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# Greening elements in the distribution networks

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***Abstract:*** Due to climate change and the increase in environmental awareness in the world, the concept of Green Supply Chain Management appeared. The concept is aimed at the reduction of several elements: energy, materials, the pollution and the waste in production and logistics processes. Power networks are a part of a supply chain of production and distribution of electrical energy, and similar principles of greening could be applied. Currently, the losses within the distribution networks in the whole world are between 3.7 to 26.7 % and they primarily occur due to the losses in the conductors and the losses within distribution transformers. After an overview of the losses in the power networks and related $CO_2$ emission, some solution of how to reduce the above mentioned losses are given. Such improvements, apart from the significant economic repercussions, in the same time represent non-negligible greening element in the area of electrical energy distribution.

***Keywords:*** greening, power networks, CO2 emission

## 1 Introduction

Nowadays, the increase in greenhouse gas (GHG) emissions in the atmosphere is currently one of the most serious environmental treats. Due to GHG emissions we will be witnesses of climate change which will cause damaging impacts in the next few decades (Psomopoulos, Skoula, Karras, Chatzimpiros, & Chionidis, 2010). These will primarily affect the natural and human systems (Houghton, Jenkins, &

Ephraums, 1990). At the same time these emissions are also a limiting factor for the economical growth of some countries, especially those which are going through the transition process (Psomopoulos, Skoula, Karras, Chatzimpiros, & Chionidis, 2010; *Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel of Climate Change*; Liu, 2007). One of the reasons for that is the Kyoto protocol, adopted in December 1997 at The Third Conference of Parties (COP-3) in Kyoto, at which the industrial world agreed to reduce the emissions of greenhouse gases approximately 6 to 8 % below 1990 levels by 2008–2012 (*Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel of Climate Change*).

In the meantime, also due to the climate change and the increase in environmental awareness all over the world, the concept of Green Supply Chain Management appeared. It is often defined as integrating environmental thinking into supply chain management (Srivastara, 2007). Within that concept many greening elements aimed at the reduction of materials, energy, waste, pollution and emissions, or promoting the usage of recyclable materials and renewable energy sources are introduced in various segments of supply chains (Opetuk, Dukic, & Radic, 2009). Power networks are a part of the supply chain of production and distribution of electrical energy, and the principles of greening supply chains could also be applied. In the next chapter, an overview of the losses in the power networks of the EU and Croatia has been given, followed by a proposition of some possible technological improvements to reduce the losses, which represent at the same time the implementation of some important greening elements in this field.

## 2 Losses in power networks

The losses in power networks can be divided in two major groups. The first one refers to the losses in transmission networks and the second refers to the losses in distribution networks. In this paper, authors focus on the losses within the distribution networks because of significantly high losses in that part of power networks, with amount of 1279 TWh worldwide, according to (Belmans et al., 2005). They vary from 3.7 % to 26.7 % of the electricity used (Belmans et al., 2005). The losses within the distribution networks in the EU 27 are 6.67 % while the losses in EU 15 are 6.33 % of energy used (Psomopoulos, Skoula, Karras, Chatzimpiros, & Chionidis, 2010). By switching to high efficiency transformers, the worldwide electricity savings potential is estimated to be to be at least 200 TWh (Belmans et al., 2005).

Figure 1 shows the loss components in the European power networks which consist of transmission and distribution networks. Losses in transformers account for 45 % of total losses, with 25 % are attributed to distribution transformers. Authors of this paper will present the ways how to reduce losses in that part of the network.

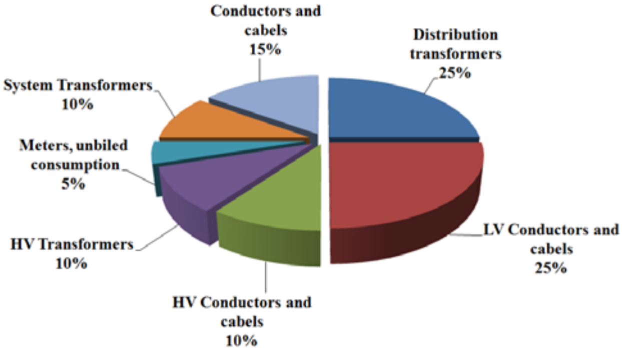

Figure 1. “Power transmission and distribution loss components in European Networks”. Source: Psomopoulos, Skoula, Karras, Chatzimpiros & Chionidis (2010).

## 2.1 Losses in Croatian power networks

According to the annual reports of the Croatian Electricity Company (HEP Group), the losses in the Croatian power networks are shown in Table 1.

| | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
| The amount of power transport in transmission network [GWh] | 14831 | 15527 | 16095 | 16706.9 | 17178 | 17626 | 17996 |
| Power losses in transmission network [%] | 4.51 | 4.25 | 3.65 | 3.35 | 3.17 | 3.10 | 2.69 |
| Power losses in transmission network [GWh] | 669 | 660 | 586.7 | 560.4 | 544 | 547 | 484 |
| The amount of power transport in distribution networks [GWh] | 14022 | 14737 | 15328.7 | 15942.4 | 16423.3 | 16810.7 | 16958.3 |
| Power losses in distribution networks [%] | 10.03 | 12.78 | 10.68 | 9.85 | 8.31 | 9.83 | 7.21 |
| Power losses in distribution networks [GWh] | 1406 | 1883 | 1637 | 1570 | 1365 | 1652 | 1223 |
| Total transport power losses [%] | 14.54 | 17.03 | 14.33 | 13.20 | 11.48 | 12.93 | 9.90 |
| Total transport power losses [GWh] | 2075 | 2543 | 2224 | 2130 | 1909 | 2199 | 1707 |

Table 1. “Losses in Croatian power networks”. Source: *HEP d.d. annual reports; HEP ODS d.o.o. annual reports; HEP OPS d.o.o. annual reports*

Authors of this paper estimate that the losses in distribution transformers are 330.77 GWh for 2008, using calculation tool in (Irrek, Topalis, Targosz, Rialhe, & Endesa 2008). That means that the power losses in distribution transformers make approximately 19.38 % of the total transport power losses, or 27.04 % of the losses within the transfer energy in distribution networks.

## 2.2 CO2 emission in Croatian energy production

The Croatian energy production is mainly based on 2 main types of power plants: thermal power plants and hydroelectric power plants, with 1601 MW installed power in thermal power plants and 2071.26 MW in hydroelectric power plants. Additionally, 348 MW (50 % of the total installed power) is in The Krsko Nuclear Power Plant which is a joint venture with Slovenia (*Croatian Electric Power System*). However, recently some small amount of energy is produced in wind power plants.

Fig. 2 shows the structure of fuel used in the thermal power plants. The amount of $CO_2$ emission per kWh varies from year to year (from 304.41 $gCO_2$/kWh to 426.63 $gCO_2$/kWh), primarily due to the amount of energy generated in hydroelectric power plant, as shown in Table 2. In 2008 emission was 356.27 $gCO_2$/kWh, similar to average emission of 361.65 $gCO_2$/kWh for total produced energy in analyzed 7 years.

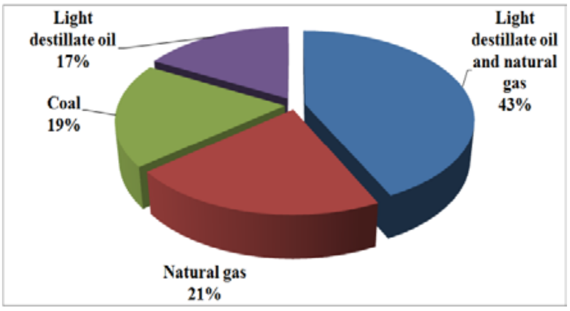

Figure 2. “Fuel used in thermal power plants”. Source: *Croatian Electric Power System*

| Year | | Technology | | | | Sum |
|---|---|---|---|---|---|---|
| | | Termal power plants | Hydroelectric power plants | Nuclear power plants | Wind power plants | |
| 2002 | [MWh] | 5372 | 5899 | 0 | 0 | 11271 |
| | [%] | 47,66% | 52,34% | 0,00% | 0,00% | |
| | [gCO2/kWh] | 830,6 | 12 | 16 | 10 | 402,14 |
| 2003 | [MWh] | 6703 | 4897 | 1623 | 0 | 13223 |
| | [%] | 50,69% | 37,03% | 12,27% | 0,00% | |
| | [gCO2/kWh] | 816,9 | 12 | 66 | 10 | 426,63 |
| 2004 | [MWh] | 5388 | 7001 | 2606 | 0,8 | 14995,8 |
| | [%] | 35,93% | 46,69% | 17,38% | 0,01% | |
| | [gCO2/kWh] | 799,7 | 12 | 66 | 10 | 304,41 |
| 2005 | [MWh] | 5150 | 6388 | 2807 | 9,5 | 14354,5 |
| | [%] | 35,88% | 44,50% | 19,55% | 0,07% | |
| | [gCO2/kWh] | 840 | 12 | 66 | 10 | 319,64 |
| 2006 | [MWh] | 5435 | 6070 | 2645 | 19,1 | 14169,1 |
| | [%] | 38,36% | 42,84% | 18,67% | 0,13% | |
| | [gCO2/kWh] | 819,5 | 12 | 66 | 10 | 331,84 |
| 2007 | [MWh] | 6845 | 4357 | 2714 | 34,9 | 13950,9 |
| | [%] | 49,06% | 31,23% | 19,45% | 0,25% | |
| | [gCO2/kWh] | 797,7 | 12 | 66 | 10 | 407,96 |
| 2008 | [MWh] | 6075 | 5277 | 2986 | 40 | 14378 |
| | [%] | 42,25% | 36,70% | 20,77% | 0,28% | |
| | [gCO2/kWh] | 800,3 | 12 | 66 | 10 | 356,27 |

Table 2. “$CO_2$ emission in Croatian energy production”. Source: *HEP d.d. annual reports*; Sovacool (2008)

## 3 Losses in transformers

There are two main components of the transformer losses: no-load losses and load losses. The third component is cooling loss, caused by power consumption of fan, therefore occurring only in transformers with fan cooling. The higher no-load and load losses, the more cooling is needed, which consequently creates higher cooling losses (Belmans et al., 2005).

### 3.1 No-load losses

No-load losses ($P_0$), sometimes called core losses or iron losses are present whenever the transformer is energized, independently of the load, creating constant energy dissipation. For example, annual losses of 1600 kVA transformer with $P_0$ = 2600 W are 22.8 MWh (2600 W x 8760 hrs). Over the period of 30 years, it means energy loss of 684 MWh or total emission of 274 tones of $CO_2$ (0.4 kg $CO_2$/kWh). These losses are mainly caused by hysteresis and eddy current in the core, due to successively reversed magnetization (Belmans et al., 2005).

- Eddy current losses are caused by varying magnetic fields inducing eddy currents in the laminations and thus generating heat. They usually account for 30 to 50 % of total no-load losses (*Polish Cooper Promotion Center and European Copper Institute*).

The amount of losses caused by eddy current is equal to:

$$P_e = \frac{1{,}65 f^2 B_m^2 t^2}{\rho d} m = \sigma_e (f B_m t)^2 m$$

Equation 1. “The amount of losses caused by eddy current”. Source: Karsai, Kerényi, & Kiss (1987)

where:

- $P_e$ is the eddy-current loss in W
- $F$ is the frequency in Hz
- $B_m$ is the peak value of the flux density in T
- $t$ is the thickness of the individual steel lamination sheets in m
- $\rho$ is the specific resistance of the sheet material in Ωm
- $d$ is its density in kg $m^{-3}$ and
- $m$ is mass of the iron core in kg

- Hysteresis losses, caused by the frictional movement of magnetic domains in the core that is magnetized and demagnetized by alternation of the magnetic field. These losses depend on the type of material used to build a core and they are responsible for more than a half of total no-load losses (~50 % to ~70 %) (*Polish Cooper Promotion Center and European Copper Institute*).

The amount of hysteresis losses is equal to:

$$P_h = \sigma_h f B_m^n m,$$

Equation 2. “Amount of hysteresis losses”. Source: Karsai, Kerényi, & Kiss (1987)

where:

- $P_h$ is the hysteresis loss in W
- $f$ is the frequency in Hz
- $B_m$ is the peak value of flux density in T
- $n$ is the Steinmetz exponent
- $m$ is the mass of the iron core in kg and
- the values of $\sigma_h$ vary in the range of $3\text{x}10^{-3}$ to $20\text{x}10^{-3}$

About 1 % of total no-load losses are marginal stray and dielectric losses which occur in the transformer core (*Polish Cooper Promotion Center and European Copper Institute*).

### 3.2 Load losses

Load losses, sometimes called short circuit losses or copper losses, are caused by the resistive losses in the windings and leads. Load losses vary according to the transformer loading with the square of the load current (Belmans et al., 2005). They consist of two components: ohmic heat loss and conductor eddy current losses.

- Ohmic heat loss or copper loss occurs in the transformer windings and is caused by the resistance of the conductor. It varies with the square of the load current and is proportional to the resistance of the winding.
- Conductor eddy current losses occur due to magnetic fields caused by alternating current (*Polish Cooper Promotion Center and European Copper Institute*).

### 3.3 Extra losses

*Losses due to harmonics*

These losses are caused by non-linear loads, such as power electronic devices, computers, UPS systems, TV sets. These devices cause harmonic currents on the network. They increase both load and no-load losses due to increased skin effect, eddy current and hysteresis losses. The most important and the biggest of these losses are the ones caused by eddy current losses in the winding**.** The transformer that is heavily loaded with harmonic currents can have a shorter life span and it can be damaged (*Polish Cooper Promotion Center and European Copper Institute*).

*Losses resulting from the deviation of magnetic field from the direction of rolling (Karsai, Kerényi, & Kiss, 1987; Moses, 2003)*

Minimum losses occur when the rolling direction coincides with that of the flux lines. If these two directions differ then the increase of magnetizing power is very significant. Additional losses occur when the magnetic field is forced to pass from a larger cross-section through a more restricted area.

- Additional losses occur due to inaccurately fitted joints, where the magnetic field becomes compressed towards the smaller air gap. Along the path following the larger air gap, the utilization of material is reduced. Air gaps at joints reduce the effective core permeability and causes localized variable flux distribution, which in turn increases the losses according to the gap length.

- The passage of the magnetic field through the narrow interstices between the holes arranged behind one another is restricted and it causes additional losses in the core. Bolt holes cause additional losses of 1 to 3 % of the nominal value in regions around holes. These losses depend on holes diameter relative to sheet width.

- It is estimated that an increase of around 5 % of the nominal loss occurs due to non-linear loss characterization of the material. This varies with the nominal flux density and the estimated curve is shown in Figure 3. The drop at the high flux density occurs as the material begins to act more homogeneously within the core volume close to magnetic saturation.

### *Losses due to mechanical processing of sheets*

The various processing and mounting methods used in transformer factories lead to additional losses and growth of no-load losses. Here are some of the losses resulting from manufacturing.

### *Losses due to cutting and punching*

During these processes, the sheets suffer deformations near cut or punched edges. Consequently, mechanical stresses arise in the material, which cause the magnetic permeability of the affected section to drop. These deformations cause the divertion of flux lines and the increase in losses. The fineness of processing determines the width of the strip where deformation is brought about by cutting or punching tools. The finer the processing, the narrower is the strip within which the magnetic properties are affected. The width of sheets influences the additional losses incurred by mechanical processing. The deformation strip affects by a lower percentage the losses in wider sheets than in the narrower ones.

### *Losses due to transport and reloading*

During transport and reloading, because of careless handling, the sheets may be bent through radii below 300 mm.

### *Losses due to defective insulation*

Injured sheet insulation within the core increases the losses caused by eddy currents.

## 4 Solutions for reducing losses in transformers production

New technologies and improved processes in production of transformers could greatly reduce power losses and the unnecessary CO2 emission in the electricity distribution. Having in mind the positive green effect on total supply chain of electrical energy, they could be presented as the greening elements in transformers production as well.

In the past, the no-load losses had a share of 80 % in the total losses of distribution transformers. Nowadays, they still account for about two thirds of the total losses (Targosz & Topalis, 2008), but this significant reduction happened due to application of gradually improved better grades of non-oriented steel, cutting technology and decreasing laminations thickness. During the last fifty years the improving technology of the transformer sheets rolling, with techniques to refine the domains of the iron crystals, proper cut, fabrication and assembling techniques reduced unit losses from 3 W/kg to less than 1 W/kg in traditional technologies (Irrek, Topalis, Targosz, Rialhe & Endesa, 2008).

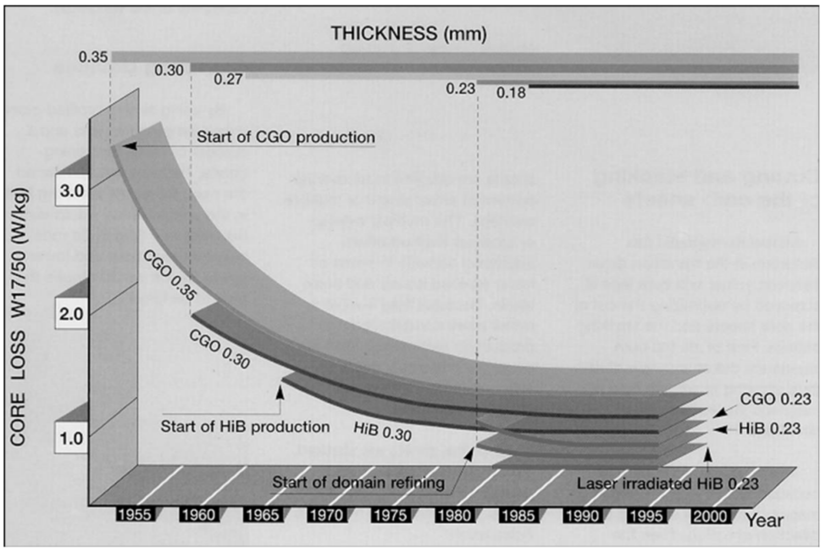

Figure 3. “Core loss evolution”. Source: De Keulenaer (2002)

Development in the core loss reduction during the last 50 years is illustrated in Figure 3. There are no amorphous cores on the chart. Their losses amount, approximately, to 0.25 W/kg.

Reducing the no-load losses is mainly done by enlarging the core and by changing the steel type of the core, but it has impact on the weight and size of the transformer. An Amorphous transformer core is 50 % bigger (Belmans et al., 2005).

Reducing losses due to inaccurately fitted joints can be achieved with more accurate machining. On the other hand, the punching losses may be somewhat reduced by decreasing the diameter of holes (Karsai, Kerényi, & Kiss, 1987). Losses that occur during transport, reloading and defective insulation can be eliminated by organizational measures taken in the production process.

### 4.1 Amorphous cores

A relatively new technology which is widely used in Japan and in a smaller scale in North America uses amorphous cores, as illustrated in Figure 4. Using amorphous metal core, no-load losses can be reduced by additional 70 to 80 % compared to the best silicon steel reaching levels of 0.065 W/kg (Irrek, Topalis, Targosz, Rialhe, & Endesa 2008). Amorphous alloys do not have a crystal structure unlike ordinary alloys and amorphous metal cores are suitable for power networks with high frequency harmonics, which occur due to dramatic increase in the use of power electronics and lead to increased transformer core losses, especially in distribution transformers that use conventional steel core materials. It has low loss performance under higher frequencies (Targosz & Topalis, 2008). Comparison of amorphous versus conventional cores is given in the Table 3.

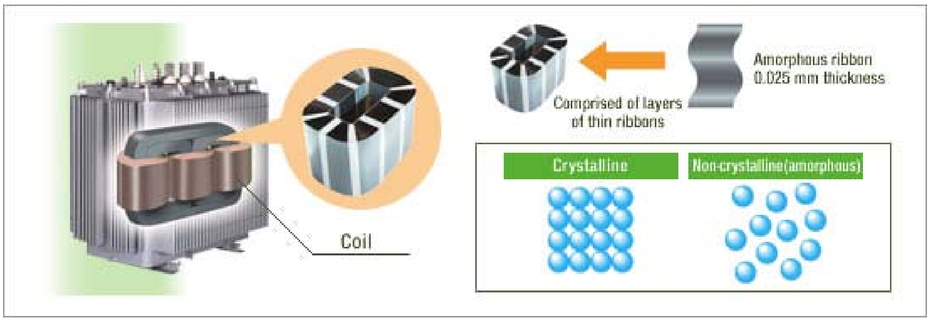

Figure 4. “Amorphous core transformer”. Source: *Amorphous Core Transformers*

The initial purchase price of the amorphous metal based transformer is higher than the initial price of conventional based transformer. But a life cycle cost, or a total cost of ownership during the life span of a transformer includes a future cost of the power losses during the life span of the equipment. If we compare the use of conventional silicon steel core transformer to the use of amorphous metal based distribution transformers we realize that the later results in an overall financial savings of utilities during the life span of the transformer, as illustrated in Figure 5 (Irrek, Topalis, Targosz, Rialhe & Endesa 2008; Targosz, & Topalis, 2008).

Figure 5. “Advantages of amorphous transformers”. Source: Targosz & Topalis (2008)

| Loss (W) | Amorphous Metal | Silicon Steel |
|---|---|---|
| Hysteresis | 99 | 155 |
| Eddy Current | 33 | 311 |
| Total Core loss | 132 | 466 |
| Coil Loss | 966 | 1084 |
| Loading Level (%) | 55 | 58 |
| Total transformer Loss | 1098 | 1550 |

Table 3. “Comparison of loss of amorphous versus conventional cores”. Source: Targosz, & Topalis (2008)

### 4.2 Superconducting transformers

Another non-traditional solution for reducing losses is the use of superconducting transformers. These transformers use high temperature superconducting material (HTS) which need to be cooled to the temperature of about minus 200 °C. These transformers are cooled by the flow of liquid nitrogen. In conventional transformers the basic insulation is paper and oil. High temperature affects the aging rate of this insulation and it is assumed that transformer shall work for 30 years. The temperature of the hottest spot of insulation shall not reach over 110 °C. Usage of the transformer at the temperature increased by 20 °C over 100 days reduces the service life span of the insulation by 25 %. HTS transformers do not have a problem of degradation of the insulation. The rated efficiency is greater than the efficiency of the conventional transformer, but the investment cost of the transformer with HTS windings is high. It is compensated with the decreased costs of use over the whole service life of the transformer. For now, the use of transformers with HTS windings is not economically justified, but it shall be more and more attractive due to the improvement of cooling system, the fall of prices and the cheaper process of nitrogen condensation. One example is illustrated in

Figure 6, along with some design parameters and pros and cons given in Tables 4 and 5 (Irrek, Topalis, Targosz, Rialhe & Endesa 2008; Targosz, & Topalis, 2008).

Figure 6. "Fuji/SEC/Kyushu University HTS transformer unit". Source: *HTS transformer development in Japan*

| | |
|---|---|
| Capacity | 500 kVA |
| Frequency | 60 Hz |
| Voltage (primary/secondary) | 6600 V/ 3300 V |
| Current (primary/secondary) | 76 A / 152 A |
| Core<br>Height/width<br>Cross sectional area<br>Magnetic induction | Silicon steel plate<br>1580 mm / 1100 mm<br>986 cm2<br>1.7 T |
| Winding diameter (primary / secondary) | 465, 553 / 509, 597 |
| Winding height | 748 mm |
| Secondary load | 500 kVA inductive coil |

Table 4. "HTS Transformer design parameters". Source: *HTS transformer development in Japan*

| PROS | CONS |
|---|---|
| Oil free, (liquid nitrogen)<br>20 % lower weight<br>50 % lower load losses compared to $A_k$ level, operational efficiency 99.3 % - 99.5 %<br>Slightly smaller volume<br>Short circuit reactance 50% of conventional<br>25% overloading without accelerated ageing<br>Lower lifecycle cost | 150 % - 200 % of the price of traditional transformer<br>Additional maintenance cost<br>Installation site (extra requirements) |

Table 5. "Pros and cons of HTS transformers". Source: Targosz & Topalis (2008)

### 4.3 Hexagonal core design

The usage of the hexagonal core designs, as illustrated in Figure 7, can also decrease total losses of transformer. Compared with conventional designs, by using the hexagonal core designs, no-load losses can be reduced by up to 50 %, total operating costs can be reduced by up to 50 % as well, the weight can be reduced by up to 30 5, the volume can be reduced by up to 40 %.

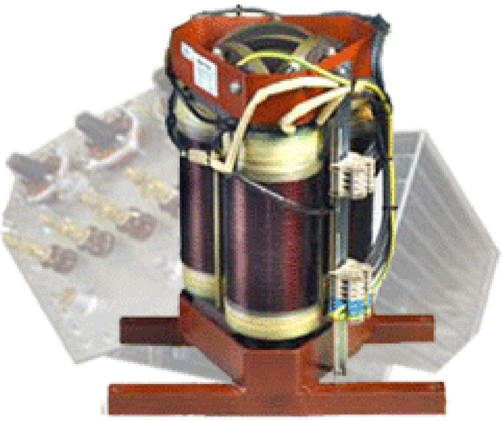

Figure 7. “Design of hexagonal transformer”. Source: *Hexaformer*

## 5 Conclusion

This paper presents preliminary research on the topic of how to reduce losses within the electrical distribution network. If Croatia decides to use more efficient transformers, distribution transformers in class $A_0$ and $A_k$ (according to EN 50464-1:2007) and power transformers, whose losses are lower by 10 % (losses can be reduced by up to 20 %), losses in the distribution network could be reduced by 77.22 GWh, or to the value of 253.54 GWh. Furthermore, losses can be also reduced if the analysis included transformers which belong to the transmission network. As can be seen from the given data of $CO_2$/kWh emission for 2008 year, $CO_2$ emissions could be reduced for 27511.17 tones. Apart from the reduction of the emissions, the usage of high efficiency transformers would also enable the development of production. This is so because, according to Kyoto Protocol, each country has agreed to reduce $CO_2$ emissions, which, in turn, could slow the economic growth. Also here should be mentioned that the implementation process of more efficient transformers is a long process because the lifetime of transformer is a 20-40 years. It follows that the decades will be needed to reach a specified reduction.

The above mentioned methods are greening elements in the production of transformers, and as such can be used as the guidelines for the reduction of power losses, which would result in reduction of $CO_2$ emissions in distribution networks.

Many initiatives and projects aimed at the reduction of emissions have been undertaken all over the world. Therefore, this paper indicates the possible application of these techniques in Croatia. According to a study by *Leonardo Energy Transformers,* investment for high efficiency transformers can be repaid in a period of 1-7 years depending on the price of electricity (Opetuk, Dukic & Radic, 2009). Furthermore, as mentioned earlier, this is a preliminary study on this subject and further research should include an economic analysis of the cost effectiveness of the usage of more efficient transformers in Croatia.

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