Enhancement of magnetic flux distribution in a DC superconducting electric motor

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Abstract. Most motor designs require an air gap between the rotor and stator to enable the armature to rotate freely. The interaction of magnetic flux from rotor and stator within the air gap will provide the thrust for rotational motion. Thus, the understanding of magnetic flux in the vicinity of the air gap is very important to mathematically calculate the magnetic flux generated in the area. In this work, a finite element analysis was employed to study the behavior of the magnetic flux in view of designing a synchronous DC superconducting electric motor. The analysis provides an ideal magnetic flux distribution within the components of the motor. From the flux plot analysis, it indicates that flux losses are mainly in the forms of leakage and fringe effect. The analysis also shows that the flux density is high at the area around the air gap and the rotor. The high flux density will provide a high force area that enables the rotor to rotate. In contrast, the other parts of the motor body do not show high flux density indicating low distribution of flux. Consequently, a bench top model of a DC superconducting motor was developed where by motor with a 2-pole type winding was chosen. Each field coil was designed with a racetrack-shaped double pancake wound using DI-BSCCO Bi-2223 superconducting tapes. The performance and energy efficiency of the superconducting motor was superior when compared to the conventional motor with similar capacity.

1. Introduction
With the success of fabrication of long length superconducting wire with a very reliable performance, the development of superconducting devices is further intensified [1,2]. Superconducting devices such as magnetic resonance imaging (MRI) and superconducting quantum interference devices (SQUID) have been used extensively. Several others electrical power devices such as motors, generators, fault current limiter, and magnetic storage system had been developed and tested [3-5]. Superconductor required cooling down below the critical temperature, $T_c$ to reach zero resistance. The conventional low temperature superconductors operate at below 20 K, where cooling by liquid helium is required. With the discovery of high-temperature superconductor in 1986 [6], any devices should be able to operate at higher temperatures. Therefore, the used of cheaper refrigerant such as liquid nitrogen is sufficient to cool down the superconducting materials and achieved superconductivity [7].

The special properties of high-temperature superconductor wires such as zero resistivity, high critical current density and high operating temperature, enable the development of high efficiency energy devices. In an electric motor for instance, it estimated that superconducting motor is able to reduce in size and minimize energy losses when compared to the conventional copper-base motor [8]. In developing a superconducting motor, one of the important aspects to be investigated is the magnetic

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flux behavior within the components of the motor. By employing the finite element method, the performance and behavior of a system is able to be predicted without the necessity of developing the actual system. In this work, a finite element analysis was employed to study the behavior of the magnetic flux in view of designing a synchronous DC superconducting electric motor. Consequently, a low-power superconducting electric motor is assembled and its performance is compared with a conventional electric motor. All the specifications for both types of motor are similar except for the coils.

2. Experimental procedures

2.1. Finite elements method
In the present work, the finite element analysis method is used to study the behavior of the magnetic flux in a motor system. The scope of the analysis is focused on investigating the behavior of the flux and not its strength. This will help to forecast the behavior of the magnetic flux when subjected to various circuit elements in the motor system.

2.2. Fabrication of motor and performance test
Based on the results from finite element analysis for several preliminary models, a model where the stator is designed with a deep U-shape was chosen. The rotor was mounted at the opening of the U-shape stator together with rotor housing, and the coils were assembled at one of the stator leg. The generated flux produced by the field coils required a magnetic path so that the interaction of opposing magnetic fields at the opening of the U-shape stator resulted in high flux density that provide a high force area, and thus enable the rotor to rotate. DC current was used to provide the input current to the field coils and the rotor. Motor torque measurement was used to gauge the performance of the fabricated motor. Motor torque is one of the motor ratings which is used to indicate motor rotary force produced on its output shaft [9]. During performance tests for both type of motors, a constant current was supplied to the rotor, while the current applied to the coils was varied at fixed intervals as the load mounted on the shaft is increased. The data was taken once the rotor starts to rotate. Testing for the conventional copper coils was repeated with the same procedures except for the cooling procedures.

3. Results and analysis

3.1. Finite elements method
The wireframe of a single coil motor was constructed based on the finite element analysis. The wireframe model which is in the 2-dimension, was converted into a solid 3-dimensional model. All the dimensions and specifications of the model were built with a full scale dimensions. Figure 1 shows the simulation of magnetic flux path in the circuit. Most of the flux is distributed on the desired flux path and followed the designed path. Only small portion of the flux is lost to the surrounding in the forms of flux leakage and fringe effect. The occurrence of leakage is due to the presence of weak flux lines that do not have sufficient energy to flow through the desired path. Apparently, the weaker flux and the flux due to fringe effect at the air gap are dispersed to the surrounding, or are attracted back to the magnetic flux path. Figure 2 shows the simulated result of the flux density contour of the motor system. As shown in the figure, the flux density is highest at the areas around the air-gap and the rotor. The high concentration of the flux at the air-gap is due to the accumulation of the flux generated by the coils and rotor over a small cross sectional area. In contrast, the other parts of the motor body do not show high flux density indicating low distribution of flux. The high flux density at the rotor in the vicinity of air-gap is needed to establish a high force area that enables the rotor to rotate.
3.2. Performance test results

Figure 3 and figure 4 show the graphs of input power against the horizontal torque generated by the shaft for each type of motor. The graphs show that the input power to establish a certain level of torque for the superconducting coils motor is much lower than the conventional copper coils motor. For instance, in order for the motor to generate 0.07 Nm of torque, only about 2.0 W of input power is required by the motor with superconducting coils. In contrast, the motor with copper coils requires 60 times more input power to generate the same amount of torque. This shows that for the same volume of conductor used in the fabrication, motor with superconducting coils performed much better than the motor with copper coils.

The energy saving in terms of percentage of input power for the motor with superconducting coils when compared to the conventional motor with copper coils is significantly higher. But the trend in energy saving is decreasing as torque is increased. Nevertheless, it was reported that with the application of flux collector technology, the energy efficiency of almost 99% could be achieved at all time [10]. The superior performance and better energy efficiency of the electric motor with superconducting coils is attributed to the magnetic properties of the superconducting coils. The Meissner effect contributed to much higher magnetic field concentration along the magnetic flux path in the layered lamination sheets of the stator’s core. In addition, the efficiency of the superconducting motor is attributed to lower hysteresis loss inside the superconductor coils [11].
4. Conclusion
The finite element method has proved to be a very useful tool in the designing and fabrication of a bench-top model synchronous DC superconducting electric motor. The model was developed based on the modeling and simulation of the magnetic flux distribution. Successful testing of the superconducting motor proved that the efficiency and performance of motor with superconductor coils is much superior when compared to the conventional copper coils motor with similar capacity. The encouraging results indicate the potential of superconductor applications in machine devices and the possibility of commercialization in the near future.

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