The design and construction of a controllable reactor with a HTS control winding.

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Abstract. Reactive power compensation is vital for obtaining efficient operation of long transmission power lines or cables. The need of reactive power changes with the load of the transmission line. Discrete units of conventional reactors are therefore switched in and out in order to obtain more efficient reactive power compensation. A continuous reactive compensation will reduce the transmission losses and increase the transmission capacity of active power. We have designed and constructed a one phase small scale prototype of a controllable shunt reactor with a high temperature superconducting control winding. The reactor consists basically of two windings and an iron core. The control winding is placed so that it generates a DC magnetic field perpendicular to the main AC magnetic field. Thus the DC current in the control winding can control the direction of the magnetization of the iron core and thereby the reactance of the reactor. Such a control winding will have low losses and give the reactor a large dynamic range. For this small scale reactor we found that the reactive power could be varied with a factor six. We have demonstrated the feasibility to design large scale controllable shunt reactors with large dynamic range and low losses utilizing a control winding made of a high temperature superconductor.

1. Introduction

Reactive power compensation is vital for obtaining efficient operation of long transmission power lines or cables. Long transmission power lines have a non negligible capacitance and inductance therefore shunt reactors are used to control the power flow by reactive compensation. The need of reactive compensation changes with the load. Discrete units of conventional reactors are therefore switched in and out in order of need for reactive power. If the reactance of the reactor could be controlled, this reactance could be adjusted to the load of the transmission line and thus providing a continuously reactive compensation reducing the transmission losses and increasing transmission capacity of active power.

There are two types of controllable reactors commercial available the transductor [1] also called the saturable reactor (SR) and the thyristor controlled reactor (TCR) [2]. A transductor is a device with two windings on a ferromagnetic core. A DC current through a control winding saturates the iron core and the reactance of the reactor is decreased. The TCR is a thyristor valve and a reactor in series. The reactive power is changed by controlling the current through the reactor by the thyristor valve.

The conventional shunt reactors are built in two different ways, either with a coreless design or with an iron core with air gaps. Both types store most of the magnetic energy in an air gaps. The controllable reactor presented in this paper and the transductor store magnetic energy in the iron core, and the magnetizability of the iron core is changed with a DC current through a control winding. The
main difference between the two is the position of the control winding. In the controllable reactor the control winding is placed so that it generates a DC magnetic field perpendicular to the main AC magnetic field. Thus the current in the control winding can control the direction of the magnetization of the core and thereby the reactance of the reactor without generating the harmonics associated with the transductor. The control winding can be made of copper [3]. A HTS (high temperature superconductor) control winding will increase the dynamic range due to the high current density and dramatically reduce the losses in the control winding.

We have designed and constructed a one phase small scale prototype of a controllable shunt reactor with a HTS control winding.

2. Design and Construction

2.1. Overview

Figure 1 shows a schematic view of the reactor. The reactor consists of two winding and a magnetic circuit. The magnetic circuit comprises of tree limbs and two yokes. The central limb is in the shape of a hollow cylinder. The two return limbs and the yokes return the magnetic flux to the cylinder. The yokes have holes in the center so that a HTS can be wound through the hollow cylinder and through the yokes. The whole reactor is submerged in LN2 (liquid nitrogen) keeping the HTS winding cooled. The main winding is made of copper and is placed over the iron cylinder. The DC current through the HTS control winding $I_{DC}$ generates a DC magnetic field in the azimuthal direction of the iron cylinder. The AC current through the main winding $I_{AC}$ generates a main AC magnetic field in the direction of the cylinder axis. As the DC magnetic field is directed perpendicular to the AC magnetic field the DC magnetic field tilt the magnetic field from the cylinder axis direction and the magnetizability in the direction of the cylinder axis is reduced. To maintain the AC voltage $I_{AC}$ increases. Thus more magnetic energy is stored in the iron core and thus the reactance of the reactor is controlled by $I_{DC}$.

![Figure 1. Schematic view of the reactor](image-url)

2.2. Magnetic Circuit

The central limb is constructed of hollow cylinders made of grain oriented steel with grade M120-23. The steel sheet is cut into long stripes in the rolling direction. The stripes are then rolled into hollow cylinders with outer diameter 52 mm, inner diameter 30 mm and height 25 mm. Five of these cylinders are stacked into a limb with height 125 mm. In order to reduce eddy currents the cylinders and the yokes are electrical insulated from each other with a 75 μm Mylar film. The main AC magnetic field is directed across the rolling direction of the steel sheet and the DC magnetic field in
the rolling direction. The hollow cylinder has the geometry that gives the most uniformly distributed 
magnetic field and therefore gives the most uniformly stored magnetic energy. An unevenly 
distributed magnetic energy gives rise to harmonics and reduces the dynamic control range of the 
reactor.

The two return limbs and the yokes are made of strips of grain oriented steel with grade M120-23. 
The cross section of the yokes and the two return limbs is twice the area of the central limb. Thus the 
saturations of these parts are avoided.

2.3. HTS control windings
The HTS control windings consists of four coils of total 190 turns made of AMSC [4] high strength 
wire. Each coil consists of double pancakes in the form of racetracks. The HTS is wound onto four 
bobbin made of glass fibre reinforced epoxy. The coils are vacuum impregnated with a low viscosity 
epoxy making them mechanically stable. The HTS is exposed to a DC magnetic field from the 
transport current through itself and an AC magnetic field from the main winding. In the bore of the 
cylinder the AC magnetic field is directed longitudinally to the tape and the DC magnetic field is 
directed both parallel and perpendicular to the HTS tape surface. The four coils were positioned so 
that the main part of the DC magnetic field is directed parallel to the tapes, see figure 1. To fill the 
circular cross section of the hollow cylinder with tapes with rectangular cross section, two of the coils 
have 59 turns and the other two coils have 36 turns, see figure 1. The critical current (1 \mu V/cm) for the 
tapes used were between 146-149 A at 77 K. The critical currents for the separate coils are 81 A and 
83 A for the coils with 36 turns and 72 A and 75 A for the coils with 59 turns. The drop in critical 
current is mainly due to the self field from the \( I_{DC} \) and not the AC longitudinal magnetic field from 
\( I_{AC} \) [5]. The coils are connected in series so that the same current goes through all four coils.

When submerge in LN2 the LN2 can flow through gaps between the double pancakes keeping the 
windings cooled. The bending radius of the HTS is 35 mm (95 % Ic retention). The bending radius 
becomes the dimensioning criteria for the coils and thus the size criteria for this small scale reactor.

2.4. AC main winding
The AC main winding are made of 187 turns of copper conductor 7 mm x 1.6 mm. This winding is 
placed over the iron cylinder and gives the main AC magnetic field in the direction of the cylinder 
axis.

3. Experiments and Results
The whole reactor is submerged in LN2. The main winding is fed by a variable voltage transformer 
operating at frequency 50 Hz. The control winding is fed with a DC constant current source. Four pick 
up coils are placed around the hollow cylinder, two near the centre and two on the edges. The pickup 
coils measure the induced voltage and thus to flux density through the cylinder. Figure 2 shows the 
AC voltage as functions of \( I_{AC} \) when \( I_{DC} \) is held constant at 0 A, 10 A, 30 A, 50 A, and 70 A. The 
average value of the applied magnetic field strength in the azimuthal direction of the cylinder \( H^\text{applied} \) 
is then 0 kA/m, 15 kA/m, 45 kA/m 75 kA/m and 105 kA/m. Figure 3 shows the reactive power \( P_r \) of 
the reactor as functions of \( I_{DC} \) when the AC voltage over the main winding \( U_{ac} \) is constant at voltages 
of 40 V, 60 V, 80 V, and 100 V. The flux density in the middle of the cylinder in the direction of the 
cylinder axis \( B_z \) is then 0.65 T, 1.00 T, 1.31 T, and 1.60 T respectively.

With \( I_{DC} = 0 \) A a large part of the reactive power is stored in the small air gaps between the iron 
rolls or in the laminated yoke. When the control current is increased the magnetic field vector is tilted 
from the cylinder axis and the magnetizability in the direction of the cylinder axis is decreased and the 
reactance decreases. The reactance is almost linear below the onset of saturation at approximately 
\( B_z = 1.6 \) T.
The reactive power at $I_{DC} = 70$ A is approximately 6 times the reactive power when $I_{DC} = 0$ A. This dynamic range could easily be increased by decreasing the small air gaps that store reactive power when $I_{DC} = 0$ A. Similar to a transformer with iron core the third harmonics on the current becomes detectable at the onset of saturation at approximately $B_z = 1.6$ T. Harmonics are also detectable when $I_{DC}$ is lower than 10 A. These harmonics are associated with the anisotropy of the grain oriented iron core. In the working range $B_z = 1.3$ T ($U_{AC} = 80$ V) between 1.5 kVA to 4 kVA no harmonic are detectable.

4. Conclusion and discussion

We have designed and constructed a small scale one phase controllable reactor with HTS control winding and demonstrated the feasibility to design large scale controllable shunt reactors with large linear dynamic range and low losses. The technique of controlling the magnetizability can also be use in other power application such as filters and power control of radio frequency generators.

References

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