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ELECTRIC ENERGY LOSSES IN SHIP'S POWER CABLE SYSTEMS

SUMMARY

The article describes the reasons for electrical energy losses during the process of energy transmission from the power source to receivers in ship's network. The results of analytic calculations show that there are new possibilities of energy transmission cost savings resulting from diversification of cable diameters.

Introduction

The electric energy transmission from the place of its generation to the place where it is consumed (change of energy form) is carried out through the so called power line consisting of an associated system of conductors, coils and similar elements. The line consists of elements of generators, energy conversion units, cables, switchboards and receivers. The direction of each line is determined by the direction of energy flow.

Electric energy is dissipated in form of heat in all elements of the electric energy transmission chain (along the whole power line). This part of energy dissipates in form of heat which is often useless in this place and sometimes even harmful and is defined as energy losses. Only in electric heaters the losses are utilized.

In accordance with the electron theory the energy losses in conductor are caused by friction of free electrons displacing under the influence of voltage acting on them in spaces inside and between atoms. A similar situation occurs in gases where electric current is possible only in case of ionization and has the form of electric arc. Also in this case dissipated heat results from friction between the flux of iones and electrons.

Two different types of losses are distinguished in permanent insulation (generally described as dielectric losses):

- active leakage conductance (of through and surface type) only different from quantity point of view from the current passing through the conductor;resistance is many times higher thus the current and losses are appropriately lower;
- dielectric hysteresis, i.e. heat dissipated when a dielectric is electrified when surmounting a number of internal forces (structural, intermolecular etc).

The source of losses in magnetic circuits and in structural elements has two reasons. In metal parts losses are caused by induced currents, including vortex currents (due to movement of electrons). On the other hand in steel parts losses are related to the shifting of magnetic hysteresis where shifting of iron crystals towards variable magnetic field is caused by magnetization.

The resistance occuring in the network results in voltage drops as well as voltage, energy and power losses. Voltage drop is defined as the difference of root-mean-square voltage values between two points of network. The value depends on the current value and resistance. In result of voltage drops different voltage values can be measured in various points of the network. Most often voltage close to the energy source is higher than in a distant place. Consumers are designed for rated voltage and their efficiency is the highest at this voltage. Of course, work at different voltage is permissible, however it is less effective. E.g., the luminous flux of a light bulb is directly proportional to the 4th exponent of voltage. This means a small change in voltage results in an important change of lumious flux. On the other hand higher voltage rapidly decreases the bulb life which is inversely proportional to the 14th exponent of voltage. Thus both the increase and decrease of voltage have a detrimental influence on the operation of the equipment.

In case of induction motors for which the torque depends on voltage square it may happen that the anti-torque exceeds the torque resulting in stall. In case of some types of motors there is a risk of stall already at a voltage drop of 10-15%.

Voltage loss is closely connected with the voltage drop. It is described as the geometric difference between voltage vectors in two different points of network. The longitudinal component of voltage vector does not differ much from voltage drop while the transverse component is negligible (does not exceed 20% of the rated voltage) [3].

Ship's power network

Due to easy servicing and simple construction as well as low costs the most often used system of energy distribution is the central distribution system. A multi switchboard system ensures high flexibility and reliability of electric energy supply. The system has been applied only on large naval vessels. The most often used solution on merchant ships is a radial network with one main switchboard. The main advantage of such a system is just the possibility of central distribution of energy.

During designing many calculations related to voltage propagation, voltage drops and cable heating are carried out. Cables chosen with consideration of heating have lower voltage drops than limits determined by classification society rules. This results from relatively short distance between electric energy source and consumer. Designers are choosing conductor diameters calculating voltage drops in the longest and most highly loaded sections.

Energy losses

Calculations and choice of conductors using the above mentioned method have been applied for many years and will probably still continue to be used in the future. As it was proven in practice the method is absolutely safe giving an appropriate safety margin in operation. However it is worth to analyse the problem from the energy transmission economy point of view.

The aim of classical methods is to try to minimize the amount of copper using criterions settled by the rules of classification societies. Calculations are obvious: economizing copper the weight and cost of cables are minimized.

However this is a static point of view determining the initial condition of ship's operation. In fact one should analyse the situation after a certain time, say after one year. This could allow to determine a different type of losses, namely losses of active and reactive power and in consequence energy losses. A different possibility arises here: to diminish power losses (i.e. also energy losses) through the increase of cable diameters and to relate the initial investment to gains from energy savings. This can be judged by the calculation of pay back period.

Active power losses are caused by resistance in network and changed into heat in accordance with the Joule's law. This results in warming up network elements and compels to such a choice that the temperature does not exceed the limit and the voltage at the end of the circuit is not lower than permissible. Reactive power losses result in inductance of transformer conductors. This lowers the power factor of network that means the real current increase without increase of transmitted power.

The above mentioned losses are generally named as longitudinal due to the character of their occurence along the cable line, transformer coils. There are also transverse losses caused by leakage conductance, i.e. by the current passing through insulation. The reason for such a phenomenon is the ionization of gas bubbles inside the imperfect structure of the dielectric. The losses depend on voltage and not on working current. However, the above mentioned losses are small comparing with the longitudinal losses and thus will not be considered further in this paper. Also power losses in transformers will not be considered. The paper concentrates mainly on power losses in cable lines. On the other hand detailed consideration of signalled losses exceeds the framework of this paper.

Generally the losses of active power can be calculated in three phase circuit from the formula:

$$\Delta P = 3\, I^2 R \tag{1}$$

assuming symmetry of the lines. In practice the formula for consumer concentrated at the end is applied:

$$\Delta P = \frac{\sqrt{3}\, I\, \Delta U_{AB}}{\cos\varphi} \tag{2}$$

This means to calculate power losses the current I and voltage drop ΔU_{AB} should be measured and power factor should be known. The approximate value of power factor is known (1.0 for lighting and heaters and 0.8 for inductive motors).

Knowing the power losses one can easily calculate the yearly energy losses. The formula considering all the usual load and loss conditions is as follows:

$$\Delta A = \int_0^{8760} \Delta P\, dt \tag{3}$$

where ΔA means energy losses and ΔP means power losses.

According to [5] one can differentiate the following service conditions:

-sea voyage,
-stay in port,
-cargo handling,
-manoeuvres,
-emergency.

Of course some simplifications can be applied in the calculation of losses. For example the emergency condition can be ignored and the stay in port integrated with cargo handling. Because of the large power discrepancy between consumers installed on board as well as different work duration it is indispensable to determine for each consumer the following probabilities:

- p_p - probability of load in the given service condition,
- p_t - probability of work time in the given service condition.

Having prepared the data it is possible to solve the integral (3) and calculate the losses as follows:

$$\Delta A = \Delta P \cdot p_p \cdot t_{cal} \cdot p_t \cdot t \tag{4}$$

where:

t_{cal} – time period considerd in calculation (year-8760 hours);
t – relative operation time in the given service condition.

The relative operation time has been taken from [1]. The publication gives quite detailed operation times for particular types of ships.

Having the data it is possible to carry out calculation of losses. Computer software described in [2] can be applied for this purpose. In other case it is possible to define a separate simple spreadsheet.

The below given results of calculation of electric energy losses made for two different cross section areas of conductors shall inform about the extensive analytic research work carried out by the Department of Ship's Electrical Power Engineering at the Merchant Marine Academy in Gdynia.

1. Profitability of increased cable cross section area (for consumers exceeding 3000 kWh)

Existing cable	Yearly energy losses	Planned cable	New energy losses	Profit	Investment in new cables	Pay back period	Consumer
–	[kWh]	–	[kWh]	[USD]	[USD]	[years]	
1x(3x70.0)	3629.2	1x(3x95.0)	2670.1	57.5	191.1	3.321	ME sw pump
1x(3x35.0)	3767.5	1x(3x50.0)	2644.0	67.4	123.5	1.832	ME crosshead LO pump
1x(3x70.0)	3580.0	1x(3x95.0)	2634.6	56.8	191.1	3.366	Fan supply swbd
1x(3x6.0)	3035.8	1x(3x10.0)	1818.7	73.0	41.2	0.564	Fans
2x(3x70.0)	4056.3	2x(3x95.0)	2984.3	64.3	83.8	1.303	Transformer No 1
3x(3x70.0)	4450.4	3x(3x95.0)	3274.2	70.6	187.8	2.661	Air cond.swbd
1x(3x95.0)	3918.6	3x(3x120.0)	3119.7	47.9	176.9	3.691	Air cond.swbd
1x(3x70.0)	4702.7	1x(3x95.0)	3450.9	74.6	164.3	2.203	Ventilation swbd
1x(3x6.0)	3173.7	1x(3x10.0)	1901.3	76.3	43.0	0.564	ER exhaust vent.
1x(3x25.0)	3993.9	1x(3x35.0)	2845.5	68.9	81.1	1.176	Contr.air compr.
3x(3x95.0)	6640.8	3x(3x120.0)	5286.8	81.2	86.6	1.066	Transformer No 2
7x(3x95.0)	33014.8	7x(3x120.0)	26283.6	403.9	120.5	0.298	Generator No 1
8x(3x95.0)	67760.7	8x(3x120.0)	53945.4	828.9	297.4	0.359	Invertor

Total electric energy losses	245956.5 [kWh]
Total electric energy losses for new cables	213099.1 [kWh]
Total profit	32857.3 [kWh]

Summary

Data used for calculation have been taken from the technical documentation of a 150000 dwt bulk carrier and from the catalogue of products of the Bydgoszcz Cable Factory. The cost of generation of 1 kWh on this type of vessel has been assumed at the level of USD 0.06. Cable prices dating from 10th May 1993 have been recalculated into USD basing on rate of exchange of June 1993 equal to about 17000 PZL/1 USD.

It resulted from the calculation that the total electric energy losses on the vessel (three phase power receivers) amounted to 245956.5 kWh. After installation of increased cross section area cables the losses calculated only for consumers giving yearly losses exceeding 3000 kWh, the number of which is 13, amounted to 32857.3 kWh, i.e. 1/8 of yearly losses. If more consumers are chosen higher savings can be expected. In the investigated cases the pay back period does not exceed 4 years whicht can be judged profitable considering 25-30 years of ship's life.

Of course the problem should not be analysed one-sidedly. When specifying larger cross sectional area cables the problem of cable laying should be considered. Bending radiuses and diameters of compensation loops in hull dilatancy gaps have to be increased. However this question exceeds the scope of this paper.

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