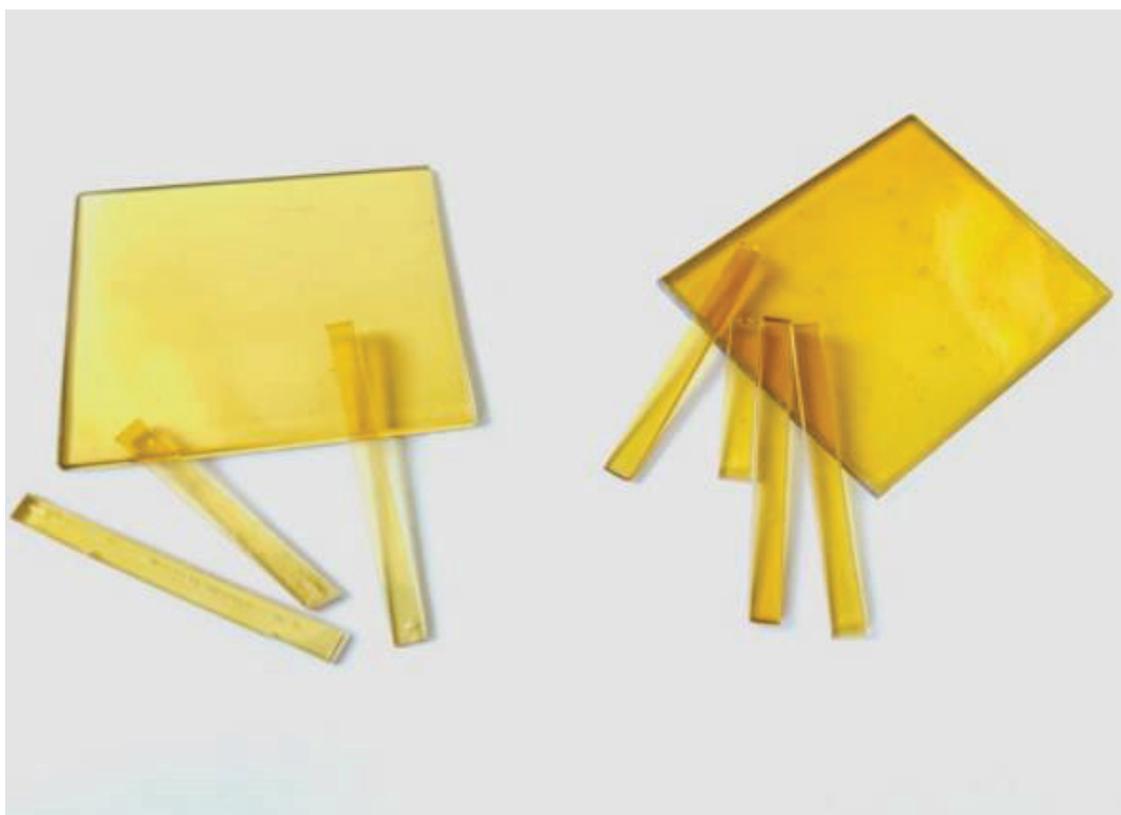


Designing high voltage motors for re-use: Increasing the circularity of motor

Public Report



Project within Circularity
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FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

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1. Summary

Modern electric motors are difficult to recycle, repair, and re-use because of their complex structure compared to traditional induction motors, where various plastic materials are essential for insulation of the motor's conducting materials, but consequently hinder the disassembly and recovery of valuable components. To allow for the separation of motor components, these plastics are currently incinerated at elevated temperatures, which is not only an energy-intensive process but also damages valuable components. Furthermore, the plastic material itself is lost entirely.

This pre-study explores how the circularity of motors can be increased through support of reuse, repair, and recycling by aiming to identify candidates and chemical modifications that can be done to develop new plastic material that has the possibility of swelling or softening at temperatures below 250 °C. Thus, allowing for release by using a stimulus such as a solvent. The projects evaluated new insulating material, relating to two main areas, including epoxy resins, used for stator applications, and polymers relating to the insulation of hairpins.

The epoxy resins were tested for chemical degradability using various solvents and conditions. While conventional epoxy systems proved resistant to degradation, modified formulations with sacrificial bonds showed potential for dissolution below temperatures of 250 °C. Although such introduction of sacrificial bonds is assumed to affect the mechanical properties and solvent resistance of the materials, which will require further investigation.

The polymer formulations developed for hairpin application were assessed through accelerated aging tests in automatic transmission fluid (ATF) and extrusion trials. The material was further evaluated through measurement of partial discharge inception and extinction voltage (PDIV/PDEV). Several formulations demonstrated strong thermal and electrical performance, indicating suitability for the intended purpose. However difference in electrical properties compared to conventional material needs further investigation.

The study concludes that both material groups offer promising paths toward more sustainable motor design. Two future research projects are proposed: one focusing on the development and screening of modified epoxy insulations, and another on the recyclability and performance of the developed polymer insulations. In conclusion, the project successfully met its objectives and established a foundation for continued cross-industry collaboration and research.

2. Sammanfattning på svenska

Moderna elmotorer är svåra att återvinna, reparera och återanvända på grund av deras komplexa struktur jämfört med traditionella induktionsmotorer. Olika plastmaterial är avgörande för isoleringen av motorernas ledande komponenter, men hindrar samtidigt demontering och återvinning av värdefulla komponenter. För att möjliggöra separation, förbränns dessa plaster idag vid höga temperaturer, vilket inte bara är energintensiv process utan skadar även värdefulla komponenter. Plastmaterialet går dessutom helt förlorat i denna process.

Denna förstudie undersöker hur motorers cirkularitet kan förbättras genom att stödja återanvändning, reparation och återvinning. Med målet är att identifiera kandidater och kemiska modifieringar som kan leda till utvecklingen av nya plastmaterial med potential att svälla eller lösas upp vid temperaturer under 250 °C, och därmed möjliggöra separation genom användning av lösningsmedel, eller annan kemisk stimulans. Projektet utvärderade nya isoleringsmaterial inom två huvudområden: epoxihartser för statorapplikationer och polymerer för isolering av så kallade hårnålar.

Epoxihartserna testades för kemisk nedbrytbarhet med olika lösningsmedel och förhållanden. Konventionella epoxisystem visade sig vara motståndskraftiga mot nedbrytning, medan modifierade formuleringar där bindingar med syfte att hjälpa nedbrytning hade introducerats i strukturer, visade potential för upplösning vid temperaturer under 250 °C. Införandet av dessa bindingar antas dock påverka materialens mekaniska egenskaper och lösningsmedelsresistens, vilket kräver vidare undersökning.

Polymerformuleringarna för hårnålarna utvärderades genom accelererade åldringstester i automatväxellådsolja (ATF) samt extruderingsstester. Materialet analyserades vidare genom mätning av "partial discharge inception" och "extinction voltage" (PDIV/PDEV). Flera formuleringar visade goda termiska och elektriska egenskaper, vilket indikerar lämplighet för det avsedda ändamålet. Skillnader i elektriska egenskaper jämfört med konventionella material understyker dock behovet av vidare utredning.

Studien belyser båda materialgrupperna som potentiella kandidater för en mer hållbar motordesign. Två framtida forskningsprojekt föreslås: ett med fokus på utveckling och screening av modifierade epoxiisoleringar, och ett annat kring återvinningsbarhet och prestanda hos de utvecklade polymerinisoleringar. Sammanfattningsvis har projektet framgångsrikt uppnått sina mål och lagt grunden för fortsatt samarbete och forskning över branschgränser.

3. Background

Modern high-voltage electric motors are increasingly used in applications such as electric vehicles, trains, and industrial systems. These motors are designed for high performance and durability, but their complex construction presents significant challenges for recycling, repair, and reuse. Unlike traditional induction motors, they incorporate permanent magnets, advanced electrical steel alloys, and a wide range of high-performance plastic materials for insulation and adhesion.

The plastics used in slot liners, wedges, wire casings, fillers, and adhesives, are essential for electrical insulation and mechanical stability. Common materials include aromatic polyamide (Nomex), polyethylene terephthalate (PET), polyether ether ketone (PEEK), and thermoset epoxy resins [1]. These materials are selected for their ability to withstand high voltages and thermal stress, especially in inverter-fed motors where repeated voltage surges from impedance mismatches place additional strain on insulation systems.

However, these same materials hinder disassembly and component recovery. Currently, the separation of motor components often involves incinerating the plastic materials at temperatures exceeding 600 °C. This process is not only energy-intensive but also damages valuable components such as rare-earth magnets and results in the complete loss of the plastic material. In production, failures in impregnation or glueing can lead to the scrapping of entire stators, contributing to substantial material waste.

From a circularity perspective, reducing the number of plastic types and enabling controlled release of adhesives and insulation materials are promising strategies. One potential solution lies in the use of a modified type of polymer, which is already used in cable insulation and could be adapted for multiple motor components, thereby reducing the number of plastics used. This polymer offers several advantages that make it attractive for wire insulation, including low permittivity, excellent breakdown voltage strength, good thermal conductivity, high flexibility, and a proven 60-year track record in cable applications. They are also easy to extrude into films or directly onto conductors. They further offer options to enhance sustainability through the utilisation of bio-feedstocks.

Recent research has shown that thermally reversible dynamic covalent bonds can be introduced into thermoset networks, enabling partial swelling or bond opening when triggered by heat or chemical stimuli [2]. This approach could allow motor components to be heated to around 300 °C, rather than the much higher temperatures required for incineration, facilitating the repair of the motor, extending its lifetime, and allowing for its reuse of its metallic components. Industrial products in the field of release adhesives have already been developed [3]. Furthermore, trials with thermoplastics instead of thermosets have also been carried out, but validated and certified solutions for electrical motors are still missing.

4. Purpose, research questions and method

In this project, the electrical and release properties of insulations were investigated through studying their chemical bonds for adhesion and release, mechanical, and electrical properties. The investigations took part as an initial screening, allowing for an assortment of candidate systems showing potential for improved end-of-life disassembly.

As part of an initial screening, various epoxy resins and polymers were evaluated. The study included three different commercial epoxy resins together with newly developed modified epoxy resins. The material was characterised using infrared (IR) spectroscopy, dynamic mechanical analysis (DMA), and nuclear magnetic resonance (NMR) spectroscopy. The different epoxy resins were further tested through a set of degradability tests, where different solvents were examined for the dissolution/swelling of the epoxy resins, with the aim of identifying materials, possible to dissolve or swell below 250 °C.

Different polymer formulations for hairpin applications were also developed and evaluated within the scope of this study, and initial testing regarding their electrical and mechanical properties was conducted via ageing test in automatic transmission fluid (ATF), followed by extrusion tests and measurements of partial discharge inception and extinction (PDIV/PDEV) levels.

Beyond the technical evaluation, the project further accounted for research regarding the life cycle of insulating plastic materials for e-motors, investigates the consequences of using fewer polymers in insulating systems, as well as how the life cycle is affected by consumer habits and challenges in regard to both practice and business opportunities.

5. Objective

This study aimed to investigate the electrical, chemical, and mechanical properties of selected formulations, with the overarching goal of increasing the reuse of materials and components in electric motors. By facilitating repair and recirculation, the intention is to extend product lifespan. To achieve this, the following objectives were defined in accordance with the application.

- Develop and screen candidate plastic materials capable of swelling or softening at temperatures below 250 °C, allowing for controlled release using external stimuli such as solvents.
- Conduct initial electrical testing on the new insulation materials by measuring PDIV and PDEV of twisted pair sample wires to assess their suitability for motor applications.
- Evaluate the mechanical durability and disassembly feasibility of selected materials through ageing studies and practical testing.
- Perform a preliminary life cycle analysis (LCA) to assess the environmental impact and recycling potential of using fewer polymer types in motor insulation systems.
- Facilitate cross-industry collaboration through workshops and lab visits to share knowledge and align technical requirements.
- Formulate a proposal for a larger FFI-funded project, building on the findings of this pre-study and targeting implementation in industrial motor design.

6. Results and deliverables

The projects successfully identified potential degrading solvents and modification processes that potentially could allow for the dissolution of epoxy resin under 250 °C. The experiments and characterisation of the plastic material allowed for a deepened understanding of epoxy insulation's degradation mechanism and how the chemical structure relates to the controlled release by external stimuli.

The study showed that the commonly used insulating epoxy resins predominantly cured through a specific linkage, and it was confirmed that the degradation methods reported in literature are ineffective for these compositions. While more extreme conditions can achieve degradation, no method was identified that satisfied the constraints of keeping temperatures below 250 °C and minimising corrosion of metal components, indicating that the challenge is highly demanding without modification of the composition.

Novel modified epoxy resins were developed through the introduction of sacrificial bonds that were successfully introduced into the structure. The modified epoxy resins displayed increased dissolving capabilities in milder conditions and further allowed for dissolution under 250 °C. These results clearly indicate that the introduction of an appropriate type and number of functional groups allows dissolution of the epoxy resin used in this study. However, as expected, this modification also seems to alter mechanical properties and likely affects solvent resistance, which has not yet been fully evaluated.

For the newly developed polymer formulations, initial evaluation of material properties was done via aging test in automatic transmission fluid (ATF) for 1 and 10 days, respectively. The formulations were further evaluated through extrusion tests and PDIV and PDEV measurements

on twisted pair samples. Overall, the results were optimistic, showing potential for future commercial applications for many of the developed formulations. Although, as a difference in electrical properties was detected between the standard material and the newly developed ones, further studies on the topic, validating their long-term performance, are required.

Cross-industry collaboration was successful with multiple in-person meetings, site visits, and lab tours held at both Scania and Borealis. Facilitating good collaborations and relationships between the project members.

A preliminary approach to LCA of the consequences of using less plastic material was conducted during a workshop held at RISE, *Den Cirkulära Plasten 2025*, where presentations on the topic of circularity and recyclability of plastic in the vehicle industry were discussed. The workshop was somewhat limited regarding its focus on the consequences of having fewer types of insulating materials, but as the topics of circularity of plastic use in the vehicle industry were broadly presented, the workshop was therefore deemed sufficient to fulfil the goals. Particularly considering the early development stages this pre-study represents.

The project has facilitated continued in-house research and allowed for a deepened scientific knowledge. The project can be concluded to have contributed to FFI's general objectives of accelerating the sustainable road transport transition through the development of sustainable solutions. The study has especially supported the sub-program Circularity by supporting research aiming to increase the reuse, recycling, and repair of electrical motors. The project has furthermore not only contributed to research supporting more sustainable products, but also supported a more sustainable process, as the findings of this study potentially may reduce the energy consumption for disassembly.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Increased knowledge on dissolution properties allowing for disassembly, initial screening has allowed for a set direction of continued research.
Be passed on to other advanced technological development projects	X	Formulations of two continued research projects have been conducted as a result of this pre-study.
Be passed on to product development projects	X	Optimistic results from this pre-study have already initiated continued internal R&D by one of the project members.
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

No publications have been submitted or published, as such actions were outside of the scope of the pre-study.

8. Conclusions and future research

The following conclusion has been reached.

- Degradation methods evaluated in this study are ineffective in dissolving or swelling epoxy resins commonly used for insulation applications.
- By the introduction of appropriate types and numbers of functional groups, dissolution can be achieved below 250 °C and by milder solvents, for the epoxy resins evaluated in this study.
- The introduction of sacrificial bonds alters the mechanical properties and likely affects solvent resistance, which will require further investigation.
- The initial material evaluation of the novel polymer formulations allowed for the identification of potential candidates, showing sufficient thermal resistance and insulating properties.
- The new materials require longer duration tests to provide a more comprehensive evaluation of performance.

This pre-study has successfully achieved its overall goals and has demonstrated potential for two new, larger projects that could be relevant for the FFI-Circularity program.

One potential project would build upon the novel polymer formulations. This study showed promising results in terms of performance, electrical properties, and chemical resistance to the ATF. A continuation of this work would focus on investigating the recyclability, testing the long-term performance of the materials, life cycle analysis, and development of a full-scale prototype. The scope of such a study could potentially also investigate this type of polymer for other applications in electrical motors, further facilitating research aiming to reduce the amount of different plastic materials used.

The second potential project would relate to epoxy materials, as the chemical investigation showed promising results regarding dissolution capabilities and the potential to, through modification of the currently used epoxy resins, disassemble stators at temperatures below 250 °C. Such a project would focus on developing novel epoxy formulations, testing their chemical and mechanical properties, and conducting corrosion studies on metals in the stator based on the most promising degrading solvent. Such a project would also benefit from including disassembly testing using a model assembly test piece.

9. Participating parties and contact persons

The following participating parties, with respective contact persons, are as follows.

Scania CV AB, Negin Yaghini and Hannes Berg.

Borealis AB, Niklas Thorn.

Dahrén Sweden AB, Kaj Sjunnesson.

RISE AB, Joni Klüss, Björn Löfving, Maria Hammarquist, Elin Gåhlin, Rikard Norling, and Stacy Tray in early project stages.

Chalmers Tekniska Högskola AB, Christian Müller, Shuichi Haraguchi.

10. Literature Reference

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