Design and market considerations for axial flux superconducting electric machine design

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Abstract. In this paper, the authors investigate a number of design and market considerations for an axial flux superconducting electric machine design that uses high temperature superconductors. The axial flux machine design is assumed to utilise high temperature superconductors in both wire (stator winding) and bulk (rotor field) forms, to operate over a temperature range of 65-77 K, and to have a power output in the range from 10s of kW up to 1 MW (typical for axial flux machines), with approximately 2-3 T as the peak trapped field in the bulk superconductors. The authors firstly investigate the applicability of this type of machine as a generator in small- and medium-sized wind turbines, including the current and forecasted market and pricing for conventional turbines. Next, a study is also carried out on the machine’s applicability as an in-wheel hub motor for electric vehicles. Some recommendations for future applications are made based on the outcome of these two studies. Finally, the cost of YBCO-based superconducting (2G HTS) wire is analysed with respect to competing wire technologies and compared with current conventional material costs and current wire costs for both 1G and 2G HTS are still too great to be economically feasible for such superconducting devices.

1. Introduction

Over many years of research, various superconducting machines have been shown to be technically feasible over a wide range of power ranges. For low temperature superconducting (LTS) materials, in particular, the complexity and cost of 4 K cryogenics hindered the commercial development of LTS machines [1], although there were a number of successful technical feasibility demonstrations [2]. The discovery of high temperature superconducting (HTS) materials in 1987 renewed enthusiasm for
applied superconductivity research with the expectation that these materials could be exploited at 77 K, the boiling point of liquid nitrogen. Since then, a number of projects around the world have demonstrated the technical feasibility of HTS machines in various forms, including 5 MW and 36.5 MW motors for ship propulsion [3,4] by American Superconductor (now AMSC); a 380 kW motor [5], which was later developed into a 4 MW project machine [6], by Siemens; a 1.7 MW hydroelectric power generator by Converteam [7]; different HTS induction/synchronous motors at Kyoto University [8,9]; a 30 kW motor for an electric passenger car by Sumitomo Electric [10]; a 1 MW class synchronous motor for industry by KERI and Doosan Heavy Industries [11]; a 1 MW class podded ship propulsion motor by Kawasaki Heavy Industries [12]; and a sub-megawatt class propulsion system by Kitano Seiki [13]. However, both economic and technical challenges have meant that so far none of these machines have been commercialised.

In this paper, the authors investigate a number of design and market considerations for an axial flux superconducting electric machine design that uses high temperature superconductors. The axial flux motor design (for examples, see [14,15]), in general, provides higher torque/power density than other motor designs [15], and the use of superconductors is expected to improve these advantages even further [13]. In this study, the axial flux machine design is assumed to utilise high temperature superconductors in both wire (stator winding) and bulk (rotor field) forms, to operate over a temperature range of 65-77 K (liquid nitrogen temperatures), and to have a power output in the range from 10s of kW up to 1 MW (typical for axial flux machines), with approximately 2-3 T as the peak trapped field in the bulk superconductors. In Section 2, the applicability of this type of machine as a generator in small- and medium-sized wind turbines and as an in-wheel hub motor for electric vehicles is investigated. In Section 3, the cost of YBCO-based superconducting (2G HTS) wire is analysed with respect to competing wire technologies and compared with current conventional material costs.

2. Application Studies

2.1 Small- & Medium-sized Wind Turbines

One potential application for this type of superconducting machine is as a generator in wind turbines, and the assumed power rating (up to 1 MW) puts this machine in the small- to medium-sized turbine category. The increased power density of a superconducting machine would mean a lighter generator and permanent magnet direct-drive (PMDD) wind turbines have received significant interest because elimination of the gearbox and slip rings can result in reduced down-time associated with maintenance and replacement, resulting in reduced cost-of-ownership and increased reliability. The low operating speed of a turbine generator require a high torque for a given power output, resulting in a physically larger machine [16]. However, the use of bulk HTS superconductors is expected to improve the machine performance even further, with trapped fields recorded as high as 17 T at 29 K [17] and up to 3 T at 77 K [18], allowing the removal of iron and an air-core design.

The wind turbine industry continues to grow and is rapidly expanding – the global wind turbine market saw 11% growth in capacity in 2010 with 39 GW delivered worldwide [19]. It is expected that by the end of 2016, global wind capacity will be close to 500 GW, in comparison with 237.7 GW at the end of 2012 [20]. Figure 1 shows the wind turbine market segmented by power output in terms of the expected amount of capacity installed each year from 2010 to 2025 [19]. In 2010, new turbines less than 1 MW accounted for 7% of the market (2.73 GW) and those greater than 3 MW accounted for 13%. In 2018, turbines greater than 3 MW are expected to account for 40% of the market, while turbines less than 1 MW are expected to shrink to 4% [19]. The wind turbine market up to 1 MW is quite mature and there are a large number of companies producing conventional turbines of a high standard Although the wind turbine market on the whole is growing, new installations within the specified power range are expected to decrease, and the 1.5-2.49 MW class of wind turbine will dominate the market for the next five years [19].
2.2 In-wheel Hub Motor for Electric Vehicles

In-wheel hub motors are a concept gaining momentum for use in electric vehicles. This type of motor is commonly found on electric bicycles, and the idea is to place an electric motor into the unused space inside of a wheel to drive the wheel directly. There are a number of advantages: 1) manufacturers can remove the conventional engine bay, which allows for new and creative car designs, 2) removal of much of the powertrain (transmission, differential) results in a significant weight saving and reduced losses in and deterioration of mechanical transmission components, and 3) directly driving each wheel may improve car safety and dynamic drivability. Figure 2 shows the electric vehicle global sales forecast for 2012-2017. For electric vehicles, a new component market is developing rapidly with growing electric motor sales [21].

![Electric Vehicle Global Sales Forecast](image)

**Figure 2.** Electric vehicle global sales forecast for 2012-2017 [22].

There are several firms developing in-wheel hub motors at various stages of commercialisation and three companies are highlighted here. YASA Motors [23] is a spin-out from the Engineering
Department at the University of Oxford, who are manufacturing high-torque axial flux motors and have just received £1.45m of funding from a private investment firm, whilst also securing their first contracts with major automotive OEMs [23]. Protean Electric is a US company manufacturing in-wheel motors, which is planning to have their latest prototype ready to present to OEMs by 2013, ready for volume production in 2014. They have just received US$84m in funding to proceed with building new manufacturing facilities in China [24]. In terms of superconducting motors for electric vehicles, the closest to commercialisation is Sumitomo Electric, but this is not an in-wheel hub motor. Sumitomo first demonstrated the use of a superconducting motor to power a passenger vehicle in 2008 [10]. However, due to the likely cost and issues with reliability and cooling for this application, they have now shifted focus to buses, small trucks and forklifts, suggesting heavy duty usage may be a more profitable sector within the electric vehicle market for superconducting motors. Therefore, suggested potential applications would be heavy duty vehicles, such as trucks and plant machinery, and buses. The desire for higher power/torque densities for these functions means that cost and cooling system requirements become less of an issue. Although still many years away, electric aircraft may be an attractive application in the long term, since the power densities required can only be achieved with HTS motors [25].

3. HTS Wire Cost
For a superconducting machine to be competitive with conventional machines, its cost-performance (C-P) ratio needs to be similar to or lower than that of conventional alternatives. The C-P ratio for wire is commonly expressed in US dollars per kилоamp metre ($/kAm), which takes into account the raw wire cost (including labour and manufacturing) in addition to any improved performance under certain operating conditions. Competitive HTS wire requires a C-P ratio of approximately $20/kAm, based on the current C-P ratio of copper wire. 1G (Bi-2212) and 2G (YBCO) HTS wire is compared with copper in Table 1.

| Wire Type                          | C-P Ratio          |
|-----------------------------------|--------------------|
| Competitive Point                 | Approx. 20         |
| Copper                            | 15 – 55            |
| 1G (Bi-2212)                      | 180 – 230          |
| 2G (YBCO, current, SuperPower)    | 450 [26] – 500     |
| 2G (YBCO, projected, SuperPower)  | 175 [26]           |

It is important to note that the superconductor C-P ratios above are for performance at 77 K in self-field (i.e., with no externally applied field), and the trapped field in the bulk superconductors of 2-3 T would further reduce the performance of the superconducting wire and increase the C-P ratio. The in-field performance of BSCCO, which has a much lower irreversibility line, is inferior to that of YBCO, so the relative increase in its C-P ratio would be much greater. The general consensus is that the current generation (2G) of HTS wire will not be competitive for some time, if at all, for the desired operating temperature range. However, this machine topology would be preferable cost-wise to a wound DC rotor topology (for example, [3,4]) because significantly less wire would be used in the overall design. The limiting factors still remain very much the same as those raised 15 years ago [27] and reasons include the inherent complexity of the manufacturing process, demand not meeting projections, and the rising raw material costs of metals such as copper (used in both BSCCO and YBCO) and silver (used in Bi-2212), both of which have seen their prices rise by about 500% over the past decade.
4. Conclusions & Recommendations

In this paper, a number of design and market considerations have been investigated for an axial flux superconducting electric machine design that uses high temperature superconductors in bulk and tape form. Although the wind turbine market on the whole is growing, new installations within the specified power range are expected to decrease to less than 4% by 2018. The likely cost and issues with reliability and cooling means it is unlikely a superconducting motor would be feasible for electric passenger vehicles, but a suggested potential application would be heavy duty vehicles, such as trucks and plant machinery, and buses. The general consensus is that the current generation (2G) of HTS wire will not be competitive for some time, if at all, for the desired operating temperature range. However, this machine topology would be preferable cost-wise to a wound DC rotor topology because significantly less wire would be used in the overall design.

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