**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY**

# ELECTRIC VEHICLE POWERTRAIN DESIGN AND IMPLEMENTATION

**M.Sc. THESIS**

**Mert Safa MÖKÜKCÜ**

**Department of Mechatronics Engineering**

**Mechatronics Engineering Programme**

**JANUARY 2014**

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**Thesis Advisor: Assoc. Prof. Dr. Özgür ÜSTÜN**

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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ**

# ELEKTRİKLİ ARAÇ SÜRÜŞ SİSTEMİ TASARIMI VE İMALATI

**YÜKSEK LİSANS TEZİ**

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**OCAK 2014**

**Mert Safa Mökükcü**, a **M.Sc.** student of ITU **Graduate School of Science Engineering And Technology** student ID **518111023**, successfully defended the **thesis** entitled "**ELECTRIC VEHICLE POWERTRAIN DESIGN AND IMPLEMENTATION**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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**Date of Submission : 16 December 2013**
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***To my family and my Julie,***

**FOREWORD**

This thesis is a part of a BAP project for ALEK community of Istanbul Technical University. The project is called Istanbul Technical University Electric Vehicle Development Project. The part that is taken into consideration is electric drivetrain design and production. The project started on 2011 and it will finish in 2014. Thesis took part in this project since summer 2012 until spring 2013. The research is funded by Istanbul Technical University.

I would like to thank my father, Ali Mökükcü, my mother, Nurgül Mökükcü, my sister Merve Mökükcü for their limitless support and couragements.

Also I would like to thank one of the companies that I work for, FIGES, all my managers, especially Asst.Prof.Dr.Deniz Bölükbaş, and my colleagues for their support to me for studying my masters degree, understanding, advises, providing software and high performance computers when I needed.

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January 2014

Mert Safa MÖKÜKCÜ
(Electrical Engineer)

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## ABBREVIATIONS

**ABS** : Anti-lock Brake System
**AC** : Alternating Current
**AIST** : National Institute of Advanced Industrial Science and Technology
**ALEK** : Alternative Energy Club
**BEV** : Battery Electric Vehicle
**BLDC** : Brushless Direct Current
**BLDCM** : Brushless Direct Current Machine
**CAD** : Computer Aided Design
**CAN** : Controller Area Network
**CNC** : Computer Numerical Control
**$CO_2$** : Carbon Dioxide
**DC** : Direct Current
**DSP** : Digital Signal Processor
**ECCVT** : Electronically Controlled Continuously Variable Transaxle
**ECU** : Engine Control Unit
**EMF** : Electromotive Force
**EPS** : Electric Power Steering
**EV** : Electric Vehicle
**FEM** : Finite Element Method
**FSCW** : Fractional Slot Concentrated Winding
**GB** : Gigabyte
**GUI** : Graphical User Interface
**HEV** : Hybrid Electric Vehicle
**ICE** : Internal Combustion Engine
**ICEV** : Internal Combustion Engine Vehicle
**IEEE** : Institute of Electrical and Electronics Engineers
**IGBT** : Insulated Gate Bipolar Transistor
**IPM** : Interior Permanent Magnet
**ITU EV** : Istanbul Technical University Electric Vehicle
**MMF** : Magnetomotive Force
**NdFeB** : Neodymium Iron Boron
**OEM** : Original Equipment Manufacturer
**PEC** : Power Electronic Circuit
**PID** : Proportional Integral Derivative
**PM** : Permanent Magnet
**PMSM** : Permanent Magnet Synchronous Motor
**SRM** : Switched Reluctance Motor
**TI** : Texas Instruments
**V2G** : Wheel to Grid
**2D** : Two Dimensional
**3D** : Three Dimensional

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**ELECTRIC VEHICLE POWERTRAIN DESIGN AND IMPLEMENTION**

## SUMMARY

In recent years all expositions of cars show that every OEM is developing at least one electric vehicle. This subject is growing because of petrol reserve limitation, advertisements of new technology, which grows more interest, and high efficiency of electric vehicles. Recent researches show that vehicles with ICE, will be always dependent on petroleum. As the petrol reserves of the world grows thinner every second, it can be foreseen that EVs will take the place of ICE vehicles and it has already begun with HEVs. In the year of 1881, Gustave Trouvé showed the world that, the best solution should be electric powered vehicles. Even if electric vehicle technology is older than ICE vehicle technology, this forgotten technology have come back. Nowadays OEMs are researching on serial production of electric vehicles. There are some examples like Tesla Model S, Nissan Leaf, Toyota Prius, Chevrolet Volt, Fiat E500, BMW i3 etc. This production growth added with developing infotaintments of these vehicles increased interest of customers. Every year market share of EVs steps up.

El-Refaie indicated that there has been growing interest electrification especially in hybrid/electrical traction and propulsion applications. Even though the main focus has been on areas like energy storage and power electronics, there is growing recognition of the importance of traction motors and generators [8].

From these ideas, Istanbul Technical University Alternative Energy Club members and it's supervisor created an electric vehicle project called ITU EV. This project is about developing a drive system for a conventional ICE vehicle. A small compatible vehicle had been chosen to use in the project which is Opel Corsa from Corsa B series, and it will be converted into an EV. Almost the entire light-duty hybrid vehicle industry has shifted to PM machines in order to meet the increasing power density and efficiency requirements [8]. For converting an ICEV to BEV, it had to be chosen a light and known vehicle. As the vehicle is known, the interior parts and connecting parts would be a lot easier to produce and design. As this vehicle weights 875 kg with its ICE, it means that vehicle chassis is approximately 650 kg. This is a perfect vehicle to convert and implement our electric motor.

ITU EV project is funded by Istanbul Technical University by every means. It's designers are ITU students and ALEK supervisors. Total project budget is 50000 TL. Starting year of the project is 2011. Project has four different main research areas. These are electric powertrain, battery part, controlling part and mechanical construction and outer design part. In this study, electric powertrain design and production parts of the project will be investigated.

First vehicle mechanical data will be examined for the motor design. Afterwards black box calculations of the motor will be given following by analytical verification of the design and electromagnetic analysis. Later on the heating anaysis and solution of the motor will be given. Finally the production and tests of the electric motor which is designed for ITU EV project will be given.

To calculate power need of the vehicle, vehicle mass, wheel diameter, car frontal area, wheel rolling resistance coefficient, aerodynamic coefficient, air density, vehicle speed, gravity will be used to prefigure wheel friction force, aerodynamic drag force and slope friction force.

If the vehicle drive needs are investigated, it can be found out that the features that affects motor design are input voltage, output power, rated speed and torque. To maintain the best electric motor design for the application, choosing the materials and optimizing the size and coils are essential.

An electrical machine is an electromechanical energy converter. If it is taken into consideration, when its input is electrical energy and its output is mechanical energy it works as electric machine. On the other hand if its input is mechanical energy and its output is electrical energy it works as electric generator.

Electrical machines can be separated into two types. These are AC Alternative Current and DC Direct Current machines. The specification of the AC machines is that alternative current flows into the coils and creates a turning magnetic field in the airgap. Unlikely in DC machines magnetic field that is created is straight. Permanent magnet brushless DC motor can have DC in its name but when this specification is held in the case, it enters to a AC machine type.

For electric drivetrain a special design 70 kW powered BLDC motor is produced and laboratory tests are made. The rated voltage is chosen as 355 V. For transmission output power of the motor shaft, vehicle's original transmission system will be used. For driving motor, an inverter design and assembly is made. The designed motor's power need calculations are made by hand and design is made by computer aided softwares. After designing electric motor, electromagnetic and computational fluid FEM analysis are made. When the verification of the design is obtanied, production is made as well as motor assembly.

For infotaintment a special vehicle user interface is created. In-vehicle communication is provided by CAN communication protocol. Data are processed on Matlab which is working in background and reflected into driver control panel. Interface shows data like temperature, speed on the panel. Data about electric motor can be monitored, safety and battery state can be controlled. Different modes for controlling electric motor is added and reflected on the panel like sport mode, eco mode etc.

Motor laboratory tests are made in ITU Electrical Machinery Laboratory with the designed inverter. For controlling the PEC, a special designed and coded DSP controller is created. The project is thought to be finished in the first half of 2014.

# ELEKTRİKLİ ARAÇ SÜRÜŞ SİSTEMİ TASARIM VE İMALATI

## ÖZET

Son yıllarda elektrikli araç geliştirme çalışmaları hız kazanmıştır. Dünyadaki petrol rezervlerinin azalması ve içten yanmalı motor ile çalışan araçların $CO_2$ emisyonlarının yüksek olması nedeniyle hava kirliliği yaratmaları bu çalışmaların gelişmesini sağlamıştır. Toyota firmasının Prius modelini çıkartmasından beri özellikle içten yanmalı motora sahip olan araç bile olsa menzili uzatmaları nedeni ile elektrikli araçlar tercih edilmektedir. Ayrıca petrol fiyatlarının özellikle ülkemizde çok yüksek olması ve buna karşılık olarak elektrik fiyatının düşük olması da tüketicilerin ilgisini çekmektedir. Şu anda neredeyse tüm otomotiv üretici firmaların seri üretime sundukları elektrikli araçları bulunmaktadır.
Elektrikli araç teknolojisi aslında en eski araç teknolojisidir. Elektrik motoru buluşu, içten yanmalı motor buluşundan önce yapılmıştır. Ancak ilk üretilen elektrikli araçların menzillerinin çok düşük olması ve hızlarının at arabalarından az olması bu teknolojinin gelişmesine ve ilerlemesine engel olmuştur. İlerleyen yıllarda bazı firmalar denemeler yapsa da, her seferinde farklı nedenlerden dolayı elektrikli araçların ortaya çıkmaları gecikmiştir. Son yıllarda sabit mıknatıslı yüksek verimli motor geliştirme alanında teknolojik ilerlemelerin oluşması ve batarya teknolojisinin de gelişmesi ile otomotiv üreticileri tekrar elektrikli araç piyasasına dönüş yapmışlardır.
Elektrikli araçlar üç farklı başlıkta ayrılabilir. Bunlar hibrit, bataryalı ve yakıt hücreli elektrikli araçlardır. Hibrit araçlar hem içten yanmalı motoru hem de elektrik motorunu aynı anda bünyesinde barındıran araçlardır. Hibrit araçların üç tipi bulunmaktadır. Bunlar seri hibrit, paralel hibrit ve seri-paralel hibrit araçlardır. Seri hibrit araçlarda bulunan içten yanmalı motor sürekli sabit hızda dönmektedir. Bu motorun mili bir jeneratöre bağlıdır. Bu jeneratör mekanik enerjiyi elektrik enerjisine çevirerek akü bankına iletir. Aracın tüm çekişini elektrik motoru sağlamaktadır. Elektrik motoru için gerekli olan enerji de akü bankından gelmektedir. Böylece içten yanmalı motor sürekli aynı devirde dönecek ve yakıt harcama miktarı minimuma inecektir. Bu da aracın aynı miktarda yakıt ile çok daha uzun mesafe gitmesini sağlamaktadır. Seri hibrit araçların en çok bilinen örneği Fisker firmasının Karma modelidir. Bir diğer hibrit araç türü paralel hibrittir. Paralel hibrit araçlarda aracın çekiş yükünü elektrik motoru ve içten yanmalı motor beraber taşırlar. Araç belirli bir hıza ulaşmadıkça elektrik motoru kullanılır. Aracın hızı elektrik motorunun kaldıramayacağı noktaya ulaştığında içten yanmalı motor devreye girer. Paralel hibrit araçlarda serilere göre nispeten daha küçük bir akü bankı bulunmaktadır. Bu akü bankının enerjisi rejeneratif frenlemeden veya içten yanmalı motorun jeneratör gibi çalışması ile sağlanır. Paralel hibrit elektrikli araçlara en kolay örnek elektrikli bisikletler verilebilir. Elektrikli bisikletlerdeki tek fark içten yanmalı motor yerine insan gücünün kullanılmasıdır. Son olarak seri-paralel hibrit araçlar örnek verilebilir. Bu tür araçlarda iki adet içten yanmalı motor kullanılmaktadır. Bunlardan biri elektrik enerjisini üretecek jeneratör olarak çalışırken, diğeri aracın çekiş yükünü elektrik motoru ile paylaşmaktadır. Bu araçlara

da örnek olarak Toyota'nın Prius modeli verilebilir. Hibrit araçlar dışında bataryalı elektrikli araçlar da son yıllarda seri üretime sunulmaktadır. Bu araçlarda tüm çekiş yükü elektrik motoru tarafından karşılanmaktadır. Enerji akü bankından sağlanmakta ve şarj işlemi dışarıdan yapılmaktadır. Bataryalı elektrikli araçlar alanında en yüksek verime sahip olan araçlardır. Özellikle batarya ve güç elektroniği alanındaki gelişmeler bu tip araçların üretimi ve geliştirilmesinin yolunu açmıştır. Geliştirilen Lityum iyon aküler kurşun asit ve diğer eski tip akülere göre çok daha hafif ve enerji kapasiteleri çok daha yüksektir. Bu tip araçlara örnek olarak BMW firmasının i3 modeli verilebilir.
Elektrikli araç piyasasının gelişmesi ile birlikte üyeleri İTÜ Elektrik Mühendisliği Bölümü ve İTÜ Makina Mühendisliği Bölümü olan öğrenciler ile birlikte İTÜ Elektrik Mühendisliği Öğretim Üyesi Doç.Dr.Özgür Üstün'ün danışmanlığında İTÜ Alternatif Enerji Kulübü kuruldu. Kulübün kurulması ile birlikte 2011 yılında İTÜ Elektrikli Araç Geliştirme Projesi – İTÜ EV Projesi'ne de başlandı. Proje bütçesi BAP komisyonu tarafından 50000 TL olarak belirlenmiştir. Projenin en önemli amaçlarından biri tasarım ve üretimin tamamıyle yerli olarak yapılmasıdır. Diğer önemli amaç ise proje bütçesini olabildiğince aşmadan sadece üniversitenin bütçesi ile projeyi tamamlamaktır. Bu amaçla proje aşamaları dört aşamaya ayrılmıştır. Motor bölümü, batarya ve elektrifikasyon bölümü, kontrol bölümü ve mekanik tasarım ve dış tasarım bölümü. Bu çalışmada motor bölümü çalışmaları incelenecektir.
Projede ilk olarak araç temini yapılmıştır. Araç şasisi tasarım ve imalatı oldukça zahmetli ve maliyetli bir iş olduğundan dolayı hafif bir binek araç satın alınıp, bu aracın elektrikli araca çevrimi yapılması planlanmıştır. Projede seçilen araç Opel Corsa Swing'dir. Seçilen araç Corsa B sınıfındandır. Aracın güç gereksinimleri hesaplandıktan sonra motor tasarımı ve imalatı gerçekleştirilmiştir.
Bir elektrik makinası, temel olarak bir elektromekanik enerji dönüştürücüsüdür. Bu anlamda ele alındığında elektrik enerjisi alarak mekanik enerji üretiyorsa elektrik motoru olarak, eğer mekanik enerji alıp bunu elektrik enerjisine dönüştürüyorsa bu kez elektrik generatörü olarak çalışmaktadır.
Elektrik makinaları başlıca iki kümede incelenir. Bunlar AA Alternatif Akım ve DA Doğru Akım makinalarıdır. AA makinalarının özelliği sargılardan alternatif akımın akması ve hava aralığında dönen bir manyetik alan oluşmasıdır. Doğru akım makinalarında ise meydana gelen manyetik alan düzgündür. Yüzey Mıknatıslı Fırçasız Doğru Akım Motoru, adında DA'nın yer almasına karşın bu sınıflandırma içerisinde AA kümesinde yer almaktadır.
Projede elektrik motor tipi olarak sabit mıknatıslı fırçasız doğru akım motoru seçilmiştir. Bu motor tipinin avantajı veriminin yüksek olması, bakım gereksinimi olmaması, imalatının daha kolay olması ve kontrolünün hassas şekilde yapılabilmesidir. Mıknatıs tipi olarak SmCo tip mıknatıs seçilmiştir. Bu tipteki mıknatıslar yüksek sıcaklığa dayanabilen ve yüksek manyetik akı yoğunluğuna sahiptir.
Yüzey mıknatıslı BLDCM'da rotor tipinin seçimi uygulama alanlarına göre farklılıklar göstermektedir. Tasarımı gerçekleştirilen BLDCM'da rotor tipi olarak yapısının getirdiği çeşitli avantajlardan (Eylemsizliğin küçüklüğü – hızlı cevap verme – küçük mekanik zaman sabiti – yataklama ve araç entegrasyon uyumu) dolayı iç rotorlu yapı tercih edilmektedir. Dış rotorlu motorlar çoğunlukla büyük çap, küçük uzunlukta yapılmaktadır ve yataklamaları iç rotorluya göre daha zordur. Bu sebeplerden dolayı iç rotorlu tasarım yapılmıştır.
Motor analitik tasarımları yapıldıktan sonra elektromanyetik ve ısıl sonlu elemanlar analizleri yapılmıştır. Motor datasının verifikasyonu sağlandıktan sonra üretim için mekanik tasarımlar gerçekleştirilmiştir. Tasarımı yapılmış olan motor, 10 kutuplu bir

fırçasız doğru akım motorudur. Motorun mıknatısları Samaryum Kobalt (SmCo) malzemeden olmakta ve stator sac paketi ise yalıtımlı özel silisli sac dilimlerinden oluşmaktadır. Motorda hava aralığı, birkaç karşılaştırma sonucunda 1 mm olarak seçilmiştir, nadir toprak elementi sürekli mıknatıs kullanılan elektrik motorlarında daha küçük hava aralıkları doymaya ve demir kayıplarının artmasına neden olduğundan; ayrıca mıknatıs yüzeylerinin çok hassas işlenememesinden dolayı en az 1 mm olarak belirlenir. Motorun statorunda 12 diş (oluk) bulunmaktadır. Daha önceki raporlarda da açıklandığı gibi oluk sayısının kutup sayısına yakın olması motorun moment üretimini arttırmakta; ayrıca konsantrik sargılar hem alan zayıflatma özelliğini güçlendirmekte hem de motorun kolay imal edilmesini sağlamaktadır.

Tasarlanan fırçasız doğru akım motoru bir prototip motor olduğundan motorun tüm bileşenleri takım tezgahlarında imal edilmiş, herhangi bir seri üretim düzeneği kullanılmamıştır. Aşağıda da anlatılacağı gibi gövde ve kapaklar dolu alüminyum malzemeden işlenmiş, motorun silisli sacları lazer tezgahında kesilmiş, diğer bileşenler numerik kontrollü torna ve freze tezgahlarında imal edilmişlerdir.

Her parça, imalat sonrası teknik resimlere göre CMM, kumpas, mastar, havalı ölçüm aletleri, mikrometre vb. hassas ölçü aletleriyle ölçülmüş, gerekli ölçü toleranslarının tutmadığı durumlarda parçalar yeniden üretilmiş veya istenen ölçüye getirilmiştir. Ölçümler, gerek görüldüğünde incelenmek üzere kaydedilmiştir.

Motor imalatı tamamlandıktan sonra İstanbul Teknik Üniversitesi Elektrik Makinaları Laboratuvarı'nda yükleme testleri gerçekleştirilmiştir. Bu testler sonucunda motorun nominal çalışma değerleri çıkarılmıştır. Projenin bir sonraki evresinde motorun araca uygulanacak ve saha deneyleri yapılacaktır.

Projede elektrik motoru tasarımı haricinde motor sürücüsü tasarımı da yapılmıştır. Bu çalışmada güç katı yani evirici tasarımı hakkında bilgilere yer verilmiştir. Evirici, tasarlanan ve imal edilen bir kontrol kartı tarafından kontrol edilmektedir. Bu kontrol kartının içinde araç içi haberleşmeyi sağlayacak ve aynı zamanda motor kontrolünü de sağlayacak olan bir DSP bulunmaktadır. DSP kodlama işlemi Mekatro Ar&Ge firması tarafından yapılmıştır.

Çalışmada incelenecek son kısım kullanıcı arayüzüdür. Elektrikli araç için tasarlanan elektrik makinasının kullanıcı tarafından kolaylıkla kontrol edilmesi gerekmektedir. Özellikle yakın gelecekte yaygın şekilde kullanımı düşünülen elektrikli araçların; sürücüler ve yolcular tarafından rahat, erişilebilir, çözüm üreten ve akıllı şekilde yönlendirme kabiliyetlerine sahip olması hedeflenmektedir. Geliştirilmeye açık ve prototipten üretime geçişi kolaylaştırmak için hızlı prototipleme yöntemine dayanarak bir veri yolu uygulaması yapılmıştır. Verilerin akışı gerçek zamanlı izlenmekte, hatalar anlık tespit edilebilmektedir.

Sistemde gerçek zamanlı çalışmaya imkan sağlayan sayısal işaret işleyici tüm sistemi kendi kontrolünde yönetebilmektedir. Geri planda çalışan bu makine kontrolünün kullanıcıya özgü bir arayüzünün olması gerekmektedir. Araç içi iletişim CAN haberleşme protokolü ile sağlanmaktadır. Bilgiler geri plan da çalışan Matlab üzerinde işlenmekte ve sürücü kontrol paneline yansımaktadır.

Sürücüye çeşitli opsiyonlar sunan arayüz; hız, sıcaklık vs. gibi bilgileri ekranda gösterir. Elektrik makinasına ait bilgiler izlenmekte, güvenlik ve batarya durumu kontrol edilmektedir. Elektrik makinasın kontrolü ayrı ayrı birimlere bölünmüş ve sürücü isteğine bağlı olarak ekranda yer alması sağlanmıştır.

# 1. INTRODUCTION

Transportation is one of the most important research areas in the world. For transportation of human beings there are two types of transportation: personal transportation and common transportation. Automobiles are the most important and most used personal transportation vehicles. In the last few years, because of more $CO_2$ production, researchers changed their goal to have new technologies for this industry. With these new developing technologies, transportation will no longer be a threat for $CO_2$ emissions and automobiles will not use an energy that will be run short in forthcoming days. Recent researches show that vehicles with ICE, will be always dependent on petroleum. As the petrol reserves of the world grows thinner every second, it can be foreseen that EVs will take the place of ICE vehicles and it has already begun with HEVs.

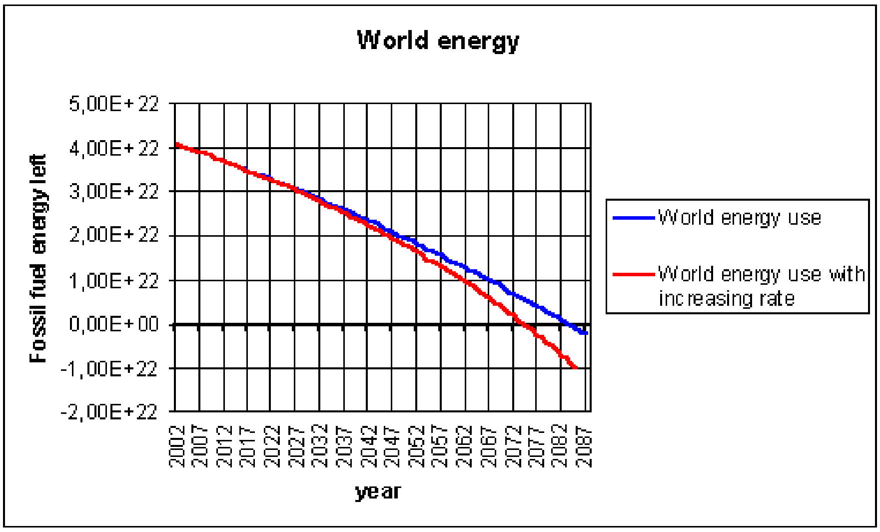



**Figure 1.1 :** World energy use – years [43].

As the fossil fuel reserves decrease over the years, the energy provided by these fossil fuels also decreases. The blue line shows the energy from fossil fuels assuming the energy consumption per person is constant and taking into account the calculated population growth. In this case there will be no more energy from fossil fuels after 2083. The red line shows the energy from fossil fuels taking into account an increase in consumption rate per person, going towards an American lifestyle. The consumption rate for Americans was kept constant and the consumption rate of the rest of the world increased by 2% per year. In this case the fossil fuels are finished in the year 2074 [43].

With the transportation need for lifetime, a need for power had been grown. Humanity searched for the best solution to produce energy from every kind of  for their daily life, as for the transportation. It all started with steam powered vehicles. They were not mass produced, they were noisy and not environment friendly at all. The main problems were maintaining the pressure of steam and supplying water to the system. To change this, people searched for more powerful engines with some different fuels. The first ones were hydrogen and oxygen in an internal combustion engine, following a mix of Lycopodium and coal dust. Those inventions and trials were always disappointments. In the year of 1881, Gustave Trouvé showed the world that, the best solution should be electric powered vehicles.

For developing EVs, especially for EVs with BLDC motors need rare earth elements for the motor production. The estimation of the rare elements production in the world according to AIST is:

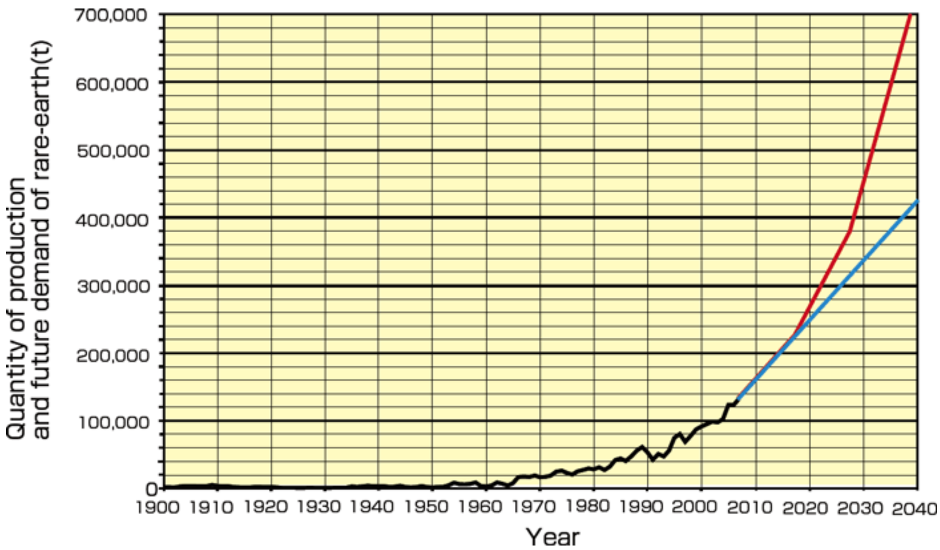



**Figure 1.2 :** Quantity of production and estimation of rare earth elements [40].

HEV, as from its name is a hybrid system. It has both internal combustion engine and electrical engine. It has some different configurations as Micro Hybrid, Mild Hybrid, Full Hybrid and Plug-in Hybrid. HEVs can be different for their usage of electric motor. If a HEV is using ICE for drive after when electric motor reaches an amount of speed it is a parallel hybrid and if ICE motor is used to generate electrical energy in order to use this energy in electric motor for drivetrain this type of HEV is series hybrid. The first hybrid car was exhibited in Paris Fair in 1899. It had ICE, electric motor and lead-acid battery. It was made Belgian-French and it was a parallel HEV. HEVs had a fame until 1914 but with the start of World War I, needs for other technologies and productions have been increased and HEVs have lost interest. Later on, Dr. Victor Vouk, who is accepted as leader of HEVs, have built a HEV, Buick Skylark in 1975. The Buick Skylark had 15 hp DC motor, 8 of 12 V car battery and ICE by brand of Mazda. The car had acceleration from 0 to 100 km/h in 16 seconds and highest speed of 129 km/h. After 80's, researches of HEVs continued and increased. Most important works and results are made by Japan Car Manufacturers as Toyota released Prius in 1997. This vehicle now has a 54 kW electric motor and 74 kW maximum powered ICE. The electric motor is an IPM motor which is a permanent magnet synchronous motor. This IPM motor has 288 V rated voltage and 351 A at maximum torque. Furthermore the electric motor of Toyota's Prius has water cooling in order to reduce the heating losses and have more efficient drivetrain.

**Table 1.1 :** Technical specifications of Toyota's Prius (1997).

| Technical details of Toyota Prius (1997) | |
|---|---|
| IC engine size | 1.5 litre, 4 cylinder, 16 valve |
| ICE Power | 52.2 kW at 4200rpm |
| ICE Torque | 111 N.m at 4200rpm |
| Electrical motor power | 33kW |
| Electric motor torque | 350 Nm at 0-400rpm |
| Electrical energy storage | NiMH battery, 288V, 6.5 Ah |
| Hybrid system net power | 73kW |
| Fuel consumption | 22/19 $km.L^{-1}$ city/highway(EPA estimates) |
| Transmission | ECCVT, electronically controlled continuously variable transmission |
| Suspension | Independent MacPherson strut stabiliser bar and torsion beam with stabiliser bar |
| Steering | Rack and pinion with electro-hyraulic assist |
| Brakes | Front disc, rear drum, with ABS |
| Length | 4.31 m |
| Width | 1.69 m |
| Height | 1.46 m |
| Wheelbase | 2.55 m |
| Weight | 1254 kg |
| Gasoline tank capacity | 44.71, 11.8 US gallons |
| Tyres | P175/65R14 low rolling resistance |

HEV's intention is to decrease consumption of gasoline. For this, these vehicles in traffic or low speeds uses electrical engine instead of internal combustion engine. Or

ICEs are used for producing electrical energy in order to satisfy the electric motor needs. At the same time as ICE is working at constant speed, fuel consumption and $CO_2$ emissions are much more lower than the ICE drive. With these two types of HEV, they have less emission than ICE powered vehicles. Even more sometimes HEV's have zero $CO_2$ emissions. Apart from Plug-in HEVs, HEVs does not require charging from the grid as they produce their own electrical energy by their ICE.

Because of this efficiency, less $CO_2$ emissions and very importantly less fuel consumption, people have chosen HEVs instead of ICEVs and HEVs number in world is increasing every day as it can be seen from Table 1.3.

In the last years EV market share is getting bigger. Especially in 2012 and 2013 EV market have grown 1.5% which means approximately 200000 vehicles.

**Table 1.2 :** Electric vehicle market share increase with years [41].

| Electric Vehicle Market Share | |
|---|---|
| Year | Market Share |
| 2007 | 2.99% |
| 2008 | 2.37% |
| 2009 | 2.78% |
| 2010 | 2.37% |
| 2011 | 2.23% |
| 2012 | 3.38% |
| 2013 | 3.85% |

**Table 1.3 :** Electric drive sales in USA [41].

| 2013 Electric Drive Sales in USA | | | | |
|---|---|---|---|---|
| Months | Hybrids (HEVs) | Plug-in Hybrid incl. Extended Range | Battery (BEVs) | Total |
| January | 34611 | 2354 | 2022 | 38987 |
| February | 40173 | 2789 | 2616 | 45578 |
| March | 46327 | 3079 | 4553 | 53959 |
| April | 42804 | 2735 | 4403 | 49942 |
| May | 48796 | 3209 | 4545 | 56550 |
| June | 44924 | 4169 | 4573 | 53666 |
| July | 45494 | 3499 | 3943 | 52936 |
| August | 53020 | 6407 | 4956 | 64383 |
| September | 33576 | 4477 | 3650 | 41703 |
| October | 33565 | 6367 | 3733 | 43665 |
| November | 36085 | 4903 | 3930 | 44918 |
| Total | 459375 | All plug-ins: | 86912 | 546247 |
| | | Total Vehicle Sales in 2013 | | 14179416 |
| | | Electric Drive Market Share | | 3.85% |

HEVs are really important in automotive industry because they will be a way to pass to BEVs. In this great change, HEVs are playing a essential role. With HEVs, there will be more charging stations, less fuel consumption, less $CO_2$ emission and people will be used to drive EVs. HEVs are the bridge to pass through EVs.

As the time will bring BEVs finally, its history should be investigated. BEVs are thought as a new technology but it is older than ICE driven vehicles. The first known BEV is made by a French electrical engineer and inventor, Gustave Trouvé, in 1881. It had Lead-Acid batteries and 0.1 hp DC electric motor inside it. Its range was 16 km and speed was 15km/h, so it had less speed than the carts, it lost reputation and interest. In 1894, at the race of Paris-Rouen, electric vehicles had finished a race within range of more than 1000 km in two days so they gained a lot of reputation from this event. With the increased reputation, BEVs had a war against ICEVs in the following 20 years. One of the most important innovation at that time was in 1897, a French engineer, M.A. Darracq found regenerative breaking. After this innovation, in 1899, a BEV, La Jamais Contente, made by a Belgian engineer Camille Jenatzy, was the first vehicle that had passed the speed, 100 km/h.

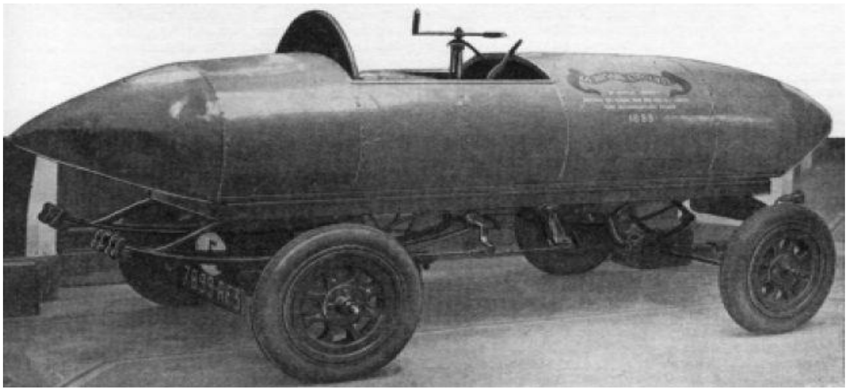


**Figure 1.3 :** La jamais contente.

But these innovations couldn't help to BEVs to win the war against ICEVs. With more powerful engines, effective ranges and lighter ICEVs, in the following 60 years, erased BEVs from market. In 60's with environmental ideas, BEVs had grown their interest again and General Motors made "Electrovan" in 1966. Within the developments in battery technologies and power electronics, because of the range and price BEVs couldn't increase in industry. After in 90's, General Motors started to show interest in BEVs and in these years, they put the first mass production BEV in the world, EV-1.

**Figure 1.4 :** First mass production BEV – EV1.

EV-1s had a different type of marketing as they were rented to costumers for 3 years. But at the mid of the year 1990, gasoline prices went down distinctively. With some different factors and petrol prices, the production of EV-1 was stopped tragically. What happened to EV-1, affected BEV production very badly. But in the late 2000's, with environmental thinking, prices of petrol and decreasement of remaining petrol reserves in the world showed to people that the production will be BEVs in the future.

## 1.1 Purpose of Thesis

The purpose of this thesis is designing electrical power train for a light electric vehicle. This vehicle can be a Go-Kart, which is designed for this thesis too, or a conventional light car like Opel Corsa, etc. In this project, a conventional vehicle is taken into consideration and designs are made in order to replace its ICE motor with a BLDC motor. Its analytical and electromagnetic design and analysis are made in this thesis and its motor driver too is taken into consideration. In the end of the thesis, whole electrical drivetrain system will be given.

## 1.2 Literature Review

As in the last years the interest for electric vehicles is highly increased, there are lots of articles and books about this subject nowadays. The articles from IEEE have been taken into consideration for literature review.

Bradley C. Keoun from Solar Car Corporation mentioned in his paper *“Designing an Electric Vehicle Conversion”* that from gas powered vehicle, building an electric vehicle. In his paper he has mentioned about removals of ICE and related parts as well as how to choose batteries for the EV. In his work, an EV component block diagram is built in order to show which parts are necessary. After calculation of number of batteries in an EV, it is described how to choose the best electric drivetrain for the “conversion wanted vehicle”. After giving specific details of installation of electric drivetrain to the vehicle, integration of accessory, power brake, power steering and climate control systems are told. At the end of the work two converted vehicles are presented [17].

The paper “*Novel Motors and Controllers for High Performance Electric Vehicle with 4 In-wheel Motors”* which was published in 1996 by M. Terashima, T. Ashikaga, T. Mizuno, K. Natori, N. Fujiwara and M. Yada shows that with 4 hub motors they have developed a vehicle named IZA. This vehicle had maximum speed of 176 km / h and a range of 548 km per charge with a constant speed of 40 km/ h. Furthermore the vehicle has an acceleration from 0 to 400 m in 18 seconds. For high performance characteristics, they have designed and produced direct drive in-wheel motors and controllers. Motor type is outer rotor and the used magnet type is Sm-Co. In their work, microcontroller consisted a 3-phase inverter with a microprocessor-based controller. Maximum output and maximum torque of their drivetrain was 25 kW and 42.5 kgm. The system was consisted over 90% efficiency at the rated speed. The performance tests have been applied and the vehicle’s drivetrain system have been confirmed [36].

H. Shimizu, J. Harada, C. Bland, K. Kawakami and L. Chan wrote *“Advanced Concepts in Electric Vehicle Design”* and it was published in 1997. In their work, they have developed EVs for Eco-Vehicle Project. For this project, unique designs had to be created. The vehicle should have been high-performance, ultrasmall and battery powered. New designs for this project included hub motor drive system, battery hausings and new battery management system. Finally the design should have been able to use solar panels for battery charging, smart crash avoidance and guidance systems [32].

In 1998, H.C.Lovatt, V.S.Ramsden and B.C.Mecrow published the paper *“Design of an in-wheel motor for a solar powered electric vehicle”.* In the paper the solar powered vehicle “Aurora” which entered in 1996 3010 km Darwin – Adelaide World Solar

Challenge is explained. In comparison with other vehicles this vehicle has more efficient motor as 97.5% and it is lighter as 8.3 kg. As it is in-wheel electric motor, it is a direct-drive motor. As it is direct drive it is more efficient than all other motor/gear combinations. These parameters are achieved by high flux density, rare-earth magnets and computer aided optimisation of an axial-flux configuration for Halbach magnet array and ironless air-gap winding [21].

*"Traction Control of Electric Vehicle: Basic Experimental Results Using the Test EV "UOT Electric March""* is a paper that was published in 1998 by Y. Hori, Y. Toyoda and Y. Tsuruoka. In their work, they have proposed two different traction control techniques as model following control and optimal slip ratio control. They have demonstrated by real experiments by using the DC-motor-driven test EV "UOT – University of Tokyo" Electric March [15].

The paper *"Motion Control in an Electric Vehicle with Four Independently Driven In-Wheel Motors"* has been published by S. Sakai, H. Sado and Y. Hori in 1999. In the work, they have told methods of motion control for an EV with four independent driven in-wheel motors. Firstly they have proposed and simulated robust dynamic yaw-moment control. This control type generates yaw from torque differences between right and left wheels. Simulation results of the work shows that there is a problem with instability on slippery. They have came to find a solution to this problem with skid detection method and this leaded to a traction control system for each drive wheel. Work finishes with integrating this method to their experimental EV [30].

J. Gan, K. T. Chau, C. C. Chan and J. Z. Jiand have published the paper *"A New Surface-Inset, Permanent-Magnet, Brushless DC Motor Drive for Electric Vehicles"* in 2000. In the paper, they have proposed five-phase brushless dc motor drive. The motor drive had the advantages of both BLDCM drive and DC series motor drive. The work consisted the originality of PM excitations that generates air-gap flux of the motor and controlled by two particular phases of stator currents under the same PM pole. The motor configuration and operation principle was unusual so they have analysed magnetic field distribution and steady-state performance. Finally the work finished by experimental results for a prototype proposed motor drive and result was satisfying for EV applications [11].

In year 2001, C.L.Chu, M.C.Tsai and H.Y.Chen published *"Torque Control of Brushless DC Motors Applied to Electric Vehicles".* In their work, the goal was to present a high performance torque control system in order to achieve similar output characteristics as continuously variable transmissions of electric scooters that have brushless DC motors. In the paper phase advance control and field weakening control techniques are used to be able to have a wide range of operating speeds. In the paper, it is told that in practical applications of electric scooters the control scheme is using only one current sensor for measuring DC bus current in order to attain torque control. Furthermore three hall sensors are used to carry out phase advance control and field weakening control without an encoder. In the paper, theoretical and experimental results is shared. The hardware is based on a three phase permanent magnet motor and DSP is TI's TMS320F240 model [4].

In the paper *"Characterization of Electric Motor Drives for Traction Applications"* which was published in 2003 by M. Ehsani, Y. Gao and S. Gay studies about ideal characteristics of an electric motor drive for traction application for EV and HEV for high torque at low speed for hill climbing and low torque at high speed for normal driving. To be able to satisfy this feature the motor drive has to have a long constant power range to meet torque and speed demands. In the work effect of the motor characteristics on vehicle performances are analyzed and three type of electric motors have been investigated [6].

In 2004, Yoichi Hori's paper *"Future Vehicle Driven by Electricity and Control—Research on Four-Wheel-Motored "UOT Electric March II""* explains that electric vehicle is one of the most exciting objects to apply "advanced motion control" technique. It is told that EVs have following advantages as motor torque generation is fast and accurate, motors can be installed in two or four wheels and motor torque can be known precisely. These advantages enables to have high performance antilock braking system and traction control system with minor feedback control at each wheel, chassis motion control like direct yaw control and estimation of road surface condition. "UOT Electric March II" is an experimental EV with four in-wheel motors [14].

In the year 2004, Wu Hong-xing, Cheng Shu-kang and Cui Shu-mei have published the paper *"A Controller of Brushless DC Motor for Electric Vehicle".* In their work they have developed a controller for BLDCM for an EV and the controller was based on the mathematical model of BLDCM and special working conditions. They used digital signal processing. In the paper the hardware of the controller has been told. In the work, PID control strategy has been used. Finally in the paper flux-weakening control in high speed and method of regenerative braking have been discussed [13].

*"Magnetization Analysis of the Brushless DC Motor Used for Hybrid Electric Vehicle"* has published in 2004 by Z. Ping, L. Yong, W. Yan and C. Shukang. In the paper, component magnetization and magnetization after assembly for BLDCM for hybrid electric vehicles are compared. The comparison is made by theoretical analysis, FEM analysis and experiments. In their work it is shown that the permanent magnets can be fully magnetised by enough magnetizing MMF both component magnetization and post-assembly magnetization. They have tested their work on a rotor surface and they have shown that the test results are similar to FEM calculation. They have given their method on post-assembly magnetization in order to avoid the problem of magnetic forces and ferrous debris during the motor assembly process [24].

In 2006, Bhim Singh and Devendra Goyal told in their article "*Computer Aided Design of Permanent Magnet Brushless DC Motor for Hybrid Electric Vehicle Application"* that the aim of their project was to deal with a method of design of BLDCM which is designed for hybrid electric vehicle applications. They also considered design variables as airgap flux density, stacking factor, end turn coil factor, slot electric loading, coil fill factor, magnet fraction, slot fraction, flux density in the stator back iron. They have made a simplified design of radial flux surface mounted BLDCM for 12 kW of power and 1100 rpm. Afterwards they have used CAD algorithm for obtaining the performance of the motor which is calculated. As this project was a low voltage application, the current was high and therefore water cooling has been used. For achieving feasible and acceptable design, they have used optimization tools. In the end, finite element analysis is made to have electromagnetic characteristics of the motor and for verifying the obtained motor design [33].

In 2006, D.J. van Schalkwyk and M.J. Kamper who are from University of Stellenbosch, South Africa discussed in their article *"Effect of Hub Motor Mass on Stability and Comfort of Electric Vehicles"* that uncertainty of the wheel mass effect on the vehicle stability, safety and comfort in the vehicle should be considered. They have made frequency analysis with the simulations of the system which represents the vehicle suspension system and wheels. In the paper, the results of the hub motor driven vehicle is compared to a conventional standard vehicle. In the paper, it is told that hub motor has no effect on the stability of the vehicle and the frequency response of the system is in the accepted comfort range [38].

Again in 2006, in the article "*Design and Development of a In-Wheel Brushless D.C. Motor Drive for an Electric Scooter"* which is written by N.Ravi, S.Ekram and D.Mahajan, it is shown that with the advent of power electronics, BLDCM can be considered a potential drive for automotive applications. In the paper a design of BLDCM is presented as a direct drive. Maximum output power, maximum current, motor size has been considered as constraints. For obtaining static and dynamic characteristics of the motor analytical tools have been used. This was needed for low cost efficient design. Furthermore a low cost electronic controller has been developed for that application. The prototype of the system has been fabricated and it was tested on a light electric vehicle such as a scooter. In the paper performance results too have been presented [26].

In 2006, the paper "*Direct-Drive Wheel Motor for Fuel Cell Electric and Hybrid Electric Vehicle Propulsion System"* was written by Khwaja M.Rahman, Nitin R.Patel and Terence G.Ward and it discussed a gearless wheel motor drive system which is designed specifically for fuel cell electric and hybrid electric vehicle drivetrain application. In the system, the motor is liquid-cooled axial flux permanent magnet motor and it is designed to achieve the direct-drive requirements. The design of the motor has techniques in order to increase the inductance for improving machine constant power range and high speed efficiency. This technique reduces machine spin loss for improving efficiency. The design also optimizes the placement of the magnets on the rotor in order to reduce cogging and ripple torque. In the project, thermal activity is also considered and an aluminium casing with liquid-cooling was designed to effective decreasing on motor power loss by using high thermal conductivity [24].

In the paper *"In-wheel Motor Design for Electric Vehicles"* which is presented by K.Cakir and A.Sabanovic in 2006, an in-wheel electric motor prototype is designed for experiments. In their work, 4 in-wheel motors has been used independently. The designed motor type is outer rotor. They designed a direct drive in-wheel motor in order to show differences between central drive unit systems and direct drive systems from each tire independently. In their work, the goal was to design an outer rotor motor in order to carry loadings on each tires. The motor designed is Switched Reluctance Machine. In order to design, a 3D solid model is created and necesarry structural analyses are made. Afterwards, electromagnetic FEA analyses are made and the models have been modified in order to the results. This optimization is made until the motors have reached necesarry convergence to a set of consistent dimensions for structural and electromagnetic analyses. In the final chapter of the work, the results of the electromagnetic analysis were embedded to a general hybrid simulation model to check consistency between the design and analysis [3].

In 2006, Xose M. Lopez-Fernandez and J.Gyselinck have published the paper *"Design of an Outer-Rotor Permanent-Magnet Brushless DC Motor for Light Traction through Transient Finite Element Analysis"*. In their work they have analysed outer rotor DC motor topology by FEM. They have made both transient and steady state analysis of the motor. For their direct drive electric motor design they have used NdFeB type magnets. They have coupled analysis software with Matlab/Simulink and discussed transient simulation results [22].

*"An Introduction to Regenerative Braking of Electric Vehicle as Anti-Lock Braking System"* was published in 2007 by O. Tur, O. Ustun and R.N. Tuncay. In the work anti-lock braking systems (ABS) had been investigated as one of the most important active safety systems. This system improves safety with having decrease for breaking distance. This can be done by controlling the slip of the wheels. In their study a modeling approach has been shown on a quarter car model and ANSYS Simplorer is used as software. Hydrauling braking and EV regenerative braking concepts are taken into consideration [37].

In the paper that was published in 2008 "*A Permanent-magnet Hybrid In-wheel Motor Drive for Electric Vehicles"* by Chunhua Liu, K.T.Chau and J.Z.Jiang proposes a new outer rotor PM hybrid hub motor drive for electric vehicles. As they have proposed PM motor drive, there are two excitations as PMs and DC windings to produce magnetic field, the motor can cope up with wide range of flux control and this affects the motor to have a very high starting torque for electric vehicles cranking and extending the speed range for constant power and at the same time it keeps high efficiency at wide speed range. Furthermore as it has outer rotor, it is naturally connected to the wheel tire and this makes the system compact. A method is developed to analyse steady state and transient performances of in wheel motor drive. This method is called the circuit-field-torque time-stepping finite element method. The proposed prototype of outer rotor PM hybrid brushless is particularly suitable for BEVs [20].

Ayman M. El-Refaie, Z. Q. Zhu, Thomas M. Jahns and David Howe have published the paper *"Winding Inductances of Fractional Slot Surface-Mounted Permanent Magnet Brushless Machines"* in 2008. In their study, they have examined the permanent magnet brushless machines with fractional-slot concentrated-windings. These types of motors have the attention for their short end-windings, high slot fill factor, high efficiency and power density and their capacbilities of fault-tolerance and flux-weakening. They have talked about investigation of the various components of the winding inductance and different slot/pole number combinations. They have shown that main component of the winding inductance is slot leakage component. Finally in their work, analytical and FEM models are practiced in order to validate several prototype designs [7].

*"Unstaturated and Saturated Saliency Trends in Fractional-Slot Concentrated-Winding Interior Permanent Magnet Machines"* was published by Jagadeesh K. Tangudu, T. M. Jahns and Ayman El-Refaie in 2010. In the paper, interior permanent magnet synchronous machines (IPM) with fractional slot concentrated windings have been investigated. In their work they have studied on alternative slot-pole combinations for these machines and their key point was the saliency of designed machines was lower than IPM motors that uses conventional distributed windings. Relative advantages of FSCW-IPM machines are studied and reluctance torque and total machine torque have been focused on. Their key design parameter was the ratio $L_q/L_d$. When the stator current is near zero, this ratio is defined "unsaturated saliency ratio" and when the stator current is high, it is "saturated saliency ratio". The goal was to show machine designers being able to choose the most optimized slot-pole ratio for a FSCW-IPM machine in order to satisfy the system needs [34].

In the paper "*Design and Implementation of an Electric Drive System for In-Wheel Motor Electric Vehicle Applications"* which was published in 2011 by R. N. Tuncay, O. Ustun, M. Yilmaz, C. Gokce, U. Karakaya, it is discussed the design and application of a hub drive system for hybrid or all electric vehicles. In the work, a SIMULINK model of a hybrid electric vehicle is developed and its performance data are calculated. In the project, two BLDCM are designed and manufactured. The design power was each 15 kW. First performance tests were made in laboratory. Following laboratory tests, the two wheels are mounted to Fiat Linea vehicle. In the project, the mechanical differential is converted into electronic control technique which takes its data from detection of the angle of steering wheel. Between the system of electric drive and ECU of the vehicle a CAN bus communication is established. ICE drive and electrically driven wheels are set to work together. Some preliminary road tests are executed and design optimizations are made for ICE, Electric Drive and Battery Power for various drive cycles [36].

In the paper *"Design, Analysis and Implementation of a Subfractional Slot Concentrated Winding BLDCM with Unequal Tooth Widths"* which was published in 2011 by S. Senol and O. Ustun a study on design, analysis and implementation of a sub-fractional slot winding BLDCM with unequal tooth widths is given. This motor is wanted to be used in light electric vehicle systems. It is told that unconventional motor structures have more attention in last years because of the demans of electric vehicle technology. The main idea in the project is to design a BLDCM in order to have higher value of direct-axis phase inductance. This will enable for high performance field-weakening operation. The design and analysis are made computer aided. A software based on configurator approach is used to calculate motor parameters and the designed motor has been modeled in a FEA package for electromagnetic analysis. Then the designed motor manufactured and experimental study is made for verifying the design [31].

Wolfgang Gruber, Wolfgang Back and Wolfgang Amrhein wrote the paper *"Design and Implementation of a Wheel Hub Motor for an Electric Scooter"* in 2011 in order to show their work of optimization, design, measurements and implementation of an in-wheel motor for an electric scooter and this motor is designed to replace the in-wheel motor of a commercial electric scooter bike. In order to be able to replace the old motor, the design is made by the dimensions given by old motor which had frame size of motor and shaft as in 13-inch wheel. For having new features the goal was to achieve far higher power, torque, speed range and efficiency [12].

In the year of 2011, Ayman M. El-Refaie has published the paper *"Motors/Generators for Traction/Propulsion Applications: A Review"*. He discussed about growing needs and interest on electrification and growth in hybrid/electrical traction applications. In his review he investigated about features and state of the art with using global trends and many different technologies had been taken into consideration. Furthermore he studied the future trends and potential areas of research [8].

Dongbin Lu, Jianqiu Li, Minggao Ouyang and Jing Gu have published the paper *"Research on Hub Motor Control of Four-wheel Drive Electric Vehicle"* in 2011. Their work was about an electric vehicle which is driven by four hub motors. In this type of motors the rotor position information is coming from three hall-effect sensors. On the other hand as the back EMF of the hub motor is not trapezoidal but between sinusoidal and trapezoidal shape and the torque ripple at low speed when the EV drives at low speed, there is serious noise. In the paper, a sinusoidal current drive system of sinusoidal-wave PM motor with a low resolution position sensor is proposed. At low speed the performance of the control is perfect and measured torque ripple is much lower than the block commutation algorithm but as the EV is at middle and high speed the noise increases because of the switching noise and harmonics. The work proposes a combined BLDC and PMSM control for the hub motors. For low speed processes field oriented control (sinusoidal control) and for middle and high speed processes block commutation algorithm is used. For driving cab a low noise level in all speed range is shown by vehicle test and electric braking method is also told [22].

*"Design Considerations for Switched Reluctance Machines with a Higher Number of Rotor Poles"* was published in 2012 by Berker Bilgin, Ali Emadi and Mahesh Krishnamurthy. In their study SRM technology is shown as potential candidate for drivetrain systems for hybrid and plug-in hybrid electric vehicles as they have a wide constant power speed range and are robust for harsh working conditions. They have told that conventional SRM configurations have high number of stator poles and this number is more than rotor poles. In their paper, they have studied on advantages of choosing higher number of rotor poles against number of stator poles. Also they have worked on different designs for traction applications. They have verified their work and equations with three-phase 6/10 SRM with FEA simulations [2].

Patel B. Reddy, Ayman M. El-Refaie, Kum-Kang Huh, Jagadeesh K. Tangudu and Thomas M. Jahns have published the paper *"Comparison of Interior and Surface PM Machines Equipped with Fractional-Slot Concentrated Windings for Hybrid Traction Applications"* in 2012. In their work they have designed, analysed and tested two PM machines which were developed to satisfy the FreedomCar 2020 specifications. The goal of their study was to comparise IPM and SPM machines with same fractional-slot concentrated windings (FSCW) [28].

In 2012 the paper *"Effect of Stator Shifting on Harmonic Cancellation and Flux Weakening Performance of Interior PM Machines Equipped with Fractional-Slot Concentrated Windings for Hybrid Traction Applications"* was published by Patel B. Reddy, Kum-Kang Huh and Ayman El-Refaie. In their study they have targeted to satisfy FreedomCAR specifications. They have mentioned that IPM motors with fractional-slot concentrated-windings are good candidates for hybrid electric vehicles. They have investigated additional stator mmf sub and super harmonic components which affects as higher losses in rotor and saturation effects. In the work they have tried to cancel the harmonics in fractional slot concentrated windings by stator shifting. They have tried some designs, sinle layer and double layer 10-12 and double layer 16-18 motors. In the comparison they have shown power density, efficiency and torque ripple [29].

*"A Comparison of Electric Vehicle Integration Projects"* is the paper that was published in 2012 by Peter B. Andersen, Rodrigo Garcia-Valle and Willett Kempton. In their study they have investigated different methods for electric vehicle integrations by three projects and researched technical components that should be able to work together and offer a great number of utilization. The underlined projects are American University of Delaware's V2G research, the German e-mobility Berlin project and the Danish EDISON project [1].

Ayman El-Refaie published the paper *"Fractional-Slot Concentrated-Windings: A Paradigm Shift in Electrical Machines"* in 2013. In his study he researched about FSCW synchronous PM machines which has a growing interest due to their advantages like high power density, high efficiency, short end turns, high slot fill factor. He investigated latest updates in this subject that include reducing losses and furthermore he worked on discovering FSCW machine topologies other than PM machines and gave results [9].

In 2013 the paper *"Functional Modeling of an Electric Machine Used on Road Vehicles"* was published by Valerian Croitorescu, Iulian Croitorescu and Grigore Danciu. Their study aimed the subject of hybrid electrical vehicles. They have talked about motor efficiency which is affected negatively by heat generation of the motor.

They have built an electric motor functional and thermal model. They have taken into consider the production of torque and rotational speed of the motor for the functional model of electric motor and the thermal model for the energy losses. With this construction it is possible to calculate efficiency of the motor. The investigated motor is chosen for hybrid electric vehicle [5].

*"Advanced High Power-Density Interior Permanent Magnet Motor for Traction Applications"* was published in 2013 by Ayman M. El-Refaie, James P. Alexander, Steven Galioto, Patel Reddy, Kum-Kang Huh, Peter de Bock and Xiochun Shen. They have underlined that electric drive technologies have to supply economical cost advantage, weight and size advantage in order to have significant effect on market. They designed an advanced IPM machine for FreedomCar 2020 specifications. They have given data of analysis and testing of the designed machine. IPM machine built as 12 slot / 10 pole structure with FSCW equipped. In their work they have created several prototypes with different thermal effects that have been produced and tested [10].

### 1.3 The ITU-EV Project

The ITU EV project was created in 2011 by the creators of Istanbul Technical University Alternative Energy Club. The aim was to convert a conventional ICE driven vehicle into battery electric vehicle. The budget was taken just from university by BAP (Scientific Research Project). The consultant of the project is Asst. Prof. Dr. Ozgur USTUN as he is the consultant of ITU ALEK.


**Figure 1.5 :** ITU EV project vehicle.

After the vehicle was found technical specifications and conversion spaces in the vehicle chassis have been calculated and analysed.

Furthermore the teams were created in order to separate the main subjects. The teams were:

- Power Electronics and Control Group
  - Motor Control Circuits
  - Overall Control and In-vehicle Communication Systems
- Electrical Systems Group
  - Battery System
  - Energy Management
  - Cable Harness and Energy Distribution
- Motor Design Group
  - Design and Production of Electrical Motor
  - Tests of Electrical Motor
- Mechanical Design and Style Group
  - Vehicle Integration and Powertrain Reconfiguration
  - Outlook Style Design

In this project motor design group and battery system calculations will be taken into consideration. Motor design, analysis, production and tests from the beginning, basic power electronic circuits, battery choice and range calculation will be investigated.

First vehicle mechanical data will be examined for the motor design. Afterwards black box calculations of the motor will be given following by analytical verification of the design and electromagnetic analysis. Later on the heating anaysis and solution of the motor will be given. Finally the production and tests of the electric motor which is designed for ITU EV project will be given.

The targeted design schematic of the project is given in Figure 1.6 :

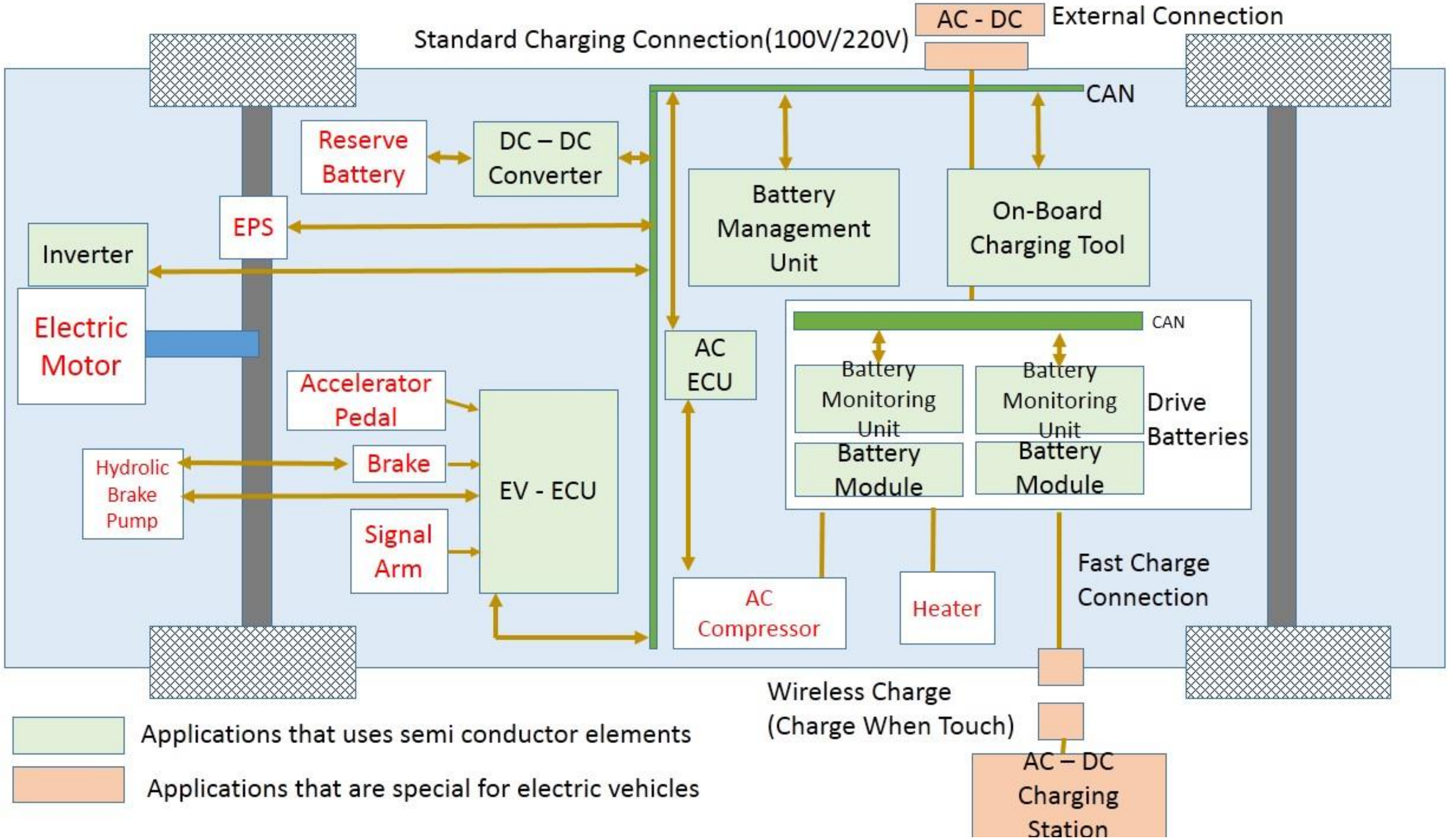



**Figure 1.6 :** ITU EV vehicle schematic.

## 2. VEHICLE MECHANICAL DATA

In the project, the chosen vehicle model is Opel’s Corsa Swing. Its model is 1997. Opel Corsa is being produced since 1982. Its type is supermini and time to time this model is sold by different companies such as Vauxhall, Chevrolet and Holden. Nowadays the production of Corsa is made in Spain and Germany. Our project vehicle is also called Corsa B series. Recently the production is for Corsa D series.

Project vehicle has 3 doors and it is Swing variant.

Technical specifications are given in Table 2.1.

**Table 2.1 :** Opel Corsa Swing ’97 specifications.

| **Opel Corsa Swing ’97 Specifications** | |
|---|---|
| **Feature** | **Value** |
| **General Features** | |
| Bodywork | 3-doors, hatchback |
| Transmission | 5 speed, manual |
| Release Date | May, 1997 |
| **Engine** | |
| Power | 44 kW (60 hp); 5200 rpm |
| **Performance** | |
| Top Speed | 155 km/h |
| Acceleration (0-100 km/h) | 15 s |
| Fuel consumption city | 10.2 l / 100 km ; (1 op 9.8) |
| Fuel consumption highway | 5.6 l / 100 km ; (1 op 17.9) |
| Combined | 7.3 l / 100 km ; (1 op 13.7) |
| **Chassis** | |
| Drive | Front |
| Tire | 165/170 TR13 |
| **Weights** | |
| Empty mass | 875 kg |
| Maximum permissible mass | 1370 kg |
| **Exterieur Sizes** | |
| Length | 3729 mm |
| Width | 1608 mm |
| Height | 1420 mm |
| Wheelbase | 2443 mm |
| Track for | 1387 mm |
| Width behind | 1388 mm |

As it can be seen from the Table 2.1, this vehicle is a light, small and compact vehicle.

### 2.1 Purpose

The purpose of converting this vehicle is as its consumption is too high for its class and weight, it will be a lot easier to compare ICEV and BEV drive costs, emissions and consumptions.

**Figure 2.1 :** Opel Corsa drawing in 3DMax.

### 2.2 Choosing the Best Vehicle

For converting an ICEV to BEV, a light and known vehicle had to be chosen. As the vehicle is known, the interior parts and connecting parts would be a lot easier to produce and design. As this vehicle weights 875 kg with its ICE, it means that vehicle chassis is approximately 650 kg. This is a perfect vehicle to convert and implement our electric motor.

### 2.3 CAD Drawing of the Vehicle

The CAD drawing of the vehicle is very important. From this drawing and calculations, the motor size had been selected and design process had started.

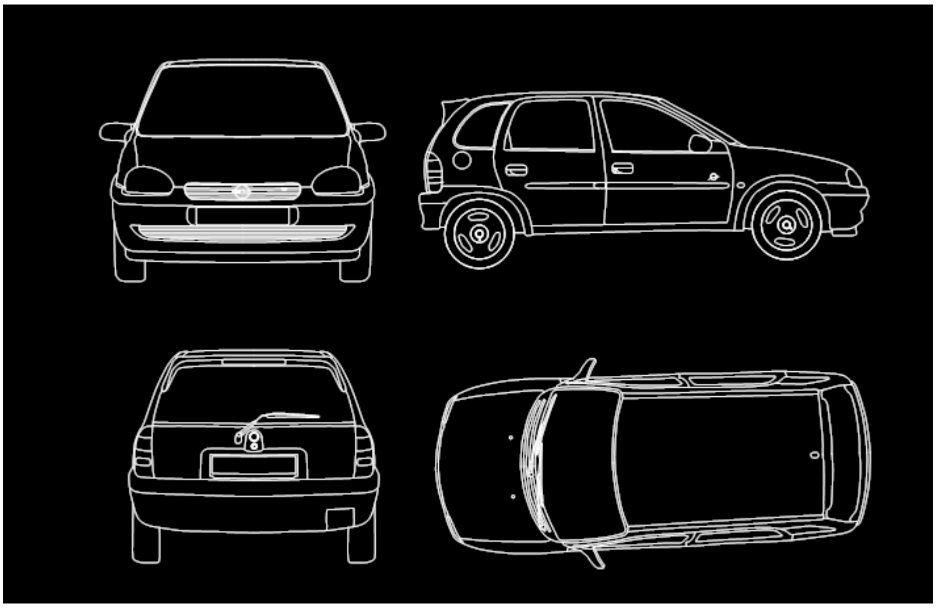


**Figure 2.2 :** 2D Model of project vehicle Opel Corsa (5-doors).

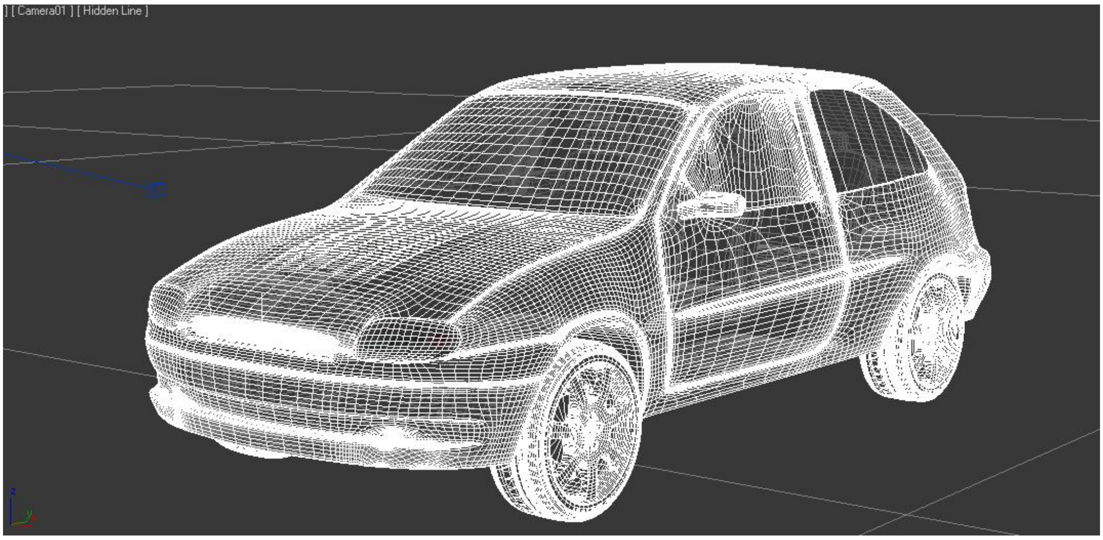



**Figure 2.3 :** Opel Corsa mesh drawing.

### 2.4 Cost

As the project budget is limited, cost is a very important issue in this study. This vehicle is searched all around Turkey and in Bursa, it is found a Corsa Swing for 6000 TL. This vehicle was bought even if its engine was broken down. As with the conversion the ICE would be removed, the cheapest but with stronger chassis vehicle had been chosen.


**Figure 2.4 :** ITU EV project vehicle.

## 2.5 Power Need Calculations

In this part of the project, the black box calculations of motor power need will be given. To calculate power need of the vehicle, vehicle mass, wheel diameter, car frontal area, wheel rolling resistance coefficient, aerodynamic coefficient, air density, vehicle speed, gravity will be used to prefigure wheel friction force, aerodynamic drag force and slope friction force. The calculated forces are needed to be overcomed in order to make vehicle move.

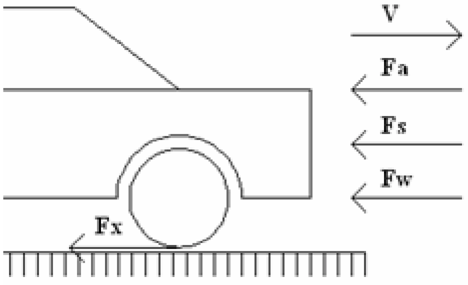



**Figure 2.5 :** Quarter car model [48].

Forces acting on a vehicle is shown in Figure 2.5, which are rolling resistance ($F_w$), aerodynamic drag force ($F_a$), slope friction force ($F_s$) and force due to vehicle inertia ($F_{acc}$). Fx denotes the tire braking force [48]. The force equations per wheel are like down below:

$$F_w = \frac{(m \cdot c_t \cdot g \cdot \cos(\frac{\alpha}{180/\pi}))}{4} \quad \textbf{(2.1)}$$

$$F_a = \frac{(c_r \cdot \delta \cdot A \cdot V)/2}{4} \quad \textbf{(2.2)}$$

$$F_s = \frac{(m \cdot g \cdot \sin(\frac{\alpha}{180/\pi}))}{4} \quad \textbf{(2.3)}$$

$$F_{acc} = m \cdot \frac{dV}{dt} \quad \textbf{(2.4)}$$

Here m, g, $c_t$, $c_r$, α, δ, A and V are the vehicle mass, gravity, aerodynamic coefficient, wheel rolling resistance coefficient, slope angle of vehicle, vehicle frontal area and vehicle speed. $F_w$, $F_a$ and $F_s$ are wheel friction force, aerodynamic drag force and slope friction force. In this study acceleration force ($F_{acc}$) will be neglected.

For ITU EV project, the vehicle data is taken from Opel Corsa.

**Table 2.2 :** Technical specifications of Opel Corsa B series.

| Technical Specifications of Opel Corsa B | |
|---|---|
| Power (W) | 44 kW (60 hp) |
| Tire | 165/70TR13 |
| Empty Mass | 875 kg |
| Frontal Area | 1.88 $m^2$ |
| Wheel Friction Coefficient | 0.3 |
| Aerodynamic Coefficient | 0.1 |
| Wheel Diameter (r) | 0.38 m |

If the data is taken from the table above and when the maximum speed is choosen as 150 km/h the maximum slope is taken as $10^0$, $F_w$, $F_a$ and $F_s$ are calculated as 634 N, 4.5 N and 372.6 N. In this work and calculations vehicle inertia is neglected. With these calculations total force need of the vehicle is 1011.1 N.

**Table 2.3 :** Power need calculations.

| Slope | Vehicle Mass | Wheel Diameter | Car Area | Wheel Rolling Resistance Coeff. | Aero. Coeff. | Air Density | Vehicle Speed | Gravity | Wheel Friction Force | Aero. Drag Force | Slope Friction Force | Total Force | Torque | Speed | Speed | Power |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| grade | kg | m | $m^2$ | $c_r$ | $c_t$ | $kg/m^3$ | km/h | $m/s^2$ | $F_w$ | $F_a$ | $F_s$ | F | T | rad/s | rpm | W |
| 1 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 643.7 | 4.5 | 37.5 | 685.6 | 130.3 | 219.3 | 2095.2 | 28567.9 |
| 2 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 643.4 | 4.5 | 74.9 | 722.8 | 137.3 | 219.3 | 2095.2 | 30115.7 |
| 3 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 642.9 | 4.5 | 112.3 | 759.7 | 144.3 | 219.3 | 2095.2 | 31654.4 |
| 4 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 642.2 | 4.5 | 149.7 | 796.4 | 151.3 | 219.3 | 2095.2 | 33183.4 |
| 5 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 641.3 | 4.5 | 187.0 | 832.9 | 158.2 | 219.3 | 2095.2 | 34702.4 |
| 5 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 160 | 9.81 | 641.3 | 4.8 | 187.0 | 833.2 | 158.3 | 233.9 | 2234.9 | 37029.2 |
| 5 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 170 | 9.81 | 641.3 | 5.1 | 187.0 | 833.5 | 158.4 | 248.5 | 2374.6 | 39357.7 |
| 5 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 180 | 9.81 | 641.3 | 5.4 | 187.0 | 833.8 | 158.4 | 263.2 | 2514.2 | 41687.9 |
| 6 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 640.3 | 4.5 | 224.3 | 869.1 | 165.1 | 219.3 | 2095.2 | 36210.9 |
| 7 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 639.0 | 4.5 | 261.5 | 905.0 | 172.0 | 219.3 | 2095.2 | 37708.4 |
| 8 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 637.5 | 4.5 | 298.7 | 940.7 | 178.7 | 219.3 | 2095.2 | 39194.5 |
| 9 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 635.9 | 4.5 | 335.7 | 976.0 | 185.4 | 219.3 | 2095.2 | 40668.7 |
| 10 | 875 | 0.38 | 1.88 | 0.1 | 0.3 | 1.2754 | 150 | 9.81 | 634.0 | 4.5 | 372.6 | 1011.1 | 192.1 | 219.3 | 2095.2 | 42130.6 |

As it can be seen from Table 2.3, the maximum force need is approximately 1011.1 N. This corresponds to 192.1 Nm with the formula below:

$$\tau = \frac{F_t}{r/2} \tag{2.5}$$

From the torque equation, the wanted motor speed is calculated too. But as this project is a conversion project, the motor speed will be multiplied with the transmission ratio which is 4:1. The wanted vehicle speed is maximum 150 km/h. From this information, the motor speed can be found by the expression:

$$V = \omega \cdot r \tag{2.6}$$

To be able to provide wanted data with the designed electric motor, the needed speed is calculated as 219.3 rad/s. If speed unit is converted into rpm, wanted speed can be found as 2100 rpm approximately. Finally as in this project, the vehicle mechanical structure is used the wanted speed will be multiplied with transmission ratio and the calculated value is approximately 8000 rpm.

Calculating power depends on calculating torque and speed need of the motor. In this example the maximum needed motor power is approximately 40 kW. If the slope is more than $10^0$, the wanted motor power can go up to 50 kW. If the inertia force is considered too, a 50 kW motor should be sufficient for this project. But for improving the performance and acceleration and excluding the mechanical losses from the system the motor design is made for 70 kW.

**Table 2.4 :** Motor design data.

| **Data** | **Value** |
|---|---|
| Power (W) | 70 kW |
| Speed (rpm) | 8000 rpm |
| Max. Outer Diameter (mm) | 370 mm |
| Output Torque (Nm) | 192.1 Nm |

# 3. ELECTRIC DRIVE TRAIN

If the vehicle drive needs are investigated, it can be found out that the features that affects motor design are input voltage, output power, rated speed and torque. To maintain the best electric motor design for the application, choosing the materials and optimizing the size and coils are essential. In this part of the study, the BLDC motor design and analysis will be given.

## 3.1 Electrical Motor

An electrical machine is an electromechanical energy converter. If it is taken into consideration, when its input is electrical energy and its output is mechanical energy it works as electric machine. On the other hand if its input is mechanical energy and its output is electrical energy it works as electric generator.

Electrical machines can be separated into two types. These are AC Alternative Current and DC Direct Current machines. The specification of the AC machines is that alternative current flows into the coils and creates a turning magnetic field in the airgap. Unlikely in DC machines magnetic field that is created is straight. Permanent magnet brushless DC motor can have DC in its name but when this specification is held in the case, it enters to a AC machine type.

### 3.1.1 Brushless DC motor

If an electrical machine is taken into consideration by mechanical features, all machines that have rotational motion have two main parts. These parts are the rotating part rotor and motionless part stator. The main theorem of electrical motor is to create a magnetic field between rotor and stator and with applying excitations to the coils that are put into rotor or stator and having a tangential force to condutors. Total force that affects to the all conductors creates a rotating torque on the shaft. By this information BLDCM are electrical machines that use permanent magnets which produces magnetic field and coil excitation interaction. By this interaction a rotating torque is produced in accordance with Biot-Savart law and energy conversion is composed.

In BLDC motors magnetic field is always produced by magnets. Besides that when conductors are under N pole (+) current is given to this conductor and the same conductor when comes under S pole (-) current is given with the help of power electronic circuit. With this processing feature BLDC motor enters to DC motor type.

If the magnetic flux that is produced by magnets is taken constant as Φ, the following equations are obtained. In here motor torque and voltage constants are equal if energy balance equation applied in SI unit system.

$$E_a(t) = K_e(t) \quad \textbf{(3.7)}$$

$$T_e(t) = K_t \cdot i_a(t) \quad \textbf{(3.8)}$$

In an ideal electromechanical energy conversion system by the energy balance equation:

$$K_e = K_t \quad \textbf{(3.9)}$$

$K_e$ can be taken into consideration as voltage constant and $K_t$ as torque constant. In these equations torque is the produced torque. If shaft torque is wanted to be found, vantilation and friction losses have to be removed from this torque value. Constants can be calculated according to number of turn (N), airgap flux density ($B_g$), motor length and rotor radius ($R_{rot}$).

$$T_e = \frac{E_i}{\omega} = 2 \cdot N \cdot B_g \cdot L_{mot} \cdot R_{rot} \cdot i = K_t \cdot i \quad \textbf{(3.10)}$$

$$K_e = K_t = 2 \cdot N \cdot B_g \cdot L_{mot} \cdot R_{rot} \quad \textbf{(3.11)}$$

In the Figure 3.1 it is shown a 2 pole BLDCM that has surface magnet outer armature winding. In inner rotor type, armature winding is on motionless part and magnets are on rotating part.

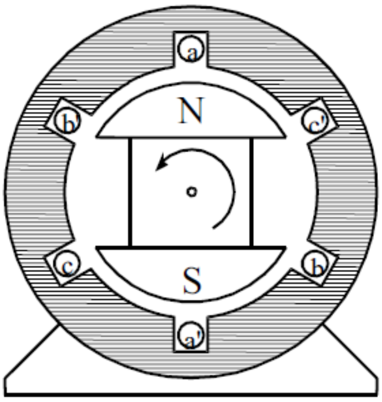



**Figure 3.1 :** Inner rotor surface magnet BLDCM [26].

From the process feature BLDCM's winding currents have to be changed in order to magnet position. For this to be done magnet movement has to be monitored. This monitoring process is done by Hall sensors. Hall sensors are semi conductors and when it comes in a magnetic field it induces voltage.

The signal that is coming from Hall sensors give the magnet position information to the power electronic circuit and semi conductors in that circuit switches on and off in order to flow the wanted current from windings.

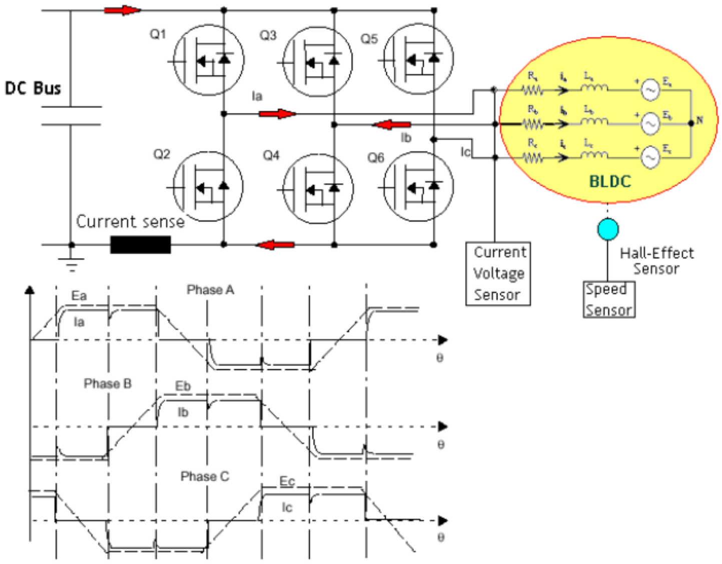



**Figure 3.2 :** BLDCM equivalent circuit and current and voltage waveforms.

In Figure 3.2 a BLDCM equivalent circuit is shown and winding current and induced voltage waveforms with an inverter have been investigated.

$i_a$, $i_b$ and $i_c$ current waveforms are produced when $Q_1$, $Q_2$, $Q_3$, $Q_4$, $Q_5$ and $Q_6$ switches conduct as a pair by $60^0$ pieces. When $Q_1$ and $Q_4$ pair conduct $i_a$ current gains positive value and $i_b$ current gains negative value. Finally by the pair conduction of switches phase currents has $120^0$ positive, $60^0$ zero and $120^0$ negative and again $60^0$ zero values.

Magnets that makes rotational motion inducts E voltage in windings. Winding currents has to be on the same phase as E voltage. The phase connection is provided by Hall sensors. Thus E(+) and I(+) or E(-) and I(-) multplies as positive value and by energy balance equation energy conversion is formed. Finaly motor produces torque and creates rotational motion.

$$E \cdot I = T \cdot \omega \quad \textbf{(3.12)}$$

#### 3.1.1.1 Rotor type

For BLDC motors rotor type can be inner or outer. For automotive applications if drivetrain is wanted to be in-wheel application or direct drive it has to be outer rotor and if the drivetrain is connected to the mechanical differential it should be inner rotor. Inner rotor applications are longer and smaller radius than outer rotor applications. This feature affects production as easier to bedding, easier for windings. Furthermore the inertia of rotating part is lower. Another advantage of inner rotor application is to have more space in stator slots. With more space it is easier to place more ampere-turns into the motor. As the stator and its windings are outer part of the motor, cooling is made easier and this helps motor to be able to load more. Disadvantages of the inner rotor applications are as magnets are in interior part with help of centrifugal force it is possible to force magnets pop out from their places and in serial production it can be harder to assembly stator windings than the outer rotor applications. In this project the chosen system is inner rotor in regard of vehicle integration.

#### 3.1.1.2 Material choice

In a BLDC motor, there are three important material choices. These are stator sheet, rotor back iron and magnets. For stator back iron and slots it has to be chosen a good quality non oriented electrical steel sheet. When these sheets are bought from the producer, the B-H curves and power losses of this material is given by them. In material type magnetic permeability which can be shown as μ should be high in order to have high relation between magnetic field strength and magnetic flux density. The difference between motor sheets are their magnetic saturation values and iron loss values. If a good quality of sheet wanted to be used it has to have the features as in lower magnetic field strength produces more magnetic flux density and has low iron losses. In this project M3629G type with 0.5 mm thickness.

Rotor back iron is made by a low carbon steel which has high magnetic permeability. If the steel is high quality, this can help decreasing weight of motor. In order to choose the thickness of the rotor back iron, the ability of producing satisfying ampere-turns when magnetic field is passing through from this iron is regarded. When this value is not passing one or two percent of air gap ampere-turns, it is preferred. In designs, the saturation of the steel which is caused by magnetic field that is produced by magnets too is important. If necessary, magnets can be moved in order to reduce cogging torque effect. For material type for rotor steel_1010 type is chosen.

In BLDC motors the preferred magnets are rare earth magnets. In this project, the magnets have to have high magnetic field strength, low demagnetization rates and magnets that can operate in higher temperatures are chosen. It is SmCo type magnet. On the other hand the biggest disadvantage of thee SmCo type magnets is their cost. By the way SmCo type magnets are cheaper than NdFeB type magnets.

SmCo type magnets can lose their magnetization ability with the effect of heat. Because of this X38GS type magnets have been chosen. X38GS type magnets are more enduring against heat and high loading. The material magnetic parameters had been taken from the magnet producer.

**Table 3.1 :** X38GS magnet parameters.

| **Parameter** | **Value** |
|---|---|
| Relative Permeability | 1.1 |
| Bulk Conductivity (Siemens/m) | 625000 |
| Magnetic Coercivity (A/m) | -800000 |
| Mass Density (kg/m$^3$) | 7400 |

Magnet thickness have been chosen as 6 mm and the pole embrace is taken 0.76.

### 3.1.2 Motor analytical design

With motor parameters and material choices, the motor analytical design is made by ANSYS RMxprt®. This analytical analyse is not a FEA analysis, it is just calculating the estimated results of the motor.

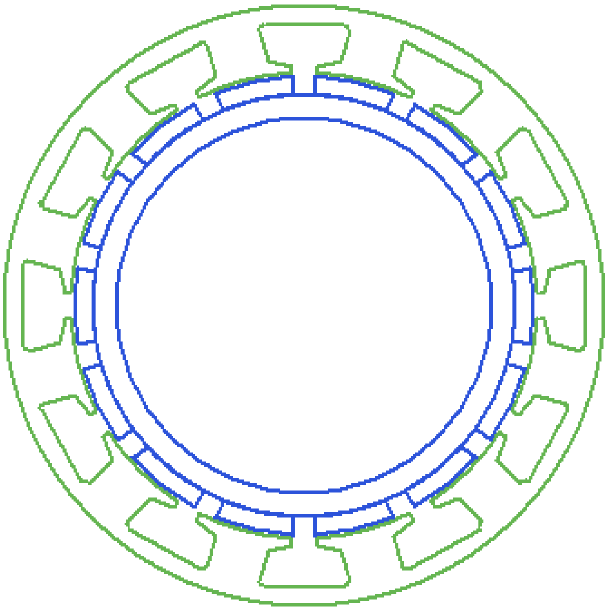


**Figure 3.3 :** RMxprt motor model.

As it can be seen from the model, the selected motor is 12 slots/ 14 pole BLDC motor. The selected windings are concentrated and star connected. To obtain analytical analysis results, some motor parameters that had been calculated have to be entered into the software as geometrical parameters, wanted power, speed parameters and voltage rate. Before analysing the model, the switching degree (electrical degree) has to be chosen. In this design it is chosen as $120^0$. Magnet parameter had been entered and stator steel and rotor steel materials were in the software library. Operating temperature have been chosen as 90 $^0$C as generally a BLDC motor operates in range of 90 $^0$C – 120 $^0$C. On the other hand, 120 $^0$C is dangerous for the motor as the magnet starts to lose it’s magnetization over that temperature value.

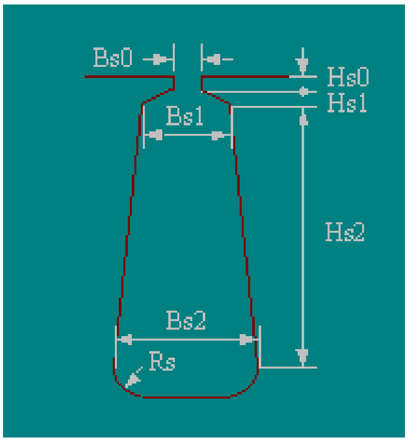



**Figure 3.4 :** Stator slot type and length.

Slot type is shown in Figure 3.4. Values here are given in Table 3.2.

**Table 3.2 :** Slot parameter lengths.

| Parameter | Length (mm) |
|---|---|
| Bs0 | 8.5 |
| Bs1 | 24.7639 |
| Bs2 | 30.3908 |
| Hs0 | 2.2 |
| Hs1 | 1.4 |
| Hs2 | 10.5 |
| Rs | 1.5 |

For analytically analysing the motor some parameters have to be entered to the software. These parameters have been calculated and estimated before the motor design. The designed machine is BLDCM 14 pole/ 12 slot concentrated winding. Rated output power is 70 kW and rated voltage is approximately 355-360 V. The RMxprt parameters that are given to the software are like in Table 3.3:

**Table 3.3 :** Entered motor parameters.

| **Parameter** | **Value** |
|---|---|
| **General** | |
| Rated Output Power (kW) | 70 |
| Rated Voltage (V) | 355 |
| Rated Speed (rpm) | 8000 |
| Frictional and Wintage Losses (W) | 700 |
| Operating Temperature ($^0$C) | 90 |
| Winding Connection Type | Y3 (star connection) |
| **Stator Data** | |
| Outer Diameter of Stator (mm) | 200 |
| Inner Diameter of Stator (mm) | 155 |
| Length of Stator Core (mm) | 150 |
| Stacking Factor | 0.95 |
| Type of Steel | M36-29G |
| Number of Conductors per Slot | 4 |
| Wire Diameter (mm) | 5.189 |
| Stator Slot Fill Factor (%) | 32.2287 |
| **Rotor Data** | |
| Airgap (mm) | 1 |
| Inner Diameter (mm) | 125 |
| Length of Rotor (mm) | 150 |
| Type of Steel | Steel_1010 |
| Type of Magnet | XGS28H |
| Thickness of Magnet (mm) | 6 |
| Width of Magnet (mm) | 25.0699 |

After entering the parameters, winding type has been set into concentrated type. In recent researches concentrated winding has the advantages of efficiency and production. In this study, production is an essential part. Thus the overhang of stator has to be smaller in order to produce easily. Furthermore when the winding is installed into the stator, if the winding type is concentrated, as in this project it is handmade, the production can be handled much more easier even it is inner rotor design. This is shown in the Figure 3.5.

As it can be seen from Figure 3.5, coils are installed to each stator teeth and after one teeth with coil, the next teeth is left free. For all phases there are two coils and the schematic of winding structure is given.

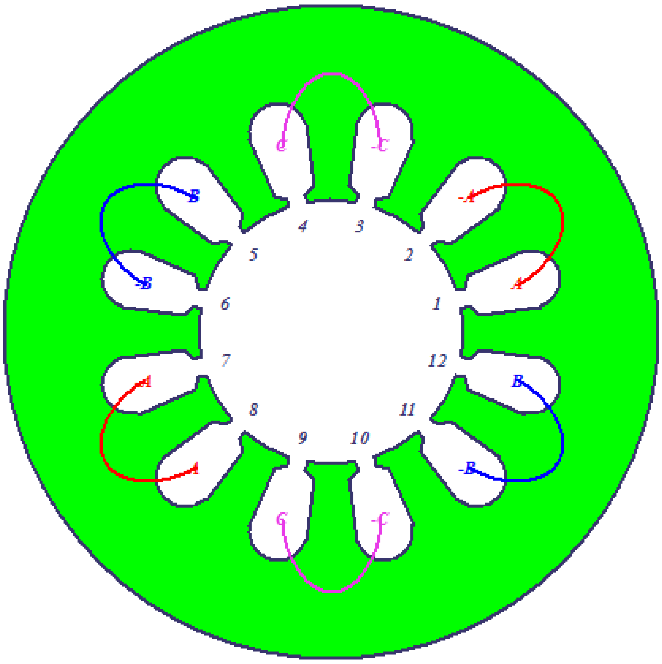



**Figure 3.5 :** Motor winding schematic.

By entering this parameters a design and analytical analysis of this design had been obtained. The analysis is made constant output power 70 kW. The motor output parameters are given in Table 3.4 and Table 3.5. Output parameters will be given in two parts. First part of output parameters will consist material consumption, steady state parameters and no load magnetic data in order to examine the designed motor when it is not loaded. In the second part of output parameters full-load calculations will be given. In full-load calculations at 70 kW of constant power, armature current, loss, rated speed and torque, locked rotor speed and torque will be given as well as efficiency of the motor.

**Table 3.4 :** Motor output parameters part 1.

| Parameter | Value |
|---|---|
| **Material Consumption** | |
| Copper Weight (kg) | 1.87 |
| Permanent Magnet Weight (kg) | 2.34 |
| Stator Core Steel Weight (kg) | 8.81 |
| Rotor Core Steel Weight (kg) | 3.75 |
| Total Net Weight (kg) | 16.77 |
| **Steady State Parameters** | |
| D and Q Axis Inductance $L_1$+$L_{ad}$ (H) | 3.38e-05 |
| Armature Leakage Inductance (H) | 2.9e-05 |
| Armature Phase Resistance at $20^0$C (Ω) | 0.0036 |
| Armature Phase Resistance at $90^0$C (Ω) | 0.0028 |
| **No-Load Magnetic Data** | |
| Stator-Teeth Flux Density (T) | 1.3201 |
| Stator-Yoke Flux Density (T) | 1.6264 |
| Rotor-Yoke Flux Density (T) | 1.48228 |
| Air-Gap Flux Density (T) | 0.8483 |
| No-Load Speed (rpm) | 11530.5 |
| Cogging Torque (Nm) | 0.503438 |

In these parameters there are winding inductances, winding resistances (which are calculated for using in FEA electromagnetic analysis), no load speed, cogging torque (which is less than 1%), yoke and teeth flux densities in order to optimize if there are any saturation of steels at full load and net material consumptions. Material consumption calculations give the designer an idea about the mechanical weight. But in this calculation bearings, shaft and cover is not taken into consideration.

In Table 3.5, full load analysis results are given.

**Table 3.5 :** Motor output parameters part 2.

| Parameter | Value |
|---|---|
| **Full-Load Data** | |
| Average Input Current (A) | 211.325 |
| Armature RMS Current (A) | 201.186 |
| Armature Current Density (A/mm$^2$) | 9.514 |
| Frictional and Windage Loss (W) | 809.544 |
| Iron-Core Loss (W) | 3781.08 |
| Armature Copper Loss (W) | 432.435 |
| Total Loss (W) | 5023.06 |
| Input Power (W) | 75020.3 |
| Output Power (W) | 69997.3 |
| Rated Speed (rpm) | 9251.93 |
| Rated Torque (Nm) | 72.247 |
| Locked-Rotor Torque (Nm) | 3524.39 |
| Locked-Rotor Current (A) | 49749.7 |
| Efficiency (%) | 93.3044 |

Full load analysis is made based on constant power. With constant power motor speed is calculated 1250 rpm more than wanted. By this information the calculated efficiency is 93.3% and calculated rated torque is 72.247 Nm at 9251.93 rpm and 70 kW. That's why efficiency-speed curve and output torque-speed curve need to be examined.

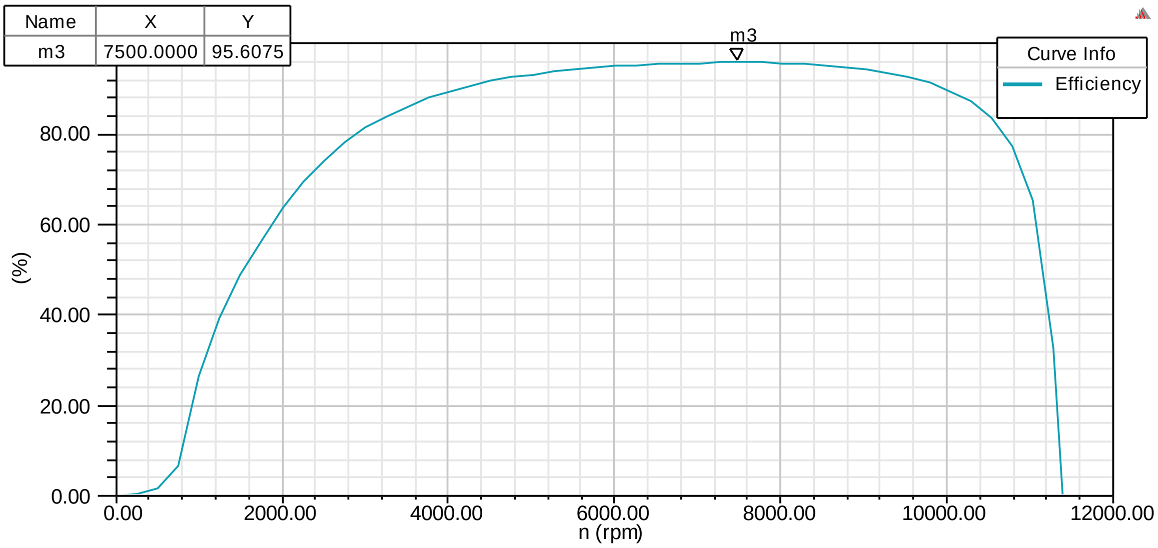



**Figure 3.6 :** Efficiency-Speed curve.

As it can be seen from the Figure 3.6 efficiency is 95.6% at 7500 rpm. This show that in wanted motor speed, higher efficiency can be taken from the motor. Furthermore from the efficiency-speed curve it can be seen that the designed motor has a wide range of high efficiency in different motor speed values which can be essential especially in automotive applications as the energy is dependent on batteries.

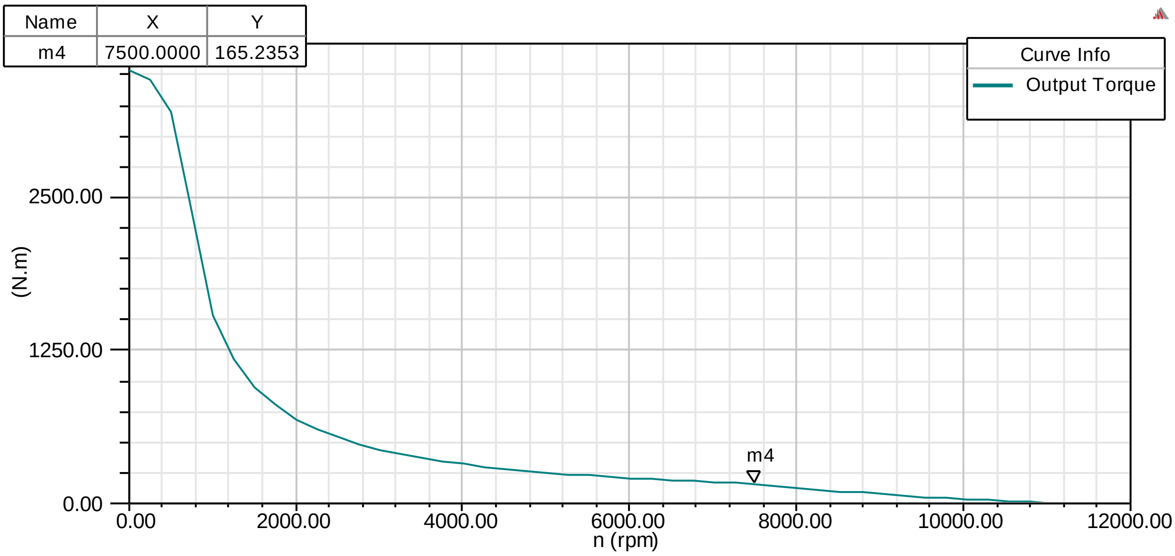



**Figure 3.7 :** Output Torque-Speed curve.

Figure 3.7 shows that at 7500 rpm the output torque is calculated as 165.2 Nm. Results show that the designed motor is sufficient for the application.

After having optimized results in analytical analysis, 2D and 3D FEA analysis is made to verify the designed motor. The data are taken from ANSYS RMxprt® and for FEA analysis ANSYS Maxwell® v.16 is used.

### 3.1.3 Motor electromagnetic analysis

For FEA electromagnetic analysis of the motor, input data and models are taken from RMxprt. The analysis is made at constant speed of 9251.93 rpm.

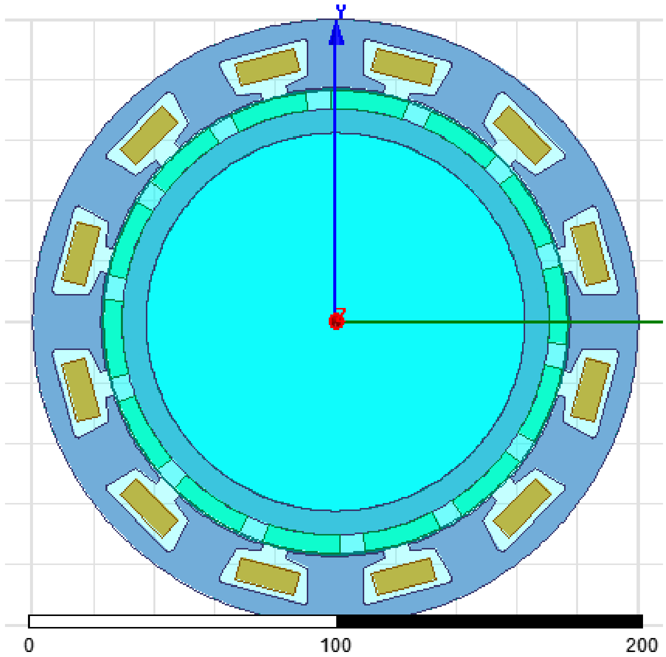



**Figure 3.8 :** Motor 2D FEA model.

The excitations of the coils have been given from external circuit model of software. The model is given in Figure 3.9. In this model, the winding resistances and inductances have been defined. The data is taken from analytical analysis results. The rated voltage of 355 V have been used. The switches are taken as ideal switches and in external circuit just the inverter part is taken into consideration.

In the analysis time step is chosen as 1 μs and stop time is 5 ms. In total 10316 mesh elements are used for the calculation. Mesh plot is given in Figure 3.10. In a 8 cored i7 processor and 8 GB ram computer the analysis took approximately 5 hours.

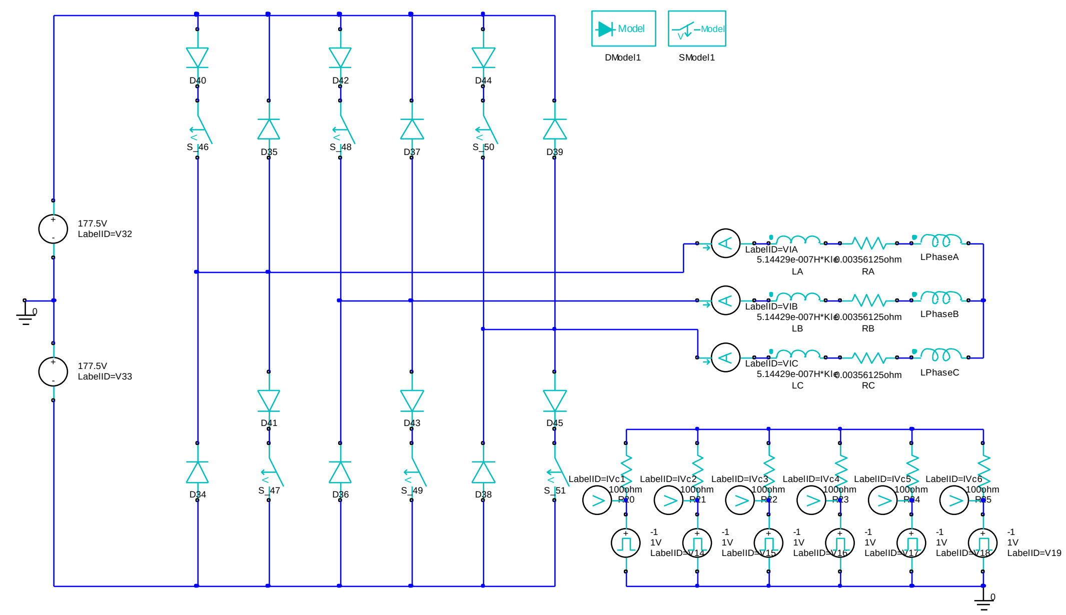



**Figure 3.9 :** Motor excitation external circuit model.

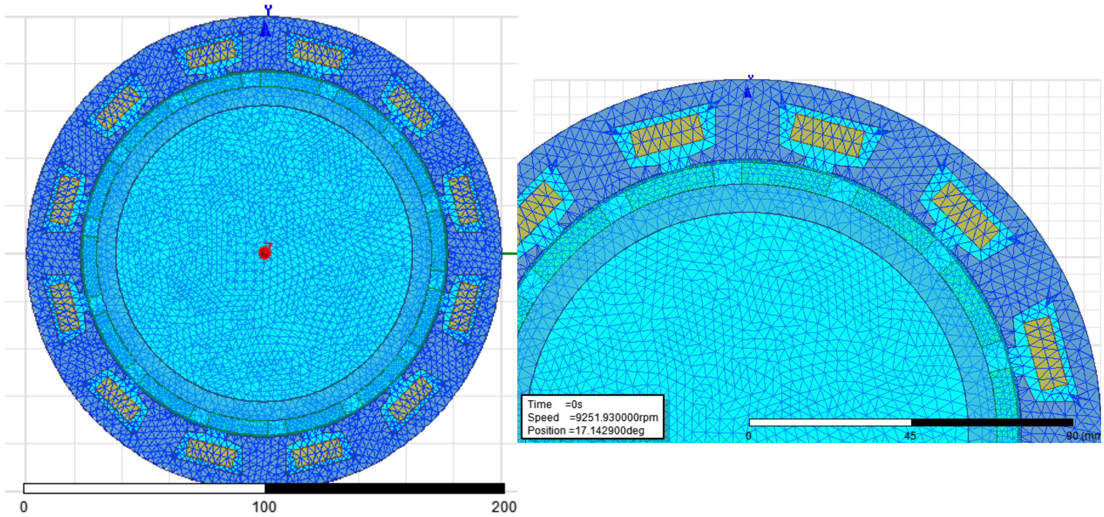



**Figure 3.10 :** Mesh plots of 2D model.

The analysis results are taken from curves and magnetic field overlays. Winding currents-time, output torque-time, flux linkage-time curves and flux line, magnetic flux density and magnetic field overlays will be given.

In these results it can be seen that when the motor operates in full load and speed of 9251.2 rpm, average output torque is calculated as 123.76 Nm. From the field overlays it can be seen from different time steps that saturation degree is low and iron core losses are low at the same time.

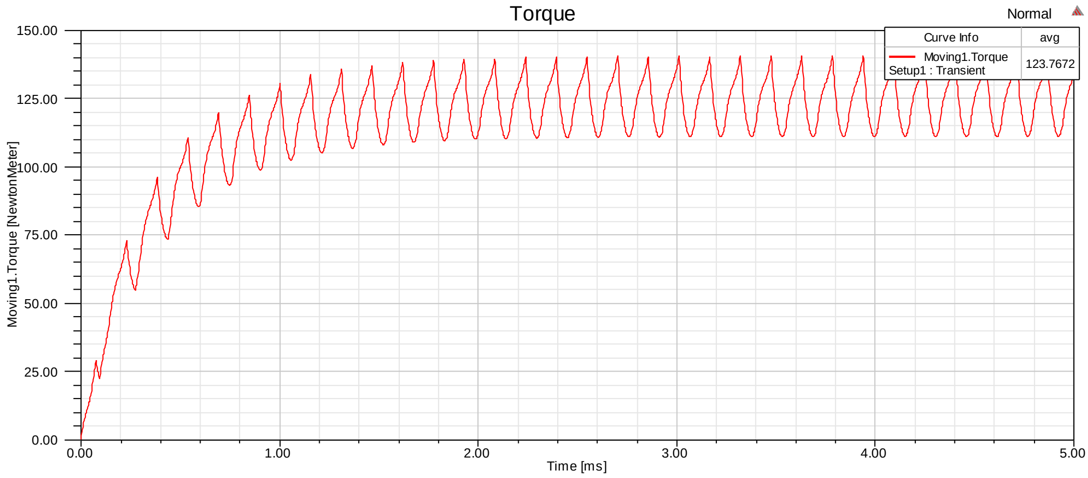



**Figure 3.11 :** Output torque-Time curve (5 ms).

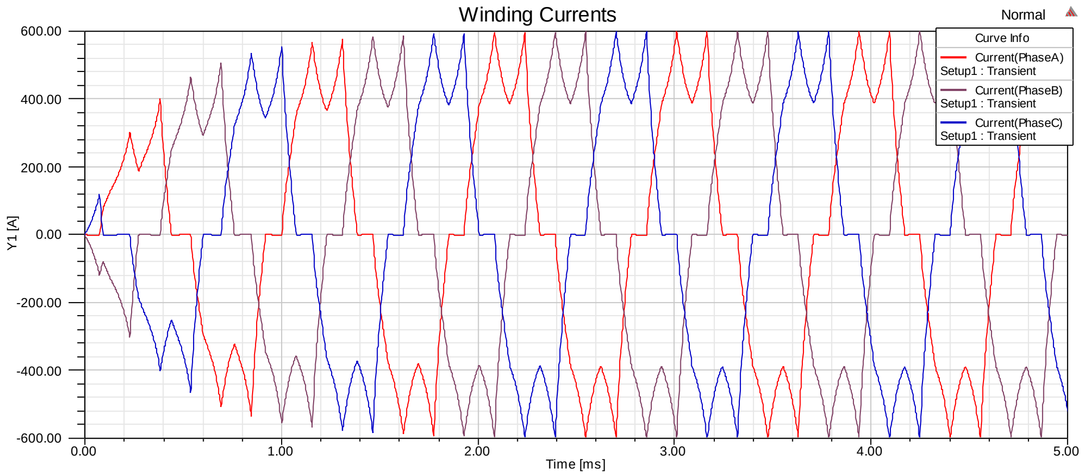



**Figure 3.12 :** Winding currents-Time curve (5 ms).

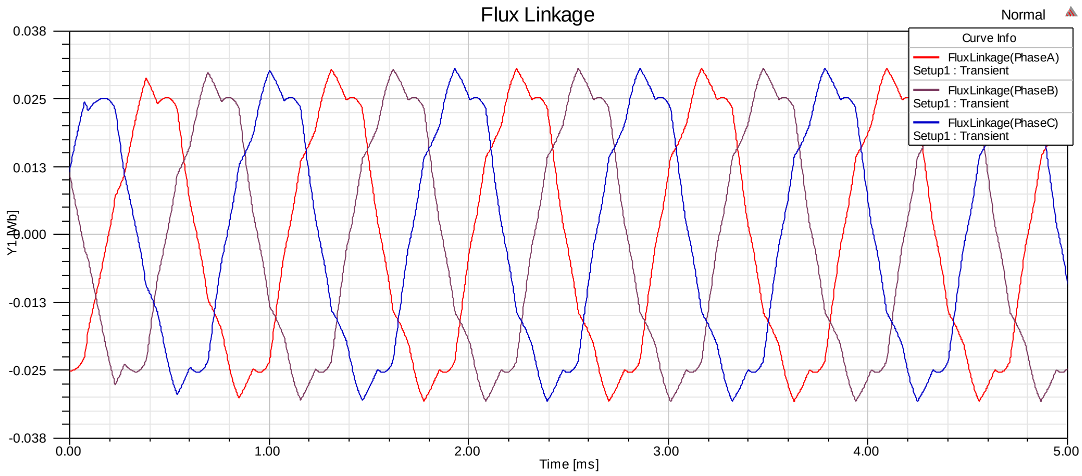
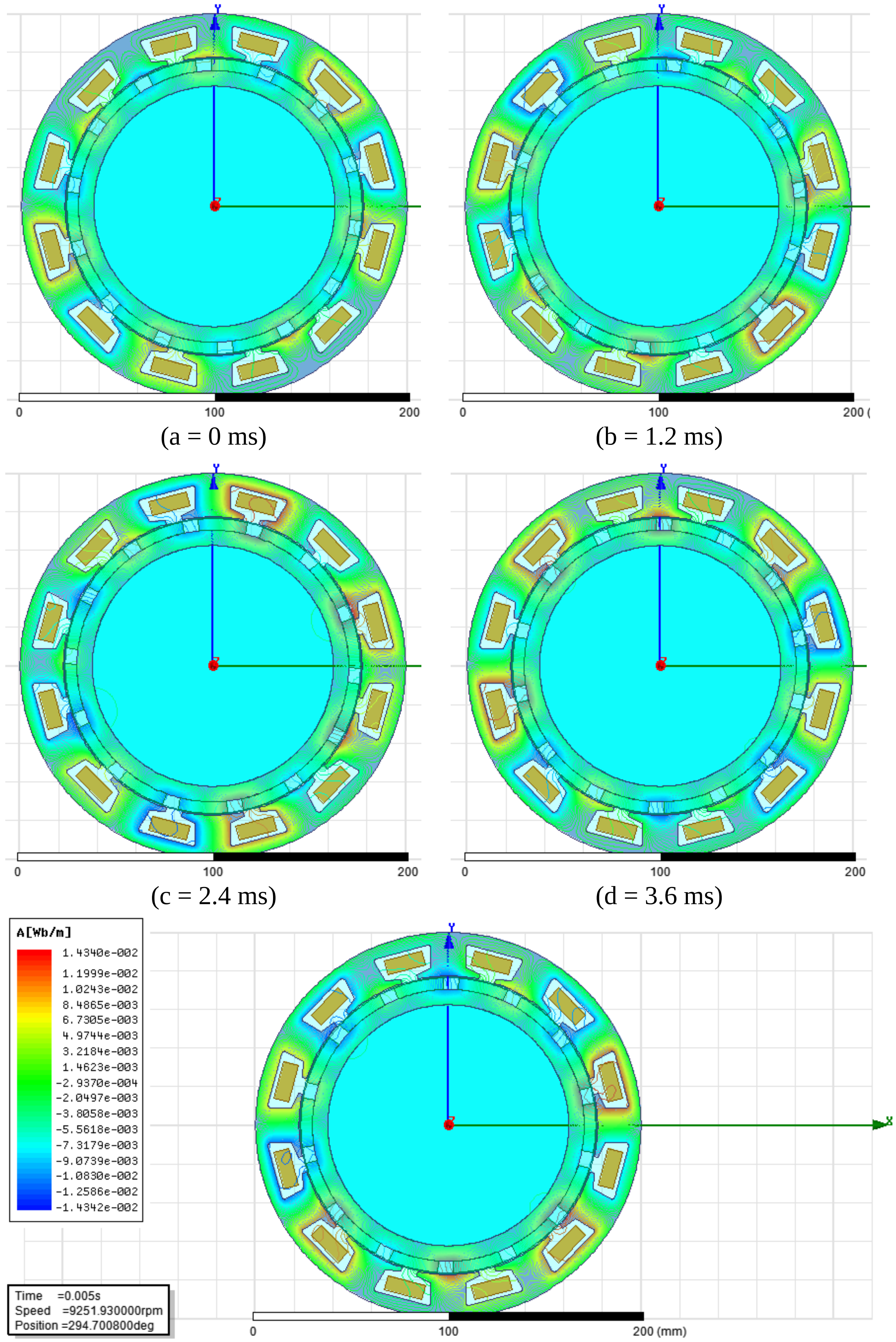



**Figure 3.13 :** Flux linkage-Time curve (5 ms).

In these curves the waveforms are spiky. For more smooth waveforms the time step have to be less and range of time on the curves should be smaller.




(a = 0 ms) (b = 1.2 ms)

(c = 2.4 ms) (d = 3.6 ms)

(e = 5 ms)

**Figure 3.14 :** Flux line overlays by time step of 1.2 ms.

It can be seen from Figure 3.14 the movement of flux lines in stop time of 5 ms.

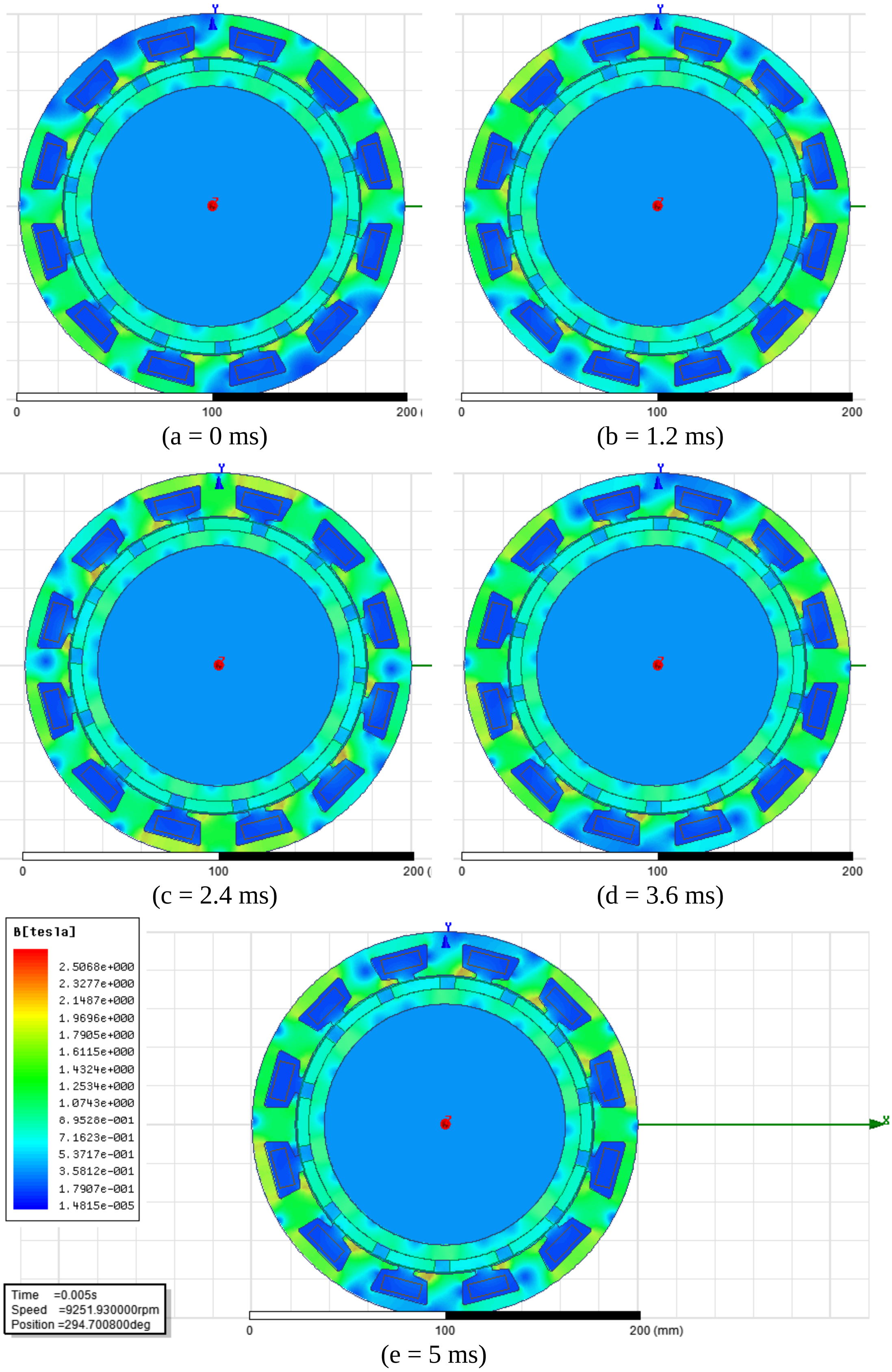



**Figure 3.15 :** Magnetic flux density overlays by time step of 1.2.

As it can be seen from magnetic flux density overlays, saturation degree is low and thus motor iron core losses are low.

2D FEA electromagnetic analysis show that this optimized motor has low level of saturation and flux line orientation is satisfying.

3D FEA electromagnetic analysis is made to create CAD model of the motor and to have an idea for winding overhangs. As 2D FEA analysis is converting the model to 3D and solving with that, 3D electromagnetic analysis is not necessary. This design has symmetry. The software is using this symmetry and calculates the 2D model as 3D model. If the stator had slot angle difference, 3D analysis had to be done. But in this scenario, it is not necessary.

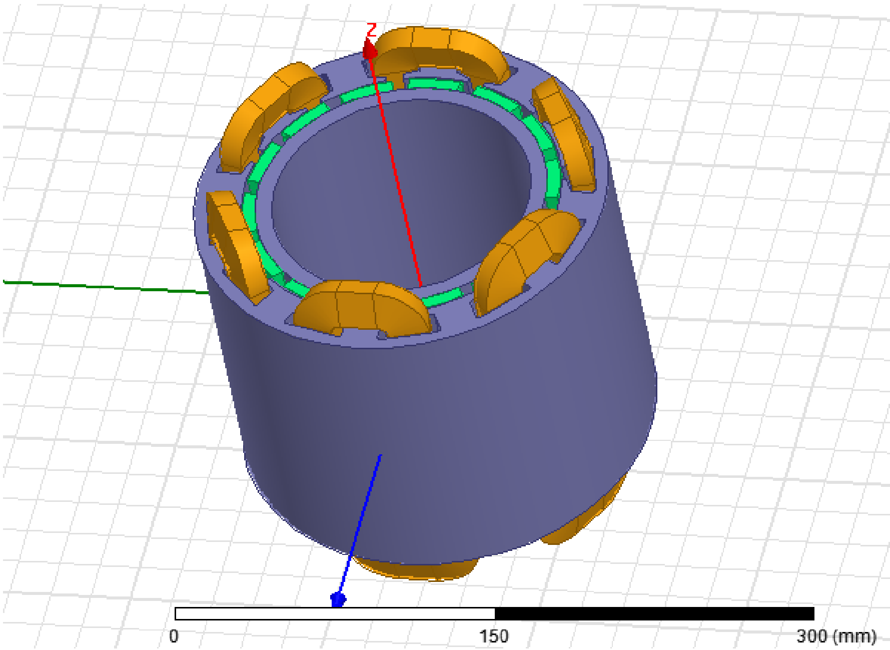



**Figure 3.16 :** BLDC motor 3D model.

3D model is taken from the software. As the winding type is concentrated, winding overhangs are low and easy to produce. Even more it gives easy assembly with the cover.

After electromagnetic FEA analysis, heating analysis and cooling analysis of the motor had been done. In electromagnetic analysis, it can be seen that if the electric motor overloads, more heating can be produced. In order to reduce this heating and satisfy the operating temperature of $90^0$C and as average input current is more than 200 A so especially to protect magnets from overheating and demagnetization water cooling have been chosen. For this structure ANSYS FLUENT® software is used.

### 3.1.4 Motor heat analysis

Cooling system of the motor is one of the most essential parts of an electric vehicle. A satisfying cooling system can prolong life of the motor and provide more efficiency. Despite the electric motor efficiencies are over 90%, dependent on terms of use they can produce higher heat. In these cases motor has to be cooled suitable in order to prevent demagnetization of the magnets and damaging windings. Even more if the cooling system is increasing the drivetrain efficiency, less energy will be used. For electric vehicle applications with less energy usage range will increase.

After design parameters of the motors, heat calculations of the motor had been done. In Table 3.6, heat parameters of the motor is given.

**Table 3.6 :** Motor heat parameters.

| Parameter | Value |
|---|---|
| Motor Power | 70 kW |
| Frictional Loss | 809.544 W |
| Iron Core Loss | 3781.08 W |
| Armature Winding Loss | 432.435 W |
| Total Loss | 5023.06 W |

For maximum cooling capacity of the system, it is needed more often in summer time. For this study, ambient temperature can be taken as 50 $^0$C as vehicle will be used in Turkey. Ambient temperature and the heat that motor will produce at full load is essential for cooling. By these parameters, cooling radiator, blower, cooling fluid flow and proper pump choice is made.

In electric motors with water cooling, a case is installed around the motor and water passes through the canals that are opened in the case. There are different types of canals. These are serpentine, helical and manifold. For this project serpentine type is analysed.

In serpentine type, water is pumped inside the case by a round section canal which is opened on the case. In the end of this canal, water goes into two different directions. The cross sectional area of the first canal is twice the canals inside the case. By this difference, water will not have any velocity differences between canals.

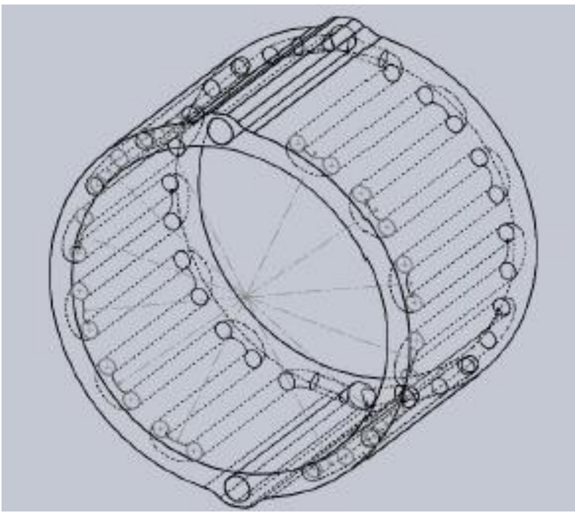


**Figure 3.17 :** Serpentine type case.

Fluid flow that splits into two pars, passes through the U turns as it will cover whole stator exterior surface. In the end, the fluid comes to the bottom of the case and exits the case by a canal which resembles to the entering canal.

In this design, as the case is covering all exterior surface of the motor, heat distribution is homogenous. Although as the fluid is getting warm around the case, bottom side of the case and motor is hotter.

For the analysis, ANSYS Workbench® environment is used. In this environment, the loss data is becoming an input for heat analysis. By using this environment, data loss is prevented and motor losses that producing heating is taken exactly from the electromagnetic analysis into Fluent software. Using the same time steps here is essential as softwares are calculating the values for each time step.

Boundary conditions and resuls of the anaylsis are given in Table 3.7.

**Table 3.7 :** Boundary conditions and analysis results.

| **Parameter** | **Value** |
|---|---|
| Ambient Temperature | 50 $^0$C |
| Air Convection Constant | 5 W/m$^2$ K |
| Fluid Temperature (When enters to case) | 55 $^0$C |
| Average Stator Temperature | 88.75 $^0$C |

As it can be seen from the analysis results, the water cooling system is keeping the operational temperature at approximately 90 $^0$C. In electromagnetic design this value is a wanted value and at full-load motor will not have any heating or demagnetization problems.

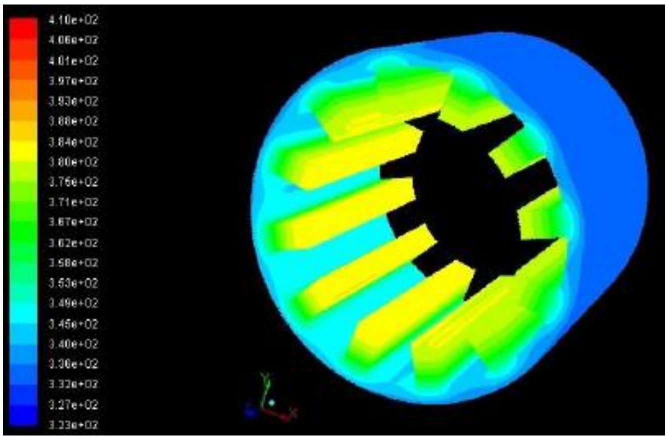



**Figure 3.18 :** Serpentine type case stator temperature distribution.

### 3.1.5 Producing electric motor

The motor that is produced is a 14 pole, 12 slot BLDC motor. Magnets of the motor is SmCo type and stator laminated sheets are laminated silica steel sheets. Airgap of the motor had been chosen as 1 mm. Winding type is designed as concentrated in order to make easier to produce. From the designer’s point of view, when the production started, the rotor outer diameter have been changed. It is because in order to prevent magnets to resist against contrifugal force a case had been installed. By this change, stator inner diameter have been changed approximately 0.5 mm in order to produce easily.

All components of the motor have been produced in benches and serial production mechanisms are not used. After having CAD design of the motor and having case with cooling system, technical drawings have been prepared in order to produce the components. For production sensitive tolerances have been used. In tolerancing operation, for general measurements ISO2768mK, and for fitting measurements DIN 7161 is used. All the componets are listed below and given in Figure 3.19.

1- Case
2- Stator Laminated Steel
3- Winding Conductor
4- Rotor Back Iron
5- Magnets
6- Rotor Cover
7- Shaft
8- Seals
9- Bearings
10- Bottom Cover
11- Top Cover

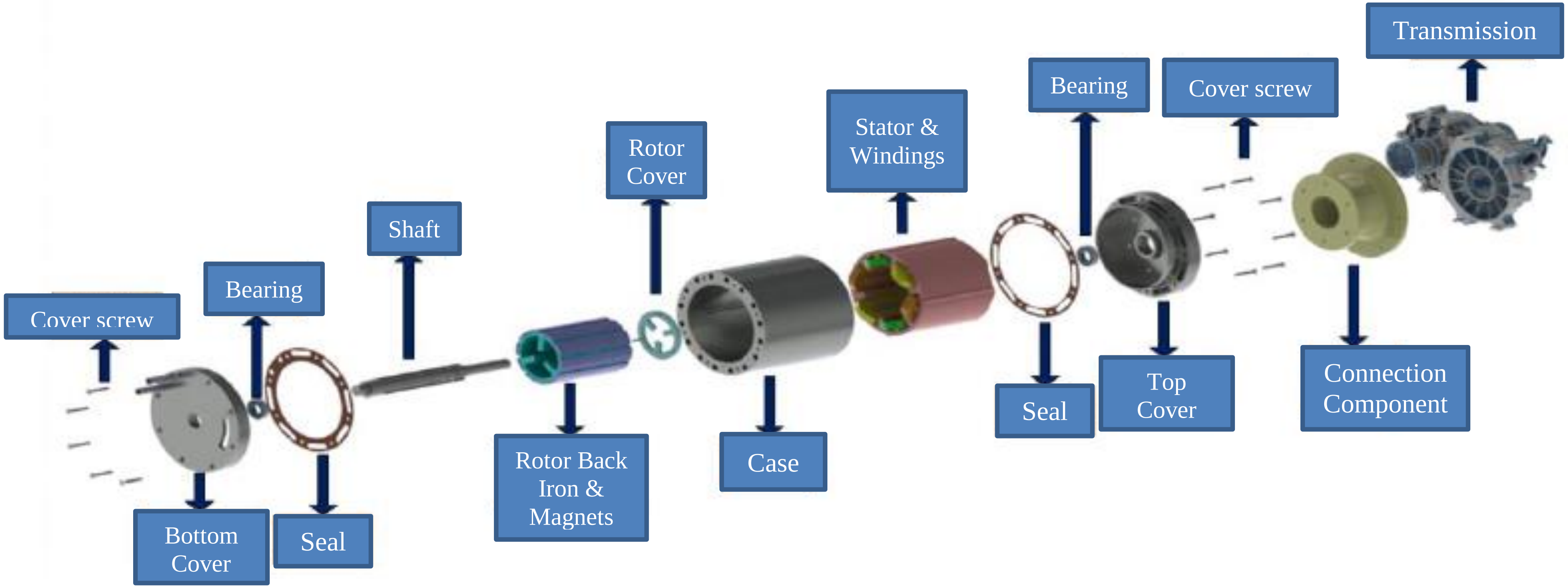



**Figure 3.19 :** Motor production parts.

There are four different production types which are used to produce and assembly the designed machine. These are 3 axed CNC tooling unit, CNC lathe tooling unit, wire erosion machine and laser beam cutting machine. The processing steps will be given step by step.

First part that is produced is rotor back iron. It is produced first in order to attach magnets to the back iron and cover the magnets in order to prevent any separation by any centrifugal forces. For rotor back iron, steel cube of Ø160x180 mm is obtained. Later on with wire erosion machine the back iron is processed into wanted measurements. After to exterior surface of back iron wanted outer diameter is processed. With holes are opened for cover screws, the rotor back iron process is finished.

**Figure 3.20 :** Motor back iron after process.

After motor back iron is obtained, shaft and rotor cover are produced. With hardening bedding of bearings with induction prevents the shaft from distorted rotational motion. After shaft and rotor cover is assemblied with rotor back iron, magnet attachment process had started.

For magnet attachment process, first of all magnets are obtained. SmCo type special design magnets are produced generally in China. This is because of this type of magnets are processed from rare earth elements and China has the mines of rare earth elements. But as there are several European companies that have some production areas in China, in this study magnets are ordered from an European company which is controlling the magnets before shipment.

Magnets had been ordered as 50 mm length in order to have 3 magnets in each pole. This helps with the production. In order to attach magnets to the rotor back iron and prevent them from linear movement, a special steel adhesive glue is used. First of all first magnets of each pole had been attached and stabilized by dogwrench. The process continued twice more and all magnets were attached to rotor back iron. Before attaching every magnet, magnets are separated into two poles as N and S in order to maintain the pole differences and magnets are attached by this rule.

**Figure 3.21 :** Magnet attachment process.

After the magnet attachment process is finished, epoxy is used to fill the blank parts between magnets. After filling the blanks, a plastic cover is attached on magnets.

Having the rotor part assemblied facilitated the stator and case production. After rotor assembly, the process followed by stator production. For stator laminated steel sheets of 0.5 mm thickness are used. To start production of stator, laminated steel which has 250x250x0.5 mm measurements are obtained in total number of 300. This laminated steel sheets are processed in laser beam cutting machine and cut into wanted measurements.

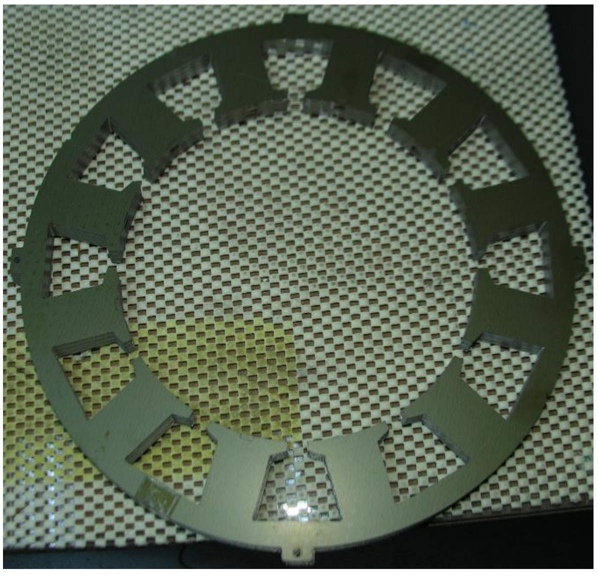


**Figure 3.22 :** Stator laminated steel sheets (after cutting process).

Later on when all the sheets are cut, they are assemblied by the help of apparatus which is made by sight of rotor. Stator parts have assemblied on this apparatus and it is followed by welding sheets process. Welding is made by Argon alloy.

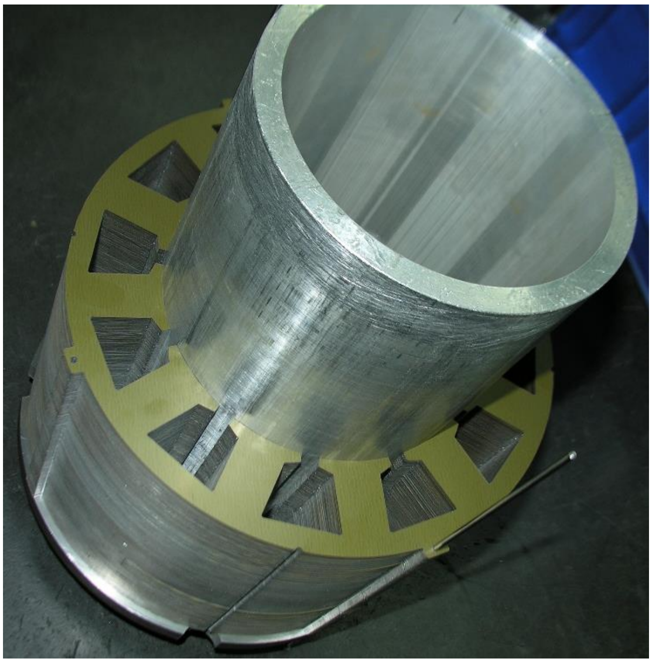


**Figure 3.23 :** Stator laminated sheet assembly.

In stator assembly process there is a main point to take care of. It is that there are 12 special cut laminated steel sheets that have to put on top of the stator. These special cuts are put for Hall sensor installation in order to send data to controller.

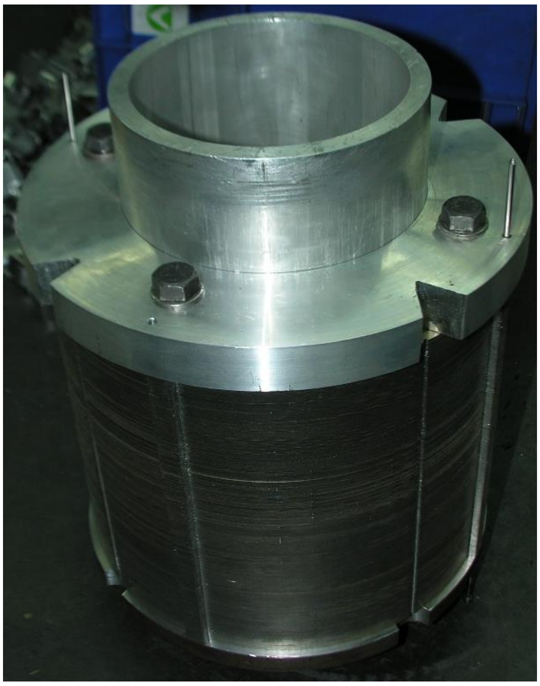


**Figure 3.24 :** Finished stator.

Winding installation process is made by hand. Within the welding of stator sheets, finished and assemblied stator is processed by windings.

**Figure 3.25 :** Stator (set ready for winding process).

For winding installation, winding schematic is also drawn.

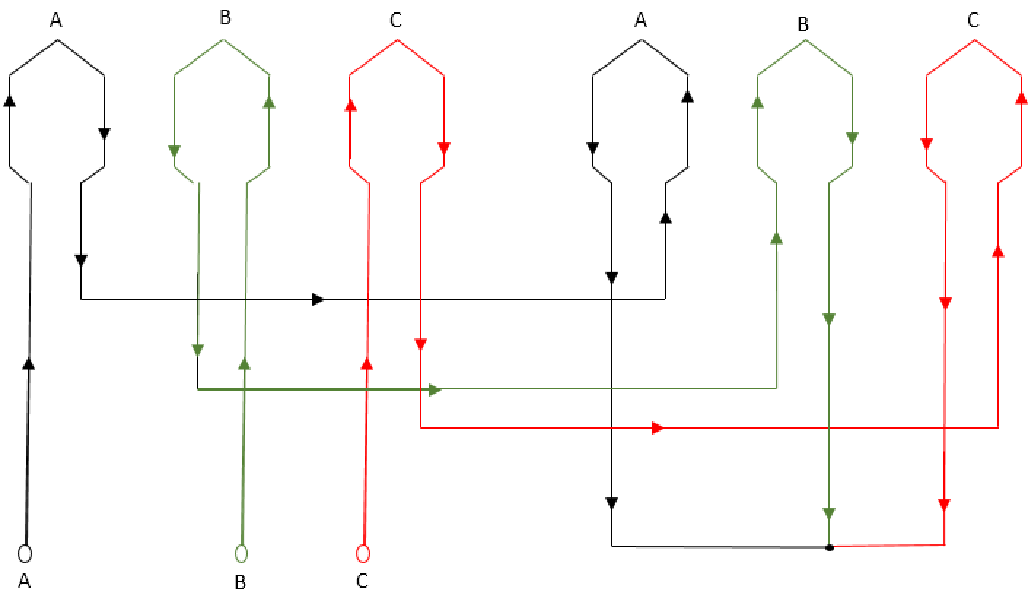



**Figure 3.26 :** Winding schematic of designed BLDCM.

Winding installation made by 5.189 mm diameter copper wire and 4 turns each slot. As the stator slot fill factor is 32.22%, it was easier to install all windings.

A 5 mm copper wire is not easy to bend. In order to have an easy solution, 5 mm wire is split into smaller diameter wires and installation made by this.

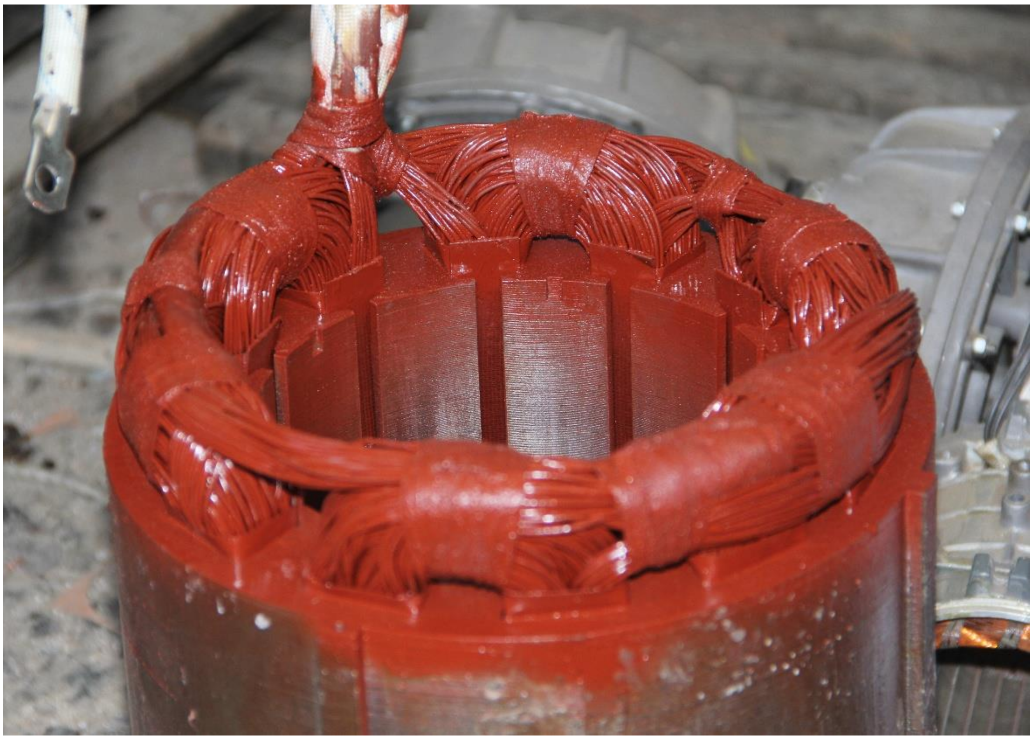


**Figure 3.27 :** Stator windings.

Installing stator windings had given a perfect design optimization idea about winding overhangs and case of the motor. Case have been made by wire erosion and CNC processing units. Its material is aluminium and water cooling holes have been opened into the case after cutting processes.

**Figure 3.28 :** Aluminium motor case.

Bottom and top covers of the case are made by aluminium like the case. In order to produce covers, CNC processing unit is used. On covers, bearing holes, screw holes for assembly and water cooling holes are opened. Just on top cover, in order to be able to assembly the motor with transmission, special assembly holes are opened.

With production of covers, a special designed seal which is preventing water leakage into the motor and bearings have been ordered.

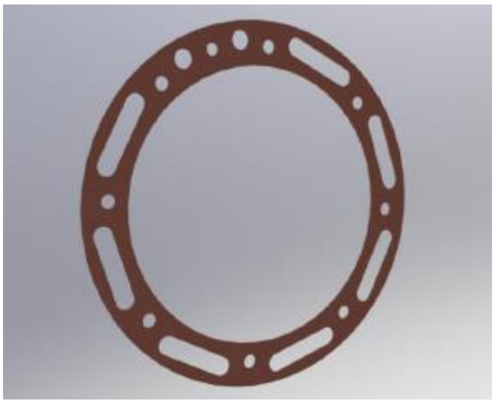


**Figure 3.29 :** Special designed seals.

Bearing have been chosen as 6006-2Z. Bearings are protecting motor from dust and external factors too.

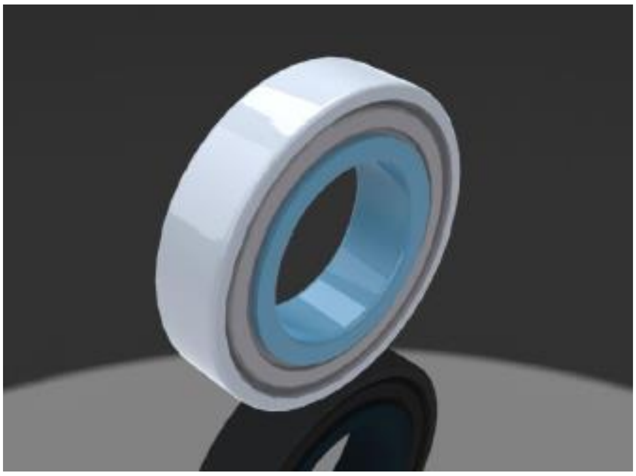


**Figure 3.30 :** 6006 2Z bearing.

**Table 3.8 :** 6006 2Z bearing technical specifications.

| Shaft Diameter (mm) | Load (kN) | | | Limit Speed (rpm) | Reference Speed (rpm) | Bearing No: |
|---|---|---|---|---|---|---|
| | Dyn. C | Stat.$C_0$ | Fatigue limit $C_u$ | | | |
| 30 | 12.7 | 8 | 0.395 | 32000 | 15000 | 3.5.1 |

Obtaining seals and bearings finished the production part. For motor assembly, the airgap is deeply investigated in order to prevent magnets from stitching to stator. To have an easier assembly, a special apparatus bedding is produced and motor is assemblied.

**Figure 3.31 :** Motor assembly.

### 3.1.6 Motor tests

Motor tests are made in Istanbul Technical University's Electrical Machines Laboratory. As the system is old, motor could be loaded until 44 kW and four more test results are added by iteration in order to obtain wanted curves.

**Figure 3.32 :** Motor test bench.

As it can be seen from Table 3.9, motor is loaded until 44 kW and its efficiency is calculated as 82.64%. Four iterated test results are included into the curves and with iterations the efficiency at 9020 rpm, should be approximately 87.69%. This shows that difference between calculations and test results is near 10%. In this difference there are power electronic circuit losses and mechanical losses from test bench.

**Table 3.9 :** ITU EV project motor test results.

| No. Test | Current [A] | Voltage [V] | Speed [rpm] | Torque [Nm] | Output Power [W] | Efficiency [%] |
|---|---|---|---|---|---|---|
| 1 | 35.44 | 357 | 11248 | 3.30 | 3886.92 | 30.72 |
| 2 | 40.90 | 357 | 11186.5 | 4.98 | 5833.64 | 39.95 |
| 3 | 49.07 | 356 | 11072.68 | 8.10 | 9391.90 | 53.76 |
| 4 | 55.33 | 356 | 10986 | 10.56 | 12148.41 | 61.68 |
| 5 | 67.86 | 356 | 10850 | 14.52 | 16497.27 | 68.29 |
| 6 | 72.58 | 356 | 10778.5 | 16.61 | 18747.52 | 72.56 |
| 7 | 97.61 | 355 | 10486 | 24.38 | 26770.68 | 77.26 |
| 8 | 152.14 | 355 | 10026.5 | 41.43 | 43499.08 | 80.54 |
| 9 | 206.38 | 355 | 9525.2 | 60.7 | 60545.04 | 82.64 |
| 10 | 264.68 | 354 | 9020 | 83 | 78397.18 | 83.67 |
| 11 | 286.09 | 353 | 8770 | 94 | 86326.33 | 85.48 |
| 12 | 311.17 | 353 | 8520 | 107 | 95463.90 | 86.91 |

The curves that are obtained from test results are given below:

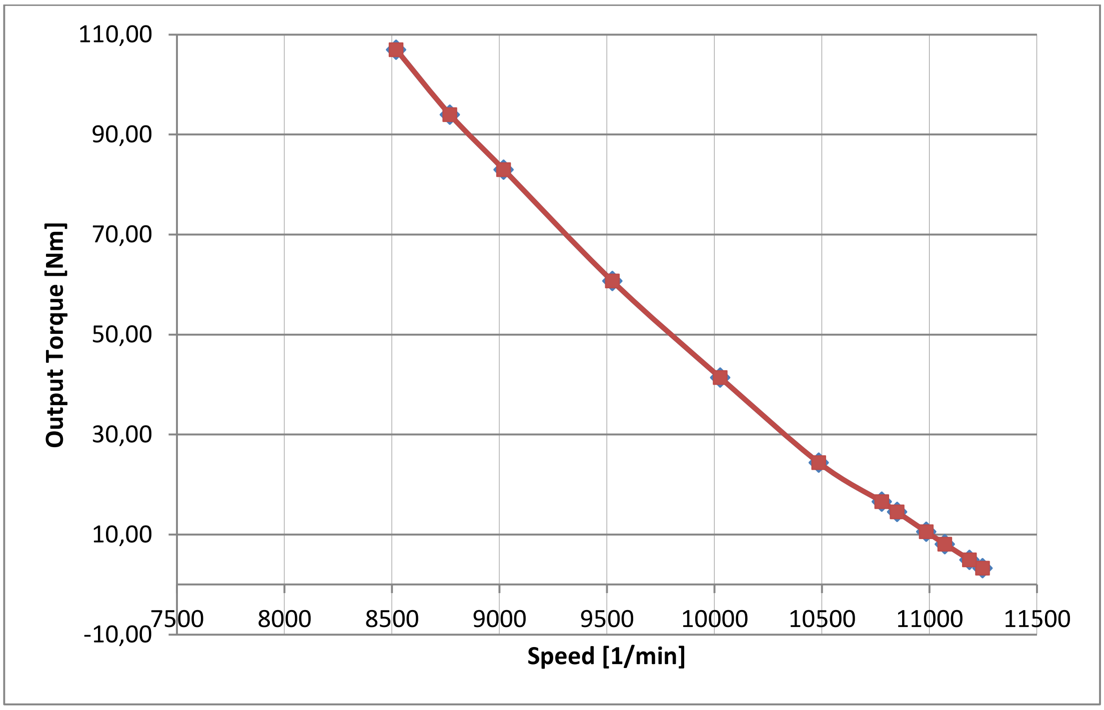



**Figure 3.33 :** Output torque – speed.

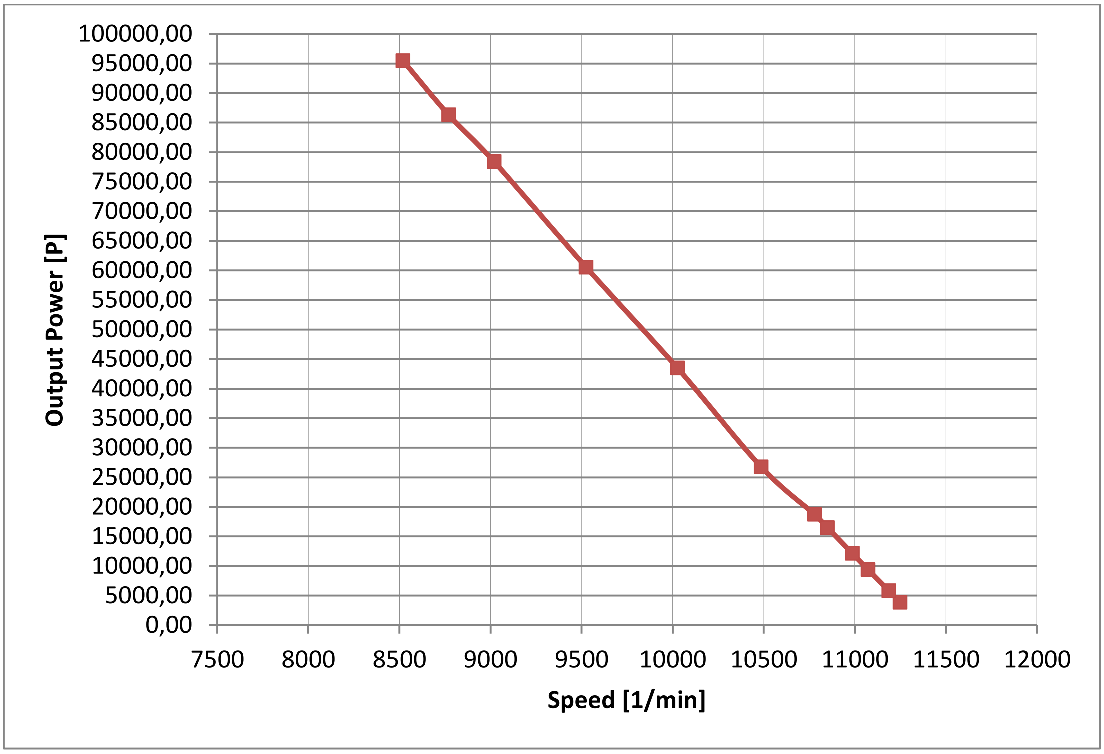



**Figure 3.34 :** Output power – speed.

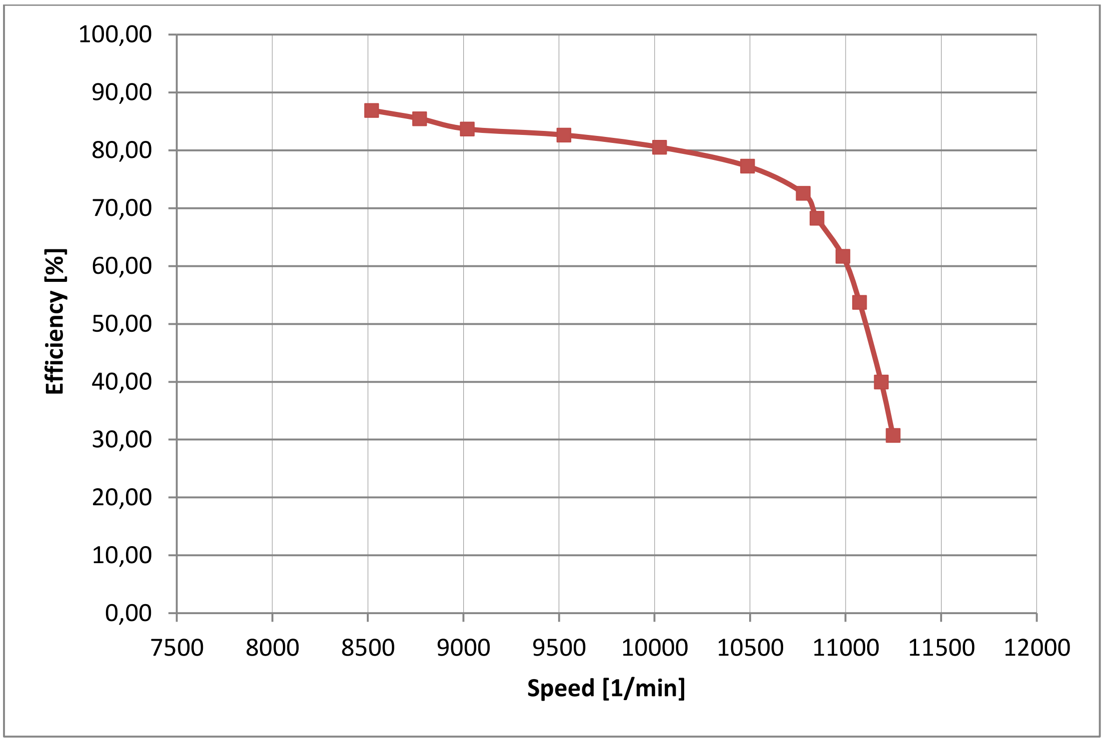



**Figure 3.35 :** Efficiency – speed.

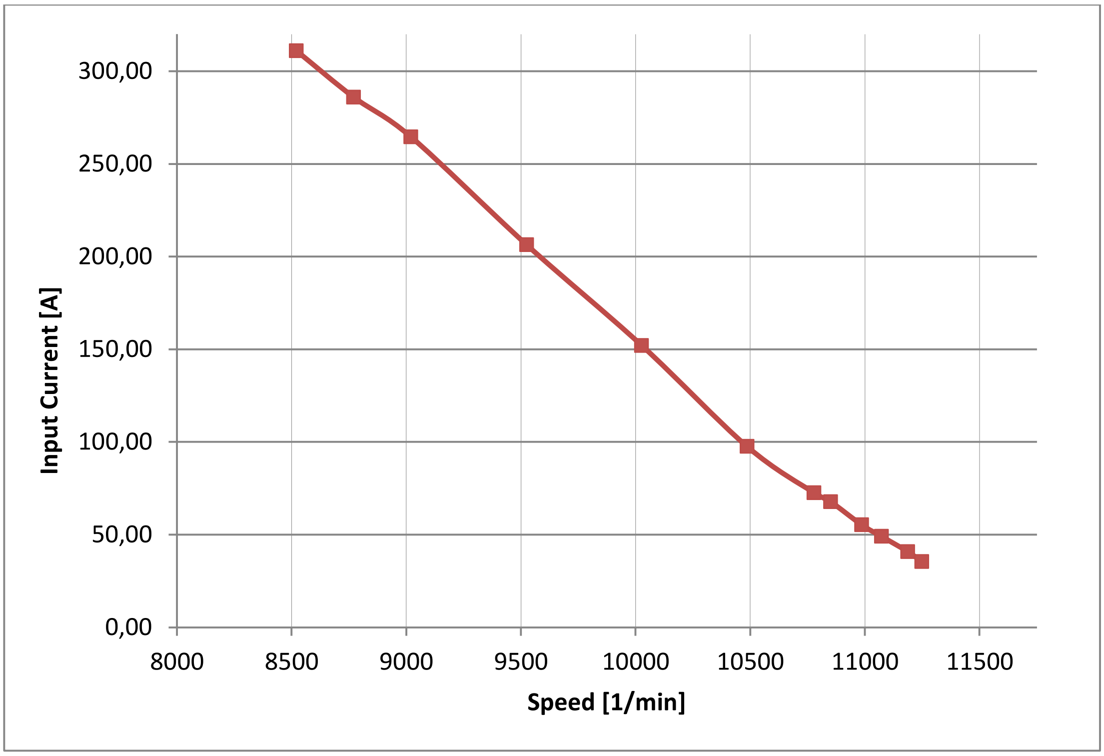



**Figure 3.36 :** Input current – speed.

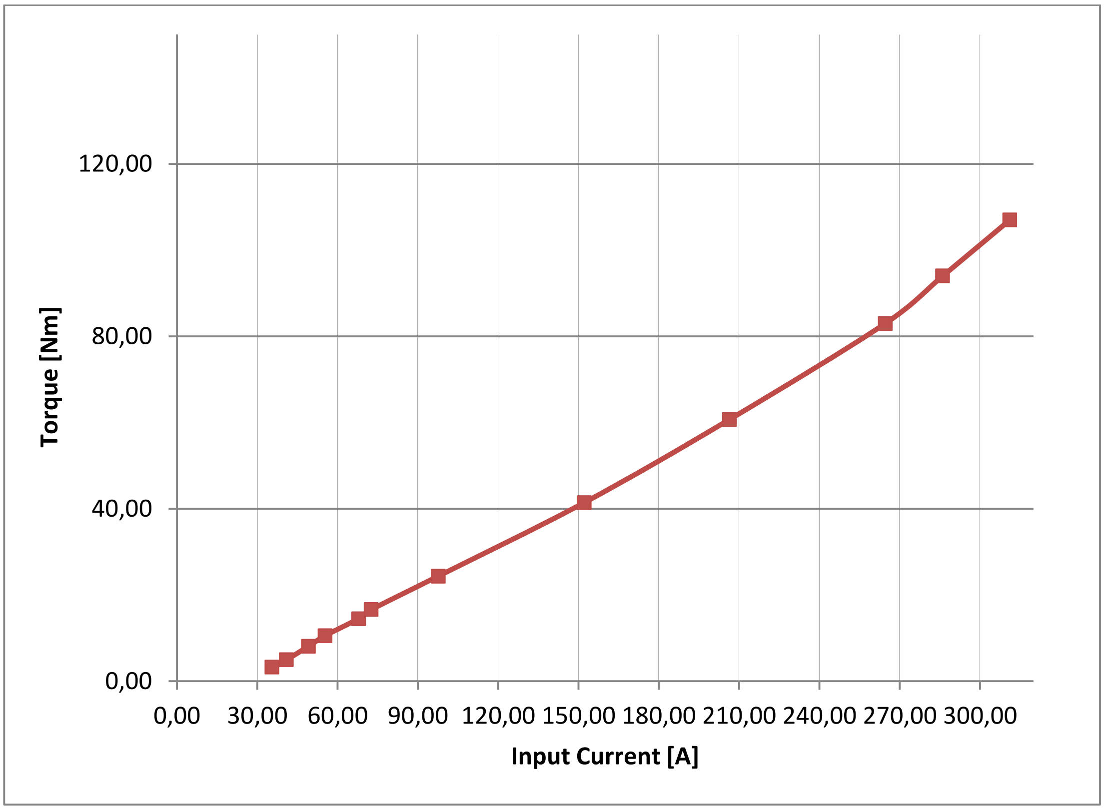



**Figure 3.37 :** Torque – input current.

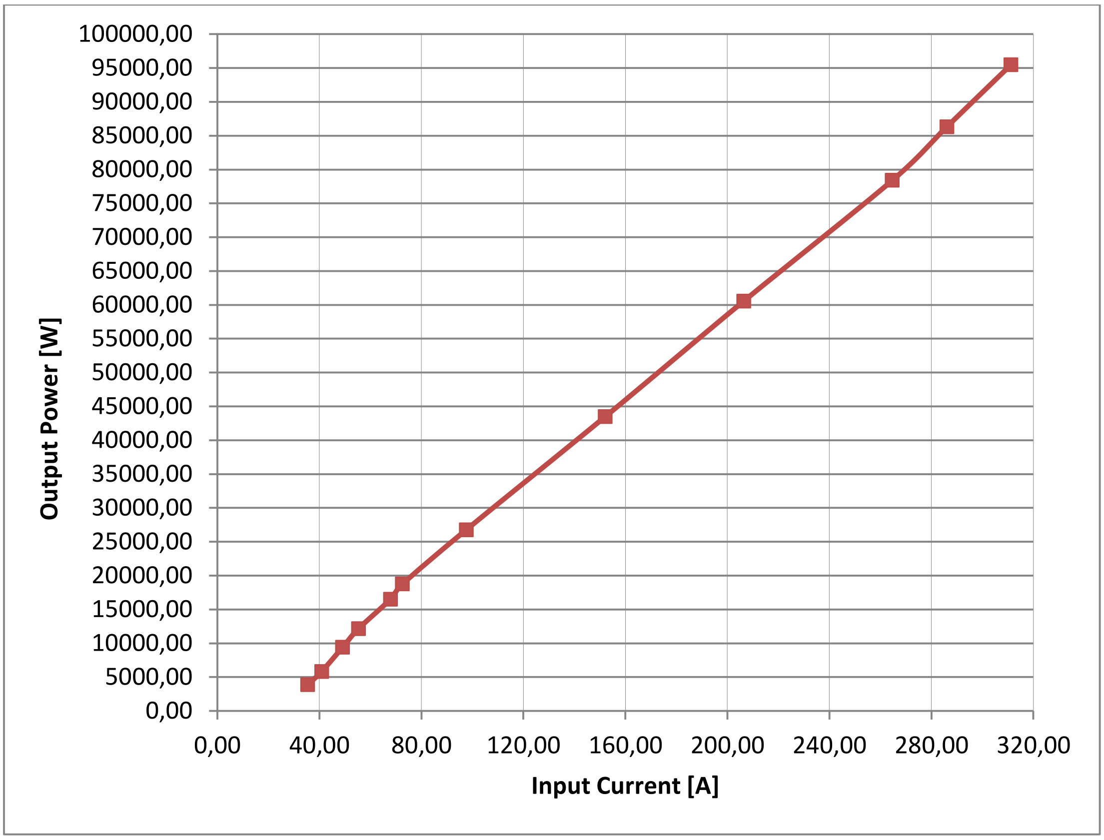



**Figure 3.38 :** Output power – input current.

### 3.1.7 Cost

Motor cost was approximately 25000 TL. This budget is high for one motor but as this motor is a prototype, the producers have to stop their processes and produce parts of the motor. This affects the price of each part as total budget.

## 3.2 Motor Control

Motor control system is formed of power electronics and control circuit which are supplied from battery pack that is composed for appropriate voltage value. All components that are used in motor control are proper to automotive standards. Main parts of drivetrain are:

- Electric motor
- Power electronic circuit (6-switch inverter)
- Motor control unit (DSP system)

- DC/DC converter (from DC busbar converting voltage to 12 V for additional loads)
- Transimission system

In this study, electric motor and power electronic circuit parts are taken into consideration. Motor control unit and coding is made by Mekatro R&D and DC/DC converter is purchased stand-by. In regard of transmission system, the system that is on vehicle will be used.

### 3.2.1 Power stage

In power stage, an inverter design is made. For mechanical design of the PEC, losses of IGBTs and diodes is calculated. After cooling solutions, snubber calculations and busbar design is made. When calculations are finished, necessary components are acquired and parts are produced. Finally the assembly of PEC is made.

#### 3.2.1.1 Losses

Losses in an inverter can be separated into two parts: switching losses and conduction losses. Switching losses occur when IGBT modules are tuning on and off moments. These losses can be taken from producers datasheets.

For this application, SKiM63 series SKIM604GD066HD 600V 400A IGBT module is chosen from SEMIKRON company. This modules have been chosen for their voltage and current limits. Maximum current and maximum busbar voltage of the vehicle can be taken as 300 A and 400 V. In order to have IGBTs that can’t be damaged from peak voltage or current, maximum voltage and maximum current values have been chosen two to three times more than the system. This module is developed especially for automotive applications and it is proper for standards.

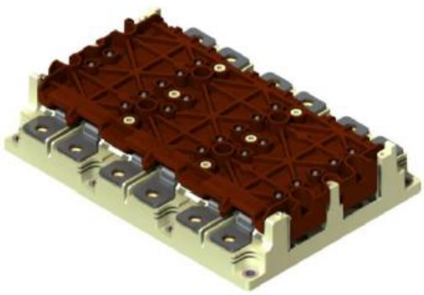


**Figure 3.39 :** SKiM 63 series IGBT module.

Modules from this series are strong against vibration and heat, as it is reliable and efficient. There are special designs in order to reduce switching losses. To do this, modules are designed to be able to connect with control circuit directly.

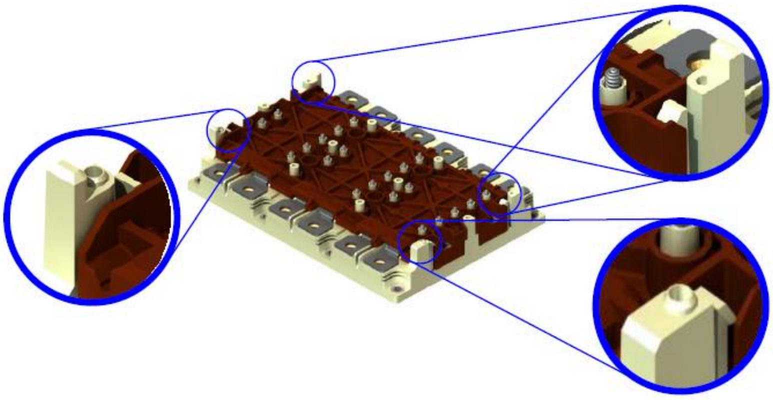


**Figure 3.40 :** PEC connection points.

As this system reduces the losses, at the same time if any error situation, fast intervention is possible. For SKiM 63 series IGBT modules, SKiM 63 Driverboards will be used.

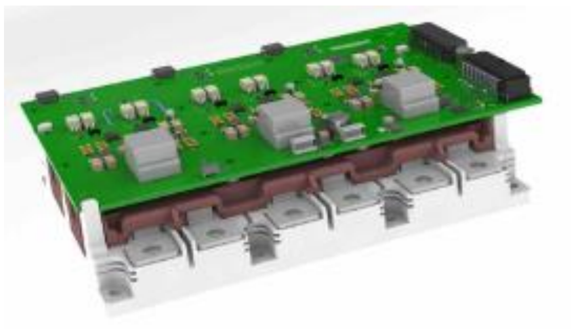


**Figure 3.41 :** SKiM 63 Driverboard.

From the datasheet, IGBT's turn on switching loss at 150 $^{0}$C junction temperature and 600 A rated current value is 35 mJ. With same conditions turn off loss is 110.4 mJ. System rated current is approximately 210 A and switching frequency is 8 kHz. Power loss is determined by;

$$ForIGBT, (Frequency(Hz) \cdot (E_{on} + E_{off} (Joule)) = PowerLoss_1 (Watt) \quad \textbf{(3.13)}$$

$$ForDiodes, (Frequency(Hz) \cdot (E_{on} (Joule)) = PowerLoss_2 (Watt) \quad \textbf{(3.14)}$$

From these equations, IGBT power loss is calculated as 1163.2 W and diodes power loss is calculated as 352 W. Total loss is 1515.2 W.

Calculations are made for 600 V, 600 A rated voltage and current values. System rated current is 210 A and rated voltage is 355 V approximate switching losses can be calculated as;

$$\frac{(210 \cdot 355)}{(600 \cdot 600)} = 0.207 \quad \textbf{(3.15)}$$

$$1515.2 \cdot 0.207 = 313.65W \quad \textbf{(3.16)}$$

This calculated value shows for one IGBT-diode system switching losses. In the system there are 6 pack of IGBT-diode system so total switching loss is 1881.9 W. This value is at maximum load. System operation reduces the loss.

Conduction losses of IGBT-diode system is calculated from internal resistance of the components. These values are taken from their datasheets.

$$P_{1\_IGBT} = V_{CEO} \cdot 210 + \tau_{CE} \cdot 210^2 = 0.8 \cdot 210 + 2.7 \cdot 10^{-3} \cdot 210^2 = 287.07W \quad \textbf{(3.17)}$$

$$P_{1\_diode} = V_{FO} \cdot 210 + \tau_{F} \cdot 210^2 = 1.1 \cdot 210 + 2.1 \cdot 10^{-3} \cdot 210^2 = 323.61W \quad \textbf{(3.18)}$$

These calculations are made for one IGBT and one diode. So total conduction loss is 3682.08 W. If this solution is adapted to ITU EV system;

$$\frac{(210^2)}{(600^2)} = 0.1225 \quad \textbf{(3.19)}$$

$$3682.08 \cdot 0.1225 = 451.0548W \quad \textbf{(3.20)}$$

From conduction and switching losses, total loss of the system can be found as 2332.9548 W. Calculated values show that there are approximately 2.3 kW total losses in PEC. From this information efficiency can be calculated as:

$$\pi = \frac{(70 - 2.3)kW}{70kW} = 0.967 \quad \textbf{(3.21)}$$

Finally PEC efficiency can be found about 96.7% but this can differ depending on operation of the electric motor.

### 3.2.1.2 Busbar design

In order to reduce stray inductance sandwich busbar design is made. This reduces the voltage that is induced by stray inductance. Induced voltage can affect DC busbar voltage and accordingly IGBT modules.

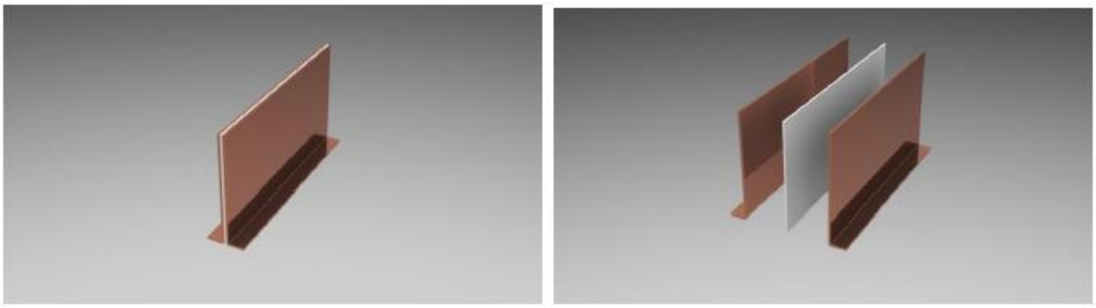


**Figure 3.42 :** Sandwich busbar design.

### 3.2.1.3 Cooling solutions

In PEC, the most heated parts are IGBT modules. The producer of the components gave an advice for positioning modulen on heatsink. When there are 20 mm between the modules, they are working the most efficiently.

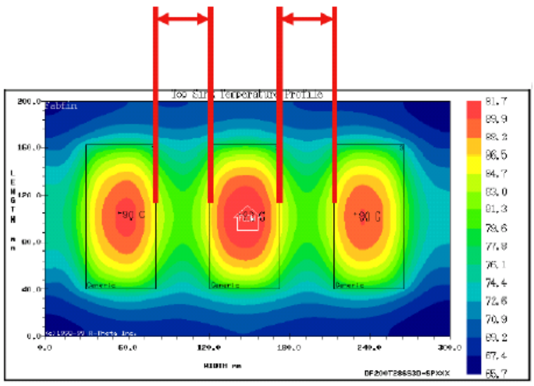
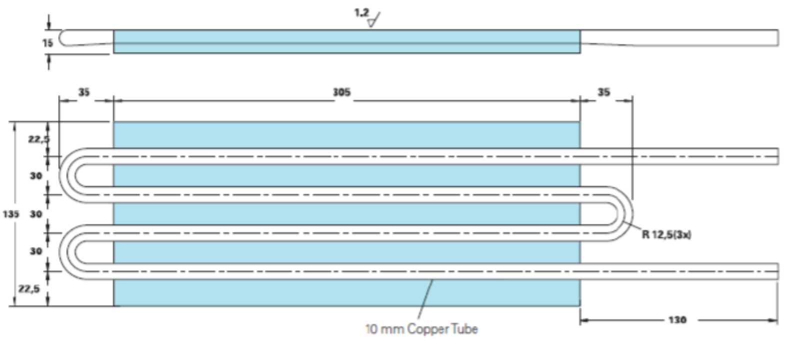


**Figure 3.43 :** IGBT module heat distribution.

In this type, operating temperature is approximately 90 $^{0}$C. This value is an optimized temperature for IGBT modules. If the space between modules is taken more, the temperature will decrease. But this process will cause stray inductace. If stray inductance is high, it can damage the system by inducting undesirable voltages.

Furthermore for PEC system, a water cooling system is acquired. This water cooling module can meet against 2500 W loss. It reduces temperature about 4 $^{0}$C from the system. In this case, heatsink surface temperature which means IGBT surface temperature is approximately 34 $^{0}$C.




Thermal results

| Power modules mounted on | | 1 side | 2 sides |
|---|---|---|---|
| Waterflow | Q | 8 L/min | 8 L/min |
| Power dissipation | Pd | 2500 W | 2500 W |
| Tin water | Ti | 16°C | 16°C |
| Tout water | Tu | 20,5°C | 20,5°C |
| Tsurface max | Ts | 34,5°C | 34,5°C |
| Thermal resistance | Rth | 0,0074 | 0,0066 |

Plate thickness: 15 mm

**Figure 3.44 :** Water cooling system specifications.

### 3.2.1.4 PEC assembly

PEC assembly was made by Mekatro R&D company. First CAD data had been drawn and tested before the assembly. After that all the components were ordered from their producers and PEC assembly was finished. After PEC, control card design and coding works had been done.

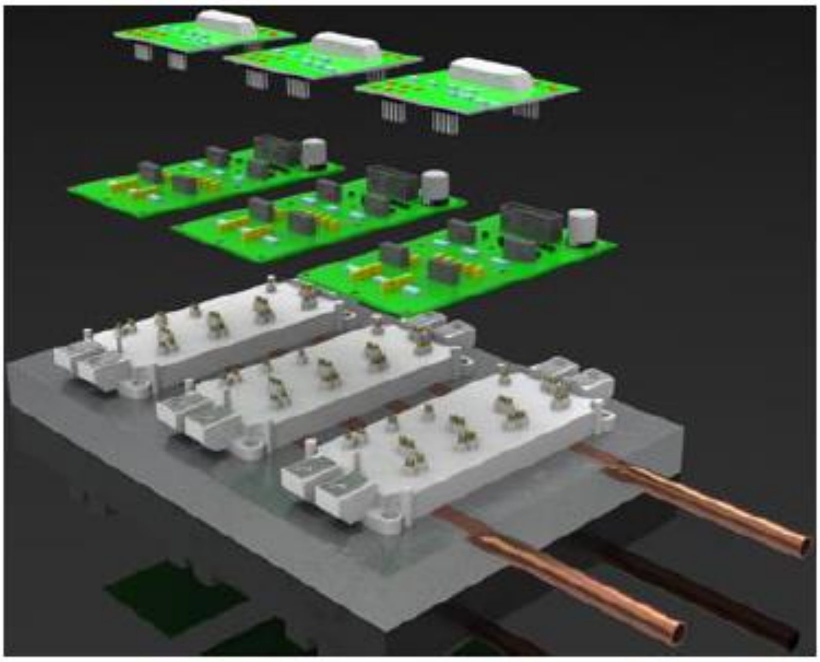


**Figure 3.45 :** PEC assembly 3D drawing.

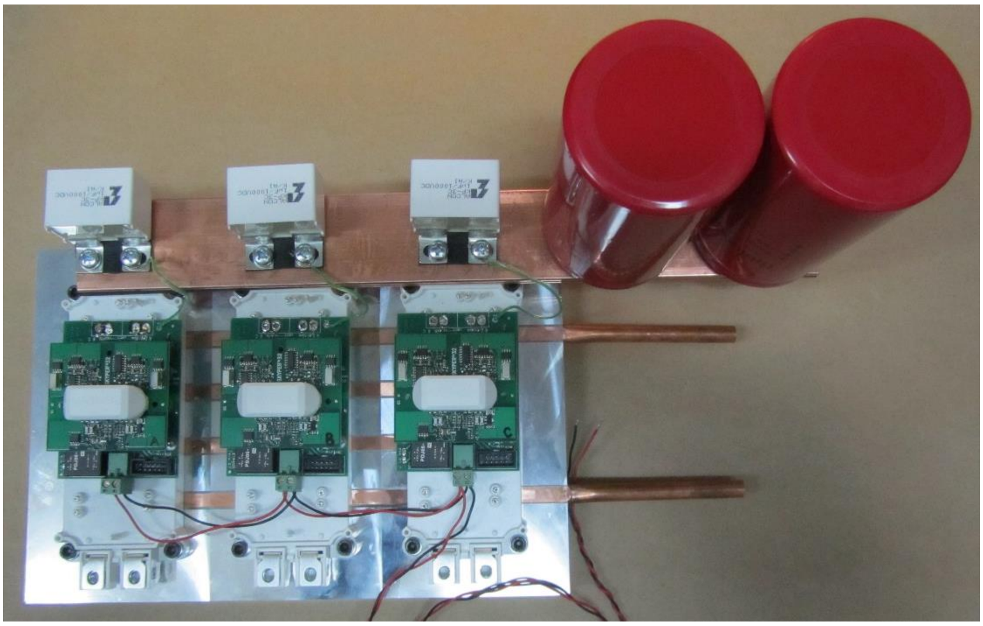


**Figure 3.46 :** PEC assembly.

### 3.2.2 Vehicle control interface

Electric motor that is designed for electric vehicle has to be controlled easily by the driver. Especially in near future as electric vehicles are thought to be used commonly, they should have abilities like comfortable, accesible, generating solutions and smart guidance for driver and passengers. This subjects open a new study case: Infotainment.

Day after day, vehicle control interfaces are developing. These systems are being ergonomic and user friendly. This development depends on electronic technologies of the vehicles as well as material science and sensor applications. Vehicle control interface of Tesla Motor Company's Tesla Model S is developed in terms of utility and visuality.

**Figure 3.47 :** Tesla Model S dashboard [tesla].

Especially in electric vehicles which have more electronic parts more dense user comfort and needs are coming into prominence. During voyages mobile communication, instant monitoring of energy consumption, notifying road situation, smart transportation advises and vehicle-user friendship is presented to the customers.

### 3.2.2.1 ITU EV project

As the solutions of in-vehicle communications are getting easier, data communication and accessibleness of vehicle is smoother. In ITU EV project, electric motor control diagram is given in Figure 3.48.

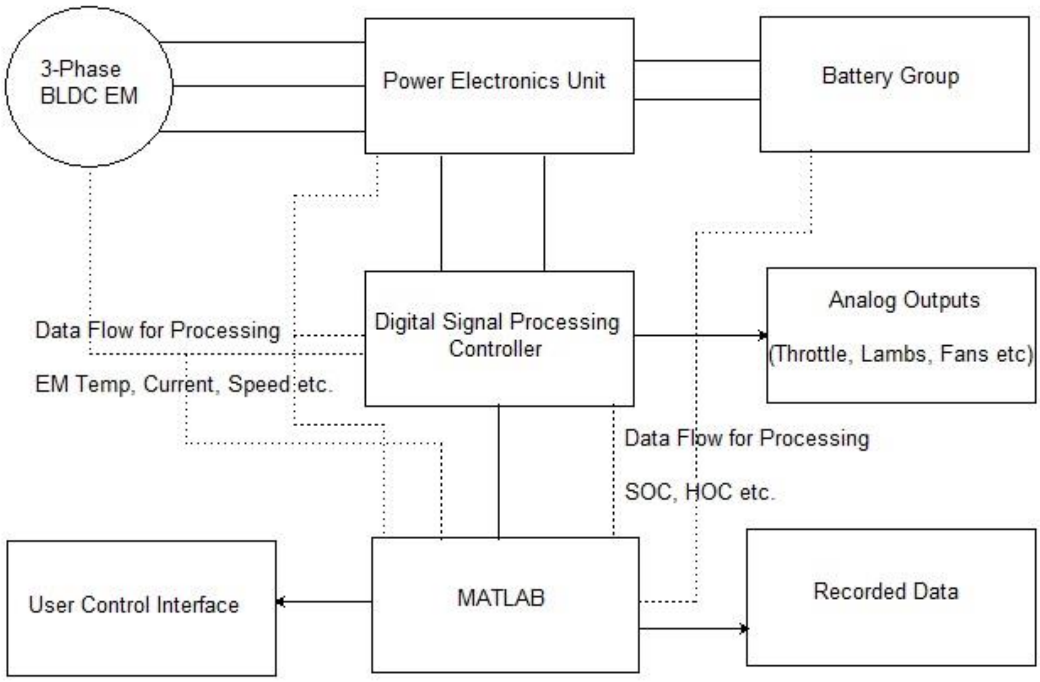



**Figure 3.48 :** In-vehicle data communication block diagram.

Data bus application is made open to develop and by fast prototyping. Data flow is monitored real-time and faults are determined instantly. In ITU EV, a DSP which provide opportunity to work real-time is controlling whole system. This microcontroller should work in the background and the vehicle has to have a particular control interface.

In-vehicle communication is provided by CAN communication protocol. Data are processed on Matlab which is working in background and reflected into driver control panel. Interface shows data like temperature, speed on the panel. Data about electric motor can be monitored, safety and battery state can be controlled. Different modes for controlling electric motor is added and reflected on the panel like sport mode, eco mode etc.

### 3.2.2.2 GUI design

Data flow and motors data tracing can be recorded and instantly can be converted into curves. In main panel, energy consumption and advised speed choices are set in regard of maximum and rated operation parameters.


**Figure 3.49 :** ITU EV GUI.

This system is still developing and when the motor will be implemented into the vehicle, it will be tested on the field. With this control interface, drive quality and comfort are wanted to be increased.

## 4. FUTURE WORKS AND CONCLUSION

### 4.1 Future Works

Future works of this project is implementing the produced and tested electric motor into the vehicle, adapting vehicle control interface and field testing.

Implementing electric motor part is already started as ICE of the vehicle had been removed from the vehicle.

**Figure 4.1 :** ITU EV after ICE removal.

**Figure 4.2 :** Transmission system of the vehicle.

As it can be seen from the pictures, vehicle implementation process is just waiting for the parts to connect electric motor into the vehicle.

## 4.2 Conclusion

Recent researches indicate that electric vehicle market is growing day by day. Every automotive OEM has turned their interes on electric vehicle development area. An electric vehicle powertrain consists an electric motor, its motor drive, controller part, user interface and battery pack. Despite an internal combustion engine efficiency can go up to 35%, an electric motor efficiency can go up to 95%. This affects whole system efficiency from grid to wheel is even lower in ICEVs.

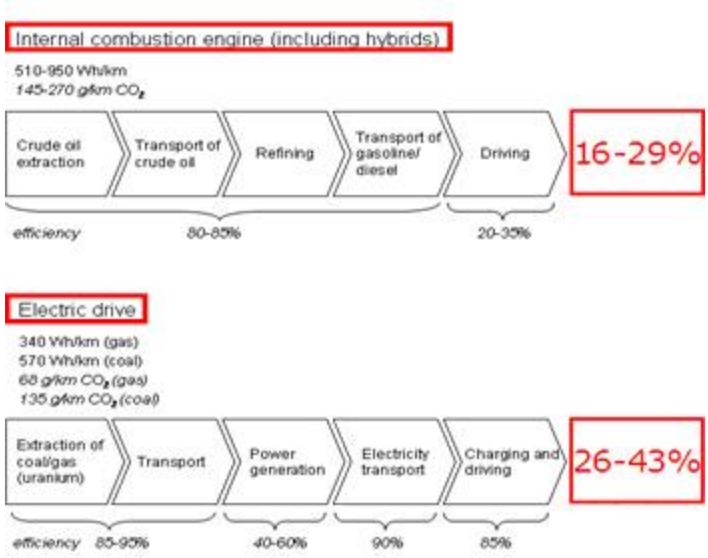



**Figure 4.3 :** Grid to wheel efficiency comparison [44].

The difference between energy comsumption is arousing customer interest on electric vehicles. To arise this interest in Turkey, in ITU, ALEK team decided to create the project ITU EV in order to introduce electric vehicle technology to the drivers. In this study electric drivetrain design and production part of the project is surveyed. A BLDCM had been chosen because of their high efficiency for this project. The motor needs had been calculated and the motor design was made. After motor design, verification of the design was made by electromagnetic FEA. When the verification of the design is completed, motor and its mechanical components are produced and assemblied. This process followed by laboratory tests and an inverter for the motor was generated. The tests show that designed electric powertrain has approximately 75% efficiency. Final part of the project is implementation drivetrain to the vehicle and vehicle user interface will be applied to the vehicle. Following these processes field tests and advertisement of the vehicle will be done.

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