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Superconducting transformers: key design aspects for power applications

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Superconducting Transformers: Key Design Aspects for Power Applications

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Abstract. Conventional power transformers are very simple and reliable electrical components and their efficiency, for large power rating, is well above 99 %. With such an excellent performance the improvement margin seems very limited. However, due to the large amount of power managed and the continuous service, also a small increase in the efficiency is desirable. As an example, consider that an efficiency increase of 0.5 % of a 25 MVA transformer may lead to savings in the order of 100 k€/year. The use of superconducting materials opens the way to efficiency improvements on power transformers, and also adds important advantages such as size and weight reduction, that are very attractive for urban substations and transport applications. Moreover superconductors eliminate the need for refrigeration oil, thus avoiding the risk of fire hazard and reducing the environmental impact, in accordance with recent EU guidelines. In this paper a design procedure for HTS power transformers is reported. This procedure, that includes an analytical method for the calculation of the AC losses, is used to design a 25 MVA – 154 kV / 20 kV transformer based on commercial BSCCO tapes, and the evaluated performance are compared with those of a conventional copper transformer. The optimal working temperature is evaluated, and allowable cooling technologies are discussed. Considerations on the use of future 2nd generation YBCO coated conductors are also reported.

1. Introduction

Conventional power transformers are very simple and reliable components that play a central role in electric systems. Their efficiency, for large power ratings, is well above 99 %. With such an excellent performance, reached through about one century of well established designing, manufacturing and operating experience, the improvement margin seems very narrow. Basically, the transformer drawbacks are the large size and, due to the presence of oil for cooling purpose, the fire hazard and their end-life environmental impact. Moreover, in the transportation sector, where they also find a broad application, the excessive weight of transformers is also a concern. It must be noted however that, due to the large amount of power managed and the continuous service, even a small efficiency increase is very desirable. As an example, consider that an efficiency increase of 0.5 % of a 25 MVA power transformer may lead to savings in the order of 100 k€/year.

Superconducting transformers based on HTS materials have the potential to offer several economic, operational and environmental advantages with respect to their conventional counterpart. First of all an increase in the efficiency, with a considerable saving in the operational costs. Second, the possibility of overload operation without increase of losses; this avoids the increase of thermal stress on insulating materials thus allowing a longer life of the whole electrical component. SC transformers are

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smaller and lighter than conventional ones and are therefore very attractive for strengthening of existing urban substations and for transport applications. Moreover by eliminating the need for refrigeration mineral oil, SC transformers avoid the risk of fire hazard and reduce the environmental impact, in accordance with recent EU guidelines. Finally, with a proper design of the HTS windings, they can have a current limiting ability and hence protect the electric equipments in case of fault without weakening the grid.
In this paper a complete procedure for the design of HTS transformers, including relations for the estimation of AC losses, is presented in section 2. Based on this procedure a 25 MVA – 154 kV / 20 kV transformer using present state of the art HTS BSCCO tapes is designed in section 3 and compared with a conventional copper transformer of same power. The cryogenic issue is discussed in section 4 and a possible cooling solution is proposed. Finally, prospects for the application of future low losses 2G HTS tapes are discussed in section 5.

2. Design procedure

In the following we consider a SC transformer made of HTS windings coupled via a ferromagnetic core operating at room temperature. In fact, even though possible in principle, an HTS transformer without an iron core [1] is not technically and economically feasible due to the large amount of conductor (and related AC losses) that would be needed to keep the magnetization current within an acceptable value. Moreover, an HTS transformer with a ferromagnetic core operating at cryogenic temperature [2], that would be desirable because of the simplified cryostat enclosing the whole machine and exposed to a reduced stray field, is also not feasible using nowadays ferromagnetic materials owing to their significant losses. Concerning the layout of the winding, basically two possibilities exist: alternate solenoids or alternate pancakes. In both cases the winding is formed by a number of groups of balanced ampere-turns, which reduces the field on the superconductor (especially the component perpendicular to the wide face of the HTS tape) as well as the leakage reactance [3, 4]. We considered only the alternate solenoids design because it is the most effective layout for reducing the magnetic field and improving the performance of the HTS tapes.
The input data available for the design of the transformer are:

- nominal power A_n (VA);
- frequency f (Hz);
- overload factor ξ (ratio between maximum allowable overload current and nominal current);
- utilization factor of the HTS tape c_u (ratio between the assumed maximum current value that the tape can carry in actual operation and the critical current);
- primary and secondary winding connections (Y or Δ).

Moreover, in order to complete the design procedure, a choice in the value of the following parameters is required:

- maximum magnetic flux density in the ferromagnetic core $B_{fe}^{\max}$ (T);
- operating temperature T (K);
- height of the coils h (m);
- volts per turn ratio u (V);
- number of groups of balanced ampere-turns g.

2.1. Number of turns

The numbers of turns of the primary and the secondary windings are given by:

$$N_1 = \mathrm{int}\left(\frac{V_1}{u}\right), \qquad N_2 = \mathrm{int}\left(\frac{V_2}{u}\right) \tag{1}$$

where the function *int* returns the nearest greater integer. Notice that the voltages V_1, V_2 of equation (1) are the actual voltages acting on the windings. They may differ by a factor $\sqrt{3}$ from the nominal primary and secondary voltages of the transformer depending on the connection (Y or Δ).

2.2. Iron core cross section

The cross section of the iron core S_{fe} and the diameter of the iron columns D_{fe} are given by:

$$S_{fe} = \sqrt{2}\,\frac{u}{\omega B_{fe}^{\max}}\,, \qquad D_{fe} = \sqrt{\frac{4\,S_{fe}}{\pi\,k}} \tag{2}$$

where k is the ratio between the cross section of the iron column and the total cross section of the surrounding circle. A typical value of $B_{fe}^{\max}$ = 1.75 T can be assumed in the design phase; the value of k ranges from 0.84 to 0.87 depending on the number of steps of the column [3, 4].

2.3. HTS coils design

In order to choose the number of HTS tapes in parallel required for the primary and the secondary coil the following multi-step procedure is applied. At first, the maximum values of the parallel induction field $B_{//}^{\max}$ (occurring at the middle of the coils) and the perpendicular induction field $B_{\perp}^{\max}$ (occurring at the two ends of the coils) are estimated by means of the following expressions [4]:

$$B_{//}^{\max} = \mu_0 \sqrt{2}\,\frac{N\,I}{g\,h}\,, \qquad B_{\perp}^{\max} = \mu_0\,\frac{N\,I}{\sqrt{2}\,\pi\,g\,h}\ln\frac{2\,h}{w} \tag{3}$$

where w is the width of the tape and N and I are respectively the number of turns and the nominal current of the primary or the secondary winding indifferently. Although these relations refer to solenoids in the vacuum, they can be applied also in the case of a transformer because the distribution of magnetic field in the windings region is not much affected by the presence of an iron core [5]. Notice that an increase in the number of groups of balanced ampere-turns g is favorable because it involves a reduction in the magnetic flux density on the coils and may lead to a reduction in the number of parallel tapes; it should be considered however that by increasing g the size of the windings (and of the transformer) increases as well.

The perpendicular component of the magnetic flux density is maximum where the parallel component is minimum and vice versa. Since the reduction in the critical current of the HTS tape due to the perpendicular component is much stronger than the reduction due to the parallel one, the critical current I_c of the tape can be evaluated with little error by considering its dependence on $B_{\perp}^{\max}$ only. The number n_1 and n_2 of parallel HTS tapes of the primary and secondary windings respectively can thus be evaluated on the basis of input data and design parameters as:

$$n_1 = \mathrm{int}\left(\frac{\sqrt{2}\,\xi\,I_1}{c_u\,I_c(T, B_{\perp}^{\max})}\right), \qquad n_2 = \mathrm{int}\left(\frac{\sqrt{2}\,\xi\,I_2}{c_u\,I_c(T, B_{\perp}^{\max})}\right) \tag{4}$$

where the function *int* returns the nearest greater integer. Notice that the currents I_1 and I_2 of equation (4) are the actual currents in the windings. Concerning the high current (low voltage) winding, the choice of an odd number of parallel tapes is favorable because it allows the assembling of an high current conductor having equal current distribution by continuous transposition of the tapes [6–10].

The calculated values of n_1 and n_2 allow the evaluation of the actual layout of the coils. The value $B_{\perp}^{\max}$ of the perpendicular magnetic flux density acting on the coils can then be exactly calculated by means of numerical tools. By introducing this value in equation (4), the number of parallel tapes can be adjusted and the procedure can be repeated until a final value is reached.

2.4. AC losses

The AC losses per unit length occurring within an HTS tape subject to transport current or exposed to an AC magnetic field parallel or perpendicular to the tape can be evaluated respectively as follows [11–13]:

$$p_{sf} = f\,I_c^2\,\frac{\mu_0}{\pi}\left[\left(1-\frac{I}{I_c}\right)\ln\left(1-\frac{I}{I_c}\right)+\left(\frac{I}{I_c}-\frac{I^2}{2\,I_c^2}\right)\right] \tag{5}$$

$$p_{//} = \begin{cases} \dfrac{2\,f\,C\,A_c}{3\mu_0 B_p} B_{//}^3 & B_{//} \le B_p \\ \dfrac{2\,f\,C\,A_c B_p}{3\mu_0}\left(3B_{//} - 2B_p\right) & B_{//} > B_p \end{cases} \tag{6}$$

$$p_{\perp} = K\ f\,\frac{w^2\pi}{\mu_0} B_c B_{\perp}\left[\frac{2B_c}{B_{\perp}}\ln\left(\cosh\frac{B_{\perp}}{B_c}\right) - \tanh\frac{B_{\perp}}{B_c}\right] \tag{7}$$

where I_c is the critical current of the tape, A_c is the total tape cross section, C is the ratio between the SC cross section and the total tape cross section, B_p is the full penetration flux density, K is a geometrical parameter and B_c is a critical penetration field. Both the parameters B_p and B_c depend on the temperature. Except for the value of the critical current density, the transport current losses do not depend very much on the applied magnetic field. Moreover, since the parallel component of the magnetic field is negligible where the perpendicular component is significant and vice versa, the total losses per unit length can be evaluated as the sum of the single contributions [4]. The total AC losses P_{AC} of the coils are then calculated through integration along the length of the conductor.

2.5. Thermal incomes through cryostat and current leads

Thermal incomes through the cryostats can be evaluated in first approximation as:

$$P_{cr} = \frac{k_{th}}{\delta_{th}} A_{cr}\ \Delta T \tag{8}$$

where A_{cr} is the total cryostat surface, ΔT is the temperature difference, δ_{th} is the thermal insulation thickness, and k_{th} is the equivalent thermal conductivity. In the following, a value of δ_{th} = 50 mm was assumed. As for the equivalent thermal conductivity, it should be noted that when considering the usual solution with a separated epoxy cryostat for each transformer phase [14], a precautionary value of the operating vacuum degree should be chosen due to the high gas permeability of polymeric materials. As a reference, considering a vacuum degree of 1 Pa, a value of $k_{th} = 2\cdot 10^{-3}$ W/(m K) can be used [15].

Total thermal incomes through the current leads for the three phases are evaluated as:

$$P_{cl} = 6\,q_{cl}\,(I_{1p} + I_{2p}) \tag{9}$$

where q_{cl} is the specific thermal income per unit current. A typical reference value of q_{cl} = 45 W/kA is used.

2.6. Iron core losses

The losses occurring in the iron core are evaluated as:

$$P_{fe} = 1.2\,c_p G_{fe} \tag{10}$$

where G_{fe} is the weight of the core, c_p is the loss per unit weight of ferromagnetic material at the working induction field B_{fe}^{max}, and the coefficient 1.2 takes into account the increase in iron losses due to non-uniform distribution of the magnetic field [3]. In the following, a value of c_p = 1.4 W/kg was assumed.

2.7. Performance evaluation

Total transformer losses are evaluated as:

$$P_{tot} = P_{fe} + C\cdot(P_{AC} + P_{cr} + P_{cl}) \tag{11}$$

where C is the cooling penalty factor, which is assumed as 5 times the ideal cooling penalty factor of a reversible machine. As a reference, C is about 18 considering a working temperature of 66 K.

The efficiency of the transformer at nominal load and power factor cosφ is thus given by:

$$\eta = \frac{A_n \cos\varphi}{A_n \cos\varphi + P_{tot}} \tag{12}$$

The per unit leakage reactance is finally evaluated with the following relation [3]:

$$x_{d1\,pu} = \omega 2\pi R_m \frac{B_{//}^{\max}}{\sqrt{2}\,u}\left(\delta_a + \frac{\delta_H + \delta_L}{6}\right) \tag{13}$$

where R_m is the average radius of the system of concentrically coils, δ_a is the distance between the coils and δ_1 and δ_2 are the thickness of the primary and secondary windings respectively divided by the number g of balanced ampere-turns groups.

3. Design of a 25 MVA – 154 kV / 20 kV transformer using BSCCO tapes

By means of the design procedure previously described, several parametric studies were carried out in order to evaluate major characteristics and performance of an HTS transformer using BSCCO tape. Since benefits of SC power transformers emerge especially at high power ratings, the considered working power was chosen as 25 MVA – 154 kV / 20 kV, with f = 50 Hz. Primary and secondary connections are respectively Y/Δ, and the assumed working temperature is T = 66 K. The main varied parameters are: the number of groups of balanced ampere-turns (g), the windings height (h) and the volts per turn (u).

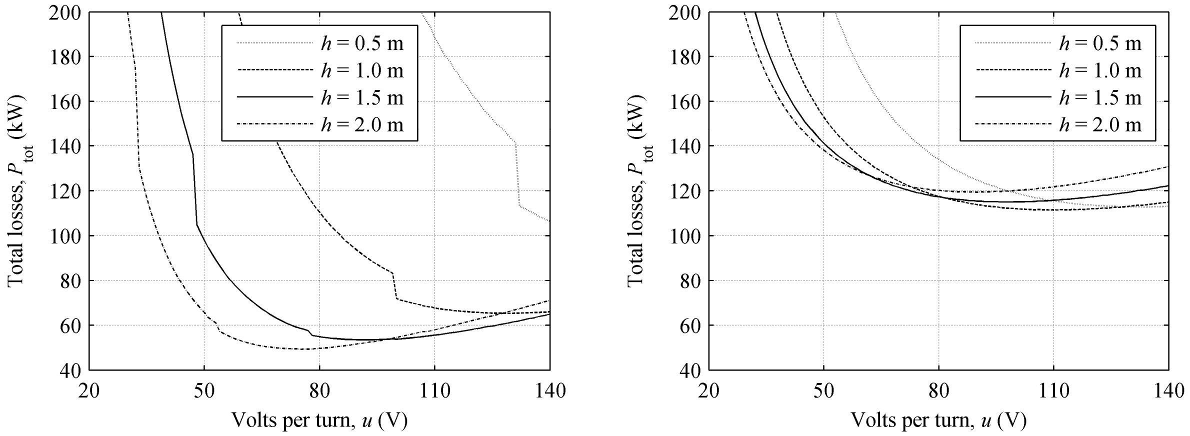
The design is carried out with reference to BSCCO-2223 tapes whose critical current was characterized in function of parallel and perpendicular field, and temperature [16]. For the choice of the required minimum number of tapes in parallel, an overload factor ξ = 1.5 and an utilization factor c_u = 0.9 are considered.

The characteristics and performance of the designed HTS transformer are compared with a conventional copper-type transformer of same power. The design of the conventional transformer is carried out by the same procedure. The only differences are the imposition of the copper current density of 4 A/mm^2 to find the required copper conduction section, and the absence of cryostat thickness (δ_{th}) when computing the transformer dimensions. Copper losses for the conventional transformer are calculated with known formulae which take into account the effect of current density concentration [3].

In the following, the values of u and h are varied respectively between 20 V and 140 V, and between 0.5 m and 2 m respectively. As for the number of groups of balanced ampere-turns, the results of the parametric studies showed that an increase of g over 2 leads to little increase in the maximum transformer efficiency at the expenses of larger size (due to the higher number of electrical insulation layers), lower leakage reactance (which may be a drawback when considering the application in a real electrical grid in case of short circuit) and higher manufacturing complexity. However, the choice of g = 1 leads to a significant performance penalization, due to the large increase in the values of parallel and perpendicular field on the windings. For these reasons, only the results referring to the configuration with g = 2 are here reported.

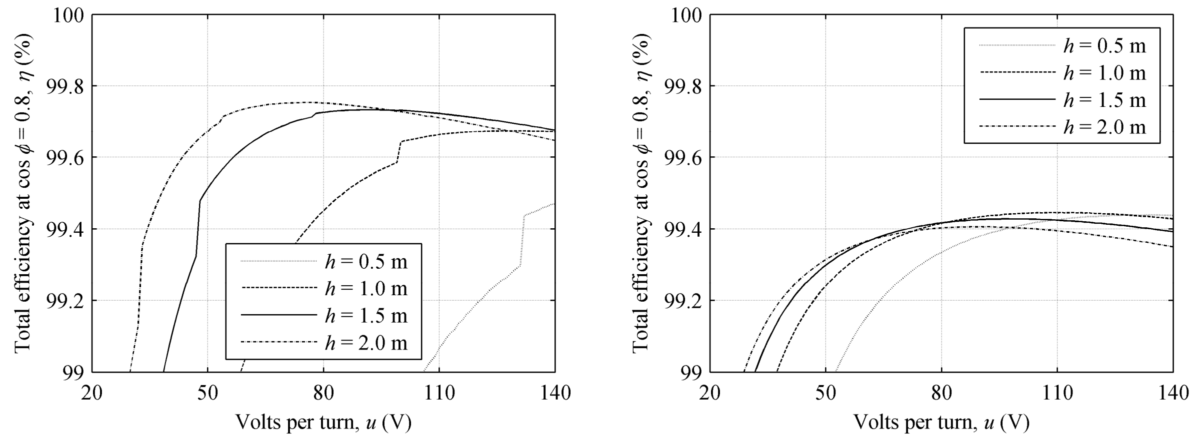
Figure 1 shows the evaluated total losses P_{tot} for the BSCCO transformer in comparison with those of the conventional transformer for different values of u (V) and h (m). Step variations in the losses of the HTS transformer are due to changes in the chosen number of tapes in parallel. It should be noted that for this power class, losses due to thermal incomes through the cryostat and along current leads are negligible with respect to AC losses, so that total losses can be considered as the sum of iron core losses and winding losses only. For low values of u, winding losses are preponderant with respect to iron losses. As shown, AC losses of the HTS transformer decrease greatly with increased winding height, as a result of the lower magnetic field components on the coils. With an increase in the volts per turn u, the total length of conductor decreases while the mass of the iron core increases. This leads to a decrease in the winding losses and an increase in the iron losses, so that the latter become predominant for higher values of u. Considering a winding height of 1.5 m, which is acceptable for a transformers of this power class, a value of u = 91 V leads to total losses P_{tot} = 53.5 kW for the

BSCCO transformer, which represents savings in the order of 60 kW with respect to the conventional transformer. Figure 2 shows the comparison of the total efficiency evaluated at power factor cos*φ* = 0.8 for the BSCCO and conventional transformers.



(a) (b)

Figure 1. Total losses for the BSCCO transformer (a) and the conventional transformer (b).



(a) (b)

Figure 2. Efficiency evaluated at nominal power and cos*φ* = 0.8 for the BSCCO transformer (a) and the conventional transformer (b).

4. Cooling solutions

Closed-cycle cooling systems are needed for maintenance free operation of large power HTS transformers. Considering that AC losses in the 25 MVA BSCCO transformer are in the range of several hundreds to thousands of watts, cryogen-free conduction-cooled solutions seem hardly applicable. In fact, the most commonly reported cooling solution for large power SC transformers in the literature is the cryogen-cooled forced flow method, usually employing liquid nitrogen (allowable operating temperatures from 64 K to 77 K) or gaseous neon or helium for lower temperatures [17–20].
The value of the design working temperature *T* directly affects the HTS transformer performance. At higher *T*, the cooling efficiency improves but AC losses and total conductor length increase as a result of the reduced performance of the HTS tapes. Figure 3 shows the efficiency evaluated at nominal power and cos*φ* = 0.8 for the BSCCO transformer with *h* = 1.5 m, *u* = 91 V at different values of the operating temperature. The step variations in the results are due to changes in the discrete number of

tapes in parallel, and are particularly evident when this happens for the primary winding, for which the number of tapes in parallel is lower and the number of turns is higher. As shown, for the considered BSCCO tapes the region of highest efficiency occurs in the temperature range of sub-cooled liquid nitrogen. Considering a cryogen input temperature of 64 K and the needed temperature gradient ΔT for proper removal of heat, an operating temperature T = 66 K of the HTS windings is chosen.

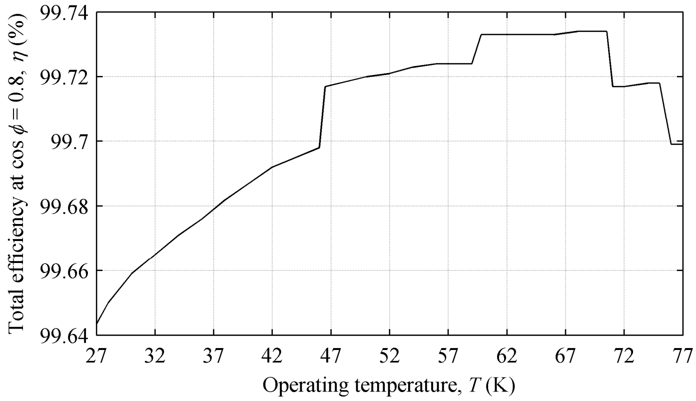


Figure 3. Efficiency evaluated at nominal power and cosφ = 0.8 for the BSCCO transformer with h = 1.5 m, u = 91 V at different values of the operating temperature.

For thermal insulation, a SC transformer with room temperature ferromagnetic core typically requires the manufacturing of three separated epoxy cryostats for the three electrical phases [14, 17]. This is needed since the cryostat walls located around the magnetic circuit form closed loops like a short circuited winding. The use of a full epoxy cryostat eliminates any induced current effect but requires the permanent use of a vacuum pump due to the large gas permeability of polymeric materials. However, an alternate solution exists in which the vacuum sealing is ensured by an outer metallic tank. The room temperature ferromagnetic core is water cooled in order to remove the P_{fe} losses. MLI can be used for thermal insulation of the HTS windings, with proper segmentation in order to interrupt short circuit rings around the ferromagnetic core. The cooling cryogen flow can by piped through heat exchangers for the cooling of the HTS windings. Figure 4 shows a possible layout scheme, in which the sub-cooled liquid nitrogen dewar is integrated into the transformer vacuum tank. A similar solution, but using gaseous helium at the temperature of 25 K, is described in [20].

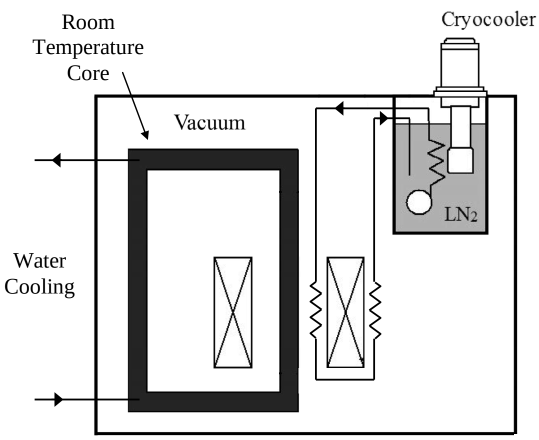


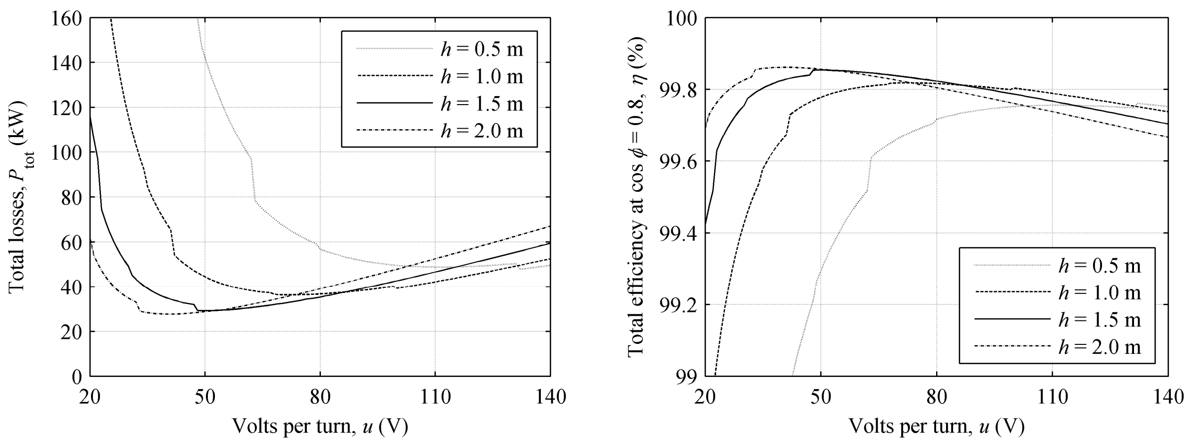
Figure 4. Scheme of liquid hydrogen cooled HTS transformer with room temperature ferromagnetic core and single metallic outer vacuum tank.

5. Prospects for YBCO coated conductors

Second generation YBCO coated conductors are close to the introduction in the HTS market. Long length tapes having 4 mm width and over 100 A critical current at 77 K can now in fact be produced [21, 22]. A great potential in the reduction of AC losses is also foreseen. In order to evaluate the prospects for future HTS transformer we postulate the existence of a 2G HTS tape having the same engineering current density J_e as the nowadays BSCCO tapes and AC losses reduced by a factor of 10 By using these assumptions the design of the transformer can be carried out through the same procedure followed in section 3.

Figure 5 shows the estimated total losses and efficiency at nominal power and at $\cos\varphi = 0.8$. The lower losses in the superconductor shift the optimal point towards lower values of volts per turn u, and therefore towards solutions with an higher “superconductor to iron ratio”. Considering the coils height $h = 1.5$ m, the point of minimal losses of 29.2 kW occurs for $u = 50$ V. It is important to point out that a lower value of u leads to a decrease in the volume and mass of the HTS transformer (being the coils thickness and weight much smaller than those of the iron core). When these factors are more important than reaching the highest efficiency, lower values of u than the minimum losses point can be chosen. As a reference, the YBCO transformer with $u = 28$ V shows same total losses as the BSCCO transformer with $u = 91$ V, but with a total volume of only 57 %, which is very attractive for transport applications.

Another important parameter which is affected by the value of u is the leakage reactance. It is known that optimal design of SC transformers usually lead to low values of the leakage reactance with respect to typical values of conventional transformers. For transformers in this power range it can be lower than 2–3 % p.u., compared to usual values of 8–10 % p.u. for conventional transformers [3]. This is the direct result of the minimization of the magnetic field on the coil region, which is needed for the reduction of AC losses. A low value of the leakage reactance is often indicated as a drawback of SC transformers when working in a real electrical grid due to the danger of high short circuit currents in case of fault. Although different approaches to address this problem exist (i.e. series connected SC fault current limiters, or the design of self-limitating transformers) it is interesting to note that the YBCO transformer with $h = 1.5$ m has a leakage reactance of 3.75 % p.u. with $u = 50$ V, which rises to 10.4 % p.u. with $u = 28$ V.



(a) (b)

Figure 5. Estimated total losses (a) and efficiency at nominal power and cos φ = 0.8 (b) for a HTS transformer employing low losses YBCO coated conductors.

6. Conclusions

A procedure for the design of power transformers employing HTS tapes was presented and used to evaluate the potentials of HTS power transformers in comparison with conventional copper transformers. Parametric studies, for varying values of coils height and volts per turn, were carried out with reference to a 25 MVA – 154 kV / 20 kV transformer. Optimal design parameters were calculated for a transformer employing commercial BSCCO tapes, which allow power losses savings in the order of 60 kW with respect to a conventional copper transformer of same power. A possible cooling solution was proposed. Finally, prospects for the use of future low-losses YBCO coated conductors in HTS transformers were evaluated. It was shown that great improvements are possible, involving not only the efficiency, but also the overall size, weight and leakage reactance value.

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