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Comparison Of Annual Electrical Energy Losses Of Conventional And Superconductive Transformers In Power Lines

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Abstract – The aim of the work is to compare performance and annual results losses of electrical energy lost by transformers superconducting and conventional. The efficiency has been calculated both transformers installed in the power plant at changing load. The example used superconducting transformer with 2G0 winding. Obtained the results show 80% less energy loss per year compared to transformers with copper windings.

Keywords – cryocooler, kyriostat, own field, iron core, efficiency, losses

1. Introduction

Electricity is produced mainly by thermal, hydro, wind and photovoltaic power plants. It is transmitted to recipients via extensive and extensive power lines. Reduction of transmission losses is possible by increasing the line voltage, as well as replacing wires, underground cables and oil and dry transformers with superconducting ones. The voltage of the power grid is determined by the distance over which it is transmitted. Transmission over longer distances is carried out via high voltage lines via transformers. The map of national power lines in Poland is shown in Figure 1. According to data [1] in Poland, electricity is transmitted via 400 and 220 kV lines (135 400 kV lines with a length of 8,950 km and 171 220 kV lines with a length of 7183 km). Transmission over a distance of several dozen kilometers is carried out via 110 kV lines, and smaller ones via local lines. Large transmission losses can be reduced by replacing traditional oil and dry transformers with superconducting ones. With the number of 261,079 MV stations, including 1,179 MV/MV and 261,079 MV/LV [2], it is worth considering the benefits that would be brought by replacing at least some of the transformers with superconducting ones.

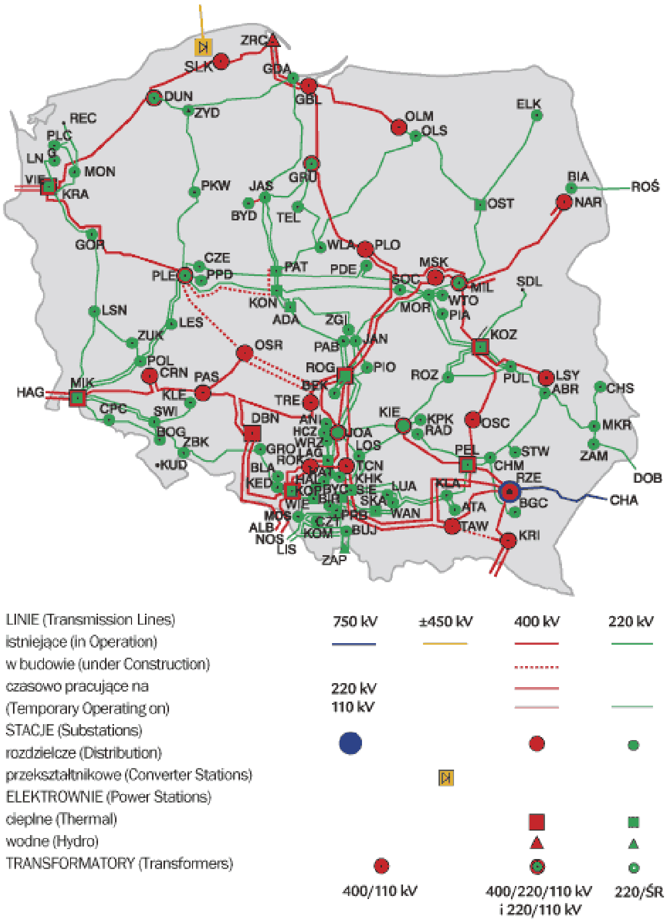

Fig. 1. Map of national high-voltage power transmission networks

2. SOLUTIONS WITH MEDIUM VOLTAGE LINES 10 TO 30 KV

The main reason for interest in superconducting transformers is to reduce power losses in the power system [3]. In the conventional power system, they are significant, which raises interest in their reduction [1-4]. The annual energy losses of a transformer in the power system are influenced by the load curve of a given power receiver and its efficiency. In the example of this article, a comparison is made of annual electricity losses in a superconducting transformer and conventional. A transformer with a characteristic curve was selected loads and a superconducting version. The concept of a transformer operating normally is given, and its data are taken from the manufacturer's catalog card. The annual losses of a conventional transformer supplying several drives consuming significant currents in a power plant were calculated as precisely as possible. At rated voltage, the transformer was loaded at 75% for 5,000 hours per year, while the rest of the year it operated at 0.5% load. During start-up, it drew a higher current, but this was omitted. Figure 2 shows the curve load to calculate the annual energy losses of both transformers. The example does not take into account the load resulting from the short start-up of the power plant. The simplified load curve in Figure 1 is intended to facilitate the calculation of the annual losses of both transformers.

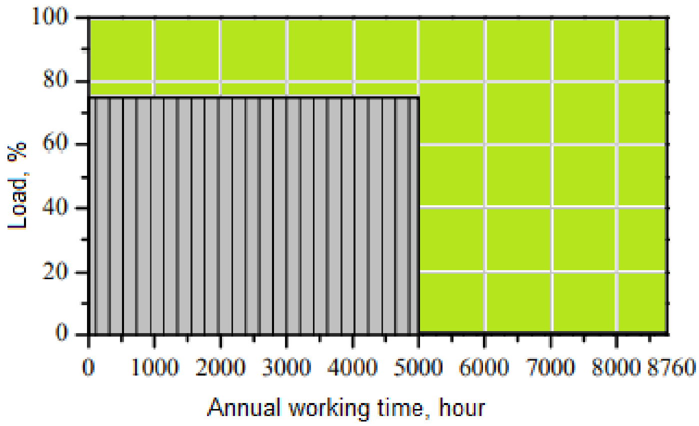

Fig. 2 Annual load curve of an auxiliary transformer for a power plant. 100% workload corresponds to 63 MVA

3. POWER PLANT OVERVIEW TRANSFORMER DATA

Conventional, three-phase oil transformer with rated power 63 MVA, primary voltage 21 kV, primary current 1000 A, Dyn5 connection system, frequency 50 Hz, network voltage 9.09 kV, network current 2309 A, winding voltage 100.9 V, winding resistance primary R1 = 39.2 mΩ, number of primary/secondary turns 216/90, leakage impedance 11.5%, secondary winding resistance 5.6 mΩ, dimensions length/width/height. 3.52/1.35/2.94 m, iron core losses 24 kW. The superconducting transformer is designed for minimal energy loss. It was made as three-phase with a warm iron core and three kyriostats for the superconducting windings. The superconductors were 4 mm wide YBCO (CO) coated tapes, the cooling medium was liquid nitrogen at a temperature of 77K. Equipping it with a primary winding consisting of 50 coated wires, connected in parallel and carrying the supply current. The wires were placed in two stacks, wound next to each other as one layer. The secondary winding consisted of 115 parallel coated conductors, divided into four stacks and wound side by side as a layer. The height of the windings was 2.97 m. His sketch shows figure 3.

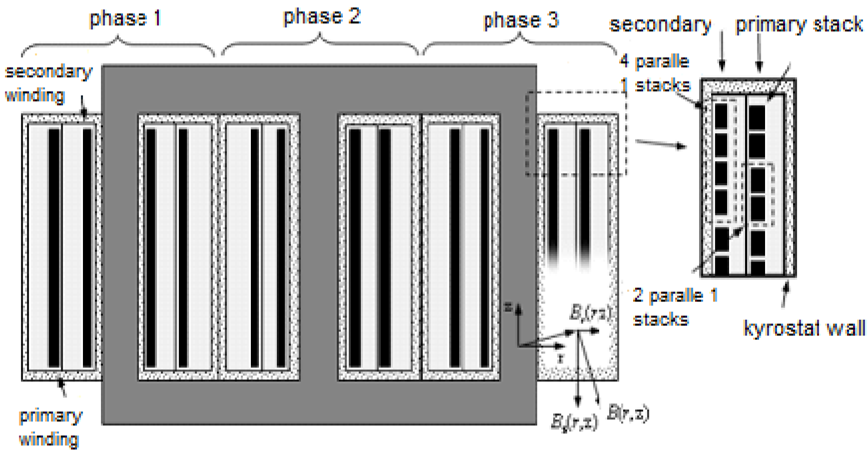

Fig. 3 Sketch of the superconducting transformer

In the self-field at a temperature of 77 K, the critical current Ic of the coated conductors was 100A. At the critical current, the stray field of the windings Ic(Bσ) decreased to 40% of the self-field Ic. The highest value of the critical conductor current in the stray field Ic(Bσ) and the maximum rated current Ir,max was assumed to be 40% (Ic(Bσ)/Ir,max = 1.4). The total length of the superconductors in this transformer was 150 km. The short-circuit impedance was lower than in a conventional transformer. The other details are; voltage in the winding, which was 85 V, number of turns of the primary winding n1/number of turns of the secondary winding n2 247/107, leakage impedance 2.6% of the critical current, single critical current CC Ic 100A. Dimensions 1/w/h 0.74/2.21/3.89 m, single critical current CC Ic in the stray field Ic(Bσ) 40A, increased stray field Bσ in air gap 162 mT, number of parallel CC turns primary z1/secondary z2 50/115, length of CC turns per phase z1/z2 27/23 km, number of stacks primary/secondary 2/4, Ic(Bσ)/Ir,max 1, 4, height of both primary/secondary windings 2.72 m, iron core weight 14.47 t, iron core diameter 546 mm, window height 2.797 m, window width 251 mm, iron core material H 085-23, 0.85 w/kg at 1,7 T, 50 Hz.

4. LOSS CALCULATION

Losses in the iron core do not depend on the load. They are provided by the manufacturer. They were PFE,NC 24 kW. For the superconducting transformer, the calculated core losses were 0.85 W/kg at 1.7 T at a network frequency of 50 Hz. The weight of the iron core was 14.47 t. After calculations, it gave losses equal to PFe,S. C. 12.3 kW. Therefore, the losses of the superconducting core were lower than those of the conventional core. The superconducting transformer had a lower winding voltage and a smaller cross-section and core mass. The losses in the copper windings P_{Cu} in a conventional transformer depend on the resistance of the primary winding R_{pri} and the secondary winding R_{sec} as well as the primary current I_{pri} and the secondary current I_{sec} and were:

$$P_{Cu} = 3(R_{pri} \cdot (I_{pri})^2 + R_{sec} \cdot (I_{sec})^2) \quad (1)$$

Losses in superconductors covered with a YBCO layer (AC losses) come from their own alternating magnetic field and from the external magnetic field. The internal field is caused by current carriers flowing in the superconductor, while the external field is caused by the field scattered in the windings. In order to calculate the losses of the current flowing in a single CC turn, the Norris equation [8] could be used. Losses in the superconducting winding P_{nadCC} (I_t) are determined by the relationship [5]:

$$P_{self,CC}(I_t) = \frac{(Ic \cdot \mu_0 \cdot f)}{\pi}\left(\left(I - \frac{It}{Ic}\right)\cdot \ln\left(I - \frac{It}{Ic}\right) + \left(I + \frac{It}{Ic}\right)\cdot\left(I + \frac{It}{Ic}\right) - \left(\frac{It}{Ic}\right)^2\right) \tag{2}$$

where: I_t – total current

The transport current I_t is the maximum current flowing in all wires and for the primary winding $I_t = I_{pri,max}/n_{CC,pri}$, where $n_{CC,pri}$ - the number of tapes (and accordingly for the secondary winding $n_{CC,sec}$. Wires stacked in parallel change the magnetic field distribution, therefore the actual losses of the self-field in the wires differ from the value resulting from the Norris equations [9]. In a stack of 25 coated conductors, the self-field loss of the entire stack was almost 50 times higher than in a single wire carrying the same current. Self-field losses of a single wire $P_{self,stack} = 50 \cdot P_{self,CC}$. The total losses of the transformer's own field P_{self} are the sum of the losses of all winding stacks.

$$P_{self} = 3\left(n_{stack,pri} \cdot 50 \cdot P_{self,CC}\left(\frac{Ipri, max}{n_{CC,pri}}\right) + n_{stack,sec} \cdot 50 \cdot P_{self,CC}\left(\frac{sec, max}{n_{CC,sec}}\right)\right) \tag{3}$$

$I_{pri\ max}$ – maximum primary current,
$I_{sec\ max}$ – maximum secondary current,
n($_{stack,pri}$)- number of stacks in the primary winding,
n($_{stack,sec}$)- number of stacks in the secondary winding,

5. EXTERNAL FIELD LOSSES

A changing magnetic field causes external field losses in coated conductors due to its perpendicular distribution in relation to the magnetic field of the conductor (anisotropy). The magnetic field in the windings B(r,z) depends on the components Br(r,z) perpendicular to the CC plane and the longitudinal component of the field Bz(r,z) parallel to this plane. The field parallel to the plane should be calculated for the position of each turn, as indicated in Fig. 2. Also due to the variable load, the magnetic field should calculate for each load separately. The calculation of the distribution of these fields was made in [7]. The field distribution can be calculated using integrals as well as FEM simulation. Magnetic hysteresis losses in superconductors arising from fields perpendicular to the plane of the superconductor could be calculated from [9]. The magnetic field loss per 1 m of winding length was calculated according to the relationships given in [8].

$$\frac{P_{extern,r} \cdot (B_r(r,z))}{\ell} = f \cdot \frac{1}{\mu_0} \cdot \pi \cdot b^2 \cdot \left(B_r\,(r,z)\right)^2 \cdot g\left(\frac{B_{r(r,z)}}{B_c}\right) \quad (4)$$

where: Br(r,z) – component perpendicular to the plane and Bs(r,z) – component parallel to the winding plane (figure 2),

$$\mathbf{g}(x) = \frac{1}{x} \cdot \pi \cdot \left(\frac{2}{x} \cdot ln[\cosh(x)] - \tanh(x)\right) \quad (5)$$

$$B_c = \frac{\mu_0 \cdot I_c}{\pi \cdot b} \quad (6)$$

In the conductive parts of coated conductors, eddy current losses are calculated according to the formula given in [20].

$$\frac{P_{ext.eddy}\,(B_{croextern,r} \cdot (r,z)\,)}{\ell} = \frac{\pi^2 \cdot (f \cdot B_{extern,r} \cdot (r,z))^2 \cdot b^3 \cdot d_s}{6 \cdot \sigma_s} \quad (7)$$

The shape of the conductors generates losses from eddy current (longitudinal field). The hysteresis losses of superconductors in parallel fields can be calculated according to the relationship given in [11]. Oblong the field component per meter of length $B_z(r,z)$ (parallel to the CC plane) is given by:

$$\frac{P_{extern,z}\,(Bz \cdot (r,z)\,)}{\ell} = \begin{cases} \begin{cases} \frac{2f \cdot t \cdot b \cdot (Bz(r,z))^3}{3\mu_0\, B_p}, & B_z\,(r,z) \leqslant B_p \end{cases} \\ \frac{2f \cdot t \cdot b}{3\mu_0} \cdot \left[3B_z\,(r,z) - 2B_p\right], B_z\,(r,z) > B_p \end{cases} \quad z \quad (8)$$

$$B_p = \mu_0 \cdot j_c \cdot t \quad (9)$$

By summing the losses in each turn of the winding, the total losses of the external field of this winding can be obtained. Eddy current losses in normally conducting parts of coated conductors are given by the formula:

$$P_{ext.} = \sum_i \sum_j \Big[\ell_{turn}(r_i, z_j) \cdot \Big(P_{ext.,r}\left(B_r(r_i, z_j)\right) + P_{ext,z}\left(B_z(r_i, z_j)\right) + P_{ext,eddy}\left(B_r(r_i, z_j)\right)\Big)\Big] \quad (10)$$

Where: r, z – coordinates of the turns, ℓ - length of one turn, ℓ_{turn} - number of turns

6. CRYOSTAT LOSSES

The loss of resistance and thermal conductivity of the current conductors causes an increase in the heat of the cryostat. The heat generated by the current conductors can be calculated using the equation given in [11].

$$Q_{CL} = \frac{(I)^2}{A_{CL}} \cdot \int_0^{L_{CL}} \sigma_{CL}(x) \cdot dx + A_{CL} \cdot \lambda_{CL}(T) \cdot \frac{dT}{dx} \tag{11}$$

where: Q_CL – heat generated by the wires

In superconducting transformers, kyriostats thermally insulate the iron cores. The windings are equipped with an outer wall and an inner wall. These walls are there insulated and have a warm and cold cylinder made of glass fiber reinforced plastic with multi-layer insulation. This solution gives a heat input of 2 W/m2, which gives 77 K [12]. Any cryostat has an area of 11.6 m^2 (added wall surfaces: upper, lower, internal and external), i.e. the total heat transfer through the walls is approximately 23.2 Wh per cryostat.

The total losses due to losses created by the alternating current flowing in the wires, superconductors and cryostat are compensated by the cryocooler, so the thermal losses increase in proportion to the increase in the efficiency of the cryocooler. Their maximum value in the cryostat is 1.54 kWh. In the example discussed, the efficiency of the cryogenic cooler is 0.11.

7. CALCULATION OF LOSSES IN A CONVENTIONAL TRANSFORMER

The no-load losses of a conventional transformer remain unchanged and amount to 24 kW in the iron core. As the load increases, the load losses increase to 248 kW. Resistive losses in windings amount to 90% of the total power losses and are a square function of the load, while the remaining 10% falls on the iron core.

8. CALCULATION OF LOSSES IN A SUPERCONDUCTING TRANSFORMER

In the no-load state in a superconducting transformer, losses range around 15.4 kW, of which 80% is due to the iron core, 16% to the cryostat and 4% comes from the heated current conductors. Losses in the cryostat constitute a negligible part of the total losses. After loading the transformer with its rated power, its losses amount to 26.2 kW, of which 47% are losses in the iron core, 32% are losses in superconductors, and 18% are losses in current conductors, the remaining 3% are losses in the cryostat. Losses in the iron core are also the highest.

9. COMPARISON OF RESULTS

The comparison of losses and efficiency of both transformers is shown in Figure 4. The total loss of the loaded superconducting transformer is very low compared to a conventional transformer. Without load, the loss of a superconducting transformer is 50%, and at full load, it is only 10% of the loss of a conventional transformer. With an efficiency of 99.9% at full load, a superconducting transformer exceeds the efficiency of a conventional transformer by 0.3%.

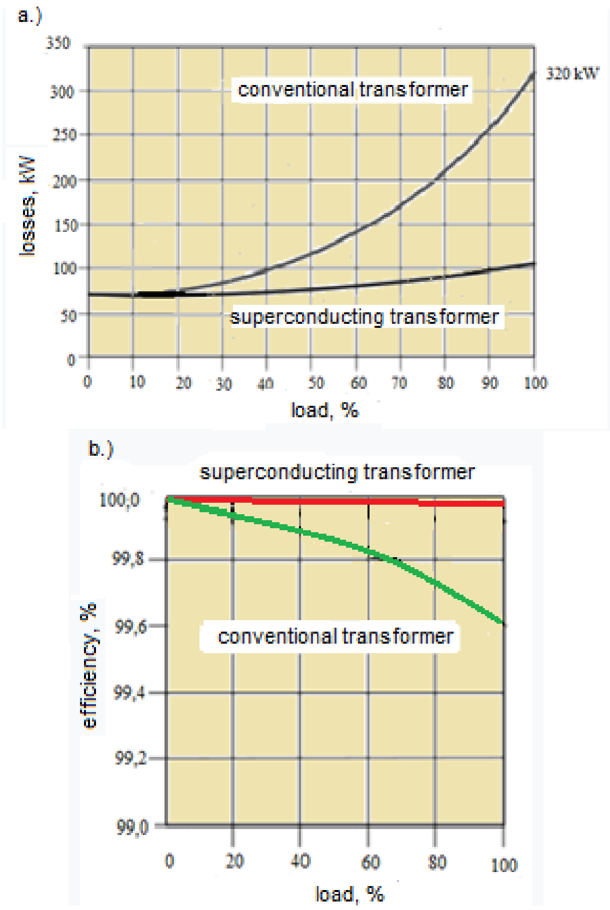

Figure 4. Conventional and superconducting transformer losses a.) and their efficiency b.)

Figure 5 shows the annual energy losses of both transformers used as power plant auxiliary transformer and superconducting transformer. The calculations used the annual load curve shown in Figure 1.

The annual energy loss of the 63 MVA conventional transformer was 839.7 MWh and 160.3 MWh for the superconducting transformer. A superconducting transformer could save 679.4 MWh of energy per year, which would mean an 81% reduction in losses. The main part of transformer losses is due to the resistance of the windings. In conventional transformers, they constitute 75%, and the rest of the losses come from the iron core.

Losses in a superconducting transformer are caused by the iron core (67.2%). Despite the low temperature, only a third of the total losses occur in the windings. Losses in power cables are 17.2%, while 12.1% are AC losses in superconductors. Only 3.1% of the losses are due to the cryostat.

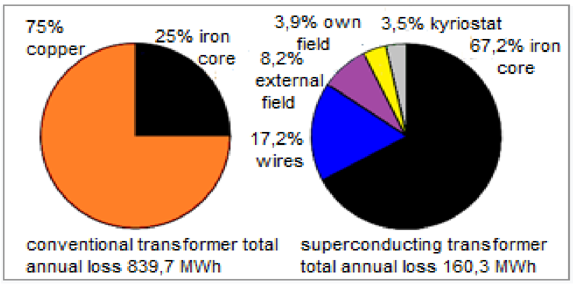

Fig. 5. Divisions of annual energy losses

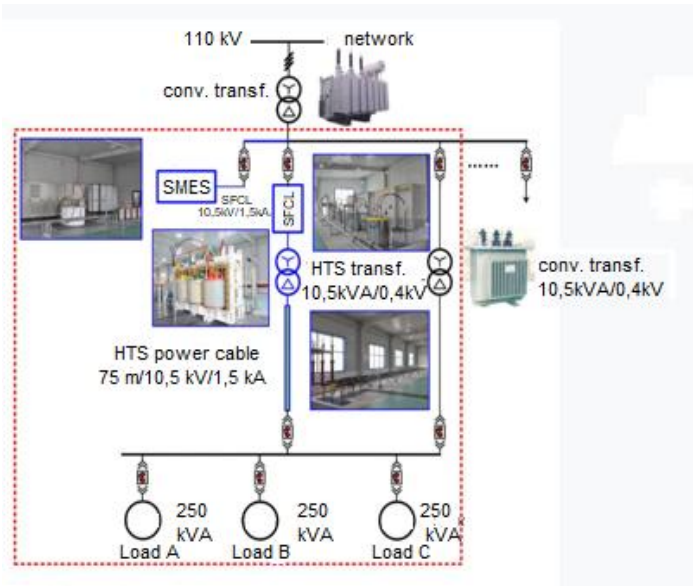

Fig. 6 Layout of a superconducting power station Figure 6 shows the 10 kV power substation in Baiyin City in Gansu Province.

A superconducting power substation was built by combining power devices such as:

- three-phase high-temperature superconducting power cable (HTS) with a length of 75 m and a rated voltage of 10 kV/1.5 kA;
- three-phase SFCL cable 10 kV/1.5 kA;
- three-phase HTS transformer 10 kV/0.4 kV with a power of 630 kVA and MSP with a power of 1 MJ/500 kVA.

Each of these superconducting components of this system have been installed in substations or distribution systems since 2004. It is worth mentioning the use of superconducting short-circuit surge arresters used to protect major substations, as is the case at Sjhigezhuang in Tianjin.

Fig. 7. A fiew of the 220 kV/0.8 kA superconducting fault current limiters after installation at Sjhigezhuang substation in Tianjin

Table 1. Parameters of a high-temperature superconducting coil for 220 kV short-circuit current limiters with a saturated iron core

Parameters	Value
Conductor	$Bi_2Sr_2Ca_2Cu_3O_{10}$
Inner diameter (mm)	1920
Outer diameter (mm)	2080
Thickness of the ring (mm)	16
Height of coil (mm)	900
Effective turns	504
Rated current (A)	300
Total numer of rings	45
Total rated magnetizing capacity (kA* turn)	176,5
Electrical insulation strength between tapes (V)	600
Electrical insulation strength of the coil (kV)	10
Total weight of the coil (kg)	800

10. SUMMARY

The cited example of a selected auxiliary transformer of a power plant with a capacity of 63 MVA and a conceptually designed superconducting transformer indicates a better technical solution of superconducting transformers, their reduced dimensions and other advantages, not forgetting the disadvantages (kyriostat). The losses of a superconducting transformer and a comparable conventional transformer were calculated. The annual energy loss was calculated using the actual load curve. The results obtained in this way suggest the possibility of increasing the efficiency of superconducting transformers from 99.6% to 99.9%. This solution can save up to 81% of energy waste per year. Considering that there are approximately 261,079 MV stations in Poland, including 1,179 MV/MV and 261,079 MV/LV, it is worth taking an interest in the benefits of introducing superconducting transformers into operation, at least where there is such a need.

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