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1 Introduction

This report describes the work undertaken and completed in Work Package 4 (WP4) of the Technology Strategy Board (TSB) funded 'Next Generation of HVDC Network for Offshore Renewable Energy Industry' Project. The main objective of this work package is to analyse the high power medium frequency transformer requirements including the choice of a suitable material for its core.

To perform this objective, a detailed market analysis will expose the key requirements for technologies in this field. Simultaneously, an extensive literary review of relevant prior art such as research papers, patents and publications from parties involved in the fields of HVDC transformers will be conducted. This research combined with the results of this study will be used to critically assess the merits of the prior art and relevance of existing technologies to the HVDC project. The key features and requirements of the novel HVDC transformer to fully realise its market potential will then become apparent. This will help to steer solutions to technical questions that arise during course of the feasibility study.

From the literary review detailed above, a separate database of transformer core materials will be created. This will enable each material to be scored based on key criteria identified in the literary search and will allow identification of the most viable option. It may prove necessary to conduct tests on one or more high ranking materials to verify results from the literary review or quantify characteristics under specific conditions. If the tests required prove to be of a small enough scale, they will be performed under the feasibility study. Otherwise an appropriate experimental procedure will be created and the test performed at a later stage.

2 Literature Review

Generally medium/high frequency transformers are in the kilowatt power range. Currently there are only three papers that have a transformer detailed in them for a frequency above line frequency (50Hz/60Hz) with a power rating of 1MW and above. The three transformers discussed are in the medium frequency range of 500Hz - 20kHz. They are a 3MW transformer at 500Hz [1], a 1MW transformer at 20kHz [2] and a 5MW transformer at 1kHz [3].

There are a number of characteristics that affect the power rating and efficiency of a power transformer. These are the core type, core material, winding type, winding material, insulation material and the cooling system of the transformer these will be described in section 2.2.

2.1 High Power Medium Frequency Transformers

As described above there are 3 transformers that have a power rating over 1MW and at medium frequency.

2.1.1 3MW transformer at 500Hz

This section makes reference to [1]. This paper describes a 3MW turbine with an operating frequency of 500Hz. This is a single phase medium frequency transformer replacement for the conventional three-phase line frequency transformers that converts electricity to HV in wind turbine applications.

The transformer within this paper [1] was designed using a E-Core type refer to section 2.2.1.3 for E-core details, the core material was an Amorphous material refer to section 2.2.2.3 for Amorphous material details, stranded Litz wire as the windings refer to section 2.2.3.2 for litz wire details and an epoxy cast resin insulation refer to section 2.2.4.1 for epoxy resin details.

The impact that the frequency of the transformer has on the core area (A_c) and the winding area (A_w) can be seen in (1):

$$\mathbf{A_w} \times \mathbf{A_c} = \frac{1}{f} \times \frac{U_{rms} \times I_{rms}}{J \times B_{pk}} \qquad (1)$$

A_w - Winding Area (m^2)
A_c - Core Area (m^2)
f - Frequency (Hz)
$U_{rms} \times I_{rms}$ - Power Rating (VA)
J - Current Density (A/ m^2)
B_{pk} - Peak Core Flux Density (T)

As seen in the equation (1), there are a number of variables that influence the winding area and the core area. To make an effect on the size of the core and winding areas and in this case to make them smaller one or more of the following would be performed; decreasing the power rating, increasing the frequency, or increasing the current density and core flux density.

Increasing the frequency of the transformers has the advantages of decreasing the size of the transformer and increasing the power density of the transformer. A decrease in size of the transformer may however, have effects where it may increase the following; the winding losses, core losses and the dielectric losses.

The number of winding turns does not only has an impact on the winding area it also has an impact on the voltage of the system and the core area of the transformer.

Losses that affect transformer performance include the leakage inductance, parasitic capacitances, winding losses, core losses and dielectric losses. Other considerations include the thermal management of the transformer.

2.1.2 1MW transformer at 20kHz

This section makes reference to [2]. This paper investigates the performance of medium frequency transformer that has two main functions. These are to step up and down the voltage levels and to provide isolation between HV and LV sides.

The purpose of this is to enable the study of different core types with the same material. The variables in this setup were the type of windings, the insulation used, the thermal management and the core types. The author uses the voltage applied to the transformer to work out core size and number of turns is determined. The core material is standardised to be Nanocrystalline material (Vitroperm 500F) refer to section 2.2.2.4 for Nanocrystalline material details.

The first core type used was a U-core with windings on both legs of the core. Refer to section 2.2.1.2 for U-core details. The LV windings were copper foil and the HV windings were Litz Wire strands. The insulation was achieved by placing 20mm dry insultation layer between the primary and secondary. The insulation material used was Micares. The extraction of the losses of the LV winding and core was achieved by placing water cooled heat sinks on the core surface and the windings. The HV cooling was achieved by placing water jacket on the HV windings. Water cooled cable was suggested by the author as an alternative.

The second core type used was a shell type that consists of two pairs of U-cores arranged in an E-core configuration. Refer to section 2.2.1.3 for E-core details. The winding was built using a copper foil around the middle leg. The 133 strand HV cable used can withstand 100kVDC by using a silicon based insulation material. This provides insulation between the LV and the HV sections but also between each lay of HV cable. The heat extraction was water cooled heat sinks placed on the core and the windings.

The third core type was the same as the second core type except for the use of litz wire on the HV side with potted insulation as per the U-core setup.

The fourth core type was with a matrix type transformer, this used the same setup as the second core type mentioned above.

The findings from the performance review are listed in the table below:

Type	Losses (Core/Copper) kW	Volume litre	Isolation type
U-Core	2.81 (1.26/1.55)	4.3	Potted
Shell Type 1	3.76 (1.83/1.93)	11.9	Cable
Shell Type 2	3.37 (0.95/2.42)	3.5	Potted
Matrix Transformer	4.51 (2.23/2.28)	11	Cable

Table 1: Performance of different transformer concepts at 1MW transferred power [2]

2.1.3 5MW transformer at 1kHz

This section makes reference to [3]. This paper describes a test that was performed on 0.18mm thick piece of silicon steel laminated core material. The rating of the proposed transformer that the core material would be used in was 5MW at 1000Hz. It does not provide the details of the transformer as it appears to be in the very early stages of development. It details a difference between calculated and bench test values.

The reason the test was preformed was to find out if the calculated core losses were representative of test results. The test was achieved by measuring the magnetic flux density in the core material, the transformer voltage, the magnetic hysteresis loop and the core loss for both the test bench experiment and the calculation.

Unfortunately, this paper does not describe the method of testing or provide the raw test data. The test bench experiment core losses were up to 32% better than the calculated core losses at a magnetic flux density of 0.1T. Although as the magnetic flux density increased to 1.5T the difference between the calculated and the test bench experiment became less apparent with the core losses only being 6% lower as seen in the Table 2.

B_{max} in T	P_s in W/kg Calculated	P_s in W/kg Experiment	$\frac{\text{Calculated}}{\text{Experiment}}$
0.1	0.54	0.41	32%
0.5	9.61	8.59	12%
1.0	33.96	31.09	9%
1.5	73.90	69.73	6%

Table 2: Core Loss Calculated against Experiment [3]

2.2 Transformer Components

2.2.1 The Core Types

There are a number of different core types. These are Pot Type (Figure 1), U-core Type (Figure 3), E-core Type (Figure 5) and Toroidal Type (Figure 7).

The power rating of the core types can be established from the Area Product (Ap) which is also referred to as the product of Window Area and Core Area (WaAc) and is used by the core suppliers as a means of summarising the core dimension and the electrical properties in their catalogues. It is a useful parameter for estimating the power handling capability of a core, if the frequency and circuit topology are known.

The equation (2) for the calculating WaAc is as follows [4]:

$$\mathbf{WaAc} = \frac{\boldsymbol{P_o} \times \boldsymbol{D_{cma}}}{\boldsymbol{K_t} \times \boldsymbol{B_{max}} \times \boldsymbol{f}} \qquad (2)$$

WaAc - Product of window area and core area (cm^4)
P_o - Power Out (VA)
D_{cma} - Current Density (kcmil /A)
K_t - Topology constant
B_{max} - Flux Density (G)
f - Frequency (Hz)

2.2.1.1 Pot Type

Figure 1 below is an image of a Pot Type transformer core. The Pot Type is setup with a bobbin in the centre of the transformer, the HV windings and the LV windings are wound around the bobbin and the two half of the Pot type transformers are placed around the windings.

Figure 1: Pot Type Transformer [5]

The advantages of a Pot type transformer are that the windings are constructed around a bobbin. This means that the bobbin can be wrapped easily irrespective of the core shape and placed within the Pot core. As the bobbin is completely enclosed within the Pot type transformer the effects of Electromagnetic Interference (EMI) are reduced. The round centre of the Pot type transformer provides a self-shielding this prevents stray magnetic fields from entering and exiting the structure so the magnetic leakage flux is reabsorbed into the core material. [6] [7]

The disadvantage of a Pot type transformer is the bobbin is enclosed so the removal of the heat from the core and the windings is not easy. Conventionally, the Pot type transformers are not used for high power applications. [8]

Typical power rating of the Pot type transformer is in the region from 0.01 to 3.7 Ap in a size range of 7-43 mm. Where the size range is the measurement 'A' in Figure 2. [9]

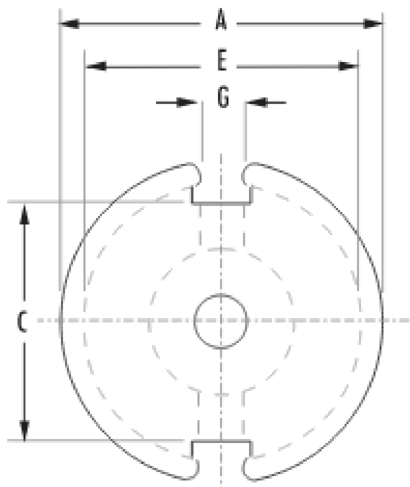

Figure 2: Pot Type Size Reference [9]

2.2.1.2 U-core Type

Figure 3 shows a U-core type transformer and the windings setup. The U-core type is sometimes referred to as C-core type. It is constructed from either two U-core halves of a magnetic core or a U-core and a I shaped magnetic core. There are two setups for the U-Core Type transformer, the first is to have the HV and the LV windings wound around both legs and the second is to have LV windings wound around one leg of the core and the HV windings are wound around the other.

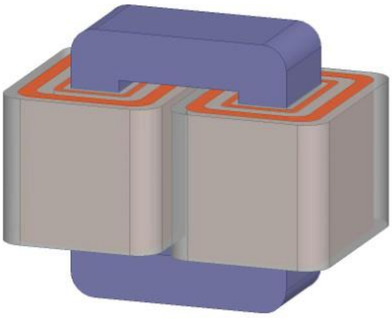

Figure 3: U Type Image [10]

The main advantage of a U-core type transformer is that the two LV windings are paralleled on the both legs this results in the reduction in height. This is achieved by reducing the overall cross sectional area of the windings by placing two windings in parallel. This advantage is dependent on the windings setup explained above, the current carrying capacity of the winding and the amount of current in the system. The advantage of having the HV and the LV windings separate legs is that this forms isolation. [10]

The disadvantage of the U-core type transformer is due to the core being surrounded by windings, the core type transformer has poor thermal properties. [10]

Typical power rating of the U-core type transformer is in the region from 0.01 to 975 Ap in a size range of 10-126 mm. Where the size range is the measurement 'A' in Figure 4. [9]

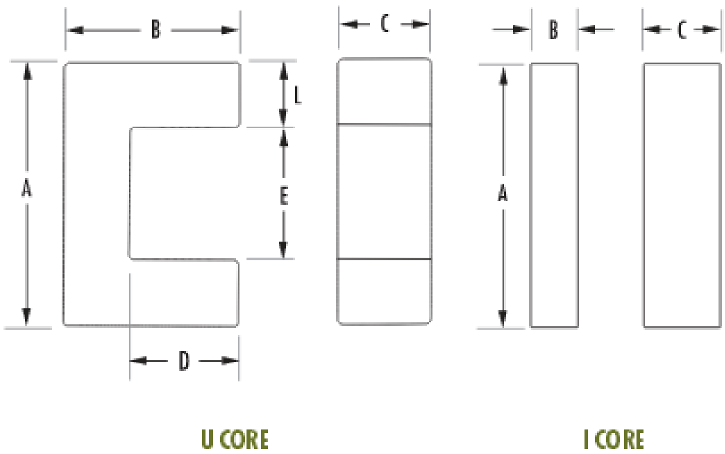

Figure 4: U-core Type Size Reference [9]

2.2.1.3 E-core Type

Figure 5 shows an E-core type transformer and its windings setup. E-core type is sometimes referred to as a Shell type. It is constructed from either two E halves of a magnetic core or an E and an I shaped magnetic core. The E-core type transformer has both the windings wound around the central single leg. The HV windings would be wound first with the LV windings wound over the HV cables. This helps with heat dispersion as the LV windings, carry higher current and therefore operate at a higher temperature. Placing the LV windings on the outside of the HV windings would not be directly heating the core material.

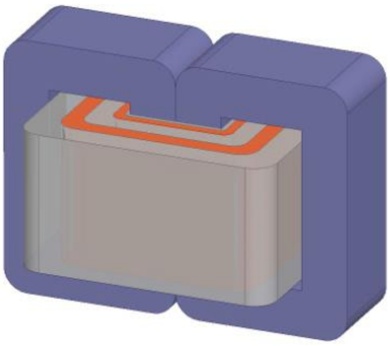

Figure 5: E-Core Type Image [10]

The advantages of E-core type transformers are; they have a higher mechanical strength than the U-core Type transformer which allows the transformer to withstand more forces experienced by the transformer in a short circuit scenario. Similar to the Pot type transformer the magnetic leakage flux from the windings are absorbed back into the core. This is not as efficient as the Pot type transformer as the windings are not completely enclosed. The shape of the E-core type transformer allows the system to be cooled easier as there are more free contact faces. The mechanical strength and the ability to cool make the E-core type transformer very reliable. [11]

The disadvantages of an E-core type transformer are the transformer is difficult to assemble. Also, due to the E-core type having more core material the cost of the transformer is more expensive compared to the U-core type transformer.

Typical power rating of the E-Core type transformer is in the region from 1.4 to 156 Ap in a size range of 40-100mm. Where the size range is the measurement ‘A’ in Figure 6. [9]

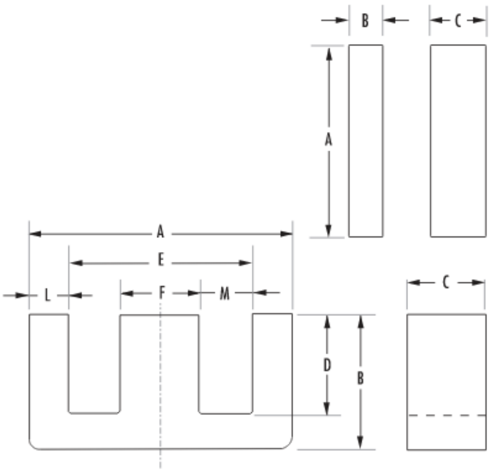

Figure 6: E-Core Type Size Reference [9]

2.2.1.4 Toroidal Type

Figure 7 show a Toroidal transformer. The Toroidal topology is a continuous 'O-Ring', it's a similar setup to the E-core type. The HV windings are wound around the Toroidal and then the LV windings are wound around the outside of the HV windings.

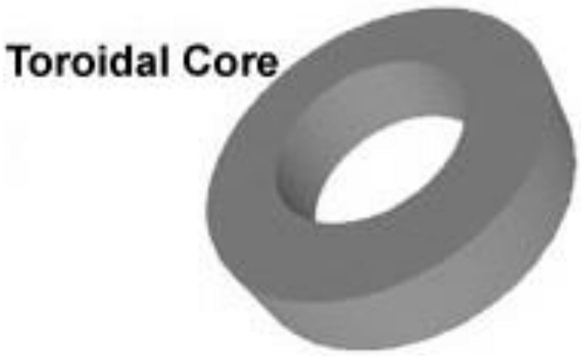

Figure 7: Toroidal Type Transformer [5]

The advantages of Toroidal transformers are; they are very efficient as there is no air gap and they are small in size.[12]

The disadvantages of Toroidal transformer are that they have a higher manufacturing cost due to the complexity due to the windings not being on a bobbin and the need to manufacture them individually. Another disadvantage is an inrush current problem is caused when the Toroidal transformer is powered off and then powered on. This is due to the absence of an air gap in the transformer, as the transformer gets switched off residual magnetism is stored in the transformer. At the point the system gets switched back on, this stored magnetism and the current applied to the transformer causes a high inrush current to the transformer. [12]

Typical power rating of the Toroidal type transformer is in the region from 15 to 373 Ap in a size range of 61-140mm. Where the size range is the measurement 'A' in Figure 8. [9]

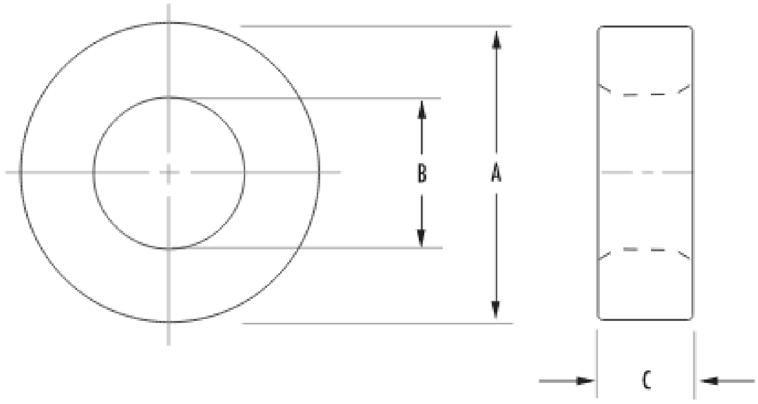

Figure 8: Toroidal Type Size Reference [9]

2.2.1.5 Conclusion

Table 3 shows that the highest power density is the U-core transformer. The most efficient is the Toroidal transformer. The E-core transformer is the easiest to cool. The literature review in section 2.1 do not use Toroidal type or Pot type transformers as they are not generally used in high power applications.

Core Type	Efficiency	Power Density	Cooling
Pot	2^{nd}	4^{th}	4^{th}
U-core	4^{th}	1^{st}	2^{nd}
E-core	3^{rd}	2^{nd}	1^{st}
Toroidal	1^{st}	3^{rd}	3^{rd}

Table 3: Core Type Classification

2.2.2 The Core Materials

The main material requirements for transformers at medium frequency high power are low core loss, high saturation flux density and high continuous operating temperature.

The core loss is the sum of the losses due to the hysteresis and the loss due to the eddy currents [13].

$$\text{Core Loss} = \text{Hysteresis Loss } (W_h) + \text{Eddy Current Loss } (W_e) \qquad (3)$$

Where Hysteresis loss (W/kg) is:

$$\boldsymbol{W_h} = \mathbf{k_1} \times \mathbf{f} \times \mathbf{B_{max}}^{\boldsymbol{n}} \ (4)$$

Where Eddy current loss (W/kg) is:

$$\mathbf{W_e} = \frac{\mathbf{k_2} \times \mathbf{f^2} \times \mathbf{t^2}\ \mathbf{B_{eff}^2}}{\boldsymbol{\rho}} \qquad (5)$$

k_1 – hysteresis constant for the material
k_2 – eddy current constant for the material
f – frequency (Hz)
t – thickness of the material (mm)
ρ – resistivity of the material (Ω·m)
B_{max} – maximum flux density, (T)
B_{eff} – flux density corresponding to the r.m.s. value of the applied voltage
n – 'Steinmetz exponent' which is a function of the material.

The saturation flux is the point where the Magnetic Flux Density (B) saturates as of the Magnetic Field Strength (H) increases. This characteristic can be seen on the B-H curves of the materials. The flux density of the core material is calculated as per [14]:

$$\boldsymbol{B} = \boldsymbol{\mu} \times \boldsymbol{H} \qquad (6)$$

Where the permeability is:

$$\boldsymbol{\mu} = \boldsymbol{\mu_r} \times \boldsymbol{\mu_0} \qquad (7)$$

B - Magnetic Flux Density (T)
H – Magnetic Field Strength (A/m)
μ – permeability (H/m)
μ_r – Relative permeability (H/m)
μ_0 – permeability of free space (H/m)

There are four different types of core material that can be used in high power medium frequency applications these are Steel, Ferrite, Amorphous and Nanocrystalline. The four different core materials have different properties and characteristics when used in these applications.

2.2.2.1 Steel

Conventionally, line frequency (50/60Hz) transformers have a core of Silicon-Steel or Nickel-Steel, this is the case because this material is the cheapest to make. These can be used for high power applications as seen in Table 4 as it has the highest saturation flux. The problem with the material becomes apparent when it is used in medium frequency applications as the transformer losses are the highest as seen in Table 4 .

2.2.2.2 Ferrite

Conventionally, ferrite materials are most commonly used in power electronic systems as it has a high volume resistivity characteristic in a high frequency application. As seen in equation (5) a high resistivity means a reduction in the losses due to the eddy currents and the overall core losses. This can be seen in Table 4 as the Ferrite material has the lowest losses of the materials.

2.2.2.3 Amorphous

Amorphous materials have large permeability, in accordance with equation (6) a large permeability increases the magnetic flux density. Hence this increases the saturation flux level for this material. Unfortunately, the losses of the core material are the second highest of the materials according to Table 4.

2.2.2.4 Nanocrystalline

Nanocrystalline has the benefits of both the amorphous and the ferrite material, as Nanocrystalline material has a high saturation flux density and a low core loss as seen in Table 4. Although, the continuous operating temperature of the Nanocrystalline is the lowest due to the curing temperature of the laminates used.

2.2.2.5 Conclusion

For a high power medium frequency transformer the most suitable material suggested in this study would be the Nanocrystalline material as it has the highest saturation flux to losses ratio. The main issue with this material is the cost as it is the most expensive and its low continuous operating temperature. A cooling system would have to be installed to keep or maintain the core temperature within the rated values. This however has cost implications.

Core Material Type	Series	Saturation Flux (T) at 25 degrees	Losses (KW/m^3) 0.1T, 100kHz	Continuous Operating temperature
Silicon Steel	10JNHF600	1.87	1757	150
Ferrite	3C93	0.52	49	140
Amorphous	2605SA1	1.56	1377	150
Nanocrystalline	Vitroperm500F	1.2	73	120

Table 4: Core Materials Example Properties [10]

2.2.3 Winding Material

The losses that are experienced by the winding material are due to the Proximity Effect and the Skin Depth. [15]

Power loss due to Skin Effect is:

$$\mathbf{P}_{skin} = \boldsymbol{R_0} \times \mathbf{I}^2 \qquad (8)$$

Where Effective Resistance is [16]:

$$\boldsymbol{R_o} = \frac{\rho \times l}{\alpha} \qquad (9)$$

P_{skin} – Power loss due to Skin Effect
R_o – Effective Resistance (Ω)
I – Current in Conductor (A)
p – Resistivity of the conductor (Ωm)
l – Length (m)
α – Cross Sectional Area (m^2)

The ideal characteristics for the windings in a high power medium frequency transformer are a large current carrying capacity, maximise the use of the winding area, have low losses and provide good thermal properties.

There is a number of form/type of conductors that can be used in this application. These are solid, circular and foil.

2.2.3.1 Solid Form Conductor

The solid form conductor (Figure 9) is ideal for high power applications. Table 5 shows that the effective resistance in a solid round conductor increases by 205% compared to its resistance in DC state, due to the skin effect when the frequency increased to 50KHz.

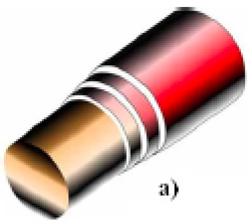

Figure 9: Solid Form Conductor Example [10]

2.2.3.2 Circular Form Conductor

The circular form conductor (Figure 10) provides a similar current carrying capacity to the solid form conductor so it can be used in high power applications. The circular wire is also stranded and/or twisted, this assists with the medium frequency application as the strands helps reduce the eddy currents in this application. This is explained via the litz wire example below. Another advantage of this topology is the cable protection can be used as an insulator.

The disadvantage of this topology is that the fill factor is lower than the foil type as the insulation increases the volume of the overall wire.

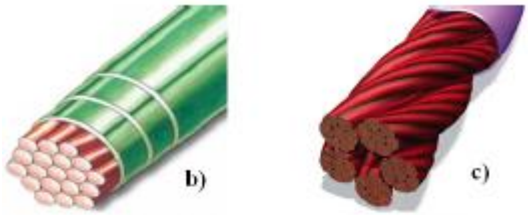

Figure 10: Circular Form Conductor Images [10]

Litz wire is a special form of circular form wire or rectangular form wire. It is constructed so that strands of the wire are insulated individually, are the exact same length and are twisted. As the litz wire is stranded the cross sectional area of the wire is increased, as equation (9) an increase in the cross sectional area means a reduction in the effective resistance of the wire hence reducing the power loss due to skin effect. A disadvantage of litz wire is it is the most expensive type of conductor.

Multi-Strand wire is considered a cheaper alternative to the litz wire but the losses in a multi-strand wire are higher than the litz wire. The way to protect the multi-strand wire from the losses is by insulating the strands, this is an additional cost but the benefit of this is determined through a cost/loss ratio versus the litz wire equivalent. [17]

2.2.3.3 Foil Form Conductor

The main advantage of the foil form conductor is the fill factor and is applicable for medium frequency application as similar to the Litz wire the cross sectional area of this foil reduces the effective resistance. The fill factor allows multiple layers to be placed around the core with each layer being an entire winding layer. The foil topology can be used on both high voltage and low voltage applications, although the foil windings are more suitable to the low voltage applications.

The disadvantage of the foil form conductor is that the high voltage application is limited by the insulation that is used. As seen in Table 5, the foil form conductor performs worse than the litz wire in a 50kHz application.

Figure 11: Foil Form Conductor Image [10]

2.2.3.4 Conclusion

The winding with the least impact on the losses in the windings is the Litz wire. This can be seen in Table 5 as the change in the effective resistance compared to the DC resistance is only 0.02% meaning at medium frequency applications the losses would be less than that of the foil and solid type conductors.

Conductor Type	**DC Resistance R_{DC} (mΩ/m)**	**Effective Resistance F (mΩ/m)**	**% Change**
Solid Round	2.0229	6.1756	205.3
Litz Wire (329 Strand)	2.0229	2.0233	0.02
Foil (thickness = 2δ)	2.0229	2.2571	11.6

Table 5: Effective Resistance due to Skin Effect for the three Conductor Types, f = 50 kHz, 6 - 12 MILS [15]

2.2.4 Insulation Material

This section will describe the two types of insulation the dry resin and the wet resin. There a number of areas or components that require insulation, these can be characterised into two categories, and these are the major and minor insulation. Major insulation is installed between the HV and LV windings, between the core and windings and between the windings and the enclosure. Minor insulation is used to insulate the windings. Although they are classed as major and minor this is with respect to their size rather than a class of insulation as they are subjected to the same voltage stresses.

2.2.4.1 Dry Resin

The use of dry resin insulation can be used for both the major and the minor insulation.

Dry resin transformers are the preferred option in the application of wind turbines, this is primarily due to the dry resin transformer being less flammable than the oil filled transformers and it reduces the environmental impact. Other advantages of a dry resin transformer are that it would reduce the weight and complexity of the cooling system as well as reducing the maintenance and operation costs during its lifetime. [1]

The disadvantage of the dry resin transformer is that they are not self-healing as the resin cannot be removed and replaced like a wet resin (oil filled) transformer if a fault was to occur.

As seen in section 2.1.2, the issue with the HV cable type of insulation is the volume of the transformer increases. Table 6 suggests that the potted epoxy would be the most suitable insulation for this application.

Isolation Type	Material	Dielectric Strength
Potted	EPOXY	16 kV/mm
Potted	Micares	8 -24 kV/mm
HV cable	Silicone	4 -28 kV/mm
HV cable	PVC	9.8 -19 kV/mm
HV cable	HDPE	19 kV/mm

Table 6: Dry Resin Examples [18]

The dry insulation can be cooled by air or by water using cooling jackets placed on the core material. The preferred option is a water cooled system as it takes the heat away from the transformer.

2.2.4.2 Wet Resin

The oil-immersed transformer use dry resin paper and pressboard material to provide insulation around the copper conductors and the enclosure.

The pressboard is used as a high dielectric material and has a higher dielectric strength than the oil. The benefit of using the oil is that it is self-healing as it can be drained, removed and replaced if a fault was to occur inside the transformer.

The cooling system for an oil filled transformer can be by air or water. Similar to the dry resin transformer examples the method of cooling depends on the services that are available. The benefit for the oil is due to it being in liquid form the oil can be pumped or moved to areas where the heat is extracted. The dry resin transformer relies of the convention of the air around the transformer.

3 Conclusion

Although there are a number of studies about high power medium frequency transformers there are not many applications in the MW range. The three that have been discussed in this literature review are the only transformers that operate above 100Hz and have a rating of 1MW and above. From the papers there is still a lot of uncertainty about the best setup of the core type, materials and thermal extraction that is best suited for a high power medium frequency transformer application.

The two main core types that are used in a medium frequency high power applications (U-core Type, E-core Type) have been tested by M. A. Bahmani et al [19] at different rated powers, frequencies, number of turns and maximum magnetic flux densities. It was concluded that based on different characteristics the E-core type was found to provide the most even profiles throughout the tests but was judged to be most applicable for low range frequencies and power. The U-Core type was better suited to higher frequencies and higher powers.

Of the four materials that were described in the core materials section 2.2.2, two of the materials can be used in high power medium frequency application. These are the amorphous material and the Nanocrystalline material. The reason why the silicon steel and the ferrite materials were not suggested for this application were due to the steel having high losses in frequencies above 50Hz and ferrite material having low saturation flux density. The preferred material for this application would be Nanocrystalline as this has the best saturation flux density and low loss combination. The issue with the Nanocrystalline material is the average operation temperature is limited by the laminated epoxy on the material being approximately 120 degrees Celsius. For this reason, if the operating temperature is above 120 degrees or the budget is limited in this application the amorphous material would be preferred.

The topology of winding that would be best suited to this application would be to use the foil topology for the LV winding and the circular strands for the HV winding. The reason for the foil LV winding is to reduce the size and the weight of the transformer. The circular strands are used in the HV application due to the mechanical strength and further dielectric strength they provide.

A dry transformer is chosen for this application as the oil filled transformer requires more maintenance, is larger and weighs more. The preferred method of insulating the transformer would be to use an epoxy material. The reason for this is due to its high di-electric strength and as the proposed of increasing the frequency is partly to reduce the size and the weight of the transformer and this has the smallest impact on this. The preferred cooling method as mentioned above would be through a water cooling system.

This literature review has established the individual components of the transformer and has discussed similar high power medium frequency applications. For this particular application further design work is required to fully understand the requirement of the transformer.

4 References

[1] S. Meier, T. Kjellqvist, S. Norrga, and H.-P. Nee, 'Design considerations for medium-frequency power transformers in offshore wind farms', in *Power Electronics and Applications, 2009. EPE'09. 13th European Conference on*, 2009, pp. 1–12.

[2] G. Ortiz, J. Biela, D. Bortis, and J. W. Kolar, '1 Megawatt, 20 kHz, isolated, bidirectional 12kV to 1.2 kV DC-DC converter for renewable energy applications', in *Power Electronics Conference (IPEC), 2010 International*, 2010, pp. 3212–3219.

[3] N. Soltau, R. W. De Doncker, D. Eggers, and K. Hameyer, 'Iron Losses in a Medium-Frequency Transformer operated in a High-Power DC-DC Converter', *IEEE Trans. Magn.*, vol. 50, no. 2, 2013.

[4] 'Transformer Design with Magnetics Ferrite Cores'. [Online]. Available: http://www.mag-inc.com/design/design-guides/Transformer-Design-with-Magnetics-Ferrite-Cores. [Accessed: 03-Mar-2014].

[5] 'Transformer Cores, Reluctance and Permeability'. [Online]. Available: http://www.learnabout-electronics.org/ac_theory/transformers02.php. [Accessed: 11-Mar-2014].

[6] C. MAGNETICS, 'About Magnetics'.

[7] 'Microsoft PowerPoint - Presentation-magnetics.ppt - fundamentals_of_magnetics_design.pdf'. [Online]. Available: http://www.ieee.li/pdf/viewgraphs/fundamentals_of_magnetics_design.pdf. [Accessed: 14-Mar-2014].

[8] 'Design_Application_Notes.pdf'. [Online]. Available: http://www.lodestonepacific.com/distrib/pdfs/Magnetics/Design_Application_Notes.pdf. [Accessed: 07-Mar-2014].

[9] 'Magnetics Short Form Cover (Page 2) - zotero://attachment/88/'. [Online]. Available: zotero://attachment/88/. [Accessed: 05-Mar-2014].

[10] E. Agheb and H. K. Hoidalen, 'Medium frequency high power transformers, state of art and challenges', in *Renewable Energy Research and Applications (ICRERA), 2012 International Conference on*, 2012, pp. 1–6.

[11] 'Shell-form transformers'. [Online]. Available: http://www.meppi.com/Products/Transformers/Power/Pages/Shell-formtransformers.aspx. [Accessed: 04-Mar-2014].

[12] G. J. Taggart and J. D. Goff, 'Optimizing linear power supply performance with line frequency toroidal transformers', in *Proc. NorthCon*, 1994, pp. 11–13.

[13] M. Heathcote, *J & p transformer book*. Oxford: Newnes, 2007.

[14] 'Magnetic properties of materials'. [Online]. Available: http://info.ee.surrey.ac.uk/Workshop/advice/coils/mu/index.html#mur. [Accessed: 13-Mar-2014].

[15] M. H. Kheraluwala, D. W. Novotny, and D. M. Divan, 'Coaxially wound transformers for high-power high-frequency applications', *Power Electron. IEEE Trans. On*, vol. 7, no. 1, pp. 54–62, 1992.

[16] 'Power System Engineering - R.K. Rajput - Google Books'. [Online]. Available: http://books.google.co.uk/books?id=E7Em_V7Zq9sC&pg=PA495&dq=power+loss+due+to+skin+effect+equals+effective+resistance&hl=en&sa=X&ei=uS8sU-mfKK6v7Aa5kIHgDA&ved=0CDsQ6AEwAA#v=onepage&q=power%20loss%20due%20to%20skin%20effect%20equals%20effective%20resistance&f=false. [Accessed: 21-Mar-2014].

[17] C. R. Sullivan, 'Cost-constrained selection of strand diameter and number in a litz-wire transformer winding', *Power Electron. IEEE Trans. On*, vol. 16, no. 2, pp. 281–288, 2001.

[18] G. Ortiz, J. Biela, and J. W. Kolar, ‘Optimized design of medium frequency transformers with high isolation requirements’, in *IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 631–638.

[19] M. A. Bahmani, E. Agheb, T. Thiringer, H. K. Høidalen, and Y. Serdyuk, ‘Core loss behavior in high frequency high power transformers—I: Effect of core topology’, *J. Renew. Sustain. Energy*, vol. 4, no. 3, p. 033112, 2012.

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