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# LIQUID COOLING OF CYLINDRICAL TRANSFORMERS MADE OF SOFT MAGNETIC COMPOSITE MATERIAL (SMC) WITH HIGH POWER-TO-WEIGHT RATIO AND OPTIMALLY SHAPED CORE

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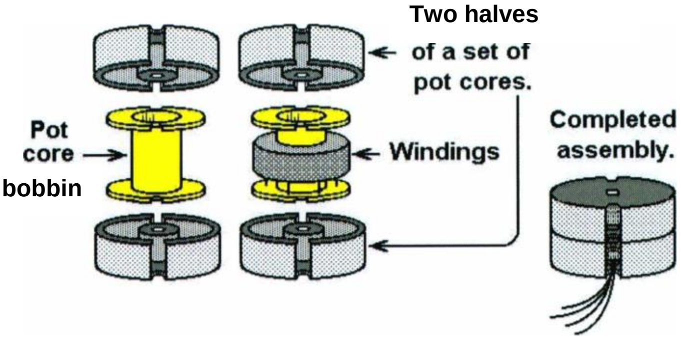
# LIQUID COOLING OF CYLINDRICAL TRANSFORMERS MADE OF SOFT MAGNETIC COMPOSITE MATERIAL (SMC) WITH HIGH POWER-TO-WEIGHT RATIO AND OPTIMALLY SHAPED CORE

**Technical task:**

Pot core transformers produce a uniformly controlled frequency through a ferrite core coil for high frequency or laminated electrical steel for low frequency applications in the electronics industry.




**Initial situation:**

Pot core transformers are widely used in the electronics industry. The material is usually ferrite. The shape of a pot core is round with an internal cavity that almost completely surrounds the coil. Usually a pot core is made in two halves that fit together. Due to the ferrite core, this material is used for high frequency >1 kHz applications. The induction of saturation of the ferrite material is relatively low, about 0.4 T. For lower frequencies, laminated electrical steel is often used as it has a higher saturation induction. (-1.2 T). Conventional soft magnetic sintered materials consist of only one material such as metal powder and are therefore magnetically conductive, which leads to electrically conductive interfaces and electrical eddy currents as well as porosity and iron losses. These properties mean that metal materials have no advantages over traditional laminated electrical sheets and are not used for electric motors. Today, a soft magnetic composite is used for this purpose. It consists of two materials: a composite material such as plastic and a soft magnetic material such as metal powder particles. Although the composite material is magnetically conductive, the composite material prevents two metal powder particles from coming into contact and thus their metallic, electrically conductive interface. This prevents electrical consumption between the metal powder particles and eddy currents. Due to the resulting low iron loss, the material can be used as a stator or rotor material for electric motors.

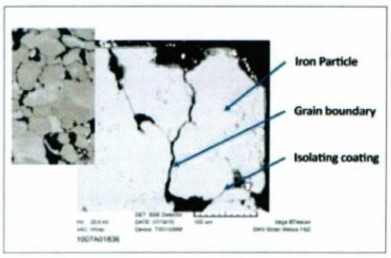
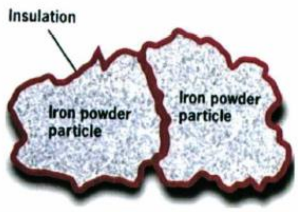
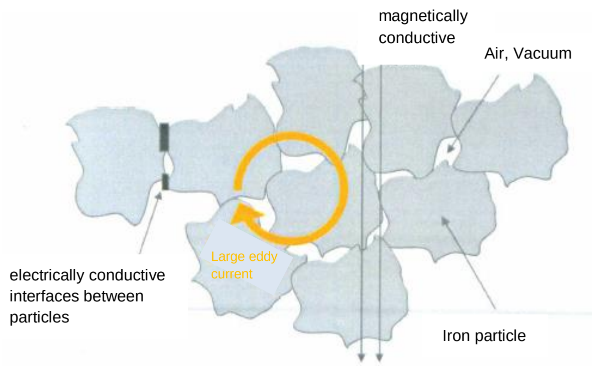
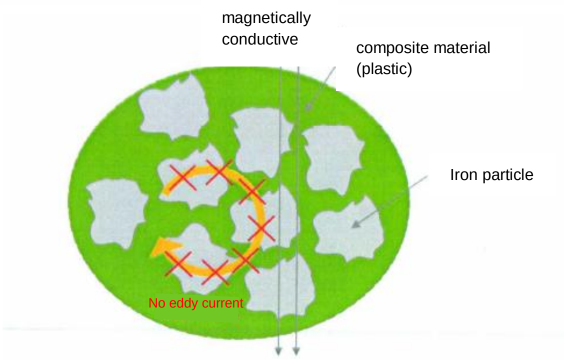



*Fig. 5 Microstructure of SMC compacts showing the isolation coatings [1] (Courtesy GKN Sinter Metals)*



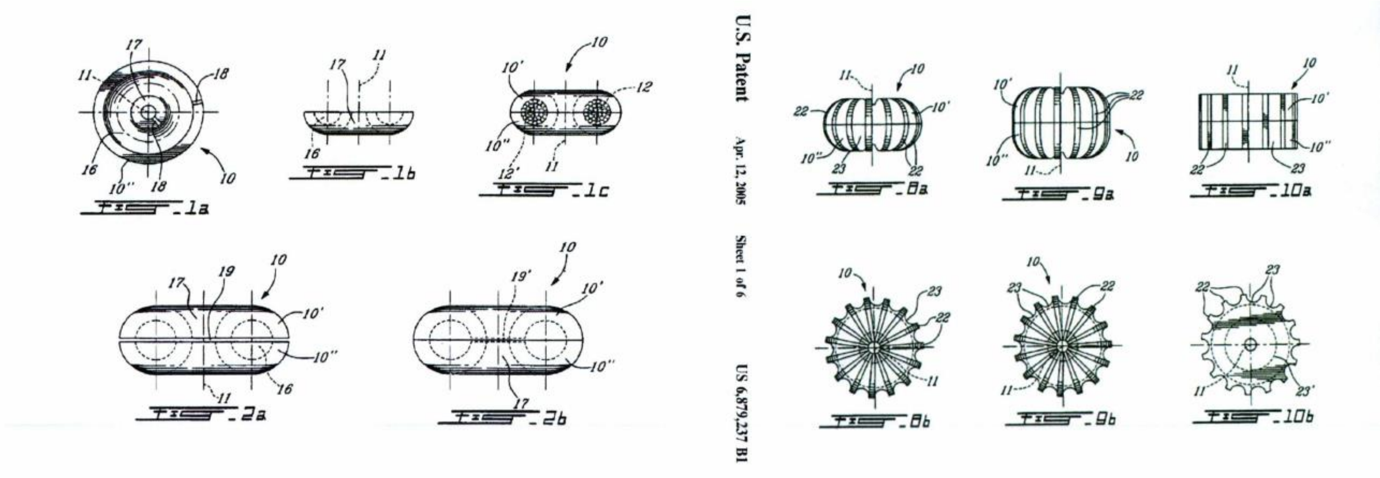

**Example:** Stator of a transverse flux machine made of SMC material



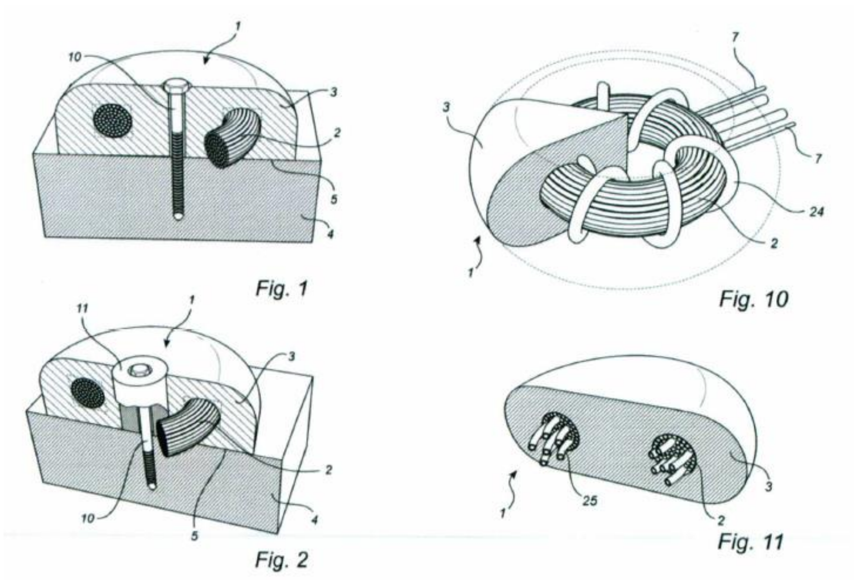



Previous patents in this area:

**CA2282636A1, US6879237B1** - Power transformers and power inductors for low frequency applications using isotropic magnetic composites with high power-to-weight ratio. This patent introduces SMC (soft magnetic composite) for pot core transformers. Air cooling with cooling fins (22) is installed on the outer surface. No liquid or oil cooling is mentioned.




**EP2797090A1** - Thermal management system for SMC inductors
The patent describes a pot-core inductor made of SMC material with improved cooling. The coil is cast (integrated) into the SMC material to achieve very good thermal conductivity. An internal liquid cooling system is introduced in Figs. 10 and 11. Internal cooling tubes (24, 25) are inserted for heat transfer from the heat exchanger (2). The patent describes an inductor (one coil), not a transformer (two coils), so the claims are more general.




**EP2709118A1** - Optimum inductor
The patent describes a pot core inductor made of SMC material with an "optimally shaped" core, which means that the core wall thickness (DI) of the larger radius is smaller than that of the lower radius (D2). The aim is to have a uniformly distributed magnetic flux in the core. Therefore, the SMC core has an elliptical cross-section. (Explanation: With a round cross-section - DI=D2 - the magnetic flux density at the outer radius would be smaller than at the inner radius, i.e. the magnetic flux would not be evenly distributed, which would also lead to inhomogeneous losses and heat formation in the core). The core also has "surface enhancing structures" (10) to increase the surface area of the core and improve the air cooling capability.

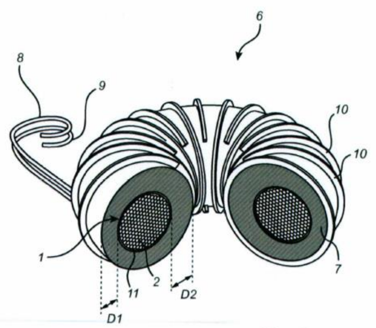


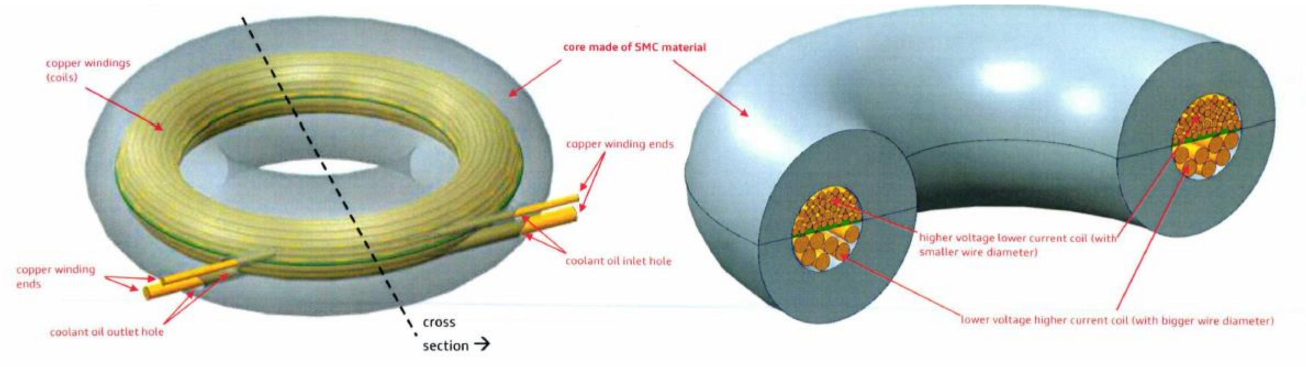

Fig. 3

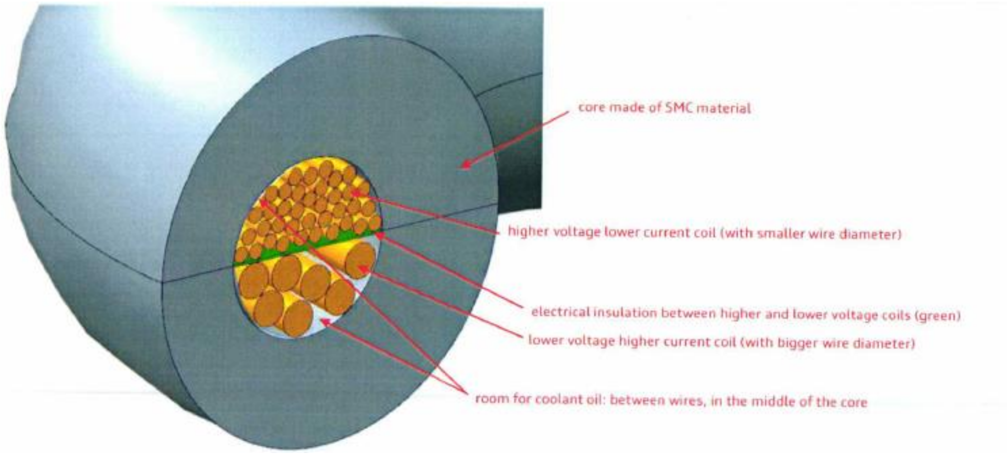
**Solution:**

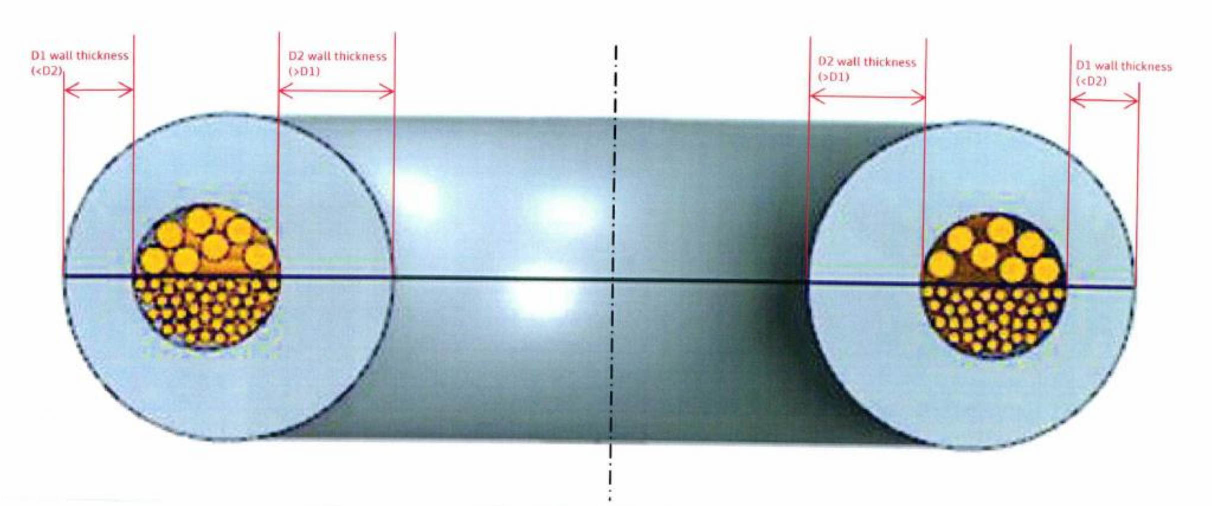
The invention is an improvement of pot-core transformers with better cooling by introducing oil-liquid cooling, using SMC material and optimized geometry of the iron core. As a result of these improvements, the power-to-weight ratio is significantly improved or, from another point of view, a reduced-weight transformer is required to convert a certain amount of electrical power.

Description and characteristics of the invention:

It is a transformer with essentially a pot-core iron core. Unlike transformers with C, U, E, E, I, or toroidal cores, this type minimizes the copper content at a given electrical load because copper is only present in an inner ring. This is important because the copper density is higher than the density of the ferrous material. The density of copper is -8.96 g/cm 3, of conventional electrical steel -7.65 g/cm 3 and 7.37-7.36 g/cm 3 for an SMC material. When designing a transformer with the lowest possible weight for a given electrical load, it is therefore advantageous to choose the pot-core type, as heavy copper is only used for an inner ring surrounded by the lighter iron. As with other core types, the low density iron core is surrounded by higher density copper, resulting in higher weight with low core losses at low frequencies. The new invention, like most transformers (except autotransformers), consists of two copper coil rings. Windings for higher voltages and lower currents have a smaller cross-sectional area, such as windings for lower voltages and higher currents. The high voltage coil is on the pictures above, while the low voltage coil is below. They are separated by an electrical insulating ring that prevents electrical discharges between two coils. The coolant is oil-based, which is also part of the electrical insulation system. Oil has a high dielectric strength and is a liquid that encloses copper coils.
An oil-based liquid - transformer oil - is used for cooling. The oil can be mineral or synthetic, it can contain special additives. With oil cooling it is possible to drastically improve the power-to-weight ratio as it effectively cools coil and wire surfaces. Therefore, a given amount of copper can absorb much more current than, for example, air cooling.
Conventional pot core transformers have air cooling. Patent CA228262636A1 proposes improved air cooling (with cooling fins). Patent EP2797090A1 describes internal liquid cooling. In this patent, however, the liquid flows in tubes. (Another difference is that it is formulated for inductors in general, it is not specified that it is intended for transformers.)
In this invention, copper is completely immersed in oil and there is no pipe wall between cooled wire and coolant. By eliminating the tube wall, thermal resistance is reduced, which improves cooling performance.
There are holes in the core for both ends of a coil. These holes are also used as an inlet and outlet for the cooling oil. Cooling oil is passed through the inlet into the interior of the transformer, where it heats up. Hot oil is then passed through the outlet of the transformer, e.g. to an external heat exchanger, where it cools down. In this way, the oil is passed through the transformer in a closed cooling circuit.
The inlet and outlet openings are designed to affect the interior and the windings. This means to avoid a too small bending radius of the wires and an interruption of the oil coolant flow or a too large amount of turbulent oil flow.
Similar to patent EP2709118A1 optimum inductor, the invention also has an "optimally shaped" core, which means that the core wall thickness (DI) of the larger radius is smaller than that of the smaller radius (D2). The aim is to have a uniformly distributed magnetic flux in the core.


copper windings
(coils)
core made of SMC material
copper winding ends
coolant oil inlet hole
copper winding
ends
coolant oil outlet hole
cross
section →
higher voltage lower current coil (with
smaller wire diameter)
lower voltage higher current coil (with bigger wire diameter)


core made of SMC material
higher voltage lower current coil (with smaller wire diameter)
electrical insulation between higher and lower voltage coils (green)
lower voltage higher current coil (with bigger wire diameter)
room for coolant oil: between wires, in the middle of the core


D1 wall thickness
(<D2)
D2 wall thickness
(>D1)
D2 wall thickness
(>D1)
D1 wall thickness
(<D2)