1 shows the electrical diagram of the power system typical of cruise ships. Next, the analysis of the normal operation regime of the two identical transformers of 11/0.44 kV (evaluation of the optimal load coefficients) will be made with reference to two states:

- state 1 a transformer in operation
- state 2 both transformers in operation

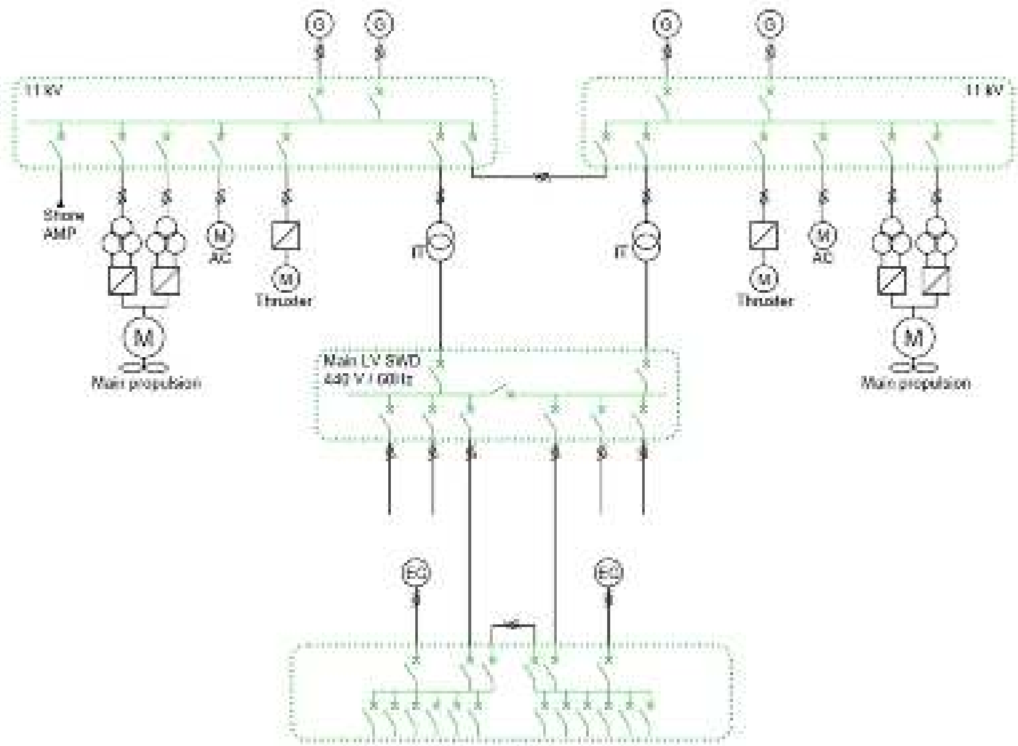

Figure 1. 11 kV network diagram with redundancy in the case of distribution transformers

Next, an analysis of the distribution transformers from the diagram in Figure 1 will be made, having the nominal data summarized in Table1.

Table 1 Input data of distribution transformers and results obtained

S_{nT} [kVA]	U_1/U_2 [kV/kV]	ΔP_{0n} [kW]	ΔP_{kn} [kW] θ_{max}=75°C	ΔP_{kn} [kW] θ_{max}=120°C	i_0 [%]	u_k [%]	$k_{ec.T}$	$k_{ec.T12}$
1600	11/0.44	2.8	12.3	14	1.2	6	0.47	0.67
							0.44	0.63
2000	11/0.44	3.5	14.9	17	1.1	6	0.48	0.68
							0.45	0.64
2500	11/0.44	4.3	18.3	21	1	6	0.48	0.68
							0.45	0.63
3150	11/0.44	5.2	21.8	25	1	6	0.48	0.69
							0.45	0.69

ABB presents a wide range of transformers used in electrical networks on board ships. In general, the transformers used for electricity distribution are transformers with two-winding AN cooling systems. They are intended to supply consumers on board for example pumps, fans, winches and other electrical installations on board.

In this configuration, own to a contingency of any equipment allows the propulsion systems to be, at least, at the 50% of the power required in normal condition, as requested by the standard rules.

Analyzing the network diagram illustrated in Figure 2, results that two levels of voltage are identified: the first level is High Voltage (i.e. 11 kV), and the second level is Low Voltages (i.e. 440 V, 230 V and 115 V at 60 Hz) [8].

Concerning the 11 kV distribution the following equipment have been implemented in the model analysis (Figure 2):

- The ship power plant consists of six synchronous generators (DG) with powers of 12.6 MW the loads being balanced equally on two distribution boards.
- The propulsion system consists of the two synchronous propulsion motors each with a nominal power of 21 MW, the propulsion transformers and variable frequency drive (in this case the (synchro-converters) each connected to a main panel.
- Six thrusters, with rated power of 1720 kW each, three of them are bow thrusters while the remaining are stern thrusters. All six thrusters are equally divided between the sections of main switchboards.
- Four compressors of air conditioning system, with rated powers of 1575 kW each, equally divided between the section of main switchboards
- Five distribution transformers of 11/0.44 kV with rated powers of 4200 kVA, 1763 kVA, 2300 kVA and 4380 kVA
- Four 11/1.5 kV propulsion transformers with a rated power of 13433 kVA

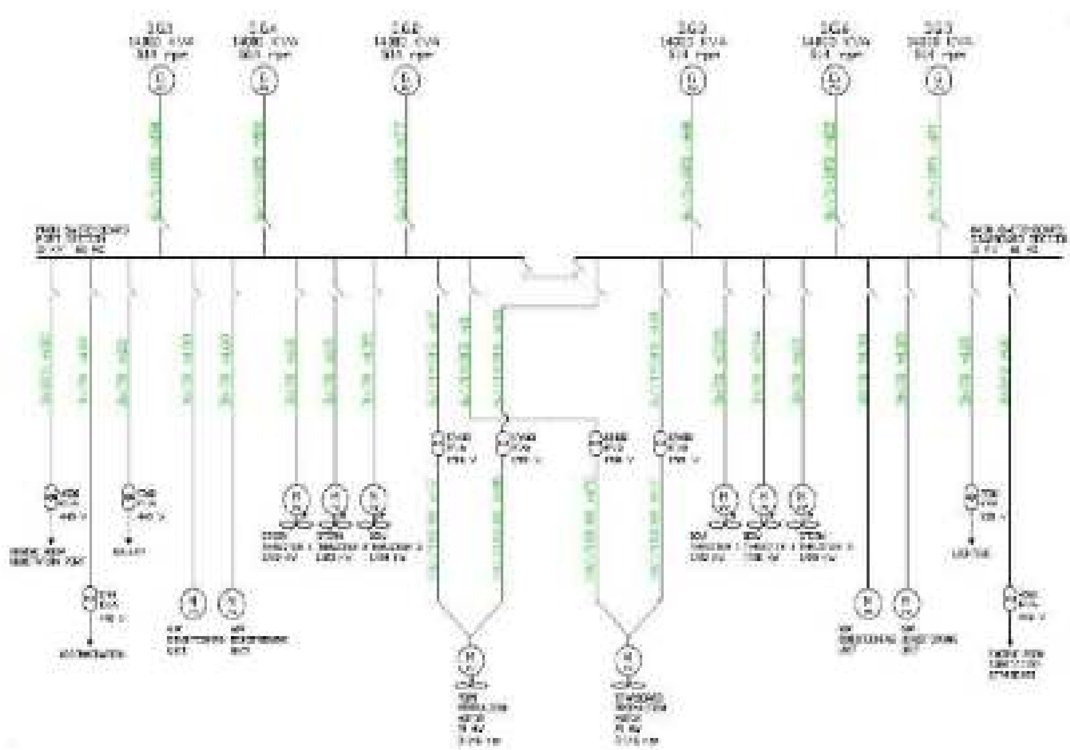

Figure 2. 11 kV network diagram with redundancy in the case of propulsion transformers

The deforming regime is introduced in the shipboard system in general by power electronics. As the vast majority of on-board electrical installations are controlled by variable frequency drive, there is the problem of an in-depth analysis of the influence of the deforming regime on the operation of electrical transformers.

Next is the analysis of the deforming regime in the case of the propulsion system having the configuration presented in Figure 2

The RMS values (on the three phases) of the quantities (U_p, f_p) are:

$$\begin{aligned} U_p &= [0.18; 0.11; 0.1; 0.08] \cdot U_1 \\ I_p &= [0.18; 0.1; 0.066; 0.06] \cdot I_1 \end{aligned} \tag{24}$$

In Table 2 shows the results obtained based on the calculation algorithm presented for the propulsion transformers in Figure 2.

The power losses in the dielectric of the transformers when operating in deforming mode will be neglected.

Table 2. Input data for propulsion transformers and result obtained

S_{nT} [kVA]	ΔP_{0n} [kW]	ΔP_{kn} [kW]	k_{DI}^2	k_{D0}	C_D	$k_{ec.T}$	$k_{D.ec.T}$	$k_{D.ec.T12}$	$k_{ec.T12}$
13433 11/1.5 kV	140	505	0.065	0.021	0.95	0.52	0.50	0.70	0.74

The presence of harmonics in the electrical networks on board ships causes, among other things, unpleasant effects, such as:

- Additional losses that cause unacceptable heating in power plants, such as: synchronous generators in the naval power plant
- Oscillating torques in induction motors
- The size of losses in electrical distribution systems
- Electrical cable insulation requirements
- Incorrect operation of protection and automation equipment in on-board electrical networks that do not register switching commands or that switch without order

4. Conclusions

When developing the calculation algorithm, we started from the premise that one of the keys to efficient energy use is energy saving and, in context, the precise determination of energy losses.

The operation of distribution and propulsion transformers in deforming regime implies the appearance of additional power losses that affect their efficiency, thermal regime and reliability.

In this paper, the problem of analytical evaluation of active and reactive power losses in the components and assembly of the electrical transformer was elucidated.

The analytical calculation expressions for the active and reactive power losses in the transformer windings, the magnetic circuit and in their dielectric were deduced, highlighting the additional power losses in case of operation of the electric transformers in deforming regime.

The coefficients of supplementation of the power losses in the deforming regime with respect to the sinusoidal reference regime were also defined and expressed analytically. The algorithm elaborated allows the correct determination of the own technological consumption, of the electric transformer in deforming regime.

In addition to the precise evaluation of power and energy losses in electrical transformers operating in deforming mode, highlighting the input variables makes it possible to adequately address some aspects of optimization specific to the operating modes of electrical transformers. In this sense, the expressions of the load factor for which the operating efficiency of the electrical transformer is maximum are presented.

Knowing these values allows the proper operation in the operation of electrical substations and distribution of electricity, in order to optimize the operating regime of the electrical transformer, by applying the criterion "minimum power loss or minimum energy loss".

With reference to the case study analyzed in the end, it can be stated:

- Distribution transformers in a pronounced deforming regime caused, especially, by the variable frequency drive of propulsion system;
- Active losses of additional powers in deforming regime represent 3.5% of the active losses of total powers in reference regime;
- Additional energy losses in deforming regime represent 7.5% of the total losses in reference regime;
- Applying the optimization criterion "minimum power or energy losses" (maximum efficiency) the following mode of operation is justified:
    - both electrical transformers - at sea cruising at full speed;
    - an electrical transformer - maneuvering in and out of port;

In order to limit the negative influences of the deforming regime and to comply with certain permissible limits, both international fora have developed rules and directives that harmonic generating installations must meet in order to be used in electrical distribution networks on board ships.

In some cases, in order to reduce the level of harmonics, the electrical installations of the consumers on board may be supplied with a higher voltage.

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