Summary

The propulsion systems are conventionally conceived for a linear business model, which considers phases from the material extraction to the product disposal and are usually optimized for the use phase. Circular Economy is one of the main research areas in recent years, driven by increasing attention to sustainability. Another significant topic over the past decades is the decarbonization of the transportation sector due to its high impact on global carbon dioxide emissions and global warming. These two fields of research have been addressed by coupling technological aspects with methodological ones, aiming to rethink an industrial product featuring circular design.

This thesis focuses on developing a Design for Circular Economy methodology and applying it to a rare earth-free electric motor, specifically a Switched Reluctance Machine designed for automotive applications, aiming to improve its environmental and economic impact. To the best knowledge of the author, the applied methodology resulted in a patented design, never presented on the market nor reported in literature.

The first portion of the thesis delves into design techniques and phases to be included in a conventional design process for an industrial product. In this process, product environmental impacts are considered from the initial development phase, implementing design features that enable circular loops (Durability, Maintenance, Reuse, Refurbish, Remanufacturing, Recycle, etc.) throughout the product lifecycle. This part of the research is dedicated to implementing a framework for identifying potential CS and related design approaches to be adopted. The process concluded with the selection of three promising strategies, respectively oriented to increase durability and the possibility of remanufacturing. The last strategy was presented in two versions, each characterized by different degrees of component substitution.

Design features, framed at a theoretical level, were then transferred into the real design of the electric motor, allowing both higher durability and complete disassembly of subparts, making motor remanufacturing possible. The developed novel concept, compared with traditional design, allows complete motor recovery at the end of life without damaging reusable parts, replacing the most critical parts like bearings and winding.

The aforementioned solutions were compared from an environmental and economic standpoint using specifically developed tools. Environmental burdens were calculated using the Life Cycle Assessment methodology with a cradle-to-grave approach.

For this analysis, a model was developed including all life cycle stages from material acquisition to end of life, simulating defined circular paths, including the recycling process. The model was also used to gain a better understanding of how electric motors affect the environment, providing guidelines on subcomponents and cycle phases' influence on overall environmental impacts, investigating the effect of geographical boundaries and vehicle applications. The same model was used to assess the baseline Switched Reluctance Machine, comparing it with a Permanent Magnet Synchronous Machine, which represents the mainstream topology for the transportation sector. Furthermore, the analysis was enriched by evaluating the improvement of an Ecodesign strategy applied to the magnet-free use case, through the virtual substitution of copper with aluminium within the stator winding. Additionally, the material flow and circularity of the identified strategies were evaluated through a Material Circularity Indicator, adapted to account for different recirculation paths, complementing the Life Cycle Assessment findings on narrower boundaries.

The economic evaluation focused mainly on motor manufacturing costs, directly impacted by CS. Other factors affecting cost, not included in the boundaries of this research, may be considered in future studies.