**T - formulation based numerical modelling of dynamic loss with a DC background field**

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**Abstract.** High-temperature superconducting (HTS) generators offer the advantages of high efficiencies and increased power densities. Most superconducting generator designs feature DC field windings to provide the required magnetomotive force. The superconducting field windings in HTS machines are subject to complex magnetic fields, which lead to dynamic losses occurring in the winding. This magnetic field environment has a large DC background component due to the self-field of the superconducting field windings. This paper investigates the dynamic loss in combination with a DC background field using a T – formulation based numerical model, where the dynamic region is used to identify the dynamic loss. Our double claw pole generator design, which offers a high power density at low superconducting tape requirements, is used as a case study for dynamic loss analysis with a DC background field. Results show that DC background field has a strong effect on the dynamic loss due to the reduced critical current. In addition it was shown that the T – formulation based numerical model in conjunction with the dynamic region requires further research to accurately predict the dynamic loss due to the changing DC current transport region.

1. **Introduction**

One of the challenges the wind energy sector is facing is to reduce the cost of energy. Higher power-rated wind turbines tackle this issue by lowering installation and maintenance costs per kWh [1]. However, as the wind turbines get bigger, the tower head mass increases significantly, which complicates the foundation of the wind turbine. The double claw pole generator is a promising candidate to enable very large wind turbines rated for 10 MW and higher due to its increased power density and hence lighter weight. It features a stationary superconducting field winding, which is supplied with a DC current. The double claw pole generator design uses significantly less superconducting tape than other 10 MW superconducting generator designs [2, 3]. Rotating claw poles are oriented around the field winding to create a North-South pole flux variation along the stator coils on each side. A schematic of the double claw pole generator is depicted in Figure 1.

![Figure 1. Double claw pole generator concept [2](image)](image)
One disadvantage of the double claw pole machine is that it is heavier than other superconducting generator concepts. However, it was shown that the power density of the generator can be further increased by adopting a novel stator design [2], increasing the electric loading [4] and by stacking machine modules [5]. The generator concepts were designed using reluctance networks in combination with finite element analysis simulations under static and transient conditions.

To further study the performance of the double claw pole design, it is necessary to investigate the superconducting field winding in more detail. One aspect that most HTS generator designs have in common is the use of superconducting field windings, which are supplied with a DC current. However due to the magnetic field harmonics that exist within the generator environment [6 – 8] and affect the superconducting tapes, dynamic losses are present [9 – 11]. The aim of this paper is to quantify this loss using the double claw pole generator design as a case study. A transient 3D FEA using the simulation software Mentor Graphics MagNet was performed to identify the magnitude and direction of the magnetic field harmonics penetrating the superconducting tape. The field winding is a large circular coil. Several points along the tapes were investigated. The magnetic field is then supplied to our in-house superconductor model to calculate the dynamic loss exhibited by the superconducting winding.

2. T – formulation based numerical model

A numerical model is used to quantify the dynamic loss that occurs within the superconducting winding, it has been verified through numerous experiments. The model will be summarized in this section, more detailed information can be found in references [9 – 11]. The T – formulation serves as the basis of the numerical model, where $T$ is defined as the current vector potential, which is related to the current density such as that $\vec{J} = \nabla \times \vec{T}$. The governing equation of the electromagnetic field in the HTS tape is derived from Faraday’s law as:

\[
-\frac{\partial}{\partial y} \frac{1}{\sigma_{sc}} \frac{\partial T}{\partial y} = -\frac{\partial}{\partial t} \left( \mu_0 t_s \int \frac{1}{y - y'} \frac{\partial T}{\partial y} dy' \right) - \frac{\partial B_\perp}{\partial y}
\]  

(1)

where $y$ is the coordinate in the lateral direction of the HTS tape, $\sigma_{sc}$ is the conductivity of the superconducting layer and $B_\perp$ is the perpendicular component of the external magnetic field. Figure 2 shows a schematic of the superconducting layer in a magnetic field, where $2w$ is the width of the tape and $t_s$ is the thickness of the superconducting layer.

![Figure 2](image)

The superconducting property is determined using the $E – J$ power law characteristic, where the equivalent conductivity of the HTS tape is defined as:

\[
\sigma_{sc} = \frac{J}{E} = \frac{J^2}{E_c J^{1-n}} = \frac{J^2}{E_c (\nabla \times T)^{1-n}}
\]  

(2)

where $E_c = 1 \times 10^{-4}$ Vm$^{-1}$. For a coated conductor carrying a DC transport current $I_t$ under an AC
magnetic field $B$, the transport current occupies the superconducting layer with width $2lw$ in the center, leaving the rest of the width $(1-i)2w$ free on both sides. The current carrying region in the center is defined as the dynamic region. The dynamic loss in the dynamic region can hence be calculated by:

\[
Q = \int_{(1-i)w}^{(1+i)w} J E_t \, dy = \int_{(1-i)w}^{(1+i)w} \frac{j^2}{\sigma_{sc}} t_s \, dy
\]

where $i$ is the ratio between transport current $I_t$ and critical current $I_c$.

3. Transient analysis of the superconducting generator

To investigate the performance of the generator and identify the magnetic environment of the superconducting coil, the finite element analysis (FEA) software Mentor Graphics MagNet is used. A 11.7 MW generator was designed and simulated. The main parameters of the generator are highlighted in table 1. Further information on the design of the generator can be found in reference [2].

| Table 1. Double claw pole generator specifications |
|-----------------------------------------------|
| Total mass                  | 189 tonnes |
| Outer diameter            | 6.14 m     |
| Poles                      | 88         |
| Coils per stator          | 66         |
| Power output              | 11.7 MW    |
| Line voltage              | 3.5 kV     |
| Rotational speed          | 10 rpm     |
| Power density             | 61.90 W/kg |

Figure 3 shows the overall flux density distribution in the generator. The full generator features 88 poles and 66 stator coils on each stator. 1/22 of the generator was modelled, hence the model consists of 4 poles and 3 stator coils on each stator.

Figure 3. Total flux density distribution in a section of the generator design.

The whole model is enclosed in a boundary box with periodic boundaries on the model faces. The claw poles are enclosed in a separate air box to the stator. The two boundaries are separate by four layers, which pass through the air gap. The two layers in the middle, which are in contact with each other, are the remesh region. As the rotor rotates past the stator coils, the mesh is remeshed for each time step. The mesh was refined in the air gap region as well as around the superconducting field winding. Vacoflux50 is used for the active mass of the generator, it is a cobalt iron alloy. It allows for high air gap flux densities due to its high saturation limit of 2.28 T without using an excess amount of superconducting tape. From the figure, it can be seen that the lower claw poles are starting to saturate around the elbows. A high air gap flux density of 1.35 T is reached.
Figure 4 shows the open-circuit voltage produced by the generator. The electrical frequency of the generator is 7.33 Hz at 10 rpm, which is equivalent to a time period of 136.4 ms. The peak voltage is approximately 260 V, giving an RMS voltage of 183 V. The stator consists of 66 coils. Each phase has 11 coils in series in two parallel strands, giving a phase voltage of 2 kV.

![Figure 4. Induced open-circuit stator coil voltages.](image)

In this section, the main parameters of the generator design were introduced. The next section will cover further analysis into the superconducting field winding itself to quantify the dynamic loss and potential hot spots on the HTS tapes.

### 3.1 Superconducting field winding

For the superconducting field winding the HTS tape model FYSC-SCH04 manufactured by Fujikura is used. The tape parameters are summarized in table 2; the parameters were derived from data provided by Fujikura.

| Parameter                  | Value          |
|----------------------------|----------------|
| Temperature                | 65 K           |
| $I_c$                      | 469 A          |
| n-value                    | 24             |
| $B_0$                      | 0.8 T          |
| $k$                        | 0.88           |
| $\alpha$                  | 0.6            |
| Tape width                 | 4 mm           |
| Superconducting layer thickness | 1.9 µm       |

The superconducting field winding of the generator consists of three separately wound coils, which are placed next to each other. Two different configurations are possible. The first configuration is a single continuous field winding. For the second configuration, the field winding is wound into four separate loops along the field core with separate cryostats to improve the modularity of the machine in case of a fault in the field winding [2]. For this paper, the first configuration with a single continuous field winding is considered. 4 mm wide tape is used for the coils. The operating temperature is set to 65 K, which gives a self-field critical current of 469 A for a single tape. Each coil has 49 turns, giving a total number of turns of 147. The self-field critical current of the coil was calculated using the method described in [12].
The E-J power law serves as the basis of the model:

\[ E = E_c \left( \frac{J}{J_c(B)} \right)^{n-1} \]  

(4)

This relationship is inverted to yield:

\[ J = J_c(B) P \]  

(5)

where

\[ P = \frac{E}{E_c} \left( \frac{E}{E_c} \right)^{\frac{1}{n-1}} \]  

(6)

When the transport current \( I_t \) reaches the critical current \( I_c \), \( P = 1 \) and \( E = E_c \), hence \( I_c \) can be determined. The variable \( P \) allows for avoiding the direct solution of the nonlinear \( E-J \) relationship, simplifying the problem and hence making it easier to solve.

Using the above described method the critical current of the coil was calculated to be 310 A. Applying a load factor of approximately 70 %, the transport current can be calculated to be equal to 220 A. The total length of superconducting tape required is 2.64 km.

Figure 5 shows a schematic of the field winding, as can be seen, three coils are placed next to each other with a gap of 1 mm, giving a width of 14 mm. The thickness of the superconducting tape is 119 µm and assuming a gap of 400 µm between turns due to the insulation and the winding process, the height of the tape stack can be approximated to be 25 mm. The inner radius of the field winding is 2.75 m.

![Figure 5. Cross-section of the superconducting field coil with perpendicular flux density distribution.](image)

The figure also highlights the perpendicular flux density distribution relative to the field winding, as discussed in the previous section; the perpendicular component is the main contributor towards the dynamic loss.
4. Dynamic loss with DC background field results

To investigate the effect of the DC background field on the dynamic loss, the magnetic field of several points on the coil is taken and applied to a single tape. The applied magnetic fields are shown in figure 6. While these magnetic fields are for the machine design described in this paper, similar fields occur on the field windings of any type of rotating synchronous machine. These fields highly depend on the machine designs and specifications such as, number of poles, rotational speed, magnetic loading and stator winding configuration.

As can be seen, the DC field ranges from approximately 70 mT to up to 0.47 T and the AC field from around 10 mT to 30 mT. The loss results for a single tape are summarized in table 3.

Table 3. Dynamic loss results.

| Location | Dynamic loss (mW/m) |
|----------|---------------------|
| Top 1    | 27.2                |
| Middle 1 | 24.9                |
| Bottom 1 | 27.8                |
| Top 2    | 12.2                |
| Middle 2 | 24.1                |
| Bottom 2 | 13.6                |
From the results it can be seen that the dynamic loss with a high DC background field are significantly higher than for a lower DC background. For instance, even though the applied AC field for the top 1 case is lower than for top 2 case, the resulting loss is higher. This is due to the DC background field lowering the critical current. In [13] further dynamic loss modelling results were published, using an $H$– formulation based numerical model. It was shown that the dynamic region is strongly affected by the DC background field. A DC applied magnetic field increases the width of the dynamic region and skews it, due to the reduced critical current and the interaction between the self-field of the tape and the applied field. Since the modelling method used in this paper uses the dynamic region as the basis, the calculated dynamic loss is lower because a portion of the DC transport current carrying region was not considered. From the results it can be seen that both the $T$– formulation and $H$– formulation based numerical models require an improved definition of the dynamic region when dealing with more complex magnetic fields such as magnetic fields with large DC components. However, the $T$– formulation based results produced in this paper can serve as an indication in regards to the loss characteristics of HTS coated conductors with a DC background field. It was shown that the dynamic loss increases when subject to an additional DC background field, which leads to higher losses in HTS coated conductors when used in the field windings of rotating machines. At low temperatures, it takes a considerable amount of input power to remove heat. At 65 K, it takes approximately 25 W to remove 1 W of heat, at 20 K the required input power can increase to up to 200 W [14]. Many generator designs operate at a temperature as low as 20 K [15 – 17]. Additionally, since the rotational speed is low and hence the frequency as well, the losses are relatively low as well. For a faster rotating machine the dynamic loss is expected to be higher. The results show that it is important to include the dynamic loss in the design of the field winding and its cooling system. An additional requirement in cooling power can be significant, especially depending on the operating temperature chosen.

5. Conclusion

Most superconducting generator designs feature DC field windings to provide the required magnetomotive force. Superconducting tapes carrying a DC current exhibit virtually no loss, however when placed in an AC magnetic field, dynamic losses occur. Since generator field windings are located in complex rotating magnetic fields, dynamic losses are present and need to be quantified. In this paper, our double claw pole generator design is used as a case study to examine the dynamic losses in superconducting tapes when subject to such magnetic fields. A numerical model based on the $T$– formulation is used to calculate the dynamic loss in the tapes by defining the transport current region. The field winding consists of three coils placed next to each other, the transport current is 220 A at 65 K. The perpendicular magnetic field for different locations in the field winding is taken and applied to single tapes to investigate the effect of the DC background field. The dynamic loss was found to be highest for the tapes with a high DC background field due to the reduced critical current. Results show that the dynamic loss can have a significant impact on the required cooling power and that it should be considered in the design of the field winding and its cooling system. Additionally, it was highlighted that the dynamic region definition does not apply anymore when a large DC background field exists due to the transport current region being strongly affected. Further research into the definition of the transport current region is required.

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References

[1] WindEurope 2019 Offshore wind in Europe, key trends and statistics 2018, available online (accessed: 28/08/2019): https://windeurope.org/about-wind/statistics/offshore/european-offshore-wind-industry-key-trends-statistics-2018/

[2] Kails K et al 2019 Novel model of stator design to reduce the mass of superconducting generators Superconductor Science and Technology 31 055009

[3] Keysan O et al 2015 A modular and cost-effective superconducting generator design for offshore wind turbines Superconductor Science and Technology 28 034004

[4] Kails K et al 2019 Mass reduction of superconducting power generators for large wind turbines The Journal of Engineering 2019 3972-3975

[5] Kails K et al 2019 Modular and stackable power generators for efficient renewable power Generation IET Renewable Power Generation 13 2774-2782

[6] Shafaie R et al 2013 Design of a 10-MW-Class wind turbine HTS synchronous generator with optimized field winding IEEE Transactions on Applied Superconductivity 23 5202307

[7] Seo J H et al 2014 Comparison study on harmonic loss of MW-Class wind generators with HTS field winding IEEE Transactions on Applied Superconductivity 24 5200105

[8] Zhou C et al 2018 Comparison of electromagnetic performance of superconducting permanent magnet wind power generator with different topologies IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), Tianjin, China,

[9] Li Q et al 2018 Numerical modelling of dynamic loss in HTS-coated conductors under perpendicular magnetic fields IEEE Transactions on Applied Superconductivity 31 1-6

[10] Jiang Z et al 2018 The dynamic resistance of YBCO coated conductor wire: effect of DC current magnitude and applied field orientation Superconductor Science and Technology 31 035002

[11] Jiang Z et al 2017 Dynamic resistance measurement of a four-tape YBCO stack in a perpendicular magnetic field IEEE Transactions on Applied Superconductivity 28 8200305

[12] Zermeño V et al 2015 A self-consistent model for estimating the critical current of superconducting devices Superconductor Science and Technology 28 085004

[13] Kails K et al 2020 Dynamic loss of HTS field windings in rotating electric machines Superconductor Science and Technology 33 045014

[14] Y F Bi 2013 Cooling and cryocoolers for HTS power applications Applied Superconductivity and Electromagnetics 4 97-108

[15] Abrahamsen A B et al 2010 Superconducting wind turbine generators Superconductor Science and Technology 23 034019

[16] Sung H J et al 2013 Practical design of a 10 MW superconducting wind power generator considering weight issue IEEE Transactions on Applied Superconductivity 23 5201805

[17] Marino I et al 2016 Lightweight MgB2 superconducting 10 MW wind generator Superconductor Science and Technology 29 024005