

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

**MODELING OF CHARGING SYSTEM AND CONTROL OF AN  
ALTERNATOR OF A VEHICLE**

**M.Sc. THESIS**

**Mustafa Gökay UNUTULMAZ**

**Department of Mechatronics Engineering**

**Mechatronics Engineering Programme**

**SEPTEMBER 2013**



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

**MODELING OF CHARGING SYSTEM AND CONTROL OF AN  
ALTERNATOR OF A VEHICLE**

**M.Sc. THESIS**

**Mustafa Gökay UNUTULMAZ  
(518101028)**

**Department of Mechatronics Engineering**

**Mechatronics Engineering Programme**

**Thesis Advisor: Assoc. Prof. Dr. Lale Tükenmez ERGENE**

**SEPTEMBER 2013**



**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ**

**ARAÇ ŞARJ SİSTEMİNİN MODELLENMESİ VE ALTERNATÖR  
KONTROLÜ**

**YÜKSEK LİSANS TEZİ**

**Mustafa Gökay UNUTULMAZ  
(518101028)**

**Mekatronik Mühendisliği Anabilim Dalı**

**Mekatronik Mühendisliği Programı**

**Tez Danışmanı: Doç. Dr. Lale Tükenmez ERGENE**

**EYLÜL 2013**



**Mustafa Gökay Unutulmaz**, a **M.Sc.** student of **ITU Graduate School of Science Engineering and Technology** student ID **518101028**, successfully defended the thesis entitled “**MODELING OF CHARGING SYSTEM AND CONTROL OF AN ALTERNATOR OF A VEHICLE**”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

**Thesis Advisor :**      **Assoc. Prof. Dr. Lale Tükenmez ERGENE**  
İstanbul Technical University

.....

**Jury Members :**      **Prof. Dr. Metin GÖKAŞAN**  
İstanbul Technical University

.....

**Assoc. Prof. Dr. Haluk GÖRGÜN**  
Yıldız Technical University

.....

**Date of Submission : 06 September 2013**  
**Date of Defense : 23 September 2013**



## **FOREWORD**

This thesis is written as completion to the master of Mechatronics Engineering at Istanbul Technical University. The master program focuses on the mechanical, electrical and control technologies. The subject of this thesis is vehicle conventional electrical charging system. Lundell type of claw pole alternator is expressed with mathematical equations and a complete model of a vehicle electrical charging system is created.

I graduated from Electrical Engineering BS program at Istanbul Technical University. My research and work areas are electric machines, power electronics and the relation of these systems with automotive industry. The main reason to choose this thesis subject is the direct relation of the automotive and mechatronic systems.

I want to thank Assoc. Prof. Dr. Lale Tukenmez Ergene because of her direct support and encouragement during my period of working. Also, I thank to Yiğit Koyuncuoğlu for his corroborative friendship about this thesis. Finally, I thank to my family and Deniz Bulgan for their unfailing patient and boosting my work enthusiasm.

September 2013

Mustafa Gökay UNUTULMAZ



## TABLE OF CONTENTS

|                                                                                                     | <u>Page</u> |
|-----------------------------------------------------------------------------------------------------|-------------|
| <b>FOREWORD .....</b>                                                                               | <b>vii</b>  |
| <b>TABLE OF CONTENTS.....</b>                                                                       | <b>ix</b>   |
| <b>ABBREVIATIONS .....</b>                                                                          | <b>xi</b>   |
| <b>LIST OF TABLES .....</b>                                                                         | <b>xiii</b> |
| <b>LIST OF FIGURES .....</b>                                                                        | <b>xv</b>   |
| <b>SUMMARY .....</b>                                                                                | <b>xvii</b> |
| <b>ÖZET.....</b>                                                                                    | <b>xix</b>  |
| <b>1. INTRODUCTION.....</b>                                                                         | <b>1</b>    |
| 1.1 Purpose of Thesis .....                                                                         | 2           |
| 1.2 Literature Review .....                                                                         | 3           |
| <b>2. LUNDELL TYPE OF ALTERNATOR AND COMPARISON WITH<br/>OTHER TYPE OF ELECTRICAL MACHINES.....</b> | <b>9</b>    |
| 2.1 Overview of the Lundell Type of Alternator .....                                                | 9           |
| 2.2 Comparison of the Lundell Type of Machine With Other Machines.....                              | 9           |
| <b>3. CONSTRUCTION OF LUNDELL TYPE OF ALTERNATOR.....</b>                                           | <b>13</b>   |
| 3.1 Alternator Component Construction and IC Engine Assembly .....                                  | 13          |
| 3.1.1 Rotor construction.....                                                                       | 14          |
| 3.1.2 Stator construction .....                                                                     | 14          |
| <b>4. MATHEMATICAL MODEL OF THE LUNDELL TYPE ALTERNATOR</b>                                         | <b>17</b>   |
| 4.1 Equivalent Circuit .....                                                                        | 17          |
| 4.2 Magnetic Circuit Equations.....                                                                 | 19          |
| <b>5. SYSTEM LOSSES AND THE POWER FACTOR CALCULATION.....</b>                                       | <b>25</b>   |
| 5.1 Electrical Losses.....                                                                          | 25          |
| 5.1.1 Stator copper loss .....                                                                      | 25          |
| 5.1.2 Rotor copper loss .....                                                                       | 25          |
| 5.1.3 Slip ring - brush loss .....                                                                  | 26          |
| 5.1.4 Diode rectifier loss .....                                                                    | 26          |
| 5.1.5 Step-down SMPS losses of the excitation circuit .....                                         | 26          |
| 5.1.5.1 On position (conducted).....                                                                | 27          |
| 5.1.5.2 Off position .....                                                                          | 28          |
| 5.1.5.3 Switching position loss .....                                                               | 28          |
| 5.2 Magnetic Losses .....                                                                           | 29          |
| 5.2.1 Hysteresis losses .....                                                                       | 29          |
| 5.2.2 Eddy current losses .....                                                                     | 31          |
| 5.2.3 Stray losses.....                                                                             | 31          |
| 5.3 Mechanical Losses .....                                                                         | 32          |
| 5.4 Power Factor Calculation .....                                                                  | 32          |
| <b>6. ALTERNATOR MEASUREMENTS .....</b>                                                             | <b>35</b>   |
| 6.1 Objective .....                                                                                 | 35          |
| 6.2 Alternator Machine Constant Calculation.....                                                    | 35          |

|                                                                             |           |
|-----------------------------------------------------------------------------|-----------|
| 6.3 Excitation Winding Resistance.....                                      | 39        |
| 6.4 Slip Ring – Brush Resistance .....                                      | 40        |
| 6.5 Excitation Winding Inductance .....                                     | 41        |
| <b>7. MATLAB® MODELING OF THE ALTERNATOR AND THE CHARGING SYSTEM .....</b>  | <b>45</b> |
| 7.1 Vehicle Loads Triggering Block .....                                    | 45        |
| 7.2 Vehicle Loads Modeling Block.....                                       | 46        |
| 7.3 Stator and Rectifier Modeling Block.....                                | 49        |
| 7.4 Stator Voltage Inducement Block .....                                   | 52        |
| 7.5 Engine-Alternator Assembly Mechanical Modeling Block .....              | 52        |
| 7.6 Excitation Current Controller Block .....                               | 55        |
| 7.7 Alternator Excitation Circuit and Magnetic Reaction Modeling Block..... | 55        |
| <b>8. RESULTS AND CONCLUSION.....</b>                                       | <b>63</b> |
| 8.1 Dynamic Model and Excitation Current Controller .....                   | 63        |
| 8.2 Static Model.....                                                       | 68        |
| <b>REFERENCES .....</b>                                                     | <b>71</b> |
| <b>APPENDICES .....</b>                                                     | <b>73</b> |
| APPENDIX A.1 .....                                                          | 74        |
| <b>CURRICULUM VITAE.....</b>                                                | <b>89</b> |

## **ABBREVIATIONS**

|               |                                                     |
|---------------|-----------------------------------------------------|
| <b>MOSFET</b> | : Metal–Oxide–Semiconductor Field-Effect Transistor |
| <b>NEDC</b>   | : New European Driving Cycle                        |
| <b>WHTC</b>   | : World Harmonized Transient Cycle                  |
| <b>OEM</b>    | : Original Equipment Manufacturer                   |
| <b>PWM</b>    | : Pulse Width Modulation                            |
| <b>SMPS</b>   | : Switch Mode Power Supply                          |



## LIST OF TABLES

|                                                                                          | <b><u>Page</u></b> |
|------------------------------------------------------------------------------------------|--------------------|
| <b>Table 4.1 :</b> Equivalent circuit parameters .....                                   | 18                 |
| <b>Table 4.2 :</b> Parameter list of the claw shape.....                                 | 20                 |
| <b>Table 6.1 :</b> Machine constant experimental measurement .....                       | 36                 |
| <b>Table 6.2 :</b> Excitation winding resistance measurement .....                       | 39                 |
| <b>Table 6.3 :</b> Brush resistance measurement .....                                    | 41                 |
| <b>Table 8.1 :</b> Vehicle loads activation timings .....                                | 68                 |
| <b>Table 8.2 :</b> Electrical loss calculation in static model during $I_s = 100A$ ..... | 70                 |



## LIST OF FIGURES

|                                                                                           | <u>Page</u> |
|-------------------------------------------------------------------------------------------|-------------|
| <b>Figure 1.1</b> : General overview of the alternator. The patent no 3184625 [10] .....  | 4           |
| <b>Figure 1.2</b> : Rotor view of the alternator from the patent no 3184625 [10].....     | 5           |
| <b>Figure 1.3</b> : The growth of the electrical component cost [11].....                 | 5           |
| <b>Figure 1.4</b> : Rising trend of the required electrical power of a vehicle [11] ..... | 6           |
| <b>Figure 1.5</b> : Total vehicle production in the world [17].....                       | 7           |
| <b>Figure 1.6</b> : Total vehicle production in Turkiye [17] .....                        | 7           |
| <b>Figure 2.1</b> : Classification of electric machinery [25] .....                       | 10          |
| <b>Figure 2.2</b> : Claw pole Lundell type of alternator [9] .....                        | 11          |
| <b>Figure 3.1</b> : The alignment of the alternator with an IC engine. [22] .....         | 13          |
| <b>Figure 3.2</b> : A cutaway view of an alternator [19] .....                            | 14          |
| <b>Figure 3.3</b> : Rotor construction of the alternator.[8] .....                        | 15          |
| <b>Figure 3.4</b> : Stator construction of the alternator.[8].....                        | 15          |
| <b>Figure 4.1</b> : 3-phase equivalent circuit.....                                       | 17          |
| <b>Figure 4.2</b> : One phase equivalent circuit .....                                    | 17          |
| <b>Figure 4.3</b> : Phasor diagram of the alternator.....                                 | 19          |
| <b>Figure 4.4</b> : Magnetic flux path of the claw pole machine [4].....                  | 20          |
| <b>Figure 4.5</b> : Shape of a claw and parameters [3].....                               | 20          |
| <b>Figure 4.6</b> : Magnetic flux density and its fundamental component [3] .....         | 22          |
| <b>Figure 5.1</b> : Duty cycle calculation .....                                          | 26          |
| <b>Figure 5.2</b> : Excitation circuit model .....                                        | 27          |
| <b>Figure 5.3</b> : Current path during the ‘on’ state.....                               | 27          |
| <b>Figure 5.4</b> : Current path during the ‘off’ state. ....                             | 28          |
| <b>Figure 5.5</b> : Switching durations [24] .....                                        | 29          |
| <b>Figure 5.6</b> : Ferromagnetic alignment.....                                          | 30          |
| <b>Figure 5.7</b> : Hysteresis curves of different materials [21].....                    | 30          |
| <b>Figure 5.8</b> : Eddy currents.....                                                    | 31          |
| <b>Figure 6.1</b> : Machine constant estimation and measurement .....                     | 37          |
| <b>Figure 6.2</b> : Induced voltage estimation and measurement.....                       | 38          |
| <b>Figure 6.3</b> : Induced voltage error .....                                           | 38          |
| <b>Figure 6.4</b> : Excitation winding resistance measurement and assumption .....        | 39          |
| <b>Figure 6.5</b> : Error between the measurement and the assumption .....                | 40          |
| <b>Figure 6.6</b> : Slip ring – Brush resistance measurements and assumption .....        | 41          |
| <b>Figure 6.7</b> : Error of slip ring – brush measurement and assumption.....            | 42          |
| <b>Figure 6.8</b> : Step response measurement.....                                        | 43          |
| <b>Figure 6.9</b> : Simulation result with calculated inductance .....                    | 43          |
| <b>Figure 7.1</b> : Vehicle loads triggering block.....                                   | 46          |
| <b>Figure 7.2</b> : Vehicle loads modeling block .....                                    | 47          |
| <b>Figure 7.3</b> : State inputs of the loads.....                                        | 47          |
| <b>Figure 7.4</b> : Example of a vehicle load list from the literature [20].....          | 48          |
| <b>Figure 7.5</b> : Resistive load modeling .....                                         | 48          |

|                                                                                                                                         |    |
|-----------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Figure 7.6 :</b> RL and RLE load modeling .....                                                                                      | 49 |
| <b>Figure 7.7 :</b> Stator and rectifier modeling block .....                                                                           | 49 |
| <b>Figure 7.8 :</b> The comparison of the MATLAB® and PSIM® simulation outputs .....                                                    | 50 |
| <b>Figure 7.9 :</b> Calculation of total load current and power .....                                                                   | 50 |
| <b>Figure 7.10 :</b> Calculation of stator and rectifier reactions.....                                                                 | 51 |
| <b>Figure 7.11 :</b> Stator voltage inducement block .....                                                                              | 52 |
| <b>Figure 7.12 :</b> Three phase sinusoidal voltage generation .....                                                                    | 52 |
| <b>Figure 7.13 :</b> Mechanical Model .....                                                                                             | 53 |
| <b>Figure 7.14 :</b> Engine-Alternator Assembly [4] .....                                                                               | 53 |
| <b>Figure 7.15 :</b> Calculations of meachanical variables .....                                                                        | 54 |
| <b>Figure 7.16 :</b> Main Controller Block.....                                                                                         | 55 |
| <b>Figure 7.17 :</b> A discrete time saturated PI type of controller .....                                                              | 55 |
| <b>Figure 7.18 :</b> Main block of the field winding modeling and loss calculation.....                                                 | 56 |
| <b>Figure 7.19 :</b> Example model to show how to create duty cycle in discrete time.....                                               | 56 |
| <b>Figure 7.20 :</b> Duty cycle creation in discrete time .....                                                                         | 57 |
| <b>Figure 7.21 :</b> Dynamic model that contains MOSFET switching modeling with high<br>speed sampling rates .....                      | 58 |
| <b>Figure 7.22 :</b> Static model excitation current calculation without modeling of<br>MOSFET switching and using average values ..... | 59 |
| <b>Figure 7.23 :</b> Dynamic modeling of field winding losses and excitation current .....                                              | 61 |
| <b>Figure 8.1 :</b> Actual and setpoint DC voltage comparison with P controller. ....                                                   | 63 |
| <b>Figure 8.2 :</b> Actual and setpoint DC voltage comparison with PI controller. ....                                                  | 64 |
| <b>Figure 8.3 :</b> Current with P gain equals to 5 and I gain equals to 10 .....                                                       | 64 |
| <b>Figure 8.4 :</b> Decreased system response time with PI controller .....                                                             | 65 |
| <b>Figure 8.5 :</b> Excitation current characteristics.....                                                                             | 65 |
| <b>Figure 8.6 :</b> Duty cycle and actual voltage comparison .....                                                                      | 66 |
| <b>Figure 8.7 :</b> Controller effort and duty cycle with the gains P=4 and I=50 .....                                                  | 67 |
| <b>Figure 8.8 :</b> DC bus voltage setpoint and the actual voltage in load condition.....                                               | 67 |
| <b>Figure 8.9 :</b> Excitation current in load condition .....                                                                          | 67 |
| <b>Figure 8.10 :</b> Load states .....                                                                                                  | 68 |
| <b>Figure A.1 :</b> Desired alternator voltage.....                                                                                     | 75 |
| <b>Figure A.2 :</b> Battery voltage (DC bus voltage) .....                                                                              | 76 |
| <b>Figure A.3 :</b> Engine speed .....                                                                                                  | 77 |
| <b>Figure A.4 :</b> Vehicle loads supply current .....                                                                                  | 78 |
| <b>Figure A.5 :</b> Excitation current in percentage .....                                                                              | 79 |
| <b>Figure A.6 :</b> Duty cycle in percentage .....                                                                                      | 80 |
| <b>Figure A.7 :</b> Total load power .....                                                                                              | 81 |
| <b>Figure A.8 :</b> Total load current.....                                                                                             | 82 |
| <b>Figure A.9 :</b> Induced voltage signal of phase A.....                                                                              | 83 |
| <b>Figure A.10 :</b> If circuit supply voltage .....                                                                                    | 84 |
| <b>Figure A.11 :</b> Excitation winding copper loss.....                                                                                | 85 |
| <b>Figure A.12 :</b> Fly wheeling diode and MOSFET conduction loss comparison .....                                                     | 86 |
| <b>Figure A.13 :</b> Total electrical loss .....                                                                                        | 87 |

# **MODELING OF CHARGING SYSTEM AND CONTROL OF AN ALTERNATOR OF A VEHICLE**

## **SUMMARY**

Vehicle electrical charging system is getting more important than the past because of the consumers' demands. The vehicle manufacturing companies add many technological specifications to their products to satisfy these demands. The additional specifications in comfort, safety and in car entertainment results in the requirement of more electrical power. Lundell type of alternator is the main component which used in the vehicles with the aim of vehicle electrical power generation. Even though the conventional methods have been still used to charge the vehicle battery system new methods of intelligent electrical power generation are becoming more popular. This thesis investigates the alternator component and vehicle electrical charging system. Alternator types, Lundell type of alternators and the charging system are investigated together with the electrical loads.

The first part of the thesis is the introduction. In addition, literature was reviewed to proof the rising importance of this topic in the future. There are also different types of electrical machines to be used as electrical power generation in vehicles. A general comparison of these machines are presented.

The Lundell type of alternator is a three phase synchronous machine that consists of a stator, claw pole rotor and the excitation current controller. The construction is overviewed and machine parameters are shown and explained. Mathematical model of the alternator is prior to set up a vehicle electrical charging simulation and control. Equivalent circuits of the stator and the rotor are derived and explained in terms of machine parameters in the second section of the thesis.

Alternator losses play an important role in the system power distribution and efficiency calculation. Although it seems to be hard to satisfy required electrical power with Lundell type of alternator, there are methods to increase the efficiency with modification of machine parameters while keeping the main construction the same. The system losses are also obtained and considered in the final simulation.

An alternator which is produced by an Original Equipment Manufacturer (OEM) is used to measure the machine parameters to finalize the system model. A test set up was prepared and alternator machine constant, excitation and armature winding resistances and inductances, slip ring-brush resistances were measured in different speeds and excitation current states. In addition, vehicle electrical load power values are measured from a test vehicle and load parameters are also calculated.

Finally, a MATLAB<sup>®</sup> model is established to see the whole control system which are investigated in the thesis. The model contains the alternator stator reactions, alternator excitation and field current controller; vehicle loads activation conditions and engine speed. All the model inputs and parameters are measured from the real systems and components to satisfy a robust simulation result.



## ARAÇ ŞARJ SİSTEMİ MODELLEMESİ VE ALTERNATOR KONTROLÜ

### ÖZET

Günümüzde teknolojinin önlemez gelişimi araçlar üzerinde de etkisini göstermektedir. Gelişen teknoloji, araçlarda yeni ek donanımlar olarak kendini göstermektedir. Güvenlik ve konfor donanımlarının artmasıyla ve araç içi eğlence sistemlerinin gelişmesiyle birlikte araçlardaki mevcut elektriksel güç gereksinimi artış eğilimi göstermektedir. İlerleyen yıllardaki bu güç gereksinimini karşılayabilmek için, mevcut elektriksel şarj sisteminin yeterliliği sorgulanmaya başlanmış ve bu konuda çok sayıda yenilikçi çalışmalar yapılmıştır. Bu tezde taşıtlardaki günümüzde kullanılan elektriksel güç üretim ve dağıtım sistemleri incelenmiş ve bu donanımları içeren bir modelleme geliştirilmiştir.

Tezin başlangıcında, konuyu ana hatlarıyla inceleyen ve konunun önemini vurgulayan noktalar literatürden toplanarak ve verilerle desteklenerek açıklanmıştır. Tezin bu aşamasında araç şarj sistemlerinin geçmişte nasıl oldukları araştırılmıştır. Ayrıca geçmişte yapılan araç şarj sistemi tasarımlarının günümüze gelene kadar yaşadığı değişiklikler anlatılmıştır. Bu değişikliklerin en temeli ise başlangıçta doğru akım generatörü olarak tasarlanan temel elektriksel güç kaynağının daha sonra neden alternatif akım generatörüne dönüştürüldüğü anlatılmıştır. Araçlarda kullanılmaya başlanan alternatif akım generatörü olan Lundell tipi makinenin geçmişteki patentleri bulunmuş ve incelenmiştir. Yine aynı bölümde, geçmişten günümüze araçlardaki elektriksel güç gereksiniminin artışı güncel kaynaklardan edinilen verilerle gösterilmiştir. Ayrıca yine güncel kaynaklardan edinilen küresel ve ülke çapındaki araç üretim sayıları ile birlikte teknolojik gelişime bir de maliyet yönünden bakılmıştır.

İkinci bölümde ise Lundell tipi; diğer bir isimle pençe kutuplu makinenin genel bir incelemesi yapılmış ve sahip olduğu avantaj ve dezavantajlar incelenmiştir. Makinenin genel özellikleri itibari ile senkron bir alternatif akım makinesi olduğu gösterilmiştir. Pençe kutuplu Lundell tipi alternatör geçmişte ve günümüzde, araçlardaki elektriksel gücün üretiminde ana donanım olarak kullanılmaktadır. Sahip olduğu fiziki özellikler, basit bir tasarıma sahip oluşu, yüksek devirlere dayanıklı oluşu ve uzun yıllardır kullanımda olması sebebiyle üretim maliyetinin düşük olması araç üreticileri tarafından tercih edilmesinin temel sebepleridir. Dezavantajları ise sahip olduğu geniş manyetik hava boşlukları nedeniyle makinenin veriminin diğer makinelere göre düşük olmasıdır. Ancak, alternatör üreticileri özel uygulamalara cevap verebilmek için başka tipte makinelerde üretmektedir. Örneğin asenkron makineler her hangi bir fırça-kolektör düzeneği bulundurmamakta ve genel anlamda pençe kutuplu makineye göre daha verimli olabilmektedir. Ancak makineyi araçta kullanabilmek için kontrollü güç elektroniği devreleri kullanılması gerekmektedir ve maliyet artımına sebep olur. Anahtarlamalı relüktans makineleri yine araçlarda alternatör olarak kullanılabilir ancak sahip olduğu fiziksel titreşimler nedeniyle

gürültülü çalışmaktadır. Bu da konfor beklentilerini karşılayamamakta ve makine sıralamada geri düşmektedir. Alternatör olarak kullanılabilen ve günümüzde de bazı alternatör üreticileri tarafından üretilen diğer bir makine tipi de sabit mıknatıslı makinedir. Sabit mıknatıslı makineler, fırça bilezik düzenekleri bulundurmadıklarından bakım gerektirmezler. Ayrıca aynı kütleye sahip bir pençe kutuplu makineye göre daha fazla güç üretebilirler. Diğer bir ifadeyle verimleri daha fazladır. Dezavantajı ise sahip oldukları sabit mıknatıslar sebebiyle maliyetlerinin klasik pençe kutuplu makineye göre yüksek olmasıdır. Fakat bu dezavantajına rağmen, motor sporları ve bazı ağır yük araçları gibi özel uygulamalarda kendilerine yer bulabilmektedirler. Tezin içerisinde farklı tiplerdeki bu alternatörlerin karşılaştırmaları detaylı bir şekilde yapılmaktadır.

Tezin üçüncü bölümünde Lundell tipi makinenin konstrüksiyonu detaylı bir şekilde incelenmiştir. Pençe kutuplu alternatörler temelde senkron generatörlerdir ve üç fazlı alternatif akım üretirler. Stator kısmında üç fazlı alternatif akım sargısı bulunur ve yapısı senkron ya da asenkron makineler gibi diğer alternatif akım makineleriyle benzerlik gösterir. Ancak pençe kutuplu rotorun konstrüktif yapısı diğer makinelerden farklılık gösterir. Genellikle döküm olarak işlenen rotorun demir kısmı, uyarma sargısının dışında etrafıca pençeler şeklinde bulunmaktadır. Rotorun bu yapıda olması, pençe kutuplu alternatöre yüksek devirlerde merkez kaç kuvvetine karşı dayanım avantajını getirir. Rotor sargıları merkez kaç kuvveti nedeniyle açılma ve dağılma eğilimi gösteremezler. Rotor ve statora ek olarak ayrıca alternatörün üzerine yerleştirilmiş bir uyarma akım kontrolcüsü bulunmaktadır. Bu kontrolcü, değişen motor devrine göre ve değişen akü gerilimi gereksinimine göre uyarma akımını sürekli olarak kontrol eder. Böylelikle değişken motor devrine rağmen alternatörün çıkış gerilimi sabit kalır. Bütün olarak alternatör parçası ise aracın içten yanmalı motorunun üzerine sabitlenir ve bir kayış kasnak mekanizması ile motor milinden güç alması sağlanır. Dolayısıyla içten yanmalı motorun ürettiği momentin bir bölümü kayış kasnak mekanizması ile birlikte alternatöre aktarılır.

Makinenin konstrüksiyonun detaylı bir şekilde anlatımıyla birlikte bir sonraki bölümde bu özelliklerin matematiksel ifadelerine geçilmiştir. Öncelikle makinenin mekanik ve elektriksel parametreleri kullanılarak makine için literatürde de kullanılan genel denklemler çıkarılmıştır. Burada rotor ve stator sargıları için öncelikle genel devre şemaları verilmiştir. Daha sonra matematiksel ifadelerin çıkarılacağı eşdeğer devreler çizilmiştir. Rotor devresi yani uyarma devresine verilen akımla birlikte ortaya çıkan manyetik akının makine içerisindeki yolu çizilmiştir. Ayrıca statorda bulunan pençelerin ve makinenin diğer yapılarının fiziksel ölçümlendirmeleri ve boyutları parametrik olarak denklemlerin içine yerleştirilmiştir. Burada endüvi reaksiyonu ile birlikte stator reaksiyonları ve endüklenen gerilimin temel bileşeni ile ifadesi sağlanmıştır. Ortaya çıkan ana denklemde makinedeki fiziksel ve tasarımsal sabitler genel bir makine sabitine indirgenmiştir. Son olarak ise uyarma akımına, alternatörün mekanik hızına ve makine sabitine bağlı bir endüklenen gerilim denkleminde ulaşılmıştır. Bütün bu denklemler uyarma akımıyla başlayarak matematiksel bir akış ile çıkarılmıştır.

Pençe kutuplu makinenin genel özelliklerinin çıkarılmasıyla birlikte, modelin tamamlanması için gerekli son aşama olan kayıpların hesaplanmasına ve modellenmesine bir sonraki bölümde geçilmiştir. Rotor ve stator için elektriksel ve manyetik kayıpların çıkarımı yapılmış ve matematiksel olarak hesaplanmıştır. Bu bölümde öncelikle makinedeki elektriksel kayıplar belirlenmiş ve matematiksel

çıkarımları yapılmıştır. Başlıca elektriksel kayıplar stator ve rotor sargı bakır kayıpları, fırça-bilezik düzeneği temas direnci kaybı ve kontrol devresinde kullanılan anahtarlama elemanının kayıplarıdır. Ayrıca alternatörün çıkış gerilimini doğrultan doğrultucuda bulunan diyotların da kaybı hesaplanmıştır. Daha sonra manyetik kayıplara geçilmiştir. Elektriksel kayıplarda olduğu gibi burada da histerizis kaybı ve girdap akım kayıpları incelenmiş ve matematiksel olarak ifade edilmiştir. Son olarak alternatörde bulunan mekanik kayıp bileşenleri açıklanmış ve matematiksel olarak ifade edilmiştir. Alternatör için belirtilen bu matematiksel ifadeler MATLAB® Simulink ortamına aktarılarak bir model haline getirilmiştir.

Tezin bir sonraki bölümünde parametrik olarak hesaplanan alternatör denklemlerini bir sonuca ulaştırabilmek için piyasadan bir alternatör seçilmiş ve bu alternatör üzerinden ölçümlendirmeler yapılmıştır. Alternatörün seçiminin yapılmasıyla birlikte, bir test düzeneği oluşturulmuştur. Oluşturulan test düzeneğinde devri okunabilen bir doğru akım motoru kullanılmıştır. Bu motora kayış kasnak düzeneği ile birlikte piyasadan edinilen alternatör bağlanmıştır. Ayrıca makinenin uyarma akımını sağlayabilmek için alternatörün kontrolcüsü devre dışı bırakılmış ve uyarma sargısından uçlar çıkartılarak, uyarma akımının ekstra bir güç kaynağı ile kontrol edilmesi sağlanmıştır. Bu test düzeneğiyle birlikte alternatörü farklı devirlerde döndürme ve uyarma gerilimi ile besleme yetenekleri kazanılmıştır. Kurulan bu test düzeneğiyle birlikte farklı devir ve uyarma akımlarından ölçümlendirmeler yapılmış ve alternatör parametrelerinin belirlenmesi sağlanmıştır. Ayrıca, stator sargı direnci ve endüktansı, rotor sargı direnci ve endüktansı, fırça-bilezik temas direnci ve makinenin diğer parametreleri ölçülmüş ve hesaplanmıştır. Yapılan bu ölçümlendirmeler tekrarlanarak, ölçüm hataları minimize edilmiştir ve çıkan sonuçların ortalamaları alınarak modelde kullanılmıştır.

Tezin bir sonraki aşamasında ise oluşturulan MATLAB® Simulink modelinin bileşenleri açıklanmıştır. Öncelikle, araç elektriksel şarj sisteminin diğer temel unsuru olan elektriksel yükler açıklanmıştır. Literatürde günümüzde kullanılan araçlarda bulunan elektriksel yükleri ve tükettiği güçler bulunabilmektedir fakat modelin araçtan toplanan veriyle birlikte uyumlu bir sonuç verebilmesi için, elektriksel yüklerin güçleri seçilen bir araçtan toplanan verilerle birlikte hesaplanmıştır. Hesaplanan bu yükler matematiksel olarak saf omik, omik ve endüktif tiplerde ifade edilerek modellenmiştir. Modellenen bu yükler oluşturulan ana modele gömülerek final simülasyonuna entegre edilmiştir. Daha sonra tezde bu aşamaya kadar anlatılan bütün matematiksel ifadelerin model haline getirilişi bloklar halinde anlatılmıştır. İlk blok olan mekanik model bloğunda içten yanmalı motorun devri olan giriş verisi alternatörün mekanik devrine dönüştürülerek diğer bloklara aktarılmaktadır. Ayrıca diğer temel veriler olan elektriksel ve mekanik frekans verileri de bu blokta hesaplanmaktadır. Daha sonra uyarma akım devresi bloğu ile birlikte modellenen kontrolcü devresi endüvi reaksiyonları bu blokta işlenmiştir. Ayrıca kontrolcüdeki anahtarlama elemanı modellenmiş ve yine bu bloğun içine konmuştur. Dolayısıyla kontrolcünün çıkışı olan darbe genişlik modülasyonu bu blokta hesaplanmaktadır. Yine aynı bloğun içinde uyarma ve kontrolcü devrelerinin kayıpları hesaplanmıştır. Bir diğer blok olan stator devresinin incelendiği model bloğunda ise stator reaksiyonları ve doğrultucu modeli gerçekleştirilmiş ve yine kayıpları bu model bloğu içerisinde hesaplanmıştır.

Yapılan bu çalışmalar ve hesaplanan değerler ışığında MATLAB® Simulink ortamında alternatörü ve araç yüklerini içeren bir bütün model oluşturulmuştur.

Modelin çalışmasını sağlayabilmek için ise, araçtan motor devri, alternatör devri, yüklerin aktivasyon zamanları ve ne kadar süre aktif kaldıkları gibi süreler toplanmıştır. Toplanan bu veriler ile birlikte model koşturularak, aktif olan yüklere karşılık gerekli olan uyarma akımı, stator akımı ve kayıplar hesaplanmıştır. Çıkan sonuçlar ve araçtan toplanan veriler karşılaştırmalı bir şekilde grafiklenerek sonuç bölümünde gösterilmiştir. Ayrıca farklı yapıdaki kontrolcünün sistemi nasıl etkilediği görülmüş ve grafiklerle açıklanmıştır. Sonuç olarak değişken referans girişine sahip olunması ve etkileyen gürültü faktörlerinin sistem çıkışına etkisini minimize edebilmek için P kontrolcü ile birlikte integratör bileşeni olan PI kontrolör kullanılmıştır. Oluşturulan Simulink modelleri sayesinde hem uzun dönemli araç verileri işlenip sistemin genel durumu hakkında fikir edinilebildiği gibi ayrıca yüklerin devreye giriş ve çıkış anlarındaki dinamik davranışlarda incelenebilmektedir.

## **1. INTRODUCTION**

The vehicle manufacturers add new specifications to their products because of the consumers' preferences and competitive pressure. The rising trend in the comfort and the safety results in more electrical power requirement. Not only the new technologies and the specifications but also changing mechanical drive components make the consumption of the electrical power rise dramatically.

Alternator have been used as a component of the vehicle to charge the battery and supply the electrical loads. In fact, the alternator was capable of supplying required electrical power of the vehicle but as the technological growth of the vehicles and electrification of the systems, the efficiency of the traditional charging system is questionable.

The requirement of supplying the electrical loads of the vehicle is not the only reason for the new developments. There are many other reason to make the charging system more efficient such as emission improvement. All the manufacturers are forced to reduce their vehicles' emissions by the governments. The legislations of the European Union or the other markets and regions, force the vehicle manufacturers to hold the vehicle emissions under certain limits. In addition to these compulsions, vehicle manufacturers compete in each other to reduce the emissions, especially CO<sub>2</sub> emissions.

The other milestone is using the electrical power on traction. As the vehicles started to use electrical energy for the traction, the importance of the charging system efficiency is increased also. Not only the efficient electrical machines but also the fast charging methods are developed to satisfy required electrical power. The hybrid vehicles are not the only ones that use powerful electrical machines as traction source. The mild hybrid vehicle also use the small alternator components to recover the electrical energy.

Due to the whole reasons mentioned above new technological improvements are required on the alternators and charging systems. Conventional charging methods are

not efficient enough for the new generation vehicles so new intelligent charging strategies have been developed by the manufacturers. Hence, both of alternator component efficiency and charging system methods play strong role on the total charging system efficiency and vehicle emissions.

## **1.1 Purpose of Thesis**

This thesis investigates the alternator component and vehicle electrical charging system. Alternator types, Lundell type of alternator and the charging system of the vehicle are investigated together with the electrical loads.

The first aim is investigating the literature to understand the technological milestones of the charging systems. Rising trend of using electrical and electronic components, need to be overviewed to make projections for the future.

The second challenge is the investigation of the claw pole Lundell type of alternator. After the mathematical modeling of the Lundell type of alternator, the control of the output supply voltage is the aim of this section. Three parts of the alternator

- Rotor and excitation current
- Stator and armature current
- Three phase diode rectifier

will be explained with mathematical expressions. Electrical and magnetic losses of the alternator are going to be calculated and considered in the charging system model. In addition to these expressions; because the alternator is commonly a variable speed generator, its output voltage needs to be controlled. An excitation current controller will be included the model of the charging system.

The third step is the modeling of the vehicle electrical charging system. The alternator will be assembled to the electrical loads such as head lamps, seat and window heaters, blowers and other electrical components etc. these loads will be added to the model as vehicle electrical loads. In addition, the activation times of the electrical loads will be considered based on a defined driver behavior. Transient behavior of the system is investigated. Undershoots and overshoots of voltage against the load activation and deactivation are searched.

The final step is running the model with standard drive cycles and electrical loads to see the total required energy and power. System losses will be also calculated.

## **1.2 Literature Review**

The early electrical supply systems consist of only a nonrechargeable and low capacity batteries in mid of 19th century [23]. By increasing electrical load demands and the invention of rechargeable batteries in the end of the 19th century, the use of the battery charging system in the vehicles became necessary. First vehicle electrical systems contain a 6V battery and a DC generator. The electrical power supplied from 6V battery source was not enough for the vehicles. Moreover, DC generators had some disadvantages such as low efficiency, low output power at low engine speeds and maintenance issues due to the brushes and collectors mechanisms.

First experiments started after the World War II in 1949 on the alternator charging systems based on the military experiments [18]. The alternators stand out with their important advantages as

- More power available when engine is idling
- The efficiency is higher
- They don't have brush-collector mechanism

In 1950's many US automotive companies started to use alternators as the power generator for their public vehicles like police cars and ambulances. Finally, Glenn S.Farrison invented the alternator that the companies are still using today, in 1965 with the patent number 3184625. The machine generates 3 phase AC current and rectifies to DC by uncontrolled diode rectifier. An excitation controller also used to regulate the output voltage.

In millennium, the vehicles are fitted with lots of electrical and electronics components. Active and passive safety systems, seat and window heaters, power assisted steering, electronically controlled valves and others are available in today's contemporary vehicles. In 1950's, a vehicle contained nearly a 45m of wiring harness but today a vehicle can contain over a 2.5 km of wiring harness and 350 connectors [12].

May 18, 1965

G. S. FARISON

3,184,625

ALTERNATOR RECTIFIER UNIT

Filed May 2, 1960

7 Sheets-Sheet 1

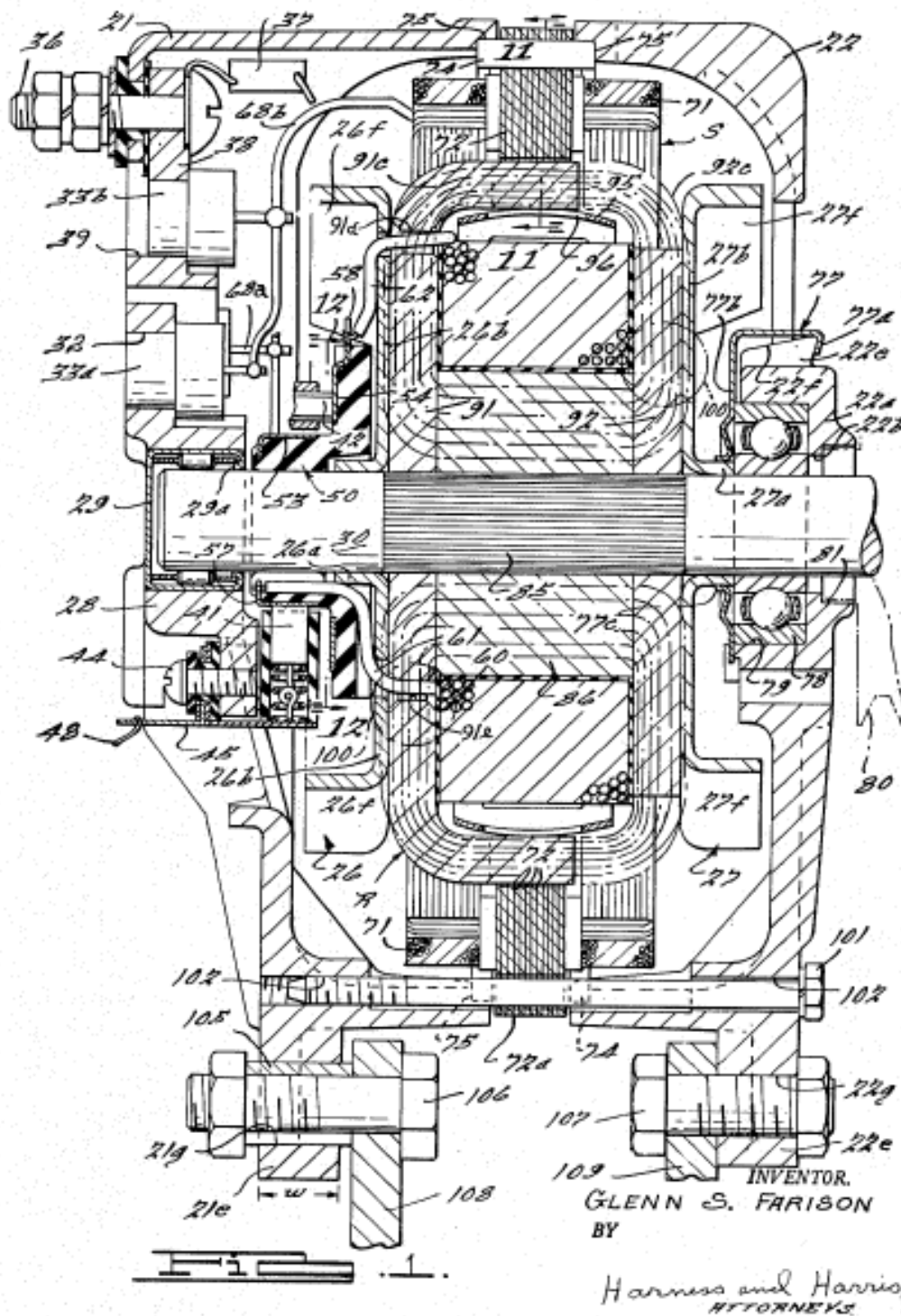
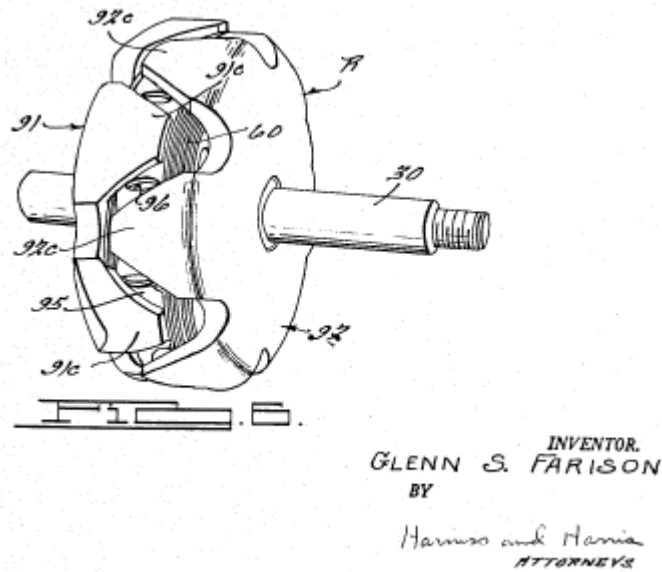
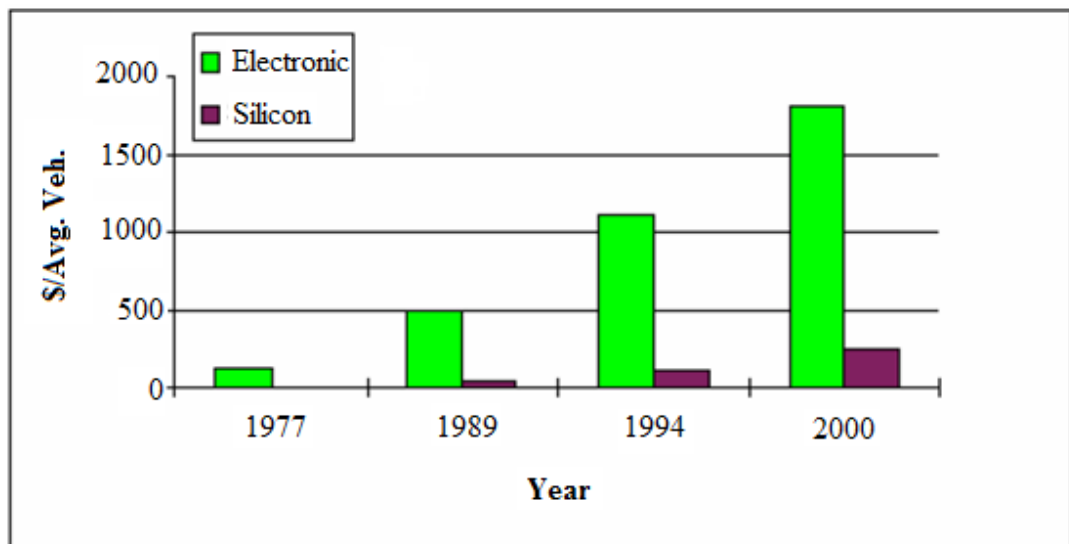


Figure 1.1 : General overview of the alternator. The patent no 3184625 [10]



**Figure 1.2 :** Rotor view of the alternator from the patent no 3184625 [10]

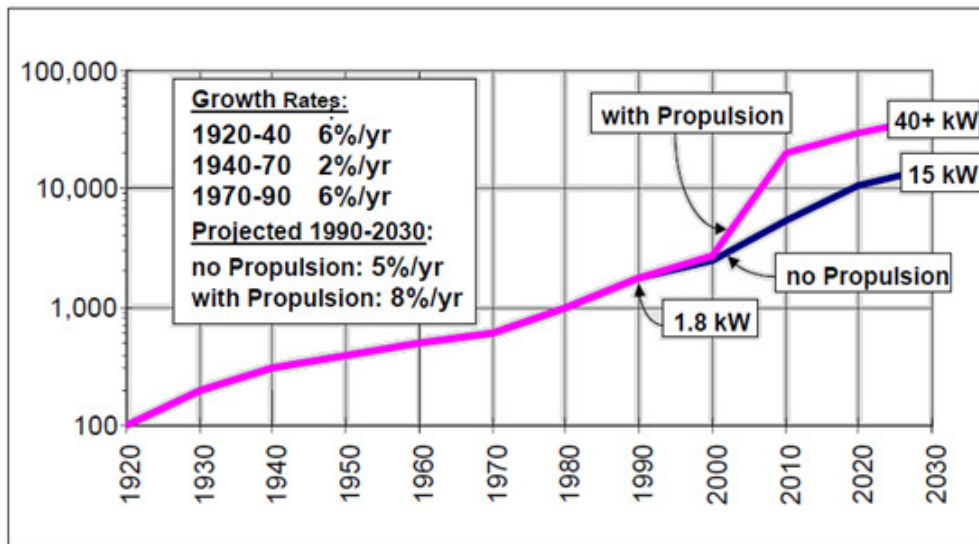
This graph shows how much the electrical demand increased over years.



**Figure 1.3 :** The growth of the electrical component cost [11]

As the electrical power sourced contents expand in vehicles, the total required electrical power increased consequently. The researches show that electrical power requirement growth will be continued in next years. In addition, propulsion with electrical power will increase the required stored electrical power sharply.

Due to the required power increase, the manufacturers started to invest lots of money to gain the efficiency of the electrical system that contains traditional battery, alternator and 12V DC bus.



**Figure 1.4 :** Rising trend of the required electrical power of a vehicle [11]

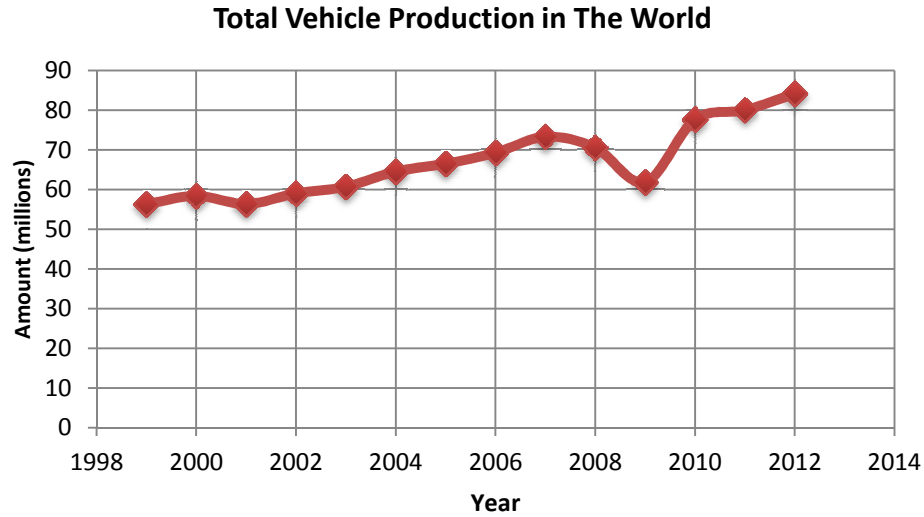
There are many ideas to increase the efficiency and prepare the electrical system for the future. Step up from 12V DC to 42V DC bus system is the main idea for the future because it is going to be possible to supply more power with higher voltage. The other point of view is to change alternator type and increase the charging efficiency. Also, redesigning the voltage regulator is the other option to upgrade the system.

The average capacity of vehicle charging systems has more than doubled in peak power rating during the past twenty years. Especially for the luxury and high class vehicles, the power consumption is four times bigger than an average class vehicle. Five years ago, the largest passenger vehicle alternators were rated at less than 100 amperes (1.4 kW). Today's alternators are approaching 150Amp capability with several manufacturers offering 140A units (2 kW) [5].

Customer and society expectations are the main reasons for the industry to use the systems which have high power density and high efficiency. While decreasing the fuel consumption and reducing the emissions are mainly forced by governments; more power, high technological specifications as safety and comfort and also low fuel consumption are the main customer demands. The achievement of both sides is possible only by increasing the efficiency of the other systems in automobiles.

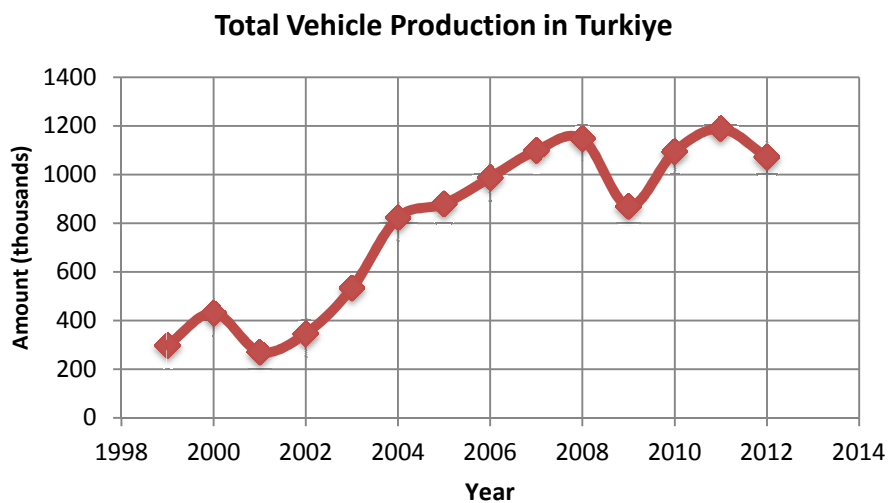
While consumers are looking for more comfortable, safer and even luxury vehicles, at the same time, neither consumers nor the vehicle producers want to increase the costs. In addition, to hold the warranty costs at low level and satisfy the consumer

confidence, the reliability and robust design of the system is mandatory. In the Figures 1.5 and 1.6, the total produced cars in the world and in Turkiye are presented.



**Figure 1.5 :** Total vehicle production in the world [17]

These huge numbers of the manufacturing vehicles are the evidences of the importance of cost and reliability. If the cost increases one Euro for a B-class vehicle, the total cost is going to be two million Euro's for the manufacturer for a two million produced B-class vehicle. In summary, cost and reliability play the most important role against the technological improvements. As a result, low cost and high efficiency methods will be the first choice of the companies to increase the efficiency of the electrical system.



**Figure 1.6 :** Total vehicle production in Turkiye [17]



## **2. LUNDELL TYPE OF ALTERNATOR AND COMPARISON WITH OTHER TYPE OF ELECTRICAL MACHINES**

### **2.1 Overview of the Lundell Type of Alternator**

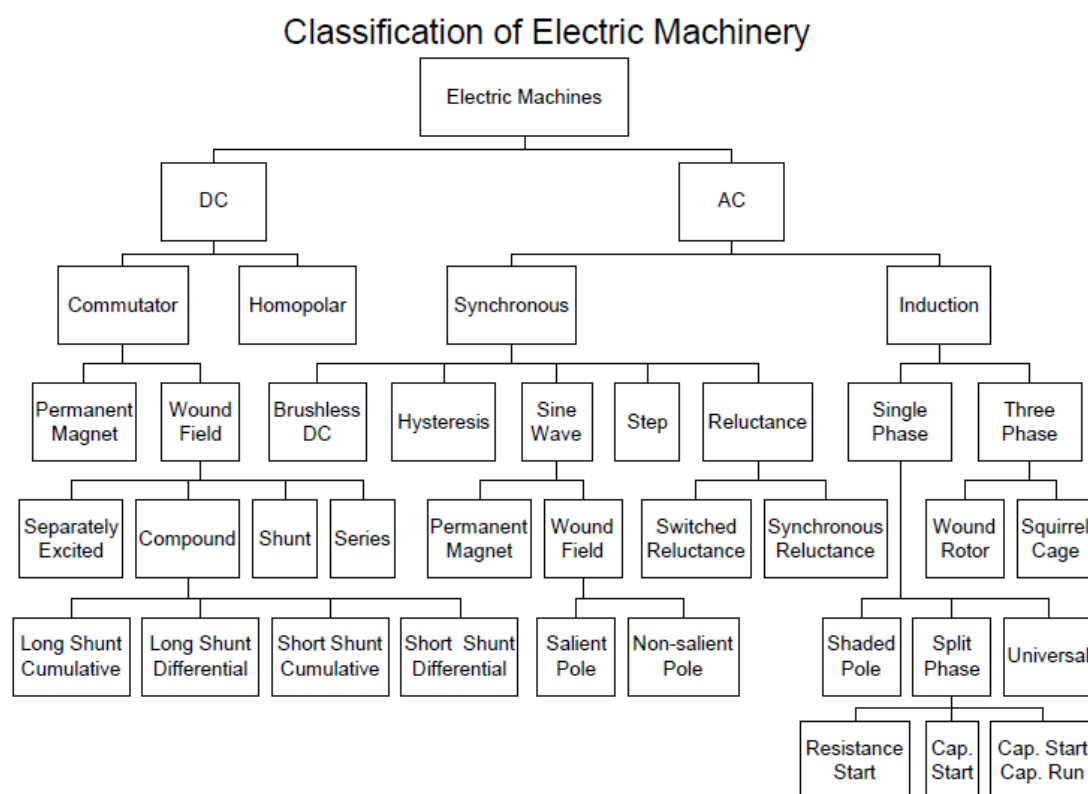
The Lundell type of alternator with claw pole rotor is the first choice of the vehicle manufacturers as an electrical power generator. This type of alternator can satisfy the required electrical power of the vehicle with low cost. However, as increasing the required power, the alternator manufacturers prefer to apply some different design methods to the machine while they keep main construction as the same. The benefits of these methods are performance increase, cost reduction, size and weight reduction of the alternator. Also, voltage regulators and alternator output rectifiers are other subjects of total efficiency.

The Lundell alternator can be classified in AC type electrical machines. Lundell machine basically is a synchronous machine with a DC excitation however it has a special rotor construction. This construction is more robust to the centrifugal forces than the ordinary rotor design of other type of synchronous machines. As a result, the machine is classified in wound rotor, sinus wave, synchronous type of AC machines.

### **2.2 Comparison of the Lundell Type of Machine With Other Machines**

Lundell machines are commonly used by the manufacturers but there are also different types of machines which are suitable to be used as a power generator. Permanent magnet DC machine, induction machine, DC generator can be used as a vehicle power generator but all of them have some positive and negative specifications. Lundell type of synchronous machine has low cost with respect to the other machines.

In addition, this machine has a robust design.. On the contrary, the total efficiency of the Lundell machine is lower than other machines due to high air gap reluctances. The other point, the rotor of the machine has big inertia especially for heavy duty vehicles, because of big mass of iron and high radius of the rotor.

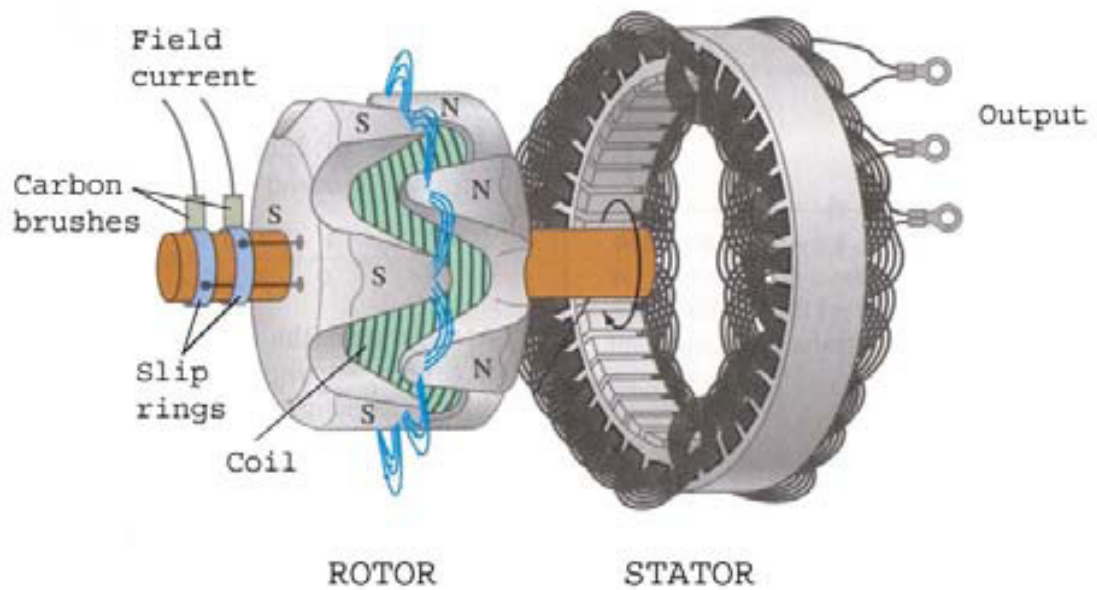


**Figure 2.1 :** Classification of electric machinery [25]

The Lundell alternator is not the only choice as a power generator. There are also other available choices.

The DC generator is the first type of alternator which had been used before the Lundell type of alternator. The DC generator is also inexpensive but it has more disadvantages than those of the Lundell machine. This machine contains commutator and brush mechanism which is a bridge of the total output power. High current values flows over this mechanism which needs the maintenance regularly. Also, rotor winding is not suitable for the high speeds because of the centrifugal force which strains the winding. The efficiency is not much better than that of Lundell type. There are also power loss on the brush and commutator.

On the other hand, the induction machine can also be used as an alternator. The three phase stator winding is similar to Lundell type of alternator which brings the manufacturing advantages. In addition, this machines do not contain any slip rings or brushes so efficiency will be better than Lundell and DC generator's efficiency. The rotor inertia is smaller than that of Lundell so it's response time is better. However, it needs to be used with an active bridge rectifier to regulate the output voltage . This requirement increases the cost.



**Figure 2.2 :** Claw pole Lundell type of alternator [9]

The switched reluctance machines are also brushless and they do not have rotor windings. So the maintenance efforts and costs will be minimized. Stator is the same with Lundell machine's one and rotor is easier to manufacture. The efficiency will be higher if the full controlled bridge rectifier has been used. The other negative point of this machine is noise and vibrations especially while it is turning at high speeds. It is not acceptable for comfort expectations.

The permanent magnet alternator is the most efficient one. Stator windings are the same with the Lundell alternator's. This machine is brushless but it is difficult to design the rotor to hold the magnets against centrifugal force at high speeds. Also, the permanent magnets are very expensive components to use in a mass production vehicle. The control of the machine is the other obstacle, however this machine capable of supplying more power. Lots of electronic devices to drive the machine are has to be used and this is the other point to increase the costs. This machine is preferred to use in motorsport vehicles or motorbikes because of being very small and having high efficiency weight rate [7]. On the other hand, some of the manufacturers produce this type of alternator for the heavy duty and off-road vehicles because of no maintenance needed.

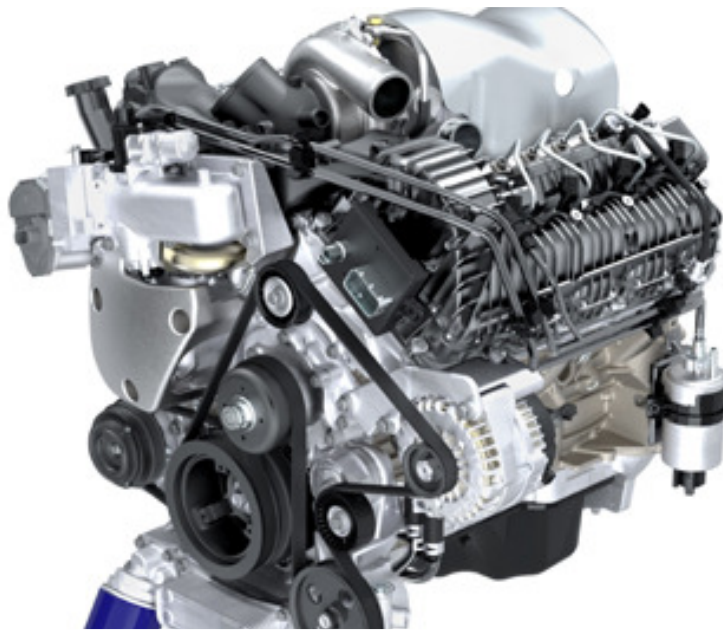
The power rates of the alternators today are in a wide range. From a motorcycle which has a 50cc engine to a heavy duty truck which has 14000cc engine are both

using an alternator. There are lots of alternator manufacturers and they produce not only Lundell machines but also different types for different applications. For example, Lundell type machines are used in the most of the vehicles but, permanent magnet machines are used in super sport motorbikes. The maximum alternator power is limited by heating of the rotor and stator windings and by magnetic saturation of the machine. Conventional Lundell alternators are limited to about 2 kW. The efficiency of these alternators is about 40 to 55%.[9]

### 3. CONSTRUCTION OF LUNDELL TYPE OF ALTERNATOR

#### 3.1 Alternator Component Construction and IC Engine Assembly

The alternators are mounted on the IC engine and driven by a belt and pulley mechanism. The gear reduction is satisfied with the alternator rotor pulley diameter.

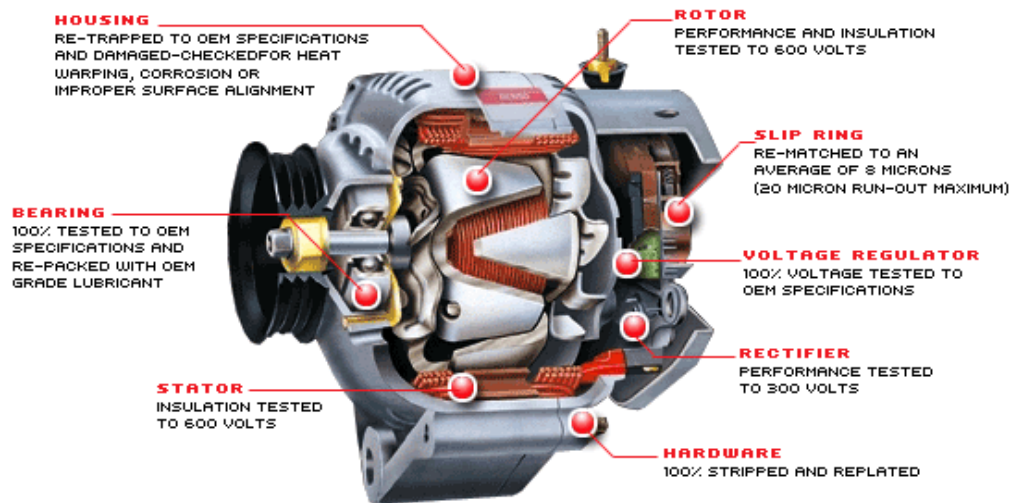


**Figure 3.1 :** The alignment of the alternator with an IC engine. [22]

A cooling fan is integrated to the rotor shaft to supply fresh air to the machine. Fan and rotor turn in same angular velocity. The alternator can be seen as the rightmost part on the belt & pulley mechanism in the Figure 3.1.

The Lundell type of an alternator consists of two main parts, the stator and the rotor. Stator is the outside and settled part of the machine. The rotor of the machine is inside and the rotating part of the machine. There are both rotor and stator winding. The stator contains three phase armature winding and the rotor contains the excitation winding. The rotor winding supplies the magnetic field to the machine which is necessary to produce electrical energy on the armature windings. The 3-phase stator winding is similar with the 3-phase synchronous or induction machine and the output current alternates.

## Alternator Cutaway



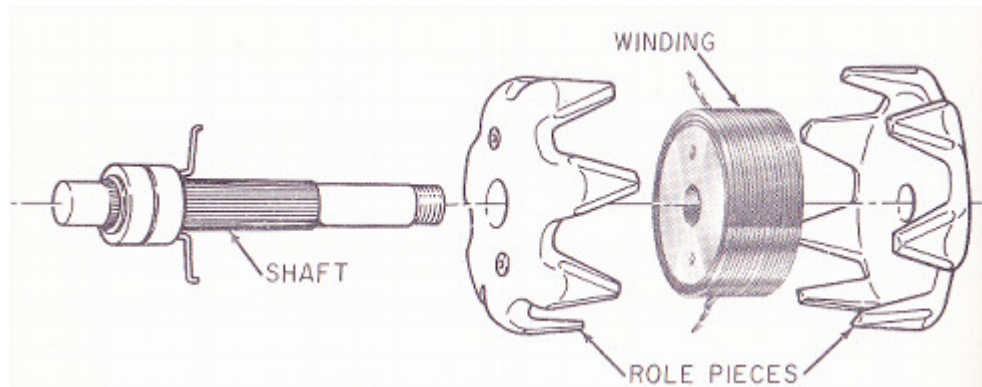
**Figure 3.2** : A cutaway view of an alternator [19]

### 3.1.1 Rotor construction

The excitation current and the excitation magnetic flux of the machine are DC, as a result, neither hysteresis nor the Foucault losses are generated in the rotor core. Consequently, there is no need to built the rotor core with laminated sheet. The rotor magnetic field is created with a rotor coil which is wounded around a magnetic core. The current flows through the slip rings. When the current starts to flow, the rotor becomes an electromagnet and magnetic field is created. This strong magnetic field flows through the two main pieces of rotor core and each of them becomes a pole N or S. The shape of the rotor core, in other words, claws of the rotor results the magnetic field flow alternately with respect to the stator. The two ends of the rotor winding are attached to the slip rings. The excitation current can be controlled from outside of the machine via the brushes.

### 3.1.2 Stator construction

As mentioned above, the armature current is an alternating current. As a result, the core of the stator is exposed to alternating magnetic flux. The flowing alternating magnetic flux generates hysteresis and Foucault losses on the core. The



**Figure 3.3 :** Rotor construction of the alternator.[8]

stator of the machine built of laminated sheets to make these losses as small as possible. The laminated sheets contain the cuttings for the slots.



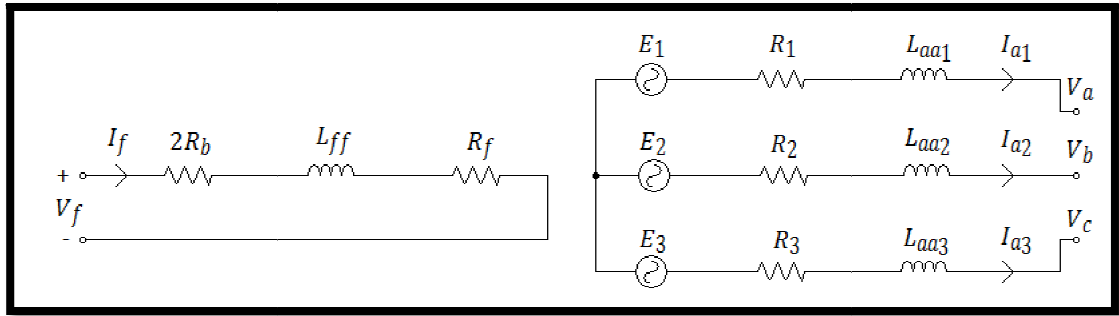
**Figure 3.4 :** Stator construction of the alternator.[8]



## 4. MATHEMATICAL MODEL OF THE LUNDELL TYPE ALTERNATOR

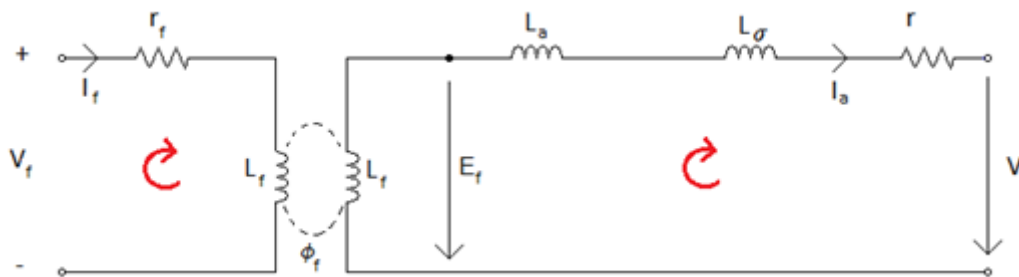
### 4.1 Equivalent Circuit

As mentioned in previous sections, the claw pole Lundell alternator machine is classified in synchronous machines. The excitation circuit consists of slip-ring voltage drop and losses, excitation winding resistance and inductance. On the other hand, three phase stator contains armature winding resistance and inductances. The induced voltages also showed in the figure 4.1.



**Figure 4.1 :** 3-phase equivalent circuit

A one phase equivalent circuit is developed to analyze the machine instead of 3 phase model. The detailed equivalent circuit of this machine that contains excitation circuit and armature circuit is given below.



**Figure 4.2 :** One phase equivalent circuit

The equivalent circuit parameters are listed in Table 4.1.

**Table 4.1 : Equivalent circuit parameters**

|       |                              |            |                                           |
|-------|------------------------------|------------|-------------------------------------------|
| $V_f$ | Excitation voltage           | $L_a$      | Armature wiring inductance                |
| $I_f$ | Excitation current           | $L_\sigma$ | Armature wiring leakage inductance        |
| $r_f$ | Excitation wiring resistance | $r_a$      | Armature wiring resistance of the phase a |
| $L_f$ | Excitation wiring inductance | $E_f$      | Induced voltage                           |
|       |                              | $V$        | Output voltage                            |

Applying the Kirchhoff's rules to the equivalent circuit above, the excitation circuit mathematical explanation derived as:

$$V_f = I_f r_f + L_f \frac{dI_f}{dt} \quad (4.1)$$

The excitation circuit self inductance can be written as,

$$L_f = \frac{\Phi_f}{I_f} \quad (4.2)$$

The armature circuit mathematical expression by the Kirchhoff's law while machine is running in generator mode,

$$E_f = I[r + j(x_a + x_\sigma)] + V \quad (4.3)$$

Here, the armature winding self inductance is

$$L_a = \frac{\Phi_a}{I_a} \quad (4.4)$$

and the leakage inductance is;

$$L_\sigma = \frac{\Phi_\sigma}{I_\sigma} \quad (4.5)$$

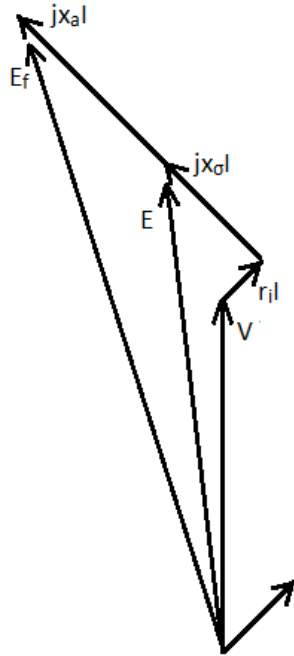
Then the reactance equations derived for the winding reactance

$$x_a = 2\pi f L_a \quad (4.6)$$

and the leakage reactance

$$x_{\sigma} = 2\pi f L_{\sigma} \quad (4.7)$$

Finally the phasor diagram of the alternator with inductive load is shown as in the figure 4.3.

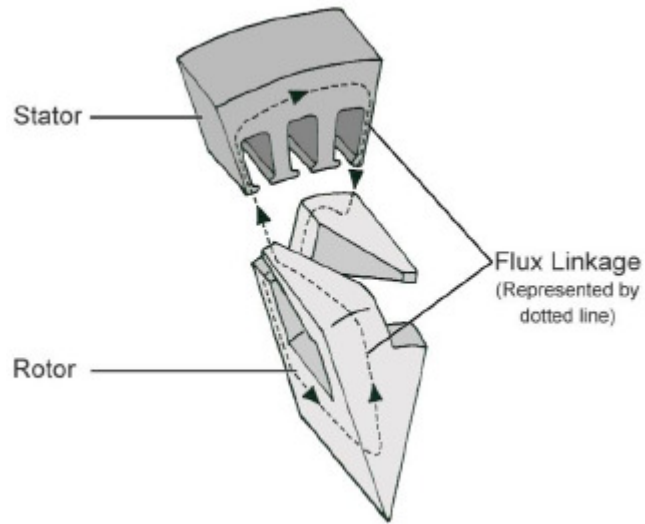


**Figure 4.3 :** Phasor diagram of the alternator

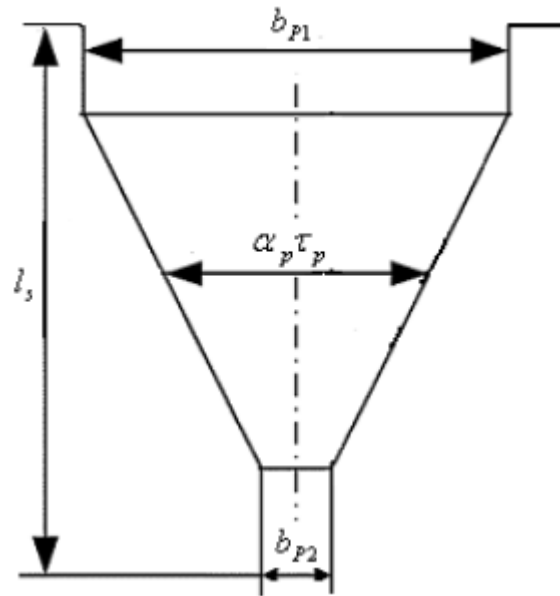
## 4.2 Magnetic Circuit Equations

The next step is identifying the induced voltage equation. The derivation of induced voltage should start with the identifying magnetic flux circuit. The magnetic flux created by the excitation circuit and each of iron claws become a pole. The flux passes through the air gap between the rotor to the stator. So, basic magnetic flux circuit can be draw like in figure 4.4.

The other important parts in the Lundell alternator are the claws. The shape of the claws are given in figure 4.5.



**Figure 4.4 :** Magnetic flux path of the claw pole machine [4]



**Figure 4.5 :** Shape of a claw and parameters [3]

Parameters of a claw shown in Figure 4.5 are listed in Table 4.2.

**Table 4.2 :** Parameter list of the claw shape.

|          |                        |       |                                        |
|----------|------------------------|-------|----------------------------------------|
| $l_s$    | Stator stack length    | $T_p$ | Pole pitch                             |
| $B_{p1}$ | Wide side claw width   | $a_p$ | Average pole width to pole pitch ratio |
| $B_{p2}$ | Narrow side claw width |       |                                        |

Electrical frequency can be expressed as

$$f = \frac{n * p}{120} \quad (4.8)$$

where  $p$  is the total number of poles and  $n$  is the mechanical speed in  $\text{min}^{-1}$ . The electrical angular speed is

$$w_e = p * w_G \quad (4.9)$$

Finally, the frequency  $f$  as a function of mechanical angular speed ( $w_G$ ) becomes

$$f = \frac{p \cdot w_G}{4\pi} \quad (4.10)$$

The general equation of the induced voltage sourced by the excitation current is

$$E_f = \frac{2\pi}{\sqrt{2}} \cdot f \cdot \Phi_f \cdot N_s \cdot k_w \quad (4.11)$$

where  $f$  is the electrical frequency,  $N_s$  is total number of stator coils,  $k_w$  is the stator winding coefficient and  $\Phi_f$  is the air gap magnetic flux.

The flux per pole value in terms of fundamental component is described as

$$\Phi_f = B_{g1} \cdot \frac{2}{\pi} \cdot T \cdot l_{stack} \quad (4.12)$$

Where  $B_{g1}$  is the fundamental flux density in the air gap,  $T$  is the pole pitch and  $l_{stack}$  is the stator stack length [3].

In the reference [3], fundamental component of the air gap flux density derived as,

$$B_{g1} = \frac{4}{\pi} \cdot B_g \cdot \sin \left( a_p \cdot \frac{\pi}{2} \right) \quad (4.13)$$

It is needed to give some basic electrical and magnetic expressions to derive the flux density.

The first expression is basically the Ampere's Law:

$$H \cdot l_g' = N_f \cdot I_f \quad (4.14)$$

In this equation  $H$  is the magnetic field (A/m) and  $l_g'$  is the effective air gap. According to the reference [16], the expression of the effective air gap is given as a product of the physical air gap, the Carter coefficient  $k_C$  and a coefficient  $k_s$  defined as the ratio of the field magnetomotive force (mmf) per air gap mmf.

$$l_g' = l_g \cdot k_s \cdot k_C \quad (4.15)$$

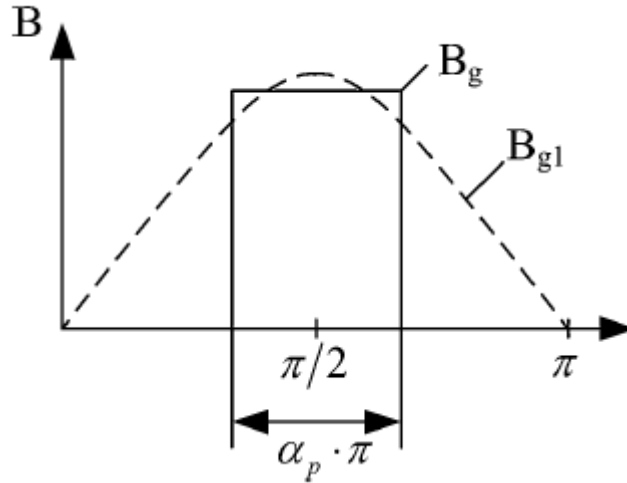
The last expression to derive the air gap flux density is

$$B_g = \mu_0 \cdot H \quad (4.16)$$

This equation explains that the air gap flux density is a product of magnetic field and permeability of free space.

Substituting the equations from 4.14 to 4.16, the final equation of the air gap flux density is

$$B_g = \frac{\mu_0 \cdot N_f \cdot I_f}{l_g \cdot k_s \cdot k_C} \quad (4.17)$$



**Figure 4.6 :** Magnetic flux density and its fundamental component [3]

Finally the fundamental air gap flux density can be obtained as,

$$B_{g1} = \frac{4}{\pi} \cdot \sin\left(a_p \cdot \frac{\pi}{2}\right) \cdot \frac{N_f \cdot I_f}{2} \cdot \frac{\mu_0}{l_g k_s k_C} \quad (4.18)$$

The next step is finalizing the induced voltage equation with the expressions above. When the frequency variable replaced by the equation 4.10,

$$E_f = \frac{2\pi}{\sqrt{2}} \cdot \frac{p \cdot w_G}{4\pi} \cdot \Phi_f \cdot N \cdot K_w \quad (4.19)$$

and magnetic flux expression written as a result of the equations 4.12 and 4.18,

$$E_f = \frac{2\pi}{\sqrt{2}} \cdot \frac{p \cdot w_G}{4\pi} \cdot \frac{4}{\pi} \cdot \sin\left(a_p \cdot \frac{\pi}{2}\right) \cdot \frac{N_f \cdot I_f}{2} \cdot \frac{\mu_0}{l_g k_s k_c} \cdot \frac{2}{\pi} \cdot T \cdot l_{stack} \cdot N_s \cdot K_w \quad (4.20)$$

Here the expression in the paranthesis contains constant numbers and machine parameters.

$$E_f = \left[ \frac{2\pi}{\sqrt{2}} \cdot \frac{p}{4\pi} \cdot \frac{4}{\pi} \cdot \sin\left(a_p \cdot \frac{\pi}{2}\right) \cdot \frac{N_f}{2} \cdot \frac{\mu_0}{l_g k_s k_c} \cdot \frac{2}{\pi} \cdot T \cdot l_{stack} \cdot N_s \cdot K_w \right] \cdot w_G \cdot I_f \quad (4.21)$$

Hence, the whole expression can be assumed a machine constant like  $K_m$ .

$$E_f = K_m \cdot w_G \cdot I_f \quad (4.22)$$



## 5. SYSTEM LOSSES AND THE POWER FACTOR CALCULATION

System losses and the power factor will be calculated analytically by means of the machine parameters and operating conditions in this section. The focus of this thesis is the Lundell alternator, so, the losses of this alternator will be investigated in detail. Other causes of the losses like vehicle wiring resistances, fuse and contacts will be neglected.

### 5.1 Electrical Losses

The electrical losses are the ohmic losses sourced by both the stator and the rotor windings. The winding resistance is the reason of the heat energy dissipation. In fact, the electrical losses depend on the temperature of the windings because the resistance of the winding depends on the temperature. The change of the winding resistance with temperature will not be covered in this part and all the losses will be assumed constant.

#### 5.1.1 Stator copper loss

Stator copper loss ( $P_{scl}$ ) is a result of the stator winding resistance. The loss is proportional to the winding resistance and the square of phase current. The loss is formulated as

$$P_{scl} = 3 \cdot R_s \cdot I_s^2 \quad (5.1)$$

where;  $R_s$  is one phase stator resistance and  $I_s$  is the one phase stator current.

#### 5.1.2 Rotor copper loss

Rotor copper loss ( $P_{rcl}$ ) is a result of the excitation winding resistance and equals to

$$P_{rcl} = R_f \cdot I_f^2 \quad (5.2)$$

where  $R_f$  is excitation winding resistance and  $I_f$  is the average excitation current.

### 5.1.3 Slip ring - brush loss

The excitation current flows from the controller to the winding over a slip-ring and brush mechanism. The contact resistance of the brushes results with a loss  $P_{bl}$  and can be formulated as

$$P_{bl} = 2 \cdot R_b \cdot I_f^2 \quad (5.3)$$

where  $R_b$  is one brush contact resistance and  $I_f$  is the rotor average current.

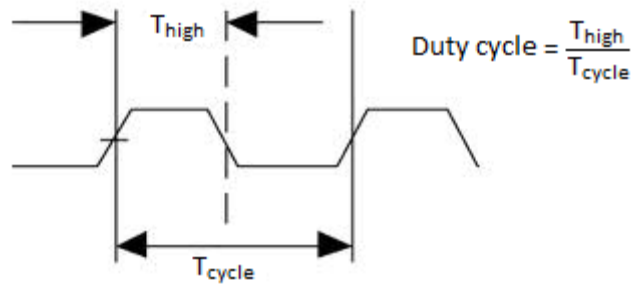
### 5.1.4 Diode rectifier loss

The uncontrolled diode rectifier loss  $P_{dl}$  is calculated based on the diode voltage drop and phase current.

$$P_{dl} = 3 \cdot V_d \cdot I_s \quad (5.4)$$

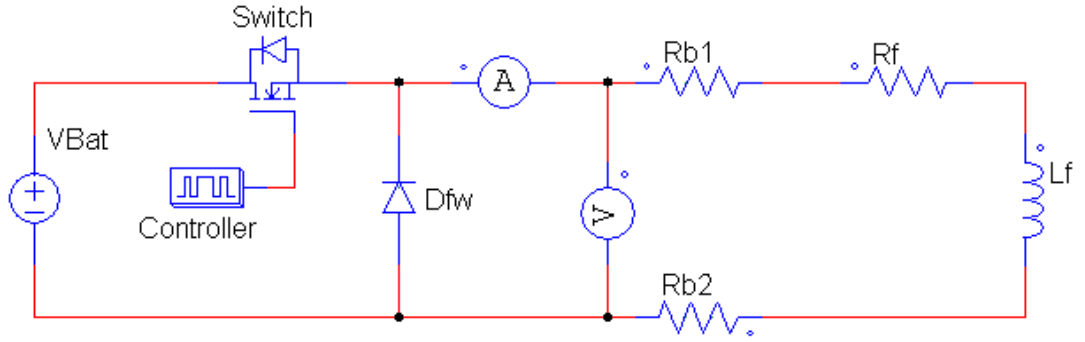
### 5.1.5 Step-down SMPS losses of the excitation circuit

Step-down SMPS is controlling the excitation current by switching the battery voltage with a constant modulation frequency. Thus results with a reduced output voltage from the SMPS which is applied to the excitation winding. Due to the high pulse width modulation (PWM) frequency and inductance effect, the current ripples could be negligible and the current can be approximated as a constant average value.



**Figure 5.1 :** Duty cycle calculation

The switching element will be assumed as a MOSFET and the duty cycle refer to the on position duration of the period. The excitation circuit can be modeled as in the figure 5.2.

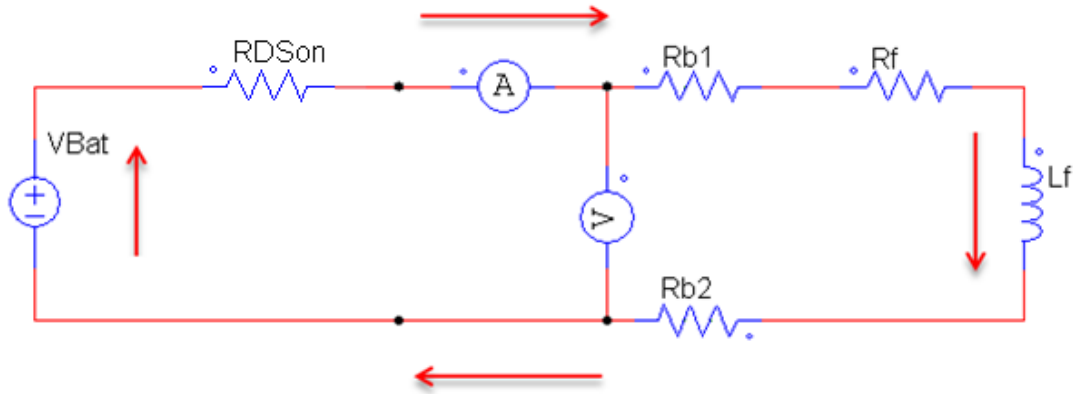


**Figure 5.2 :** Excitation circuit model

The excitation circuit consists of a switching element, controller, brush contact resistances  $R_b$ , flywheeling diode  $D_{wf}$ , excitation winding resistance  $R_f$  and inductance  $L_f$ . The SMPS works in different conditions in a period and the conditions are summarized below.

#### 5.1.5.1 On position (conducted)

The MOSFET is driven by a constant PWM frequency with a duty cycle  $D$ . During the status of conducted MOSFET, the power is supplied from the battery and current flows over the MOSFET drain to source resistance, brush contact resistances, excitation current resistance and the excitation winding inductance.



**Figure 5.3 :** Current path during the 'on' state

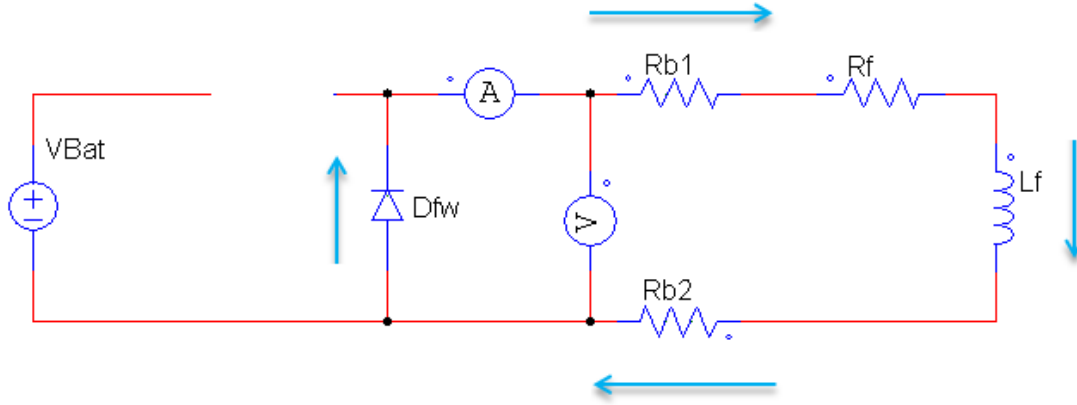
The losses of the other elements are calculated in previous parts except the MOSFET loss. The conducted MOSFET loss can be approximated like

$$P_{ConductedMosfet} = I_f^2 \cdot R_{DSon} \cdot D \quad (5.5)$$

Here,  $R_{DSon}$  is the drain to source resistance in on position and  $D$  is the duty cycle.

### 5.1.5.2 Off position

In a period, the duration except the conduction state of the MOSFET is the off position and showed in a period as  $1-D$ . At that period, the energy collected in the inductance flows over the flywheeling diode.



**Figure 5.4 :** Current path during the ‘off’ state.

Here the wasted energy over the diode  $P_{ConductedDiode}$  can be calculated as

$$P_{ConductedDiode} = I_{Diode} \cdot V_{Diode} \cdot (1 - D) \quad (5.6)$$

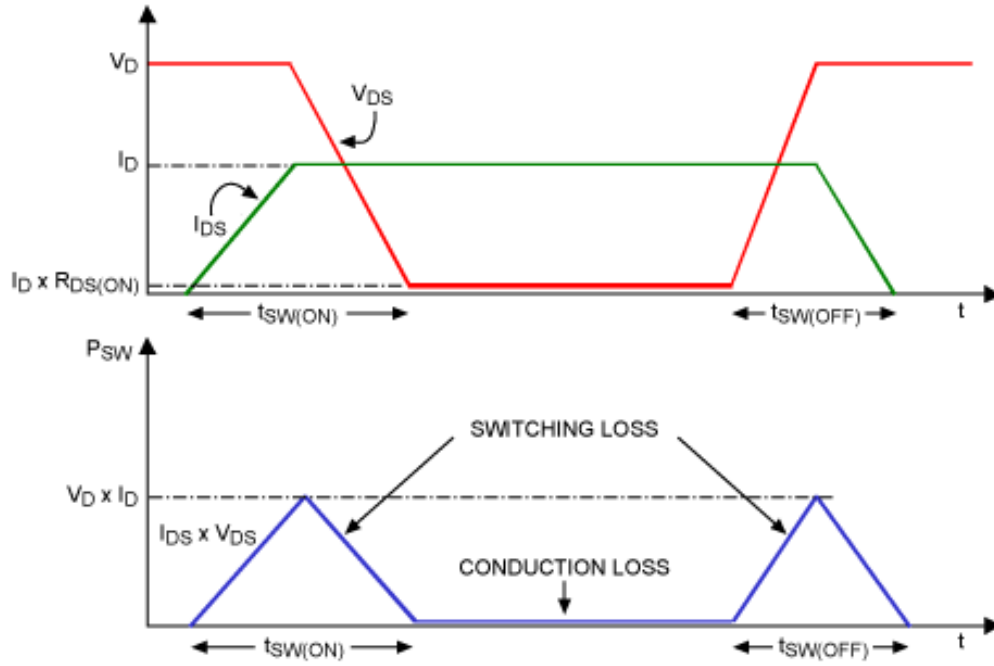
### 5.1.5.3 Switching position loss

Switching position is the transient state between the on and off positions. The voltage and current waveforms are plotted in the figure 5.5.

Here the switching losses can be calculated as applying a triangular geometry. Calculating the switching power dissipation during the off-on ( $t_{SWon}$ ) and on-off ( $t_{SWoff}$ ) transitions with area of triangle estimation results with the equation below,

$$P_{SwitchingMosfet} = \frac{1}{2} \cdot V_{Diode} \cdot I_{Diode} \cdot (t_{SWon} + t_{SWoff}) \cdot f_{sw} \quad (5.7)$$

The switching losses are directly proportional to the PWM frequency  $f_{sw}$ . If frequency is high enough to make a smooth excitation current, switching losses will also be high.



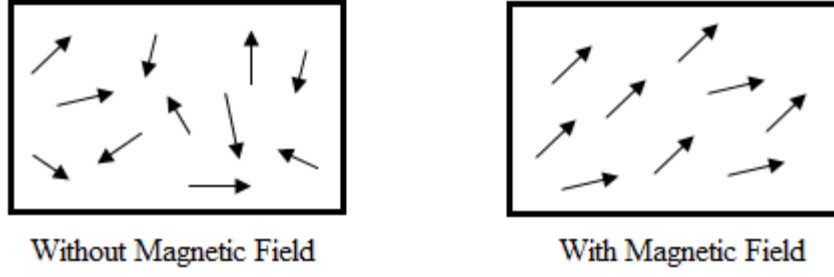
**Figure 5.5 : Switching durations [24]**

## 5.2 Magnetic Losses

Electrical losses are not the only losses need to be considered. Also the magnetic losses affect the efficiency of the alternator. As mentioned in the Lundell type of alternator construction part, the rotor is made from a cast iron material because the magnetic flux on this material does not alternate. On the other hand, stator is built from laminated material due to decrease the magnetic losses. The oscillation of the stator current results with three kind of effects on the ferromagnetic material. Two of them can be calculated but there are also additional magnetic losses need to be estimated.

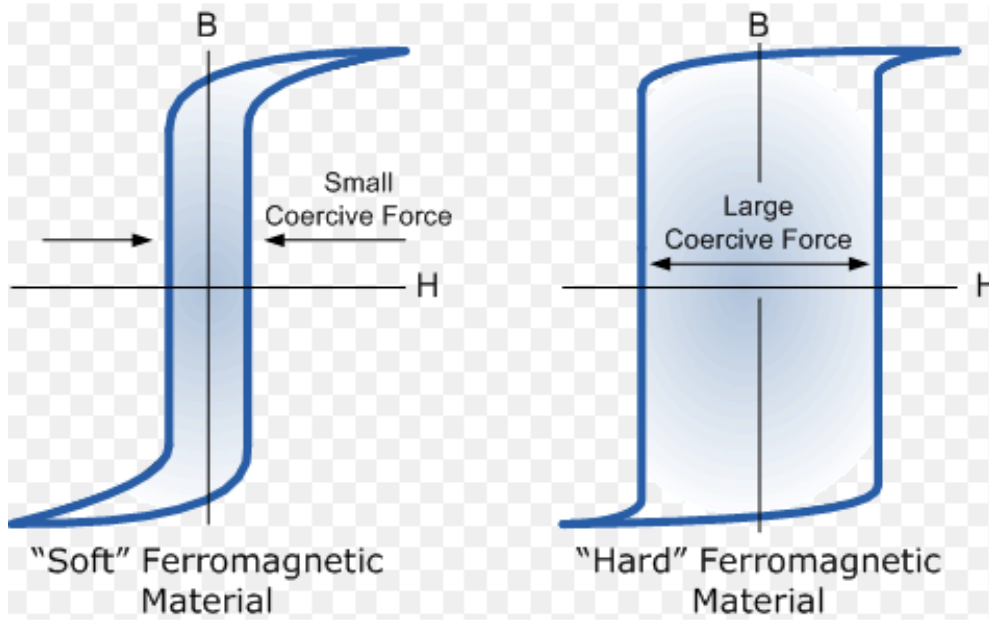
### 5.2.1 Hysteresis losses

The first effect is the change of magnetic flux density and the H-field over the material. In normal conditions, the ferromagnetic material is not conductive and the electrons are not aligned. When the first current is applied to the stator winding, magnetic flux starts to flow by the alignment of the electrons.



**Figure 5.6 :** Ferromagnetic alignment

The change of the electrical current results in the change of the polarity in ferromagnetic material and a B-H curve is plotted. The internal area of the B-H curve represents the hysteresis losses. As the magnetic strength of the material increased, the area and the loss increase.



**Figure 5.7 :** Hysteresis curves of different materials [21]

The hysteresis losses are directly depends on the ferromagnetic material specifications and can be calculated as

$$P_{hysteresis} = k_{hysteresis} \cdot G \cdot f \cdot B^x \quad (5.8)$$

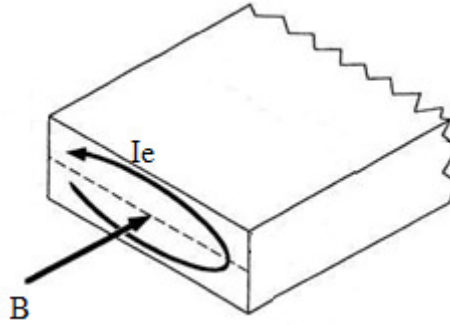
$$P_{hysteresis} = K_H \cdot f \cdot B^2 \quad (5.9)$$

Here,  $k_{hysteresis}$  is the hysteresis loss coefficient of the material in  $W/kg$ . The  $G$  is the mass of the ferromagnetic material in  $kg$ .  $B$  is the magnetic flux density in  $Wb/m^2$ . The  $x$  coefficient is depends on the ferromagnetic material and the value is

in between 0,5 and 2,3. In AC machines, the value is generally in between 1,5 and 2,0. Finally, machine specific hysteresis loss equation can be written as in equation 5.9 with the machine specific constant  $K_H$ .

### 5.2.2 Eddy current losses

The other magnetic loss is eddy current loss. As the magnetic flux flows through the ferromagnetic material, an internal voltage is induced and a current starts to flow in the ferromagnetic material. Decreasing the eddy current loss is the main reason of using the laminated material. By using the laminated material, the rotational path length of the flux decreases and the losses decreases too.



**Figure 5.8 :** Eddy currents

The eddy current losses can be calculated as

$$P_{eddy} = K_{eddy} \cdot G \cdot f^2 \cdot B^x \quad (5.10)$$

$$P_{eddy} = K_{EC} \cdot f^2 \cdot B^2 \quad (5.11)$$

Where  $K_{eddy}$  is the eddy current loss coefficient and the operating frequency is

$$f = \frac{n \cdot p}{60} \quad (5.12)$$

Finally, machine specific Eddy current loss equation can be written as in equation 5.11 with the machine specific constant  $K_{EC}$ .

### 5.2.3 Stray losses

The final magnetic loss is the stray loss which needs to be estimated. The sources of these losses are flux leakages, magnetic losses in other parts affected by alternating

current and other magnetic losses sourced from the harmonics. The approximation of the stray loss for the electrical machine is

$$P_{stray} = 0.01 \cdot P_{total \text{ loss}} \quad (5.13)$$

### 5.3 Mechanical Losses

Mechanical losses of the machines are caused by the bearing and other mechanical friction and the friction between the machine and the air. The first one called as friction loss and directly proportional to the alternator angular speed  $w$  and a friction coefficient  $k_{fr}$ .

$$P_{friction} = k_{fr} \cdot w \quad (5.14)$$

The second one is called as winding loss and proportional to the cube of the angular speed  $w$  and a friction coefficient  $k_{wd}$ .

$$P_{windage} = k_{wd} \cdot w^3 \quad (5.15)$$

### 5.4 Power Factor Calculation

The power factor can be calculated over the power balance on the diode rectifier. If the 3-phase uncontrolled diode bridge rectifier losses are considered, the power balance equation occurs like,

$$P_{AltOut} = P_{RectifierLoss} + P_{RectifierOut} \quad (5.16)$$

The equation can be rewritten by phase 1 paramters and the DC parameters as

$$3 \cdot V_1 \cdot I_1 \cdot \cos(\varphi_1) = P_{diode} + V_{DC} I_{DC} \quad (5.17)$$

Finally, the power factor can be calculated in the equation below.

$$\cos(\varphi_1) = \frac{3 \cdot V_d \cdot I_1 + V_{DC} I_{DC}}{3 \cdot V_1 \cdot I_1} \quad (5.18)$$

Here  $V_d$  is the diode voltage drop. The power factor is nearly equal to unity but there is also a reactive power produced in the alternator. That reactive power is absorbed in the stator inductances.



## **6. ALTERNATOR MEASUREMENTS**

### **6.1 Objective**

The objective of the thesis is generating a model that will be used for vehicle electrical charging system behavior investigation. As a result, the machine parameter identification is important for the model robustness and results. In the thesis, machine parameters of the alternator are not known exactly because the alternator is supplied from the OEM market. Hence, none of the machine parameters are available.

The main variables as alternator machine constant, rotor winding resistance and inductance, stator winding resistance will be calculated and estimated in this chapter.

### **6.2 Alternator Machine Constant Calculation**

The general Lundell type of alternator equation was explained in previous sections and it was written as:

$$E_f = K_m \cdot \omega_G \cdot I_f \quad (6.1)$$

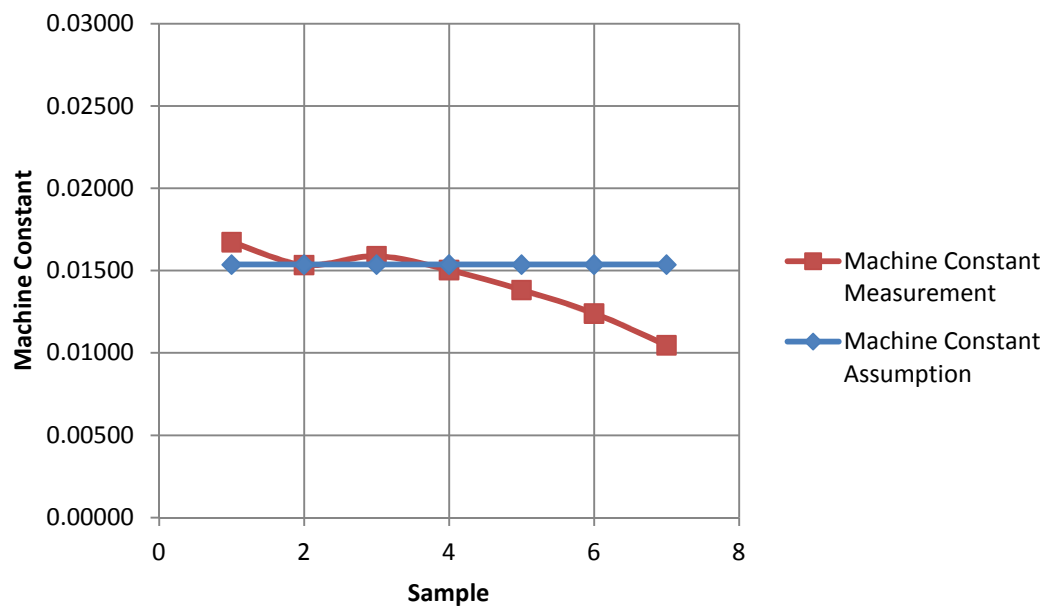
Here, it is obvious that the induced voltage is linearly proportional to alternator angular velocity, excitation current and machine constant. There are two ways of machine constant determination. One of them is supplying a constant excitation current and measurement of induced voltage with respect to different alternator speed. The other step is measurement of induced voltage with respect to different excitation current during a constant angular speed. The first way was chosen and the results are in Table 6.1.

**Table 6.1 : Machine constant experimental measurements**

| Sample | Bench (rpm) | Alternator (rpm) | Conversion Ratio | Alternator - $\omega_g$ (rad/s) | $I_f$ (A) | $V_{meanDC}$ (V) | $V_{pprms}$ (V) | $V_{pnrms}$ (V) | $V_{meanDC}$ (V)<br>$V_{pprms}$ (V) | Actual Machine Constant - $K_m$ | Assumed Machine Constant - $K_m$ |
|--------|-------------|------------------|------------------|---------------------------------|-----------|------------------|-----------------|-----------------|-------------------------------------|---------------------------------|----------------------------------|
| 1      | 500         | 1197             | 2,3940           | 125.2860                        | 3         | 14,40            | 10,90           | 6,29            | 1,32110                             | 0,01674                         | 0,01537                          |
| 2      | 675         | 1629             | 2,4133           | 170.5020                        | 3         | 18,50            | 13,60           | 7,85            | 1,36029                             | 0,01535                         | 0,01537                          |
| 3      | 750         | 1794             | 2,3920           | 187.7720                        | 3         | 20,50            | 15,50           | 8,95            | 1,32258                             | 0,01589                         | 0,01537                          |
| 4      | 850         | 2041             | 2,4012           | 213.6247                        | 3         | 21,50            | 16,70           | 9,64            | 1,28743                             | 0,01504                         | 0,01537                          |
| 5      | 1000        | 2379             | 2,3790           | 249.0020                        | 3         | 23,00            | 17,90           | 10,33           | 1,28492                             | 0,01383                         | 0,01537                          |
| 6      | 1250        | 2934             | 2,3472           | 307.0920                        | 3         | 25,60            | 19,80           | 11,43           | 1,29293                             | 0,01241                         | 0,01537                          |
| 7      | 1500        | 3492             | 2,3280           | 365.4960                        | 3         | 26,20            | 19,90           | 11,49           | 1,31658                             | 0,01048                         | 0,01537                          |

The gray columns in the tables are the measurements from the experiments. The rest of the variables are the calculations. A belt and pulley mechanism was set between the alternator and bench and the speed of the alternator was measured with an electro-optic tachometer.

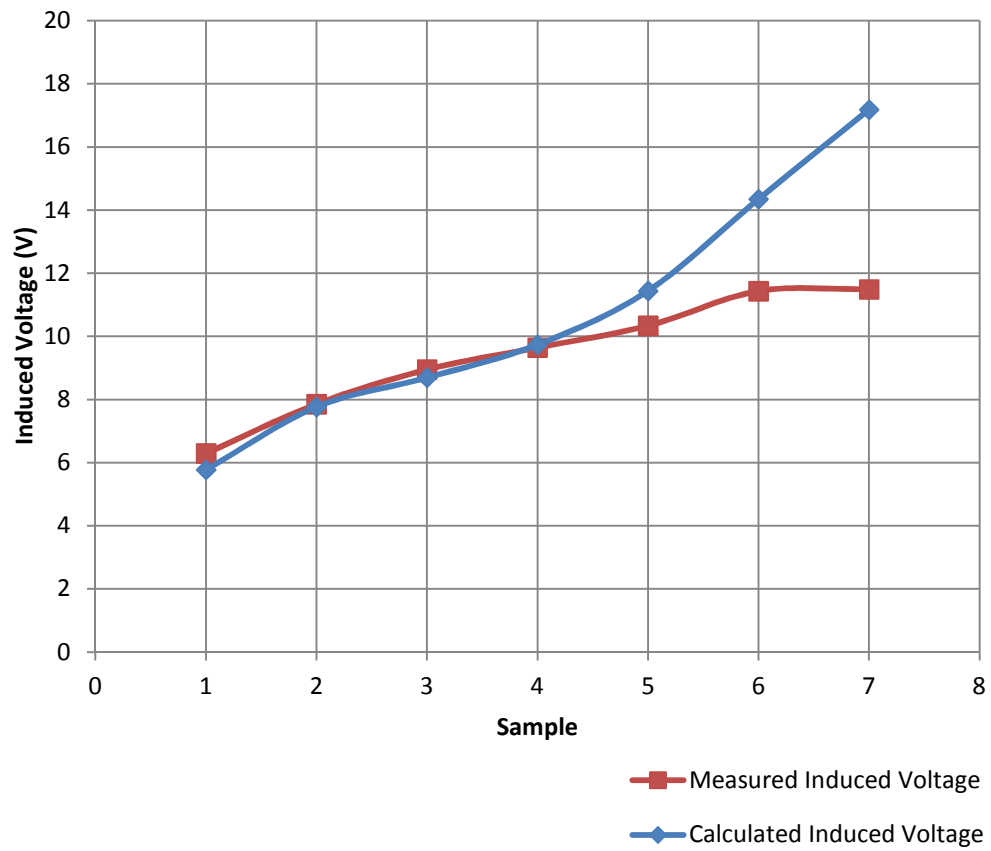
The calculated machine constant is in a linear trend until the fifth measurement. After the fifth measurement the voltage inducement stops and this directly effects on machine constant calculation. The graphical interpretation of the calculated machine constant and the estimation of the machine constant with considering first five measurements is below.



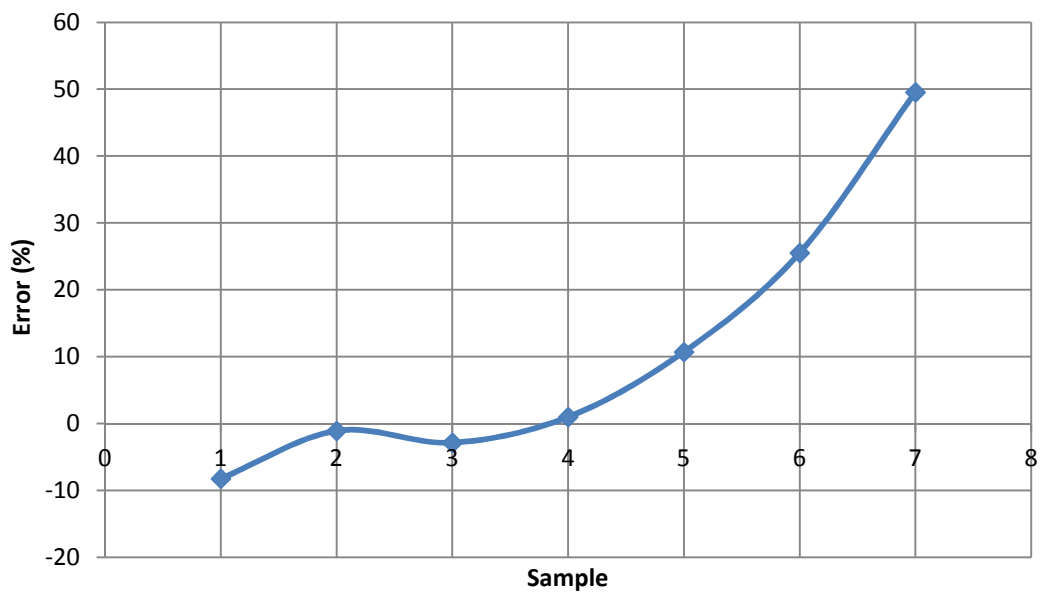
**Figure 6.1 :** Machine constant estimation and measurement

The excitation current was constant at 3 Amperes. Figure 6.2 shows that the induced voltage is linearly proportional to the angular speed of the alternator for the first five samples. However, as the machine passes its saturation state, increasing trend of the induced voltage stops.

The other result here is the percentage error in figure 6.3. The error of the first five measurement is in 10 % range and this is acceptable for an alternator supplied from an OEM.



**Figure 6.2 : Induced voltage estimation and measurement**



**Figure 6.3 : Induced voltage error**

### 6.3 Excitation Winding Resistance

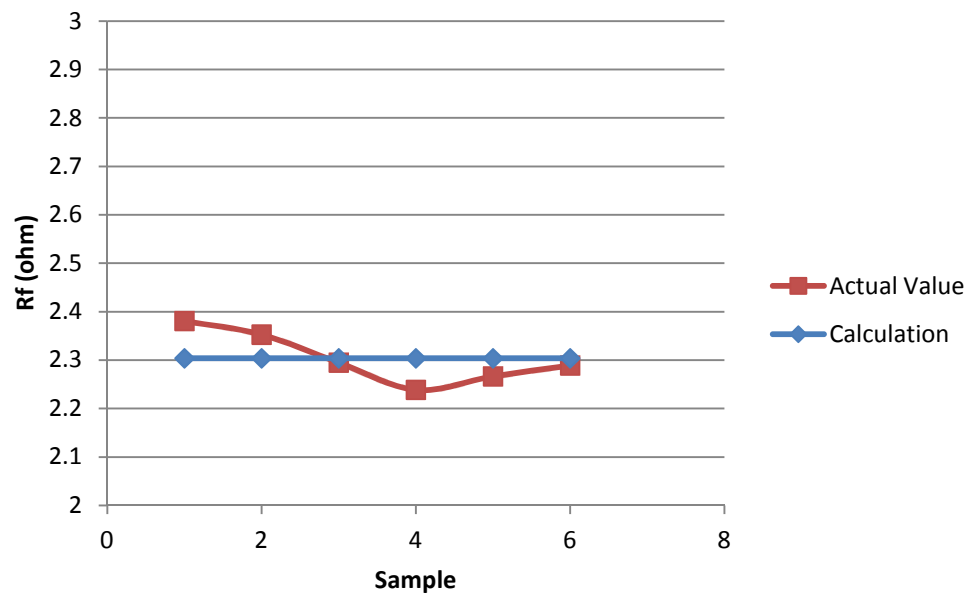
The other main variable is the rotor winding resistance. This variable is important for the controller design. The test was done with a DC power supply and current measurement. The thermal effect on the resistance during machine operation will be neglected in the model and constant winding resistance which is calculated will be used.

The test results are given in Table 6.2.

**Table 6.2 :** Excitation Winding Resistance Measurement Test Results

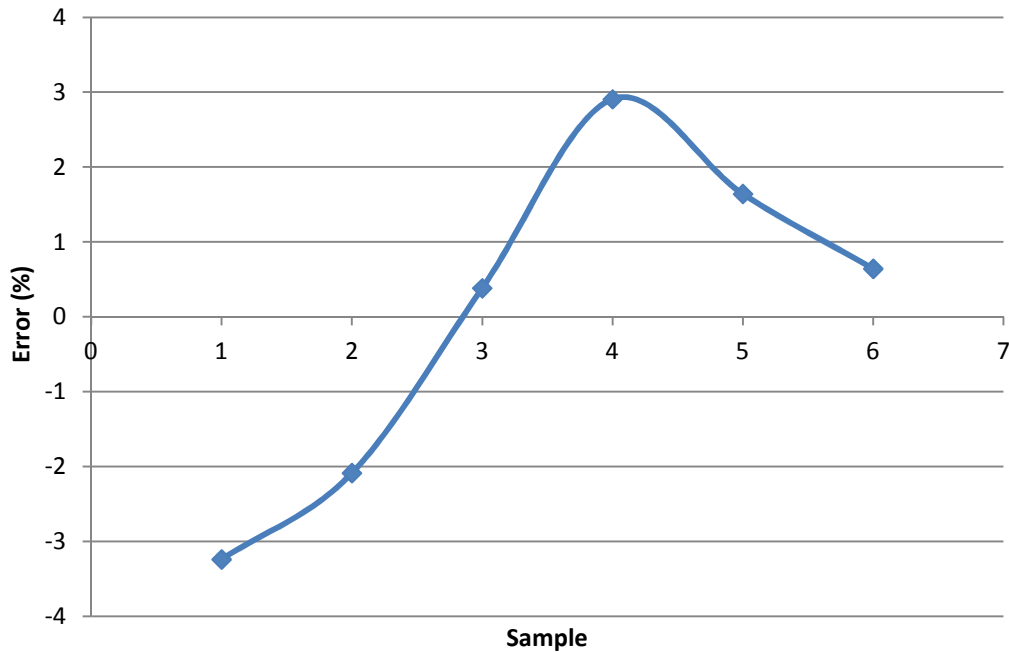
| DC supply (V) | Current (A) | R <sub>f</sub> Measured (ohms) | R <sub>f</sub> Calculated (ohms) |
|---------------|-------------|--------------------------------|----------------------------------|
| 1             | 0,42        | 2,380952381                    | 2,3039                           |
| 1,2           | 0,51        | 2,352941176                    | 2,3039                           |
| 1,4           | 0,61        | 2,295081967                    | 2,3039                           |
| 1,5           | 0,67        | 2,23880597                     | 2,3039                           |
| 1,7           | 0,75        | 2,266666667                    | 2,3039                           |
| 1,9           | 0,83        | 2,289156627                    | 2,3039                           |

The average value of the measured excitation winding resistances is 2,3039 ohms. The graphical interpretation of the calculated and the mean values is presented in Figure 6.4.



**Figure 6.4 :** Excitation winding resistance measurement and assumption

The error between the calculation and the mean value is in 3 %.



**Figure 6.5 :** Error between the measurement and the assumption

#### 6.4 Slip Ring – Brush Resistance

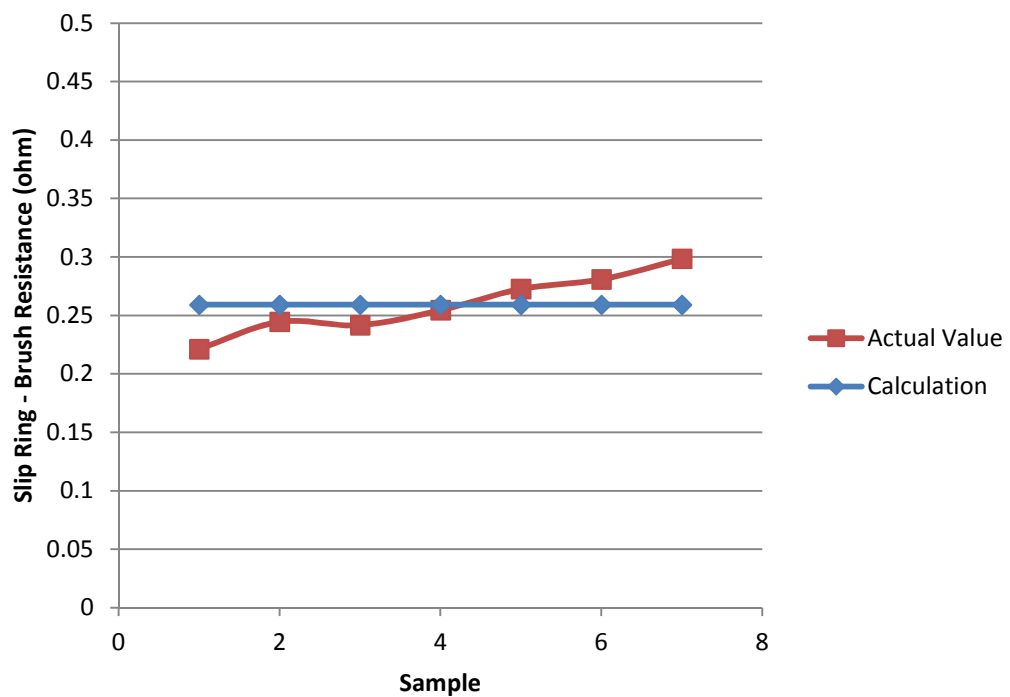
Slip ring – brush contact resistance is the additional resistance value which should be considered for the excitation circuit model design. The main obstacle here is that the contact resistance is small with respect to the winding resistance and it is a bit hard to measure that resistance value. The measurement was done with a DC power supply and current measurement. The effects of the measurement tools resistance was considered. The final tests results are given in Table 6.3.

The average value of the measured excitation winding resistances is 0,2591 ohms. The graphical interpretation of the calculated and the mean values is in figure 6.6.

The error between the calculation and the mean value is in 15 %. This can be acceptable because of the very small values.

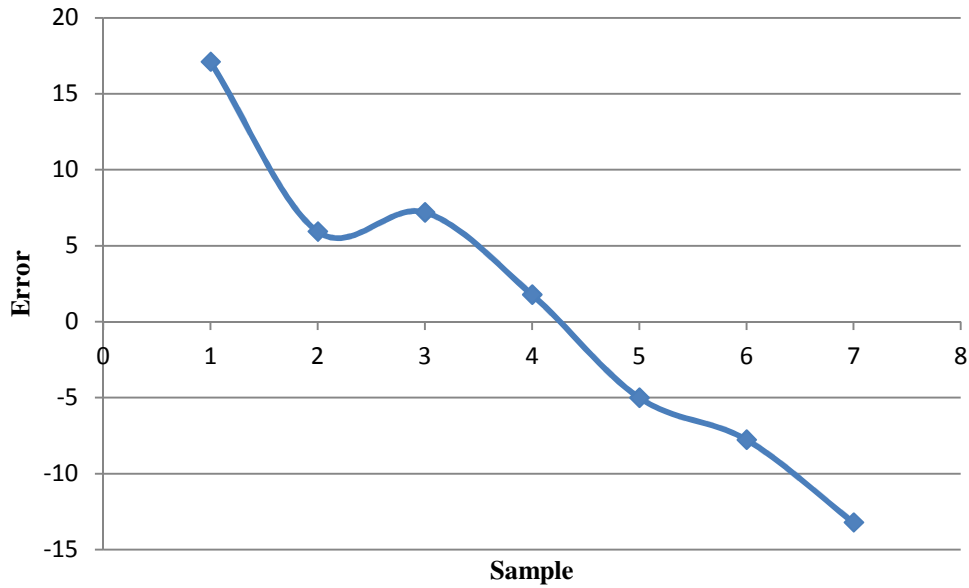
**Table 6.3 : Brush Resistance Measurement Test Results**

| DC supply (V) | Current (A) | R <sub>b</sub> Measured (ohms) | R <sub>b</sub> Calculated (ohms) |
|---------------|-------------|--------------------------------|----------------------------------|
| 1             | 4,52        | 0,221238938                    | 0,2591                           |
| 0,9           | 3,68        | 0,244565217                    | 0,2591                           |
| 0,8           | 3,31        | 0,241691843                    | 0,2591                           |
| 0,7           | 2,75        | 0,254545455                    | 0,2591                           |
| 0,6           | 2,2         | 0,272727273                    | 0,2591                           |
| 0,5           | 1,78        | 0,280898876                    | 0,2591                           |
| 0,4           | 1,34        | 0,298507463                    | 0,2591                           |

**Figure 6.6 : Slip ring – Brush resistance measurements and assumption**

## 6.5 Excitation Winding Inductance

Excitation winding resistance is the final variable which should be calculated to design a excitation current controller. As the equivalent circuit of the excitation winding explained in figure 5.2, the excitation winding can be modeled as a RL load.



**Figure 6.7 :** Error of slip ring – brush measurement and assumption.

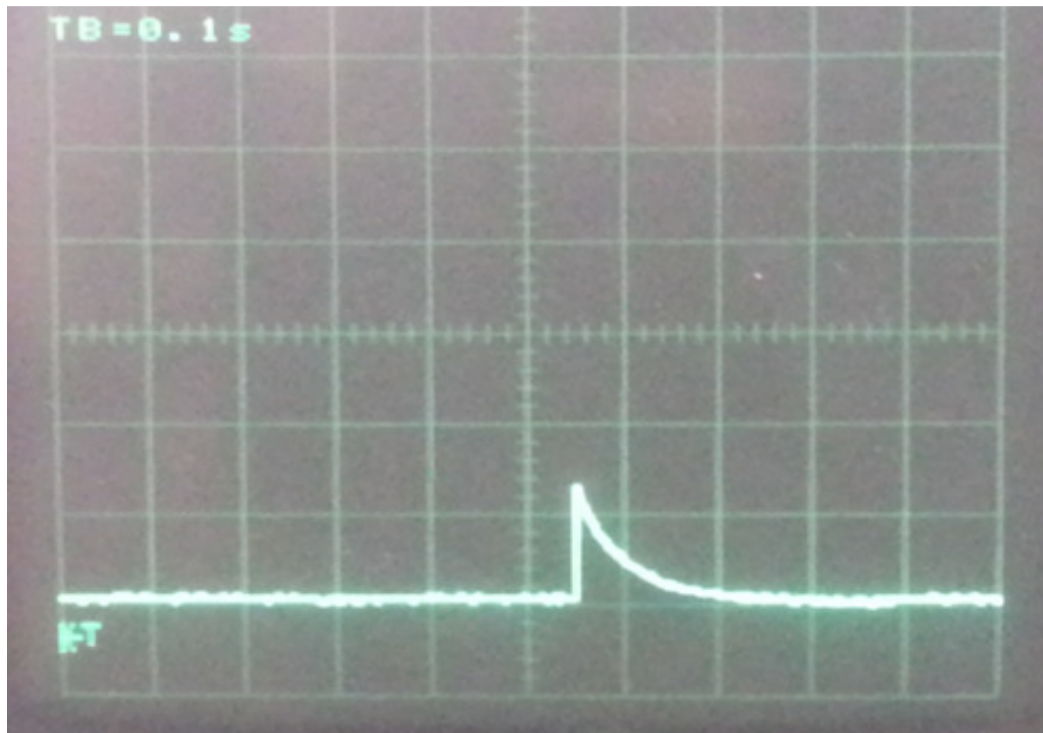
Determining the L value of the excitation winding can be possible with investigating the response of the circuit against a DC step input. The electrical equation of a RL load circuit

$$V_{DC} = R_f i_f + L_f \frac{di_f}{dt} \quad (5.6)$$

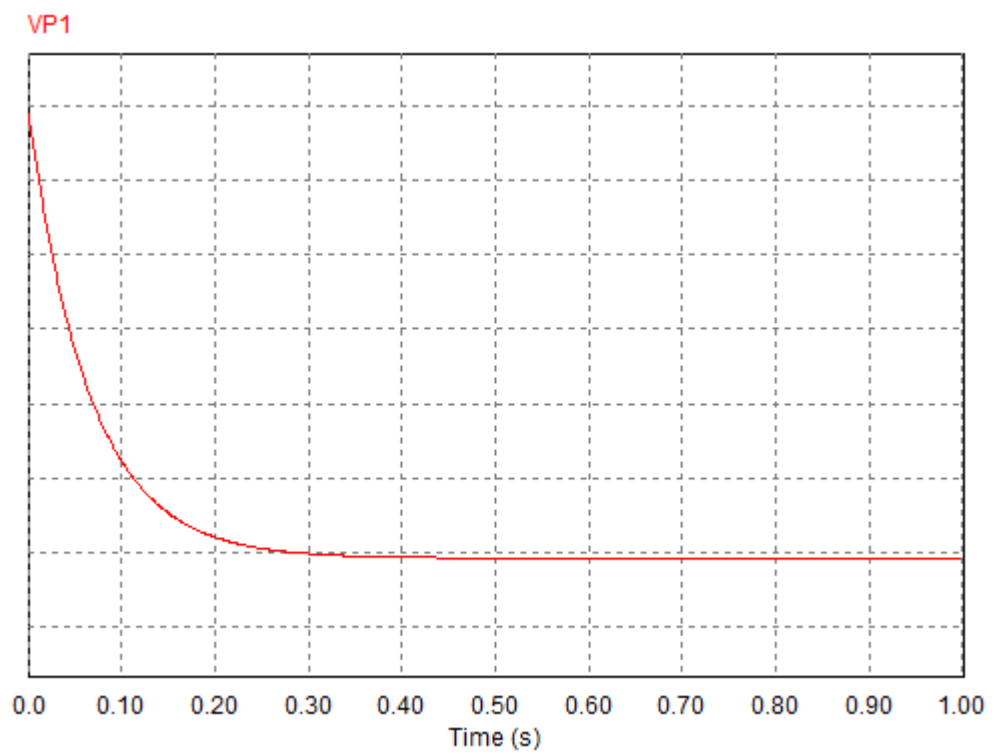
and the time constant of the system is  $\frac{R_f}{L_f}$ .

The step response of the excitation winding is determined with an oscilloscope measurement. The settling time of the step response is calculated from the oscilloscope recorder.

The next step is identifying an inductance value. The excitation winding resistance was calculated before and the step response to a DC voltage supply is known. As a result of this the excitation winding inductance can be calculated as 0,15H which can give the similar step response behaviour in the PSIM simulation in figure 6.9.



**Figure 6.8 :** Step response measurement



**Figure 6.9 :** Simulation result with calculated inductance



## **7. MATLAB® MODELING OF THE ALTERNATOR AND THE CHARGING SYSTEM**

A simulation was developed to investigate the behaviour of the alternator and vehicle charging system with different load and engine speed regions. MATLAB® Simulink was used as the development programme. The simulation model created at Simulink and m-files also developed to run the model automatically.

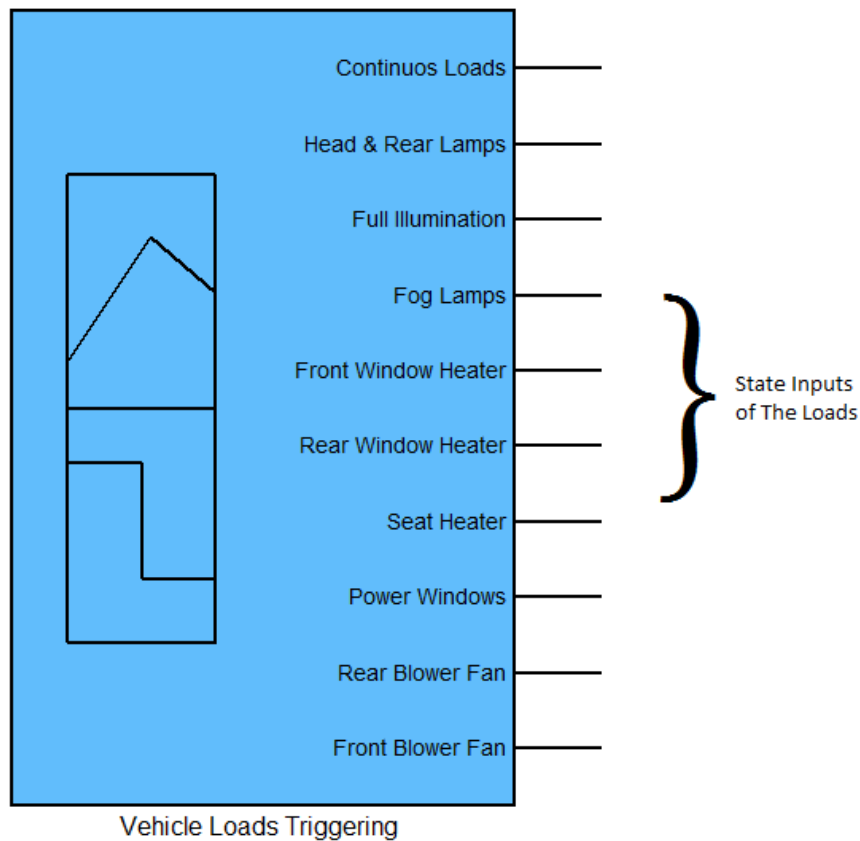
The first reason to develop this process is data acquisition from the vehicle. The data is collected from the vehicle with 100 ms sampling time. Although the model runs in discrete time, the sampling time may be different. So, an m-file established to process the logged data from the vehicle with the aim of using this data in Simulink model. The other m-file also developed to put the logged and processed data as input to the main model. In addition, this m-file automatically plots the final results and make comparisons.

In addition to the m-files, main model was developed in two types. One of them is to investigate transient states (dynamic modeling) and the other one is to investigate steady states (static modeling). The main difference of these two models is sampling time. Investigating MOSFET switching timings and active current and voltage waveform are possible with dynamic modeling. But, model running speed is slow due to the high sampling frequency. On the other side, with assuming the average current and voltage values, a static model also established to analyse longer data. The sampling frequency is lower than the dynamic one but also some assumptions like omitting current waveforms were done. This model is suitable to analyse long time vehicle drive cycles as NEDC or WHTC.

### **7.1 Vehicle Loads Triggering Block**

Vehicle load triggering block determines the load on and off position switching timings. Timings can be chosen manually same as with the logged data from the vehicle. So, it is possible to compare the model data with the logged data. On the

other hand, timings can be determined random to investigate charging system reactions.

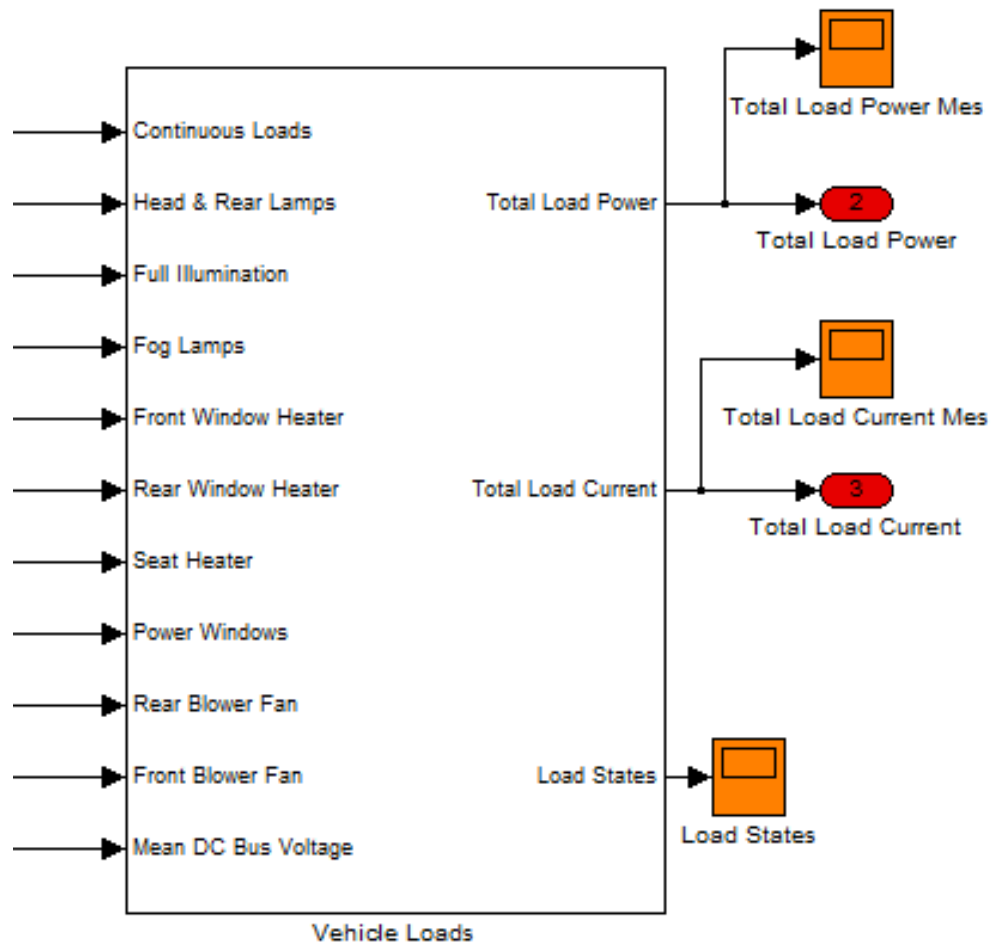


**Figure 7.1 : Vehicle loads triggering block**

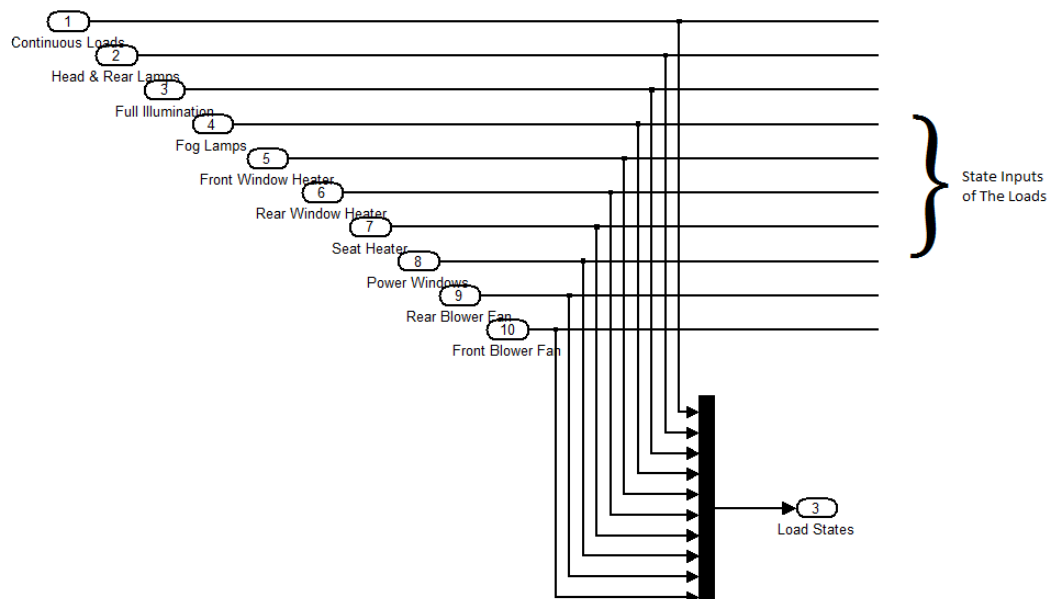
## 7.2 Vehicle Loads Modeling Block

The time triggers are handled and transferred to the each load models separately to determine the activation of the loads. Also, there is a measurement point to plot the load states in figures.

Vehicle electrical loads are modeled as resistive loads (R) or serial resistive and inductive loads (RL) or serial resistive, inductive and back emf (RLE) loads. Different load powers are found in literature research and can be used in the model. In addition, the loads can be measured and model can run for a specific application. In this thesis, load values are measured from a vehicle and modeled



**Figure 7.2 :** Vehicle loads modeling block

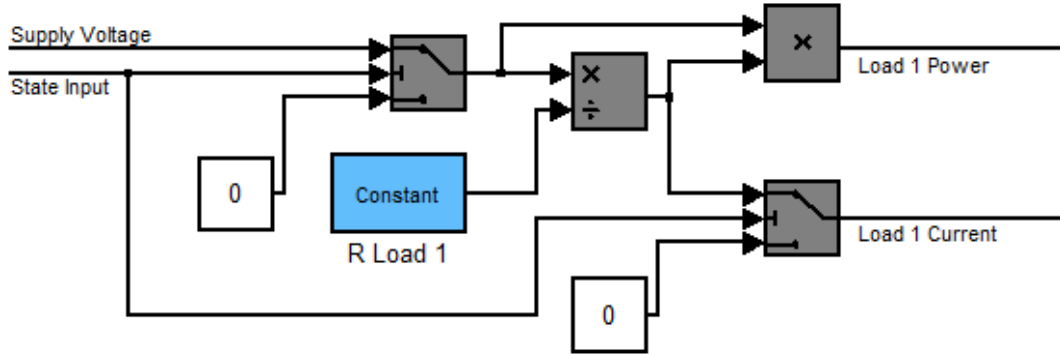


**Figure 7.3 :** State inputs of the loads

|                          |             |                                |            |                              |             |
|--------------------------|-------------|--------------------------------|------------|------------------------------|-------------|
| Engine Management        | Power (W)   | Multimedia & HVAC              | Power (W)  | Body Electrical              | Power (W)   |
| Fuel Pump& Injectors     | 135         | High end audio sys.            | 300        | Power Windows (4)            | 560         |
| Ignition System          | 60          | Navigation and GPS             | 150        | Power Door Locks (4)         | 200         |
| Electronic Throttle Sys. | 60          | Driver information display     | 30         | Wipers and washers           | 140         |
| Sensors & Actuators      | 110         | Cabin climate valves           | 75         | Heated backlight             | 500         |
| Solenoids & Relays       | 20          | Blower motor + ECU             | 370        | Power seats (2)              | 460         |
| <b>Subtotal Engine</b>   | <b>385</b>  | <b>Subtotal Cabin Sys.</b>     | <b>925</b> | <b>Subtotal Body Sys.</b>    | <b>1860</b> |
| Amps @ 14.2V             | 27.11       | Amps @ 14.2V                   | 65.14      | Amps @ 14.2V                 | 130.99      |
| Chassis Electrification  | Power (W)   | Lighting (Exterior & Interior) | Power (W)  | Future Systems               | Power (W)   |
| Electric assist steering | 300         | Headlamps (2)                  | 120        | DVD and in-seat displays     |             |
| ABS brake system         | 200         | Running/Park lights (4)        | 130        | Micro/Mild-hybrid functions  |             |
| Air suspension valves    | 50          | Turn signal lamps              | 130        | Active suspension            |             |
| Air compressor           | 500         | Center high mount stop         | 65         | Front/rear radar             |             |
| Subtotal Chassis         | <b>1050</b> | Back-up, interior, license     | 45         | Obstacle detection & Airbags |             |
| Amps @ 14.2V             | 73.94       | Subtotal lighting              | <b>490</b> | Active cruise control        |             |
|                          |             | Amps @ 14.2V                   | 34.51      | Total Electrical/Electronics | <b>4710</b> |
| Charging System          | Power (W)   |                                |            |                              |             |
| Alternator               | 3000        |                                |            |                              |             |
| Battery (80 Ah)          | 1000        |                                |            |                              |             |
| Starter motor            | 2200        |                                |            |                              |             |

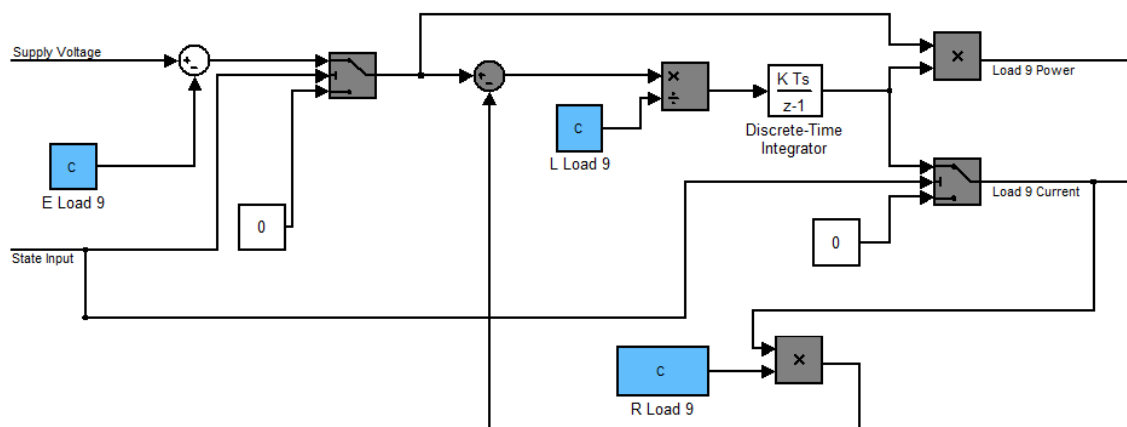
**Figure 7.4 :** Example of a vehicle load list from the literature [20]

In the model, headlamps and heaters are considered to be pure resistive loads and modeled like in figure 7.5. One of the model inputs is supply voltage of the load, in other words ‘mean DC bus voltage’. The other one is the load state which defines if the load is active or not. This data comes from vehicle load triggering block. The outputs are power consumption of the load and the load current. The resistance of the load is configurable to make capability to simulate different loads. If the state input is false, power and current will be 0, otherwise they will be calculated.



**Figure 7.5 :** Resistive load modeling

The RL and RLE loads are modeled as in the figure 7.6. There are two model inputs again, supply voltage and the load state. It is possible to change the load parameters to simulate different RL and RLE loads. A discrete time integrator is used to solve RL load mathematical modeling.

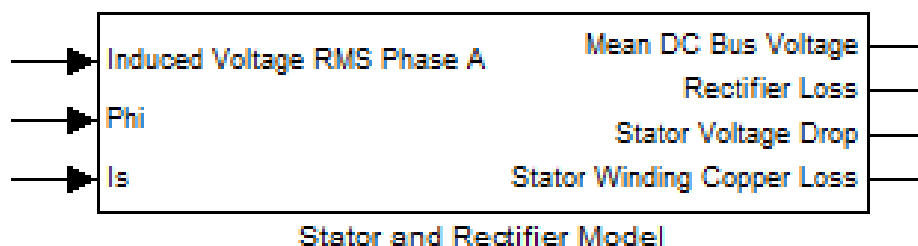


**Figure 7.6 : RL and RLE load modeling**

The discrete time load model simulation results are also compared with the PSIM<sup>®</sup> electrical circuit simulation program outputs. After the validating the MATLAB<sup>®</sup> models with PSIM<sup>®</sup>, they are imported to the main model.

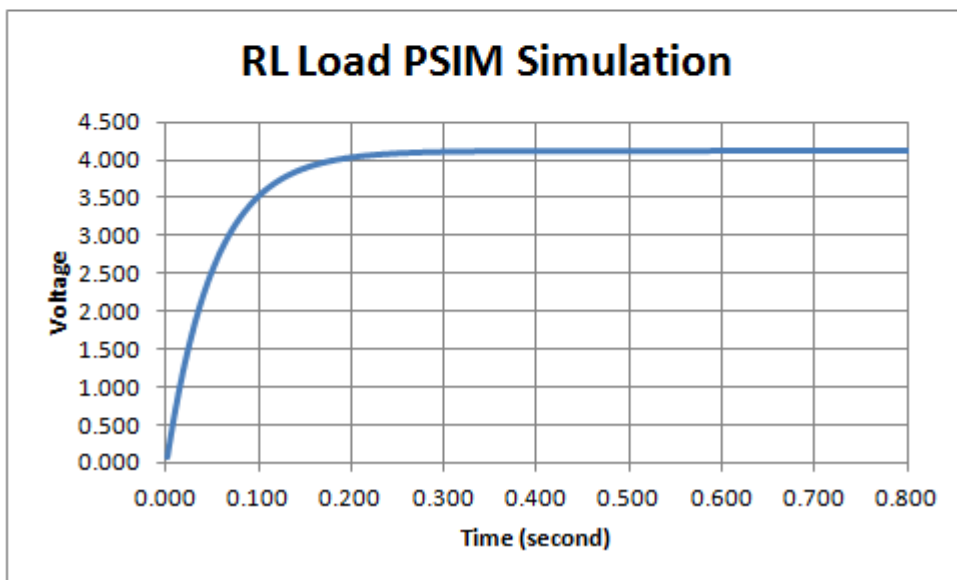
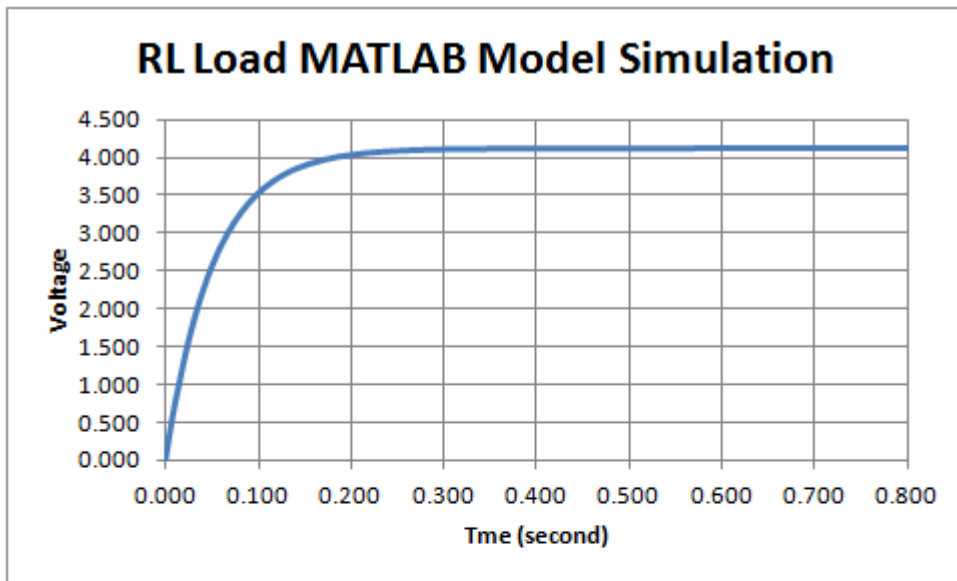
Final step of the load modelling is summing the total load current and total load power. The outputs of the main block are total load power, total load current, power and load states that showed in figure 7.9.

### 7.3 Stator and Rectifier Modeling Block

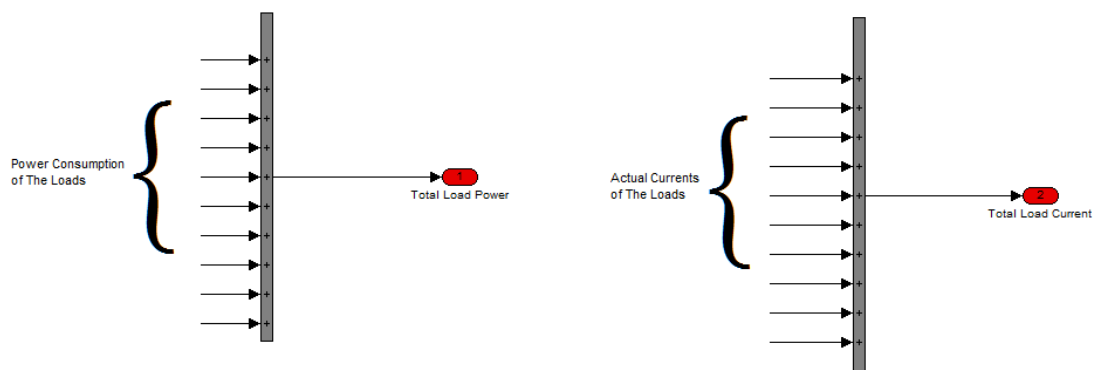


**Figure 7.7 : Stator and rectifier modeling block**

Modeling of the stator and the rectifier contains the diode voltage drops of the rectifier and the stator losses. The block has three inputs. The induced voltage, power factor and stator current are used to calculate stator reactions. Induced voltage is the

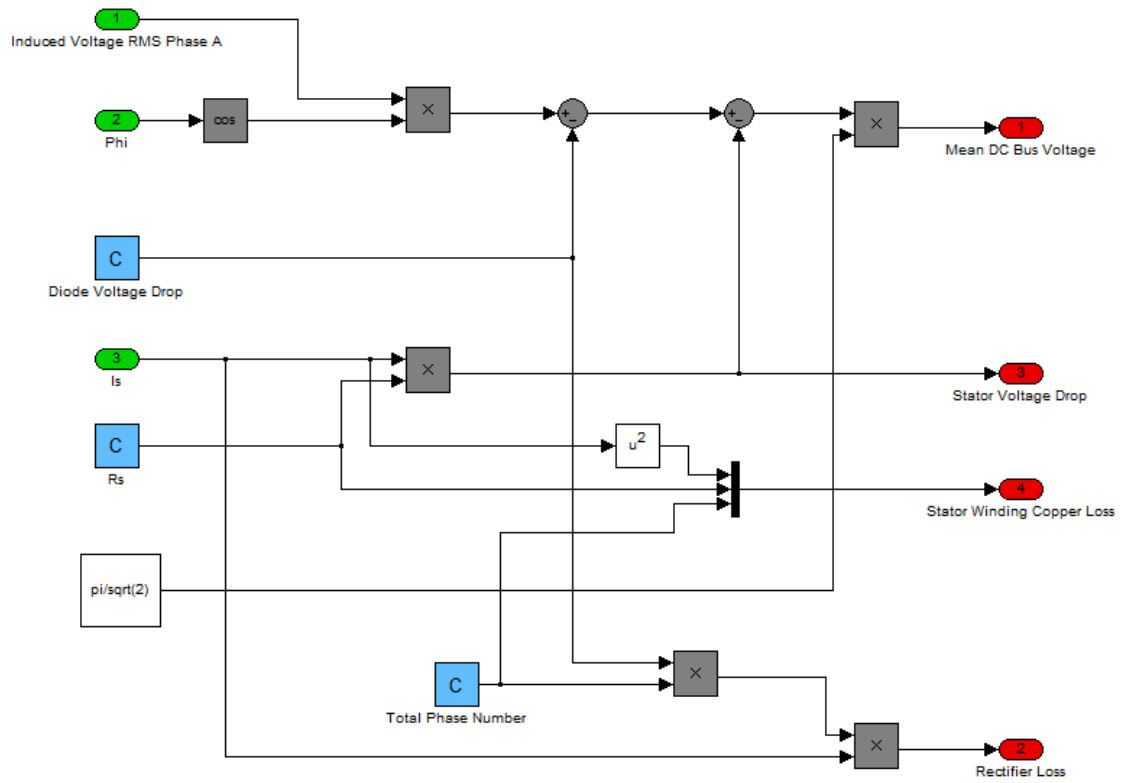


**Figure 7.8 :** The comparison of the MATLAB<sup>®</sup> and PSIM<sup>®</sup> simulation outputs



**Figure 7.9 :** Calculation of total load current and power

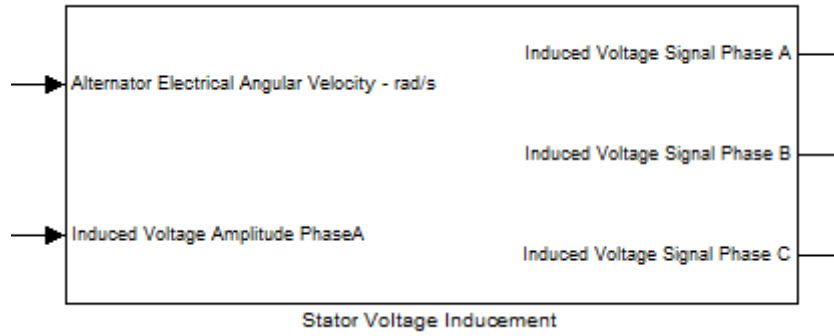
result of the rotor and magnetic reaction mathematical modeling. Power factor is a value which is close to 1 because of the high resistive loads, in this thesis, it is considered to be 1. The stator current is used to calculate stator voltage drop and losses. There are four outputs of this block. Main DC bus voltage is the result of induced voltage minus the rectifier and stator resistance voltage drops. It is showed in the figure 7.10 and also showed in the equivalent circuit in figure 4.2.



**Figure 7.10 :** Calculation of stator and rectifier reactions

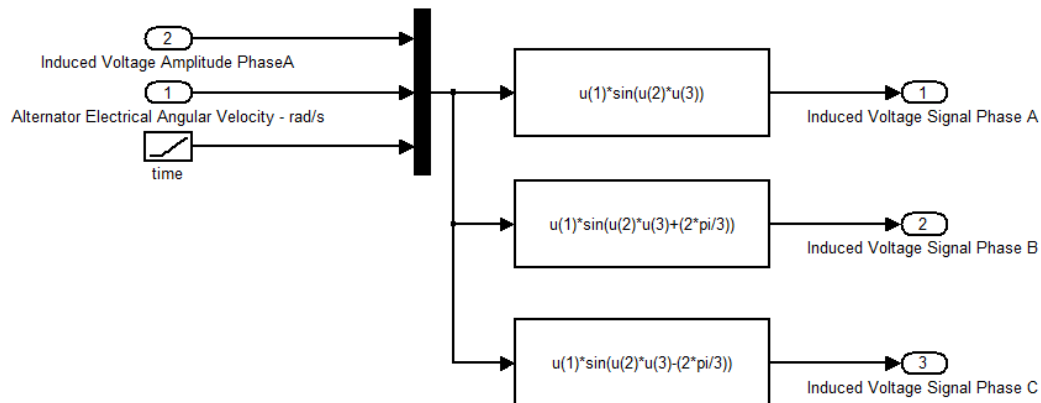
The stator voltage drop is calculated from the stator current and the stator copper resistance. Stator winding copper loss also calculated in this block. The rectifier loss is directly related with the diode voltage drop and calculated with respect to the total number of phase.

## 7.4 Stator Voltage Inducement Block



**Figure 7.11 :** Stator voltage inducement block

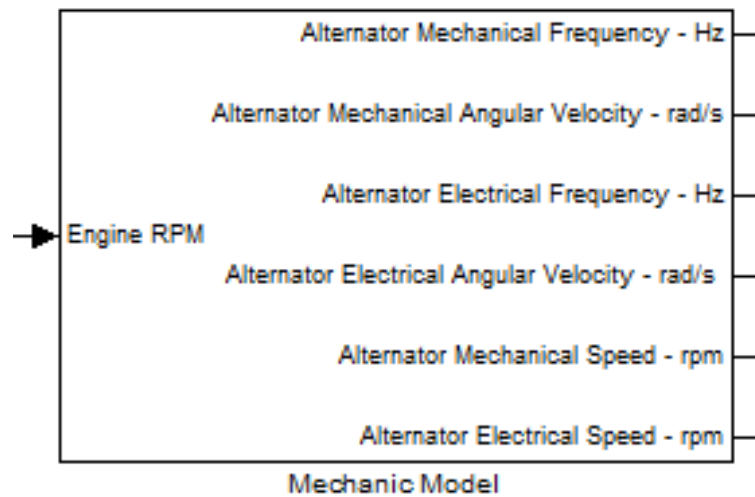
This block contains the formulations of three phase sinusoidal voltage inducement which is the result of magnetic reactions. The inputs are the alternator angular speed and the calculated amplitude voltage of phase A. A time generator is used to generate the sinusoidal voltage in time domain. Three phase voltages are calculated and the outputs of the block.



**Figure 7.12 :** Three phase sinusoidal voltage generation

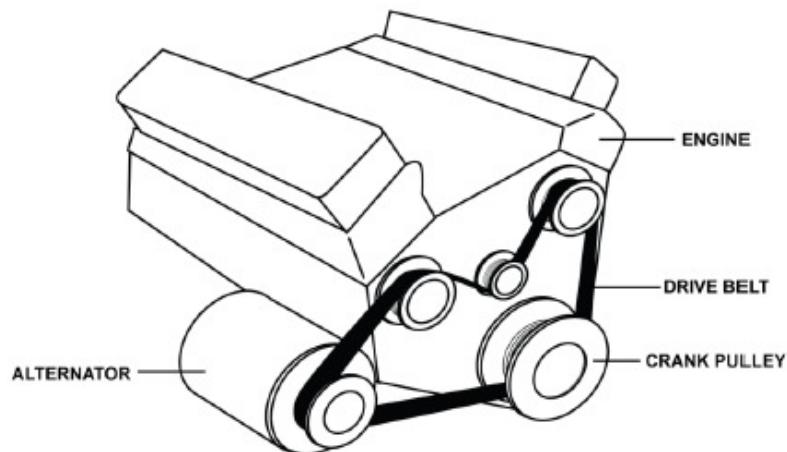
## 7.5 Engine-Alternator Assembly Mechanical Modeling Block

Mechanical model block generates the required mechanical variables for electrical model. The only input is the IC engine speed. The outputs are calculated by using the assembly parameters.



**Figure 7.13 : Mechanical Model**

The alternator is assembled to the engine by a belt and pulley mechanism. There exists a drive ratio so as to drive the alternator in high speeds. Theoretically, mechanical losses such as belt and pulley friction loss and alternator bearing loss also exist but due to the no information about these losses are available; they are neglected in this thesis.

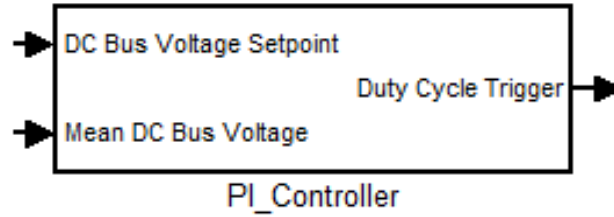


**Figure 7.14 : Engine-Alternator Assembly [4]**

In the inside of the model, there are two configurable parameters. One of them is alternator total number of pole pairs and the other one is belt and pulley mechanism drive ratio. The outputs are calculated by general mathematical expressions.

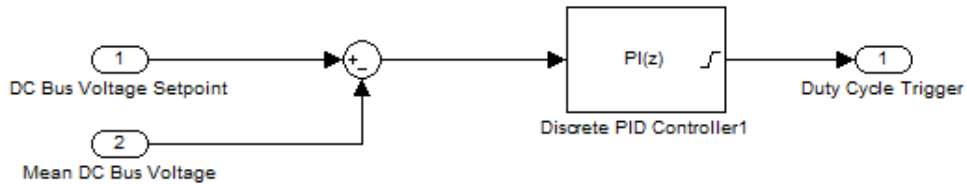


## 7.6 Excitation Current Controller Block



**Figure 7.16 :** Main Controller Block

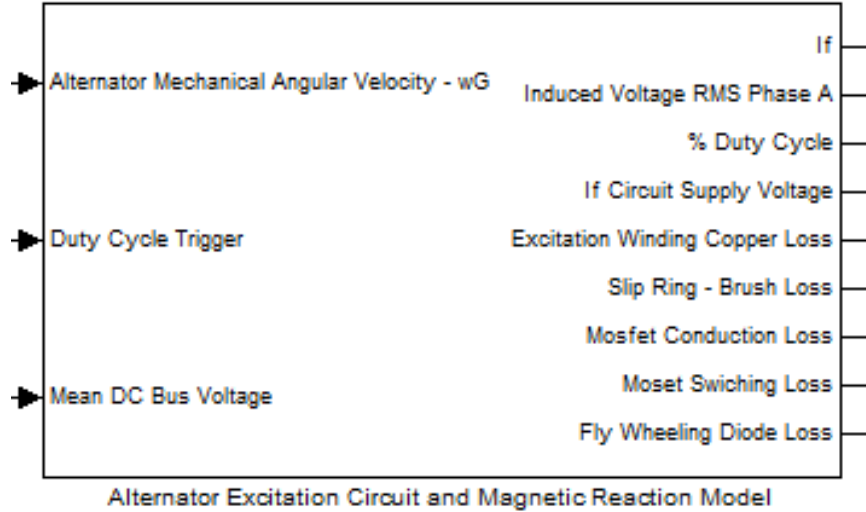
The excitation current controller is used to minimize the voltage error of the charging system. The Lundell type of alternator is a variable speed generator and the conventional way to regulate the output voltage is regulating the excitation current. The controller satisfies the voltage set point of the system against the variable angular speed and battery state of charge. Because the PI controllers are easy to calibrate with acceptable success, the other vehicle systems are generally controlled by the PI controllers and PI control method is used commonly in automotive industry. In this model, excitation current will be controlled by a PI controller instead of other type of control theories to prevent the complexity.



**Figure 7.17 :** A discrete time saturated PI type of controller

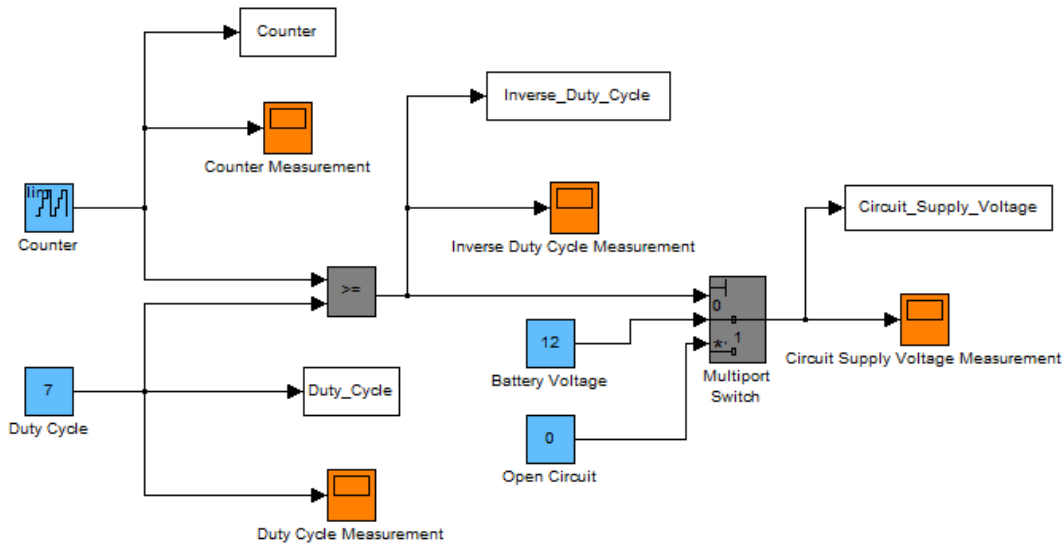
## 7.7 Alternator Excitation Circuit and Magnetic Reaction Modeling Block

Alternator excitation current and magnetic reaction block calculate the excitation circuit losses, excitation current, duty cycle percentage and also calculates the mathematical expressions of the magnetic circuit. The inputs are alternator mechanical speed, DC bus voltage and the output of the excitation current controller. The circuit in figure 4.2 is used to model the excitation winding and switching element. The controller output is the main input to generate the duty cycle in this block.



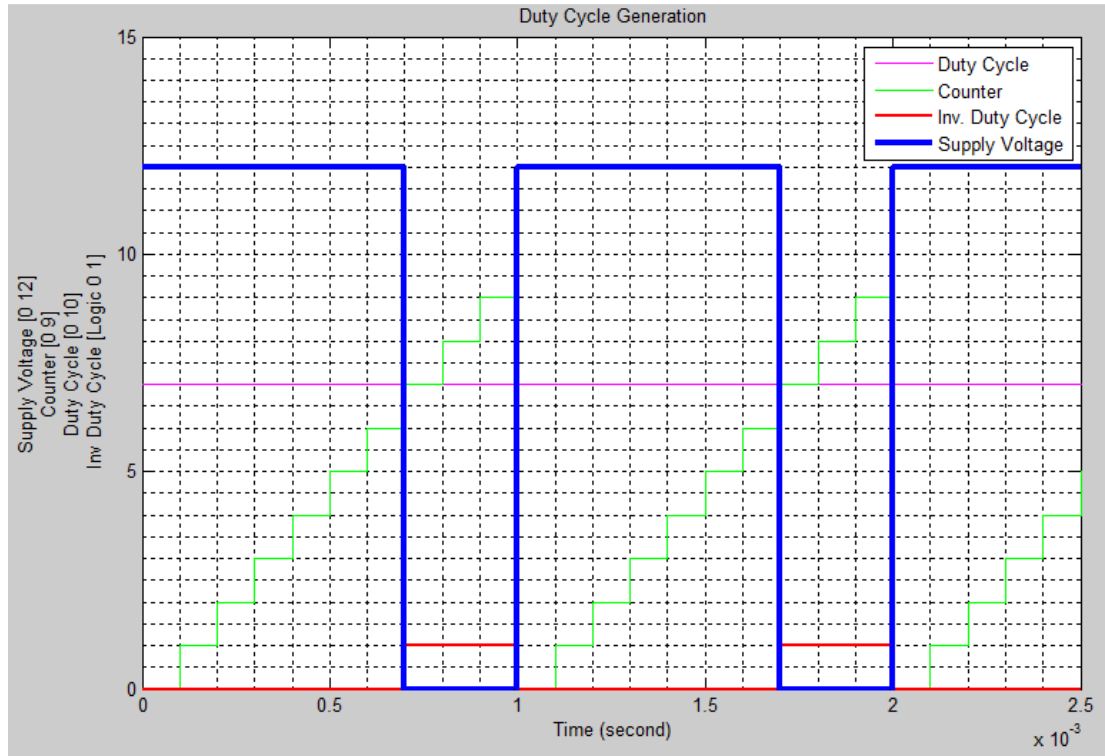
**Figure 7.18 :** Main block of the field winding modeling and loss calculation

Here, a partial model to generate the duty cycle is given in figure 7.19. A counter is used as a reference comparator. Duty cycle shows the controller output and configured as 7 to run the trial model. Battery voltage considered as 12V. Open circuit is simulated as 0V supply voltage.



**Figure 7.19 :** Example model to show how to create duty cycle in discrete time

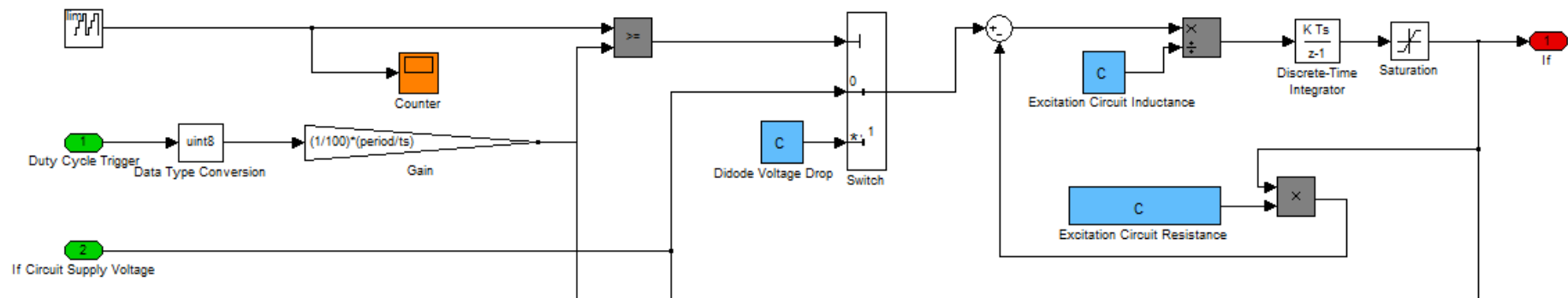
If the counter value in a period is bigger or equal to the duty cycle controller output, the circuit will be an open circuit. During the counter value is smaller than the duty cycle controller output, the circuit is supplied by the DC bus voltage. The counter value parameters are directly related how accurate model is required. If high switching frequency is required then the model has to run slower. In this thesis, the period is chosen as 1ms, in other words the frequency is chosen as 1kHz.



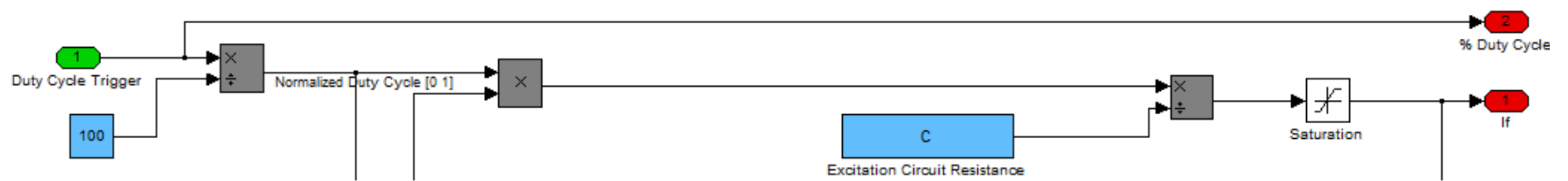
**Figure 7.20 : Duty cycle creation in discrete time**

There are two main model created to simulate the charging system. One of them named as 'dynamic model' to characterize the dynamic behavior of the charging system during the load switching. For dynamic modeling which includes the switching element of the excitation circuit, the output of the model determines the required duty cycle but cannot be used as duty cycle directly. There need to be convert the data to determine the position durations of the MOSFET. The output of the controller is processed and compared with the counter. The counter value is depends on the model frequency and required accuracy. After the signal process, the result is used to drive the MOSFET.

The other model named as 'static model' which can run long duration of times such as standard driving cycles, for example NEDC. This model does not contain the switching element model and calculates the output of the controller directly as a duty cycle. Model can run faster because of not having an active switching element model. The models of the dynamic and static conditions are given in figure 7.21.

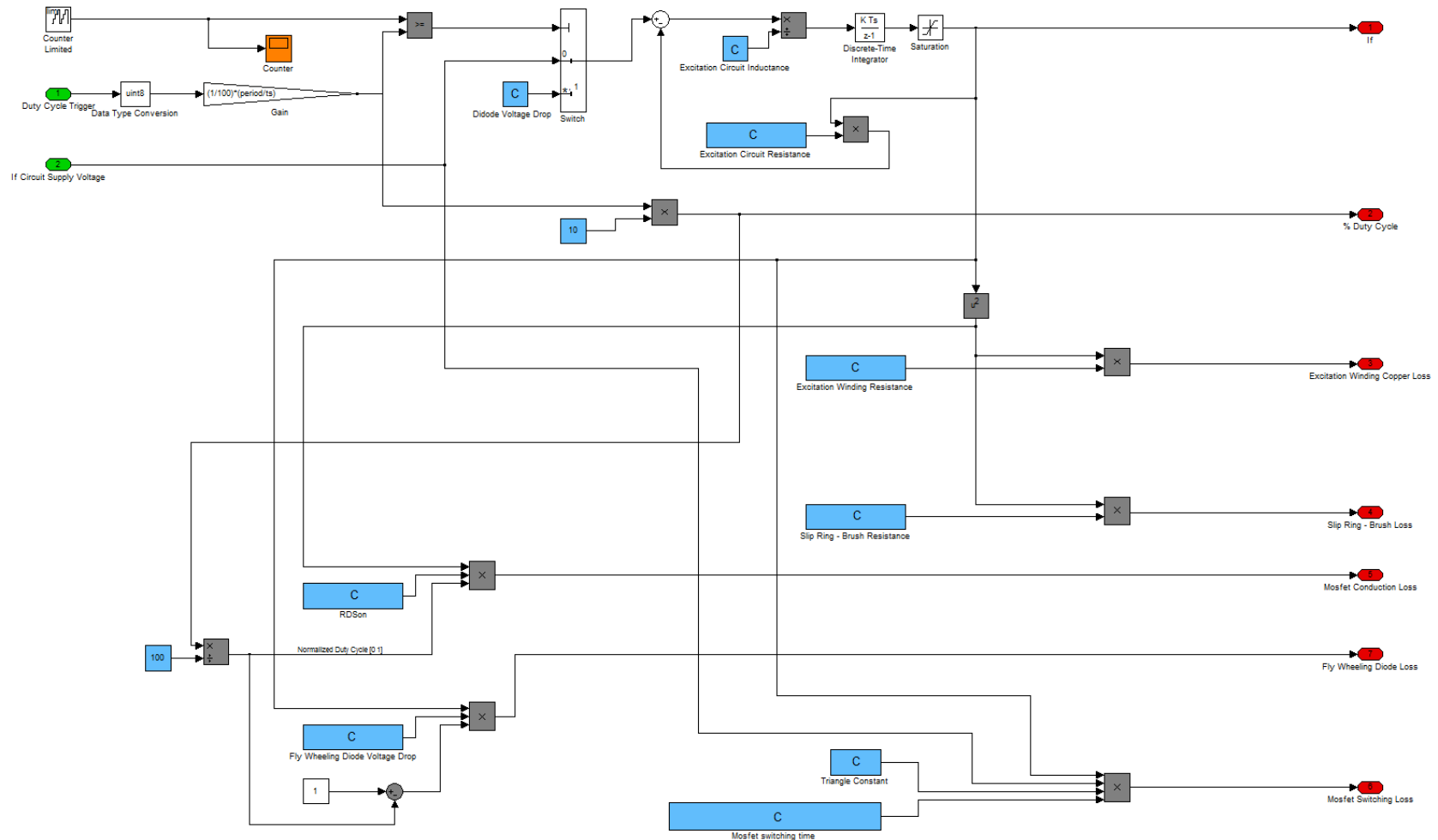


**Figure 7.21 :** Dynamic model that contains MOSFET switching modeling with high speed sampling rates



**Figure 7.22 :** Static model excitation current calculation without modeling of MOSFET switching and using average values

The excitation circuit model contains the parameters of the field winding, other parameters of switching element and duty cycle on-off position durations. The excitation circuit is given in figure 4.2 and the model is done due to that circuit. Excitation current is calculated first. Field winding copper loss is calculated by field winding resistance and square of  $I_f$ . Slip ring-brush loss is also calculated. Mosfet conduction loss and fly wheeling diode loss are calculated by using the duty cycle and component parameters. In addition mosfet switching loss is calculated by the equation 5.7.



**Figure 7.23 :** Dynamic modeling of field winding losses and excitation current

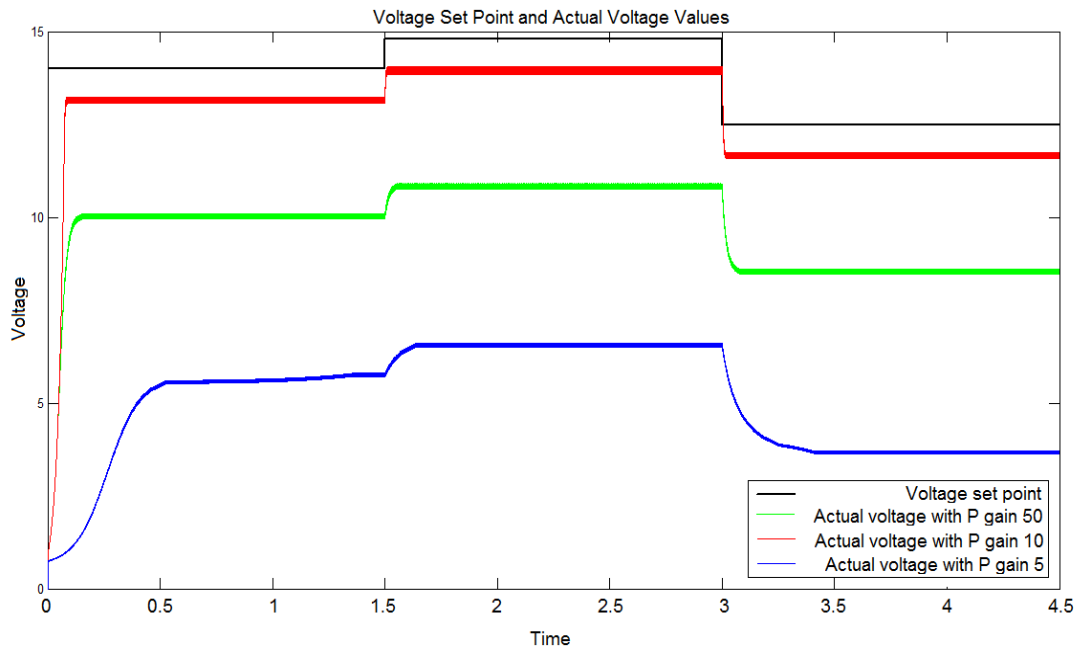


## 8. RESULTS AND CONCLUSION

### 8.1 Dynamic Model and Excitation Current Controller

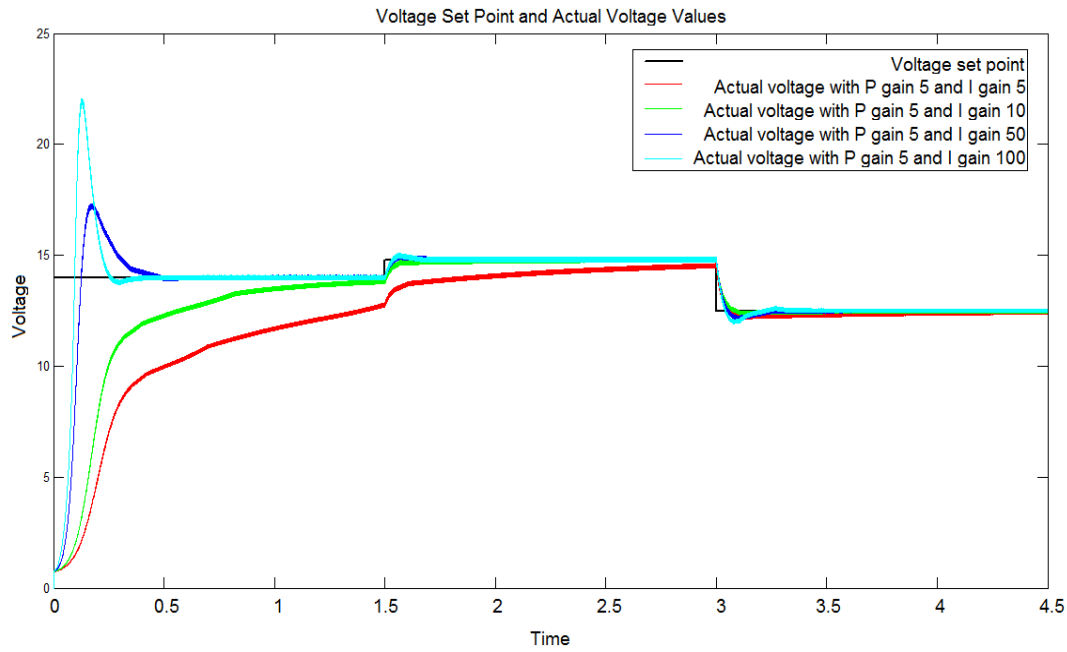
The model ran with different PI controller coefficients to compare the controller performance and the settling time. The output graphics and controller characteristics of different PI data sets are presented below.

In the figure below, the model ran with only a P controller. Different P gains are applied to the model and it is observed that using a P controller results with a steady state error. The amount of the error is depends on the P gain and as the P gain increases, the steady state error decreases in direct contradiction.



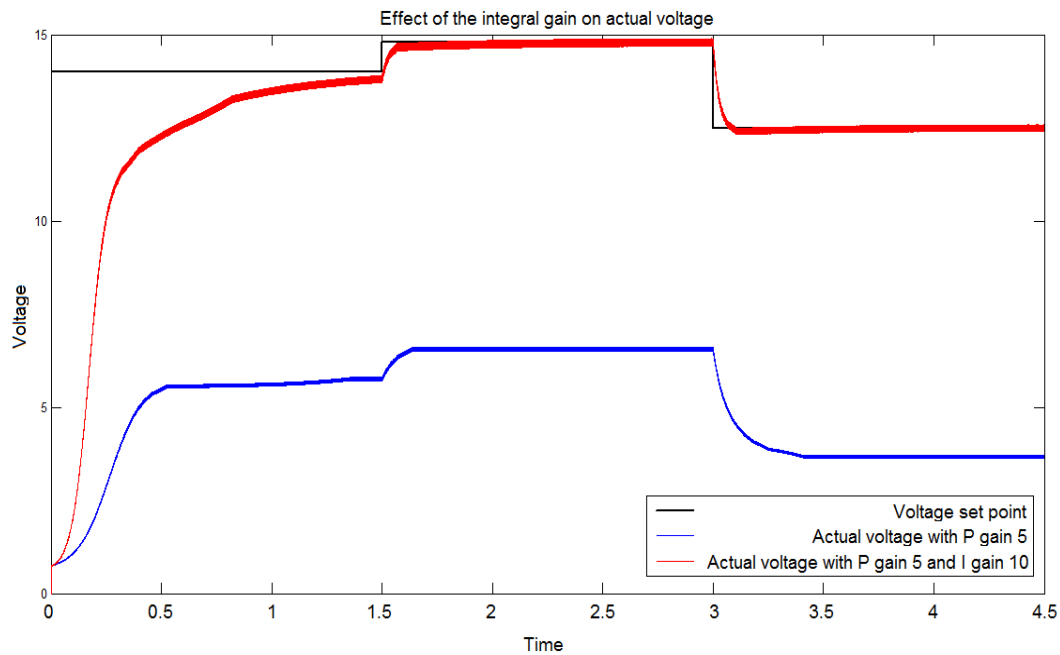
**Figure 8.1 :** Actual and setpoint DC voltage comparison with P controller.

In figure 8.2, the integral controller also included the controller to eliminate steady state error. Different integral gains are applied to the controller. Integral gain can eliminate the steady state error however, if the gain is calibrated too much, this results with over shooting of system output.



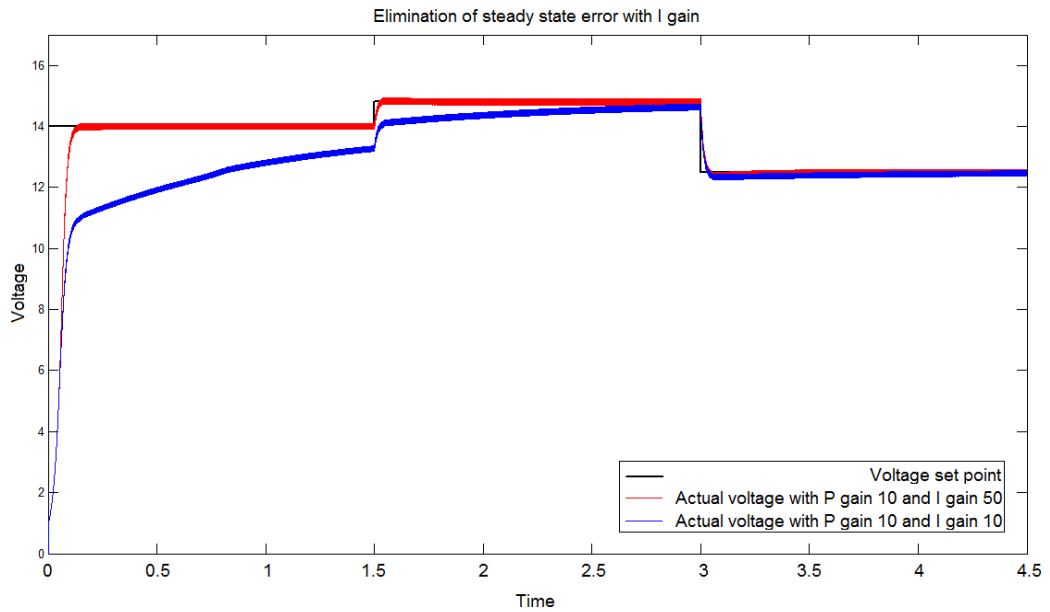
**Figure 8.2 :** Actual and setpoint DC voltage comparison with PI controller.

Figure 8.3 is the result of eliminating the steady state error by applying an integral gain. But, the system still has slow response.



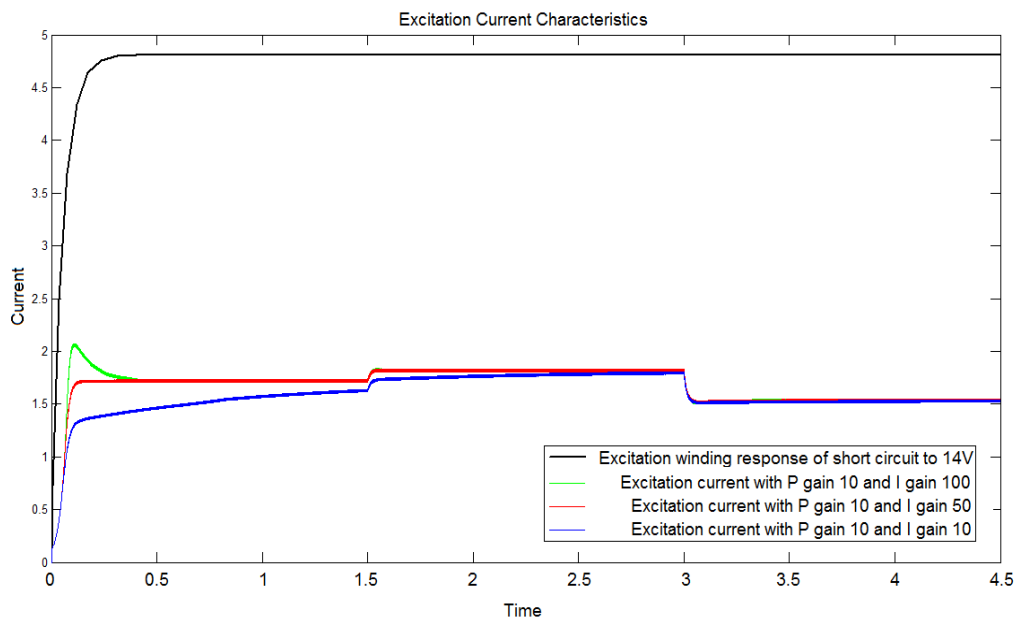
**Figure 8.3 :** Current with P gain equals to 5 and I gain equals to 10

Figure 8.4 shows the system behavior with increased P gain and steady state error elimination with increasing the integral gain.



**Figure 8.4 :** Decreased system response time with PI controller

In the next figure current response of the excitation circuit to 14V DC input is plotted. In addition, current characteristics with constant P and variable I gains are plotted.

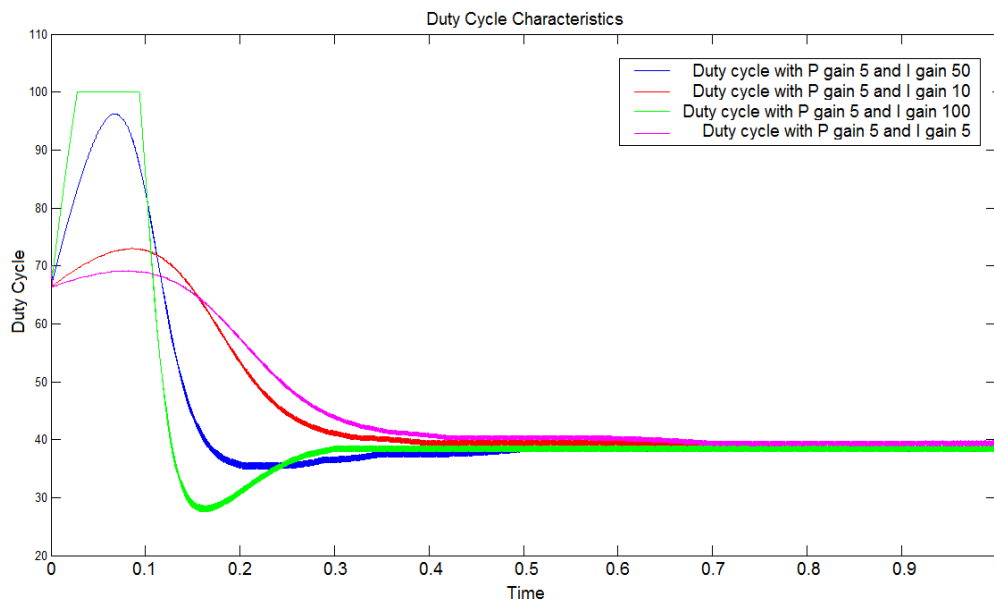


**Figure 8.5 :** Excitation current characteristics

The losses are also calculated with selected PI controller gains  $P=10$  and  $I=50$ . With a 1.8A field current and 14.8V output voltage, the main part of the electrical losses is field winding resistive loss with a 75% of the total electrical losses. Slip-ring brush loss is 17% of the electrical losses. MOSFET conduction loss is directly depends on the switching element. In this model, the conduction loss is around 1.2% of total

electrical losses during a 40% duty cycle. Fly wheeling diode holds a portion of 7% of the loss because of the voltage drop over the diode. Switching loss of the MOSFET is so small that can be omitted in low frequencies.

In the model, controller effort directly regulate the switching element duty cycle. As a result, the controller effort and duty cycle are directly proportional. In figure 8.6, system start characteristics with different PI controller coefficients are searched. Duty cycle is high at the start time to fill the RL circuit with required energy. Overshoots of the controller are observed because of the high integral gains. After the first system start, the duty cycle gets smaller because the voltage set point is around 14V and nearly constant during a high alternator speed.

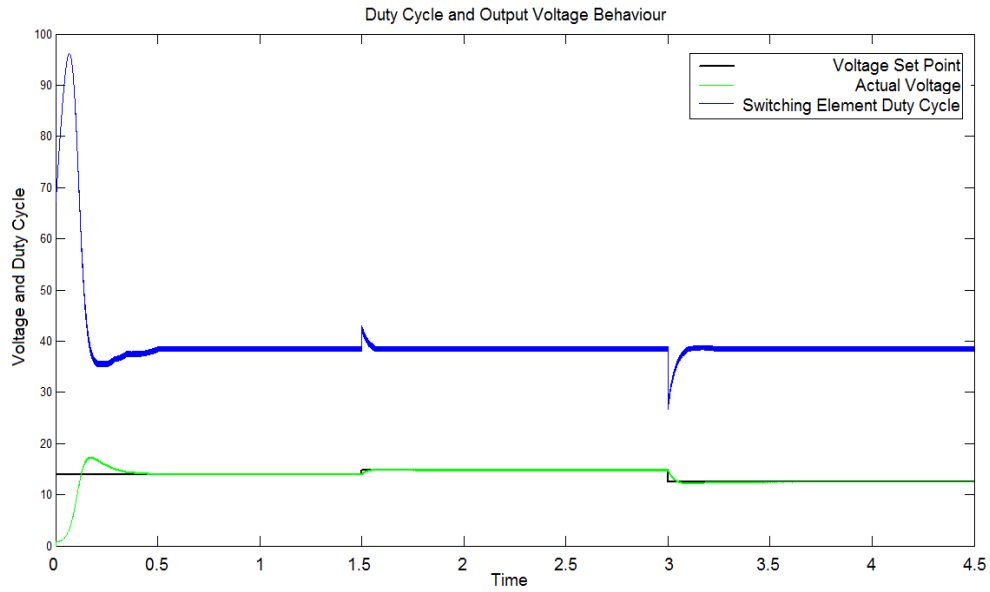


**Figure 8.6 :** Duty cycle and actual voltage comparison

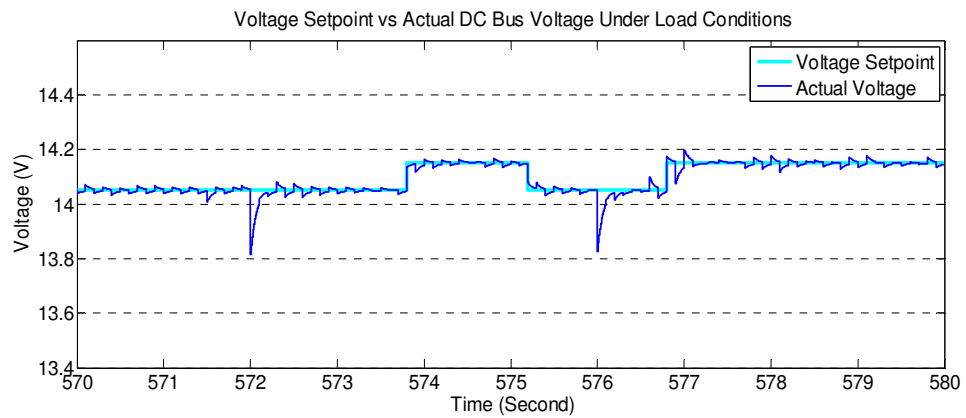
Figure 8.7 compares the duty cycle and the actual voltage response of the controller. System start behavior is similar with the observations from previous figure. In addition, step responses of the system against different voltage set points are observed.

In figure 8.8, 8.9 and 8.10; loaded conditions of the alternator are shown. Head-rear lamps and full illumination lamps are used as loads. Load values are determined with the measurements from the vehicle. Load states are shown in figure 8.10. DC bus voltage set point and the actual voltage are plotted of a part of the simulation in figure 8.8. Voltage drops can be seen during 100ms before the excitation controller

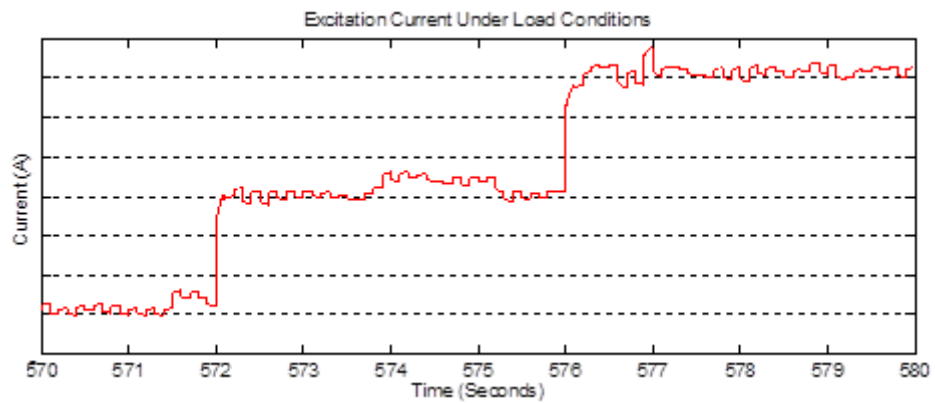
satisfy the voltage set point. The change in the excitation current at the transition of loads is plotted in figure 8.9.



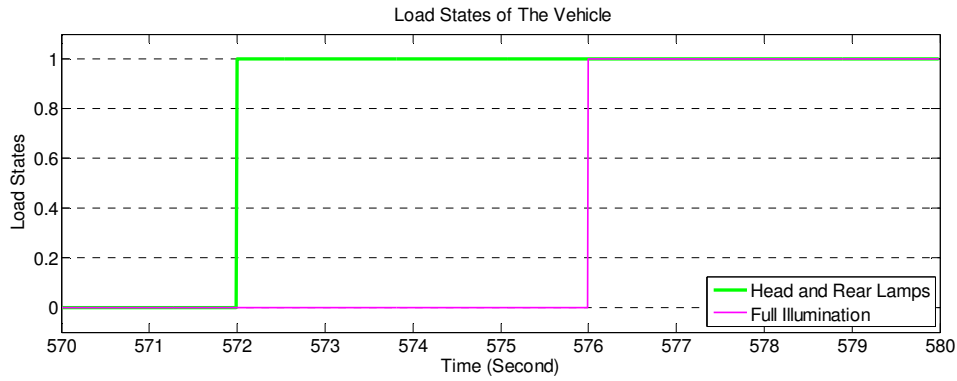
**Figure 8.7 :** Controller effort and duty cycle with the gains  $P=4$  and  $I=50$



**Figure 8.8 :** DC bus voltage setpoint and the actual voltage in load condition



**Figure 8.9 :** Excitation current in load condition



**Figure 8.10 : Load states**

The excitation current controller output simulated with the measured excitation circuit parameters as resistances and inductances of an alternator. A PI controller is used to control the field current. The P gain is chosen to reduce response time and steady state error and I gain is determined to satisfy minimum over and undershoots as well as steady state error. The final response time of the model calculated at around 100ms. The response time can be re-calibrated by changing PI coefficients to reduce the voltage spike concerns.

## 8.2 Static Model

Validation of the static model is achieved with a drive cycle data which was collected from the vehicle. During the drive cycle, different type of loads had been got activated and vehicle was driven in different speed regions. Not only the high speed region but also idle data also recorded to check the performance of the alternator in low speed region. During the drive cycle post processing, first three minutes are omitted because internal charge controller of the vehicle uses some inputs like state of charge of the battery which are not modeled. Some differences could easily be observed for the first three minute so this part of the data will be omitted. The state of the loads are given in the table 8.1.

**Table 8.1 : Vehic Loads Activation Time**

| Load Name | Activation Time (seconds) |
|-----------|---------------------------|
| Load A    | 572                       |
| Load B    | 576                       |
| Load C    | 829                       |
| Load D    | 1049                      |
| Load E    | 1272                      |

The outputs of the model and the vehicle data are given in the figures in the appendix from the figure A.1 to figure A.13.

In the figure A.1 of the static model results, desired voltage of the DC bus system is plotted. As seen in the figure, desired voltage value are increasing while the load power increasing. The voltage demand is between 14.7V and 15.3V. In figure A.2 actual DC bus voltage is plotted. The comparison of the logged data from the vehicle and the model output also done in this figure. The point in figure A.2 is time of the activation of the load E. What is observed from the logged data from the vehicle, alternator can not supply enough power for the load E. That is why a voltage drop is observed just after the time 1272 s. The voltage of the DC bus is directly drop to the vehicle battery voltage. On the other side, the model can detect that the alternator can not supply enough power for the loads and a voltage drop is observed. The difference between the model and the logged data is the absence of the battery model in the main model which is the subject of this thesis. As a result of battery absence, DC bus voltage directly goes zero and excitation circuit can not satisfy required excitation current to generate power output. This is also showed in figure A.10.

Engine speed of the logged data is directly used in the model after a post process. This post process increases the sampling rate of the logged data and prepare the data as an input of the model. Figure A.3 shows that this process is successful. Figure A.4 shows the required current to supply the loads. Vehicle loads are calculated from the logged data and the load values are calibrated in the model based on these calculations. The comparison of the vehicle data and the model data is given in Figure A.4. In this figure, after 1272 s the supply current goes to 0 because of battery absence in the model. In figure A.5, excitation current is compared between the logged data and vehicle data. For the steady state and low power regions, the results are acceptable. It is observed that the response of the model is more dynamic than the measured data. The reason is absence of damper effect of the battery. During the transient states in the vehicle, battery can supply current peaks but in the model it is impossible. All the current supplied by the alternator in the model so that is why current and voltage peaks are noticable in model outputs. Duty cycle of the field winding switching element is plotted in figure A.6. Total percentage of the duty cycle is in increasing trend and after the 1272 s, the controller works with its maximum effort and set the duty cycle to 100%. Although the duty cycle is in its

peak, it is impossible to recover the system because excitation circuit supply voltage is zero. Induced voltage of phase A is plotted in figure A.9. Because of the model equations are solved in fixed step, the results are also sinusoidal in fixed step. In figures A.11, A.12, A.13, different components of the electrical losses are plotted.

System electrical losses are calculated from the model outputs. The components of the total electrical loss are given in the Table 8.2.

**Table 8.2 :** Electrical Loss Calculation in Static Model During  $I_s=100A$

| Loss Component                 | Loss (W) | Loss (%) |
|--------------------------------|----------|----------|
| Fly Wheeling Diode Loss        | 0.6      | 0.03403  |
| Mosfet Switching Loss          | 0.0008   | 0.00005  |
| Mosfet Conduction Loss         | 0.35     | 0.01985  |
| Slip Ring – Brush Loss         | 3        | 0.17017  |
| Excitation Winding Copper Loss | 12       | 0.68068  |
| Rectifier Loss                 | 267      | 15.14506 |
| Stator Winding Copper Loss     | 1480     | 83.95016 |

The main component of the electrical losses is the stator. The main reason is the high currents that flow through the stator windings. The rectifier plays a strong role on the losses also because of the diode voltage drops. The rest of the electrical losses are in excitation winding and they are not as much as stator electrical losses. In addition, switching loss is so small for 1kHz that can be omitted in total electrical losses.

## REFERENCES

- Ajayi O.A.,** (2012). Application of Automotive Alternators in Small Wind Turbines. MSc. Thesis. Delft University of Technology. The Nederland.
- Bodur H.** (2012). Güç Elektroniği Temel Analiz ve Sayısal Uygulamalar. Birsen Yayınevi. P. 374-375. Istanbul.
- Boldea, I.** (2006). Variable Speed Generators. Taylor&Francis. USA.
- Bradfield M.,** Improving Alternator Efficiency Measurably Reduces Fuel Costs. Remy Inc. Retrieved in 2013 from <http://www.delcoremy.com/Home.aspx>.
- Ceuca, E., and Ilieana, I.** (2002). New Technology In Automotive Electronics. In Constantin Brancusi University – Engineering Faculty University's Day. 8<sup>th</sup> International Conference. Romania, 24–26 May 2002.
- Ceuca, E., Joldeş R., Olteanu E.** (2006). Simulation of automotive alternator – simulation for increasing electrical power. Automation, Quality and Testing, Robotics, 2006 IEEE International Conference on (Volume:1). Cluj-Napoca.
- Cho, C. P., and Crcelius D. R.,** (2002). Vehicle Alternator/Generator Trends Toward Next Millennium. IEEE. Indiana, USA.
- Crouse, W. H.** (1976). Automotive Electrical Equipment. McGraw-Hill. USA.
- Ertugrul N., Soong W.L. and Whaley D.M.,** (2004). Extracting More Power From The Lundell Car Alternator. In Australasian Universities Power Engineering Conference. University of Adelaide, Australia.
- Farison, G.S.** (1965). Alternator Rectifier Unit. Patent no:3184625. Published in USA.
- Keim, T. A.,** (1998). 42 Volts –The View from Today. *Making the Case for a Next Generation Automotive Electrical System*. Massachusetts Institute of Technology. USA.
- Miller M.J., and Nicastrì P.R.** (1998). The Next Generation Automotive Electrical Power System Architecture: Issues and Challenges. *IEEE*.
- Perrault D.J., Caliskan V.,** (2000). A New Design for Automotive Alternators. SAE.

**Stoia D., Cemat M. and Rabinovici R.** (2008). An Electromagnetic Model For Lundell Alternator With Switched-Mode Rectifier. IEEE.

**Perrault D.J., Caliskan V.,** (2004). Automotive Power Generation and Control. IEEE Transactions on Power Electronics, Vol 19, No.3.

**Sen, P. C.,** (1996). Principles of Electric machines and Power Electronics. 2nd Ed, John Wiley & Sons, USA.

**International Organization of Motor Vehicle Manufacturers.** Date retrieved: 29.04.2013, adress: [www.OICA.net](http://www.OICA.net)

**Url-1** <<http://www.allpar.com/eeek/alternators.html>>, date retrieved 12.04.2013.

**Url-2** <<http://www.denso.com.au>> date retrieved 24.04.2012.

**Url-3** <[http://www.eetimes.com/document.asp?doc\\_id=1272772](http://www.eetimes.com/document.asp?doc_id=1272772)> date retrieved 04.09.2013.

**Url-4** <[www.electronics-tutorials.ws](http://www.electronics-tutorials.ws)> date retrieved 04.09.2013.

**Url-5** <<http://www.howstuffworks.com/diesel.htm>> date retrieved 04.09.2013.

**Url-6** <<http://inventors.about.com/od/estartinventions/a/History-Of-Electric-Vehicles.htm>> date retrieved 17.04.2013.

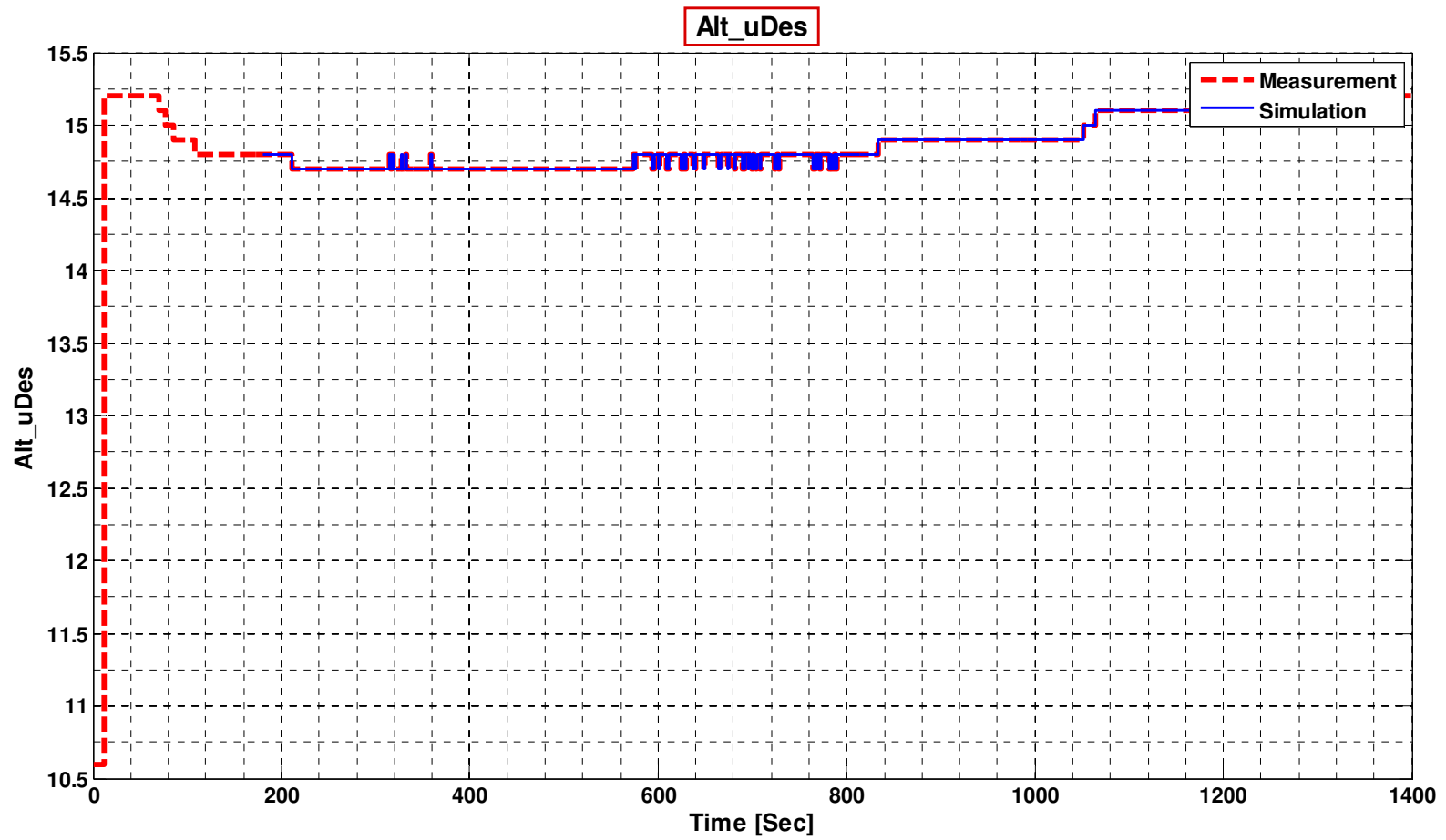
**Url-7** <[www.maximintegrated.com](http://www.maximintegrated.com)> date retrieved 04.09.2013.

**Url-8** <<http://web.eecs.utk.edu/~tolbert/teaching/ece321/handouts/machclass.pdf>> date retrieved 29.06.2013.

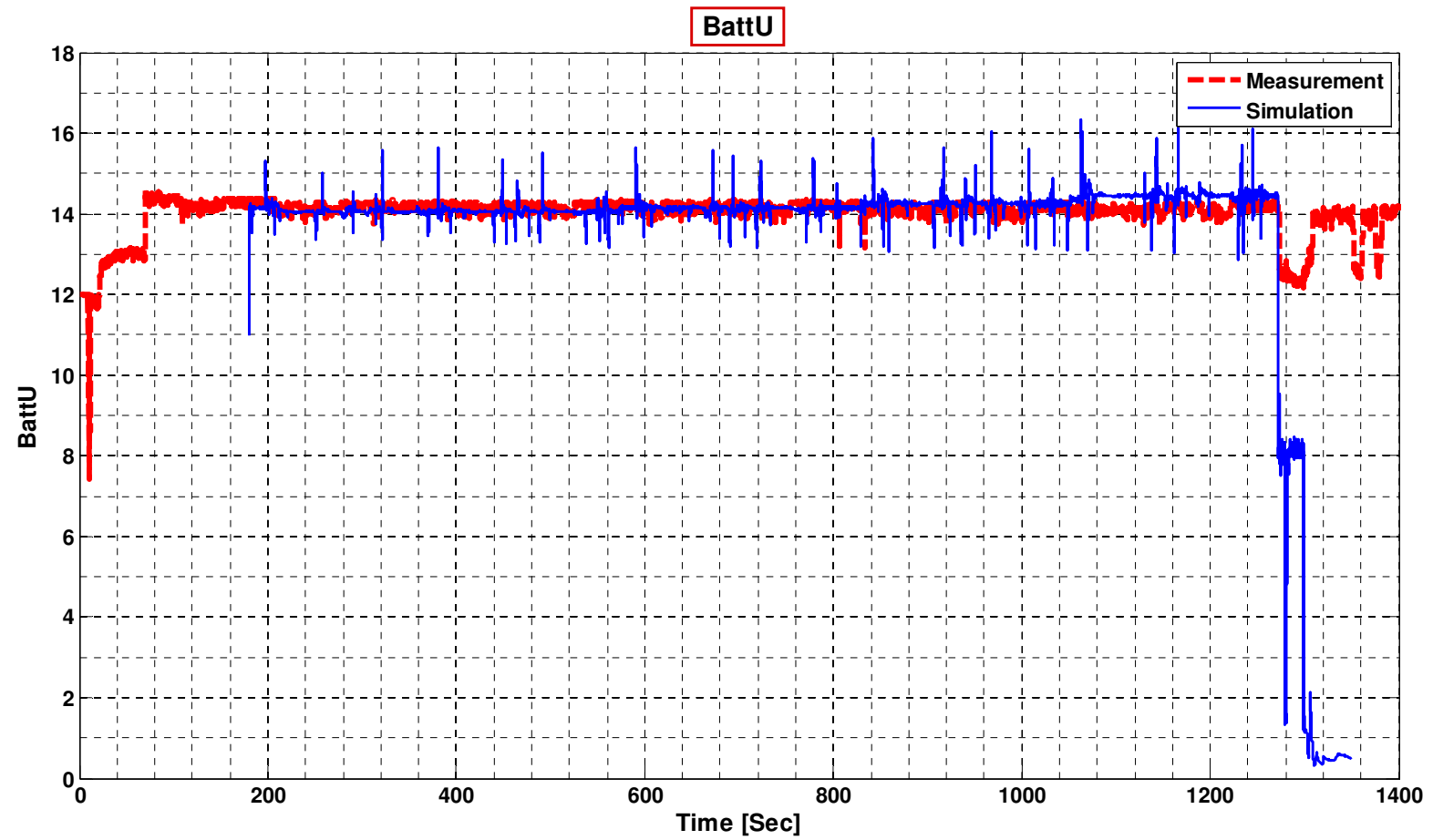
## **APPENDICES**

### **APPENDIX A: Model Results**

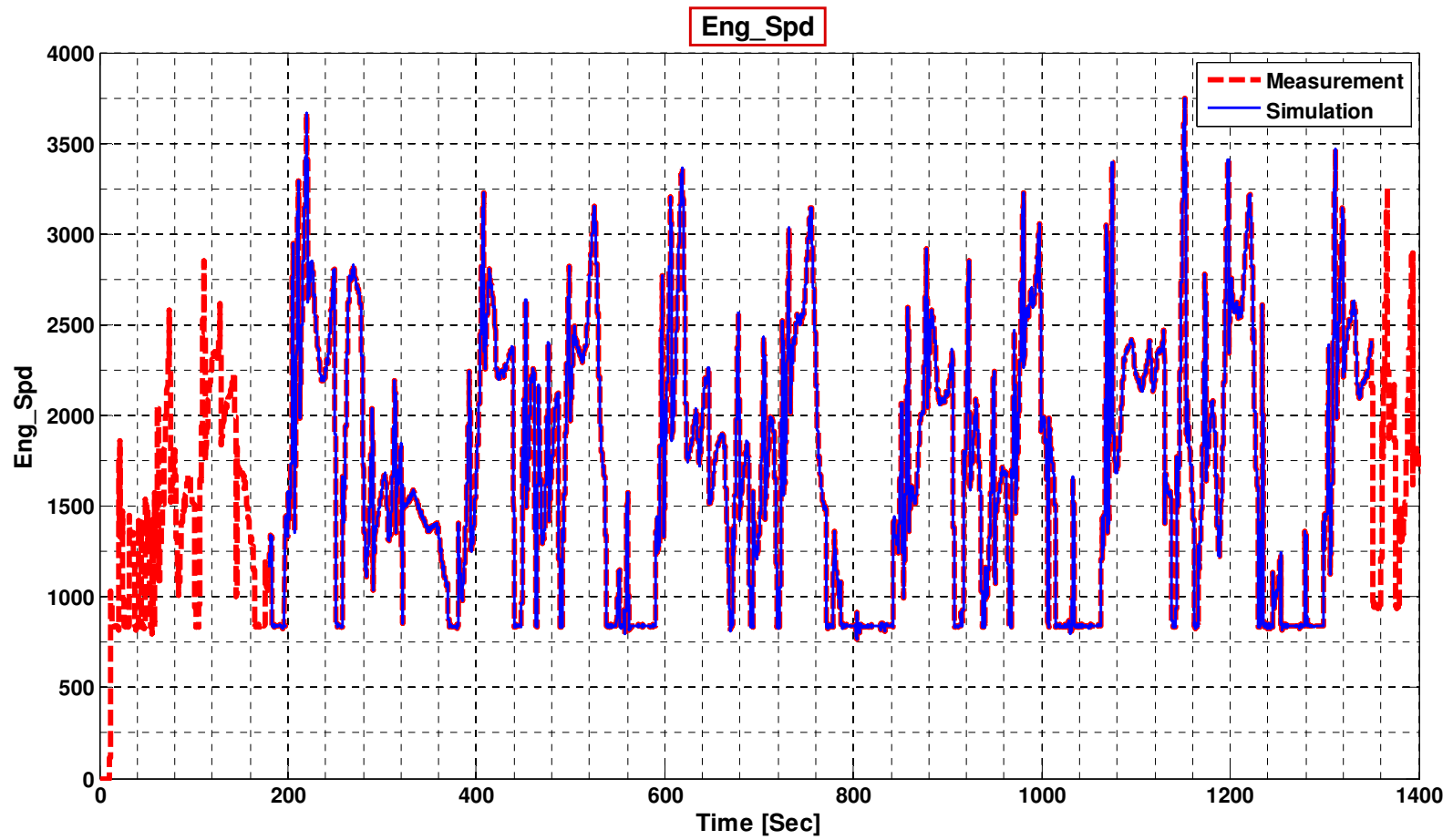
## **APPENDIX A.1**



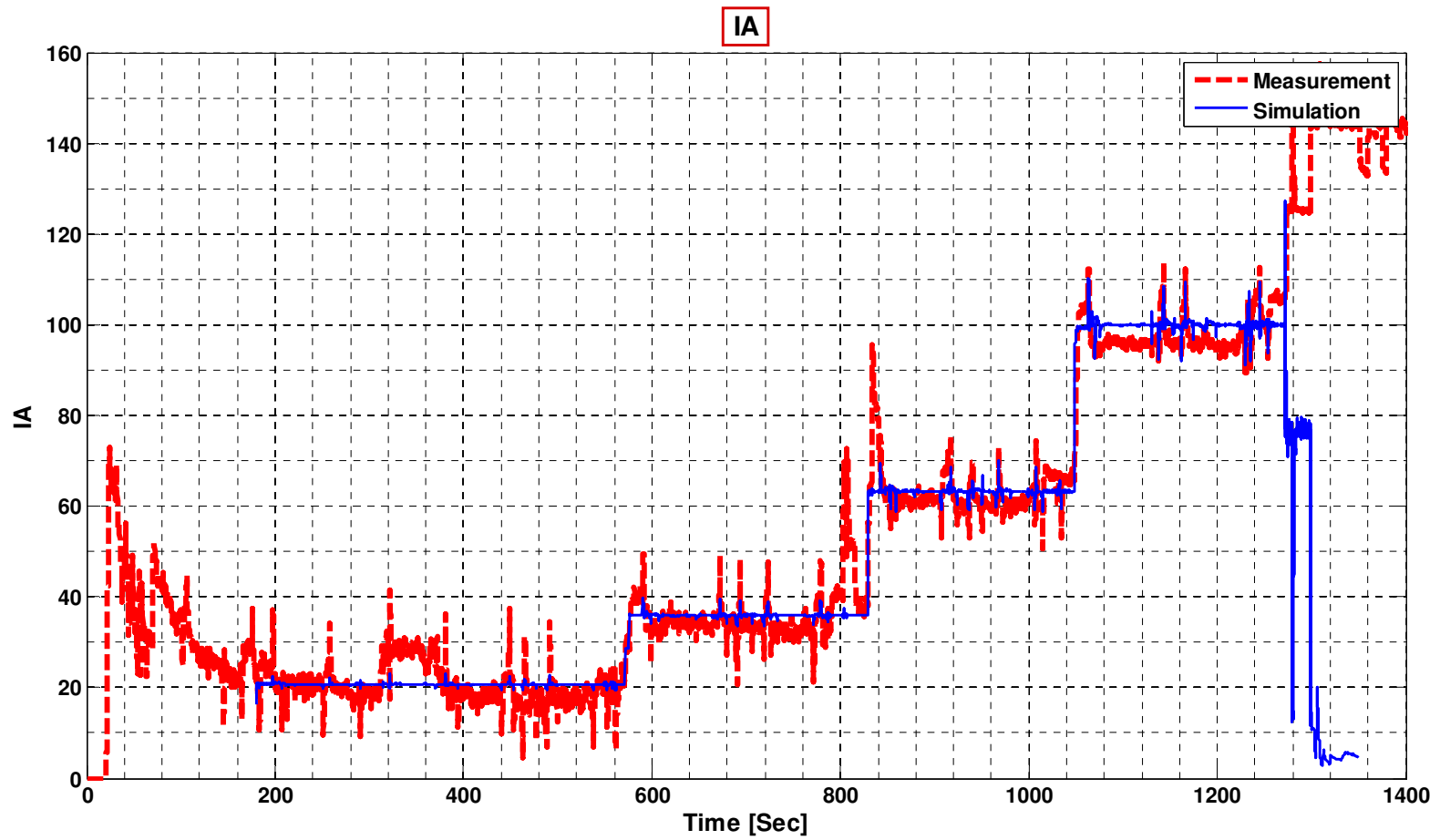
**Figure A.1 : Desired alternator voltage**



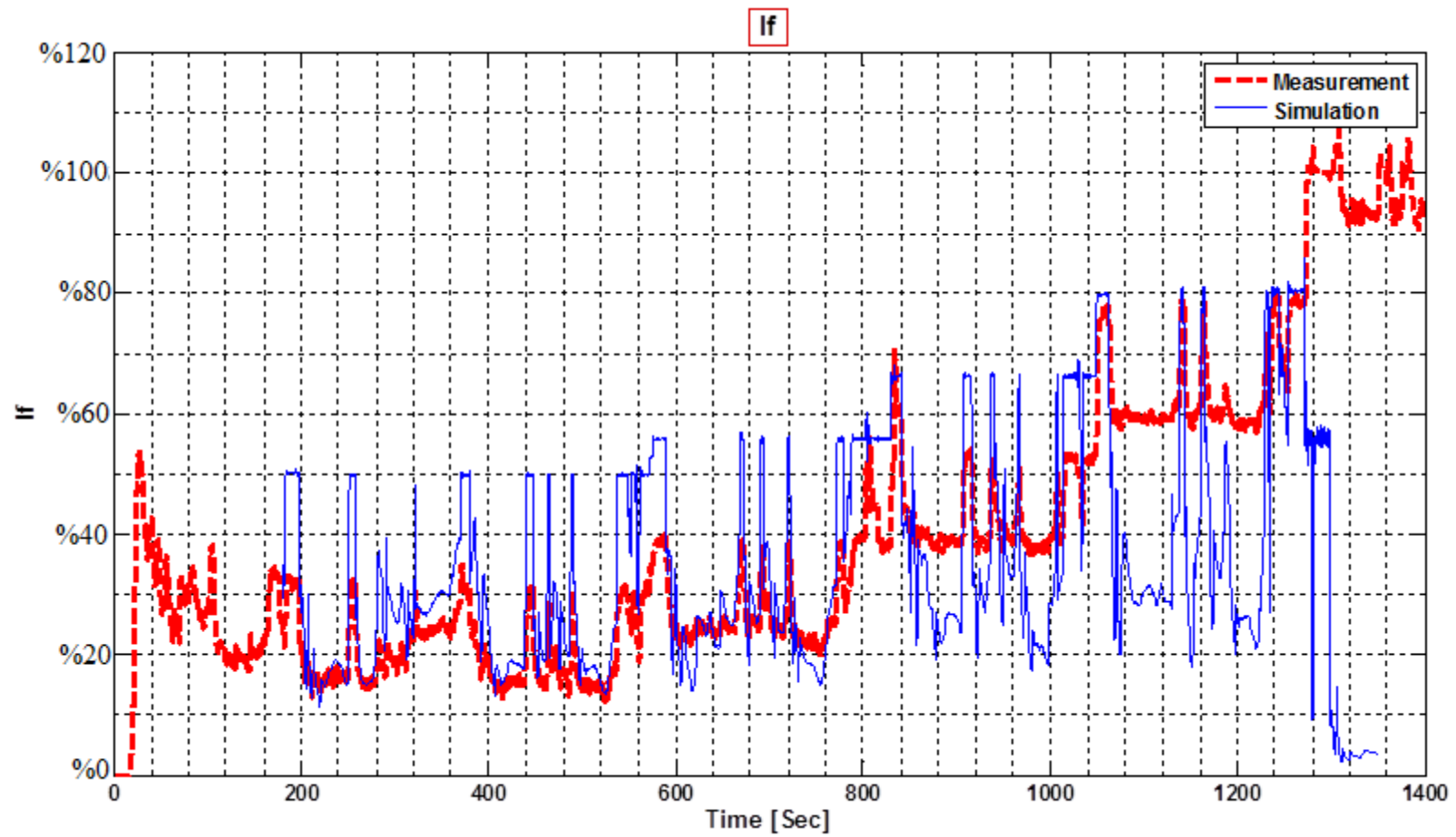
**Figure A.2 :** Battery voltage (DC bus voltage)



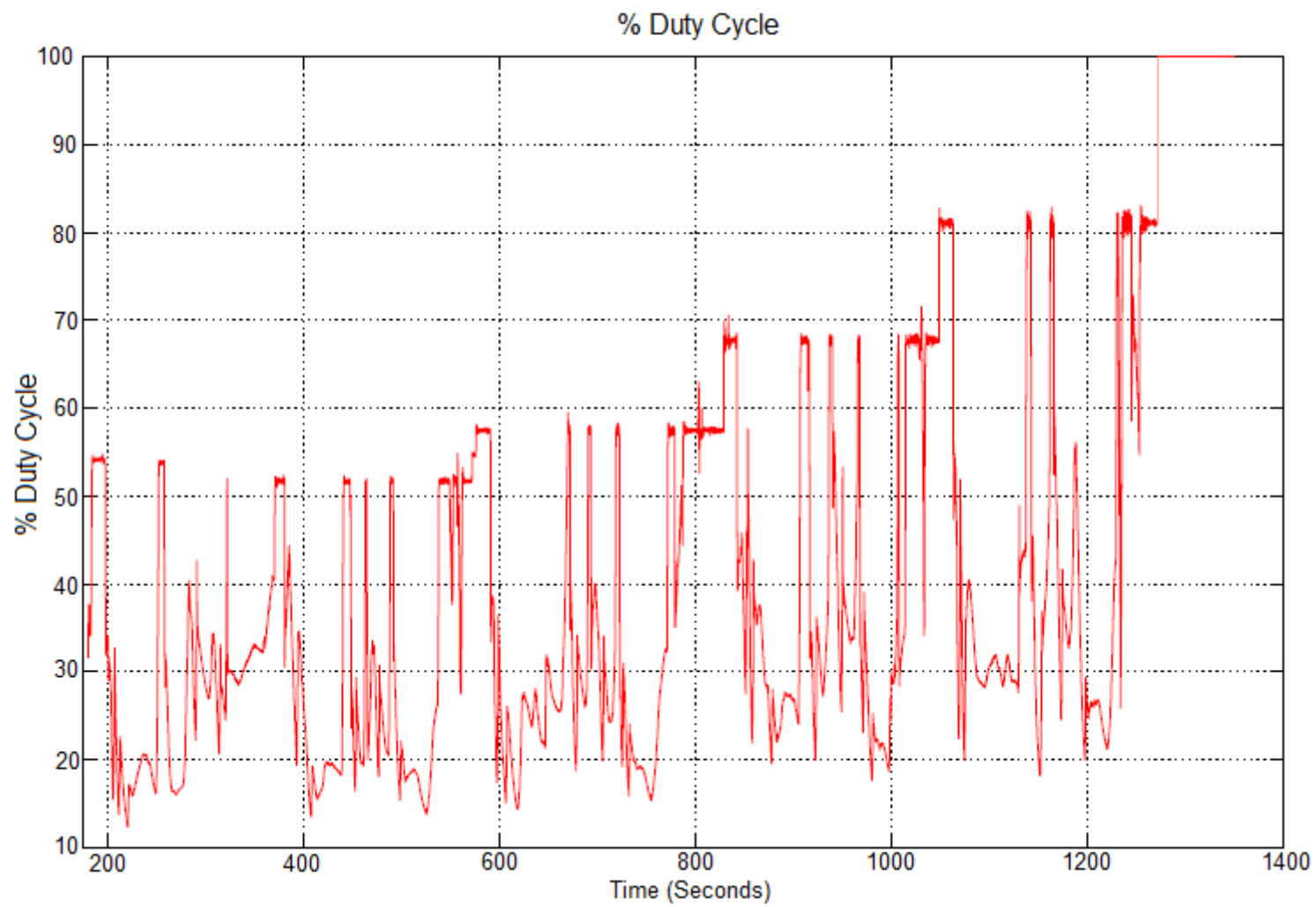
**Figure A.3 : Engine speed**



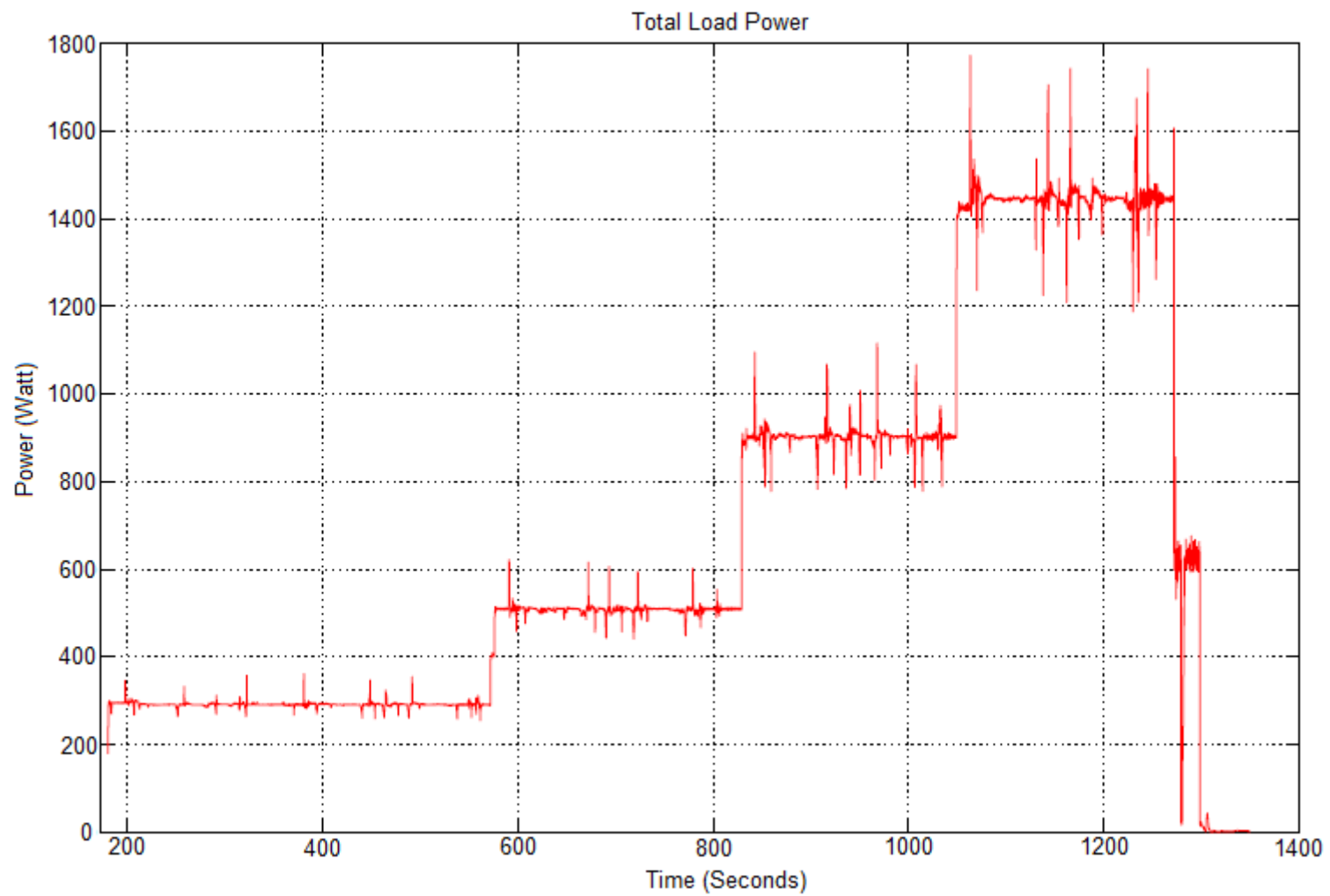
**Figure A.4 :** Vehicle loads supply current



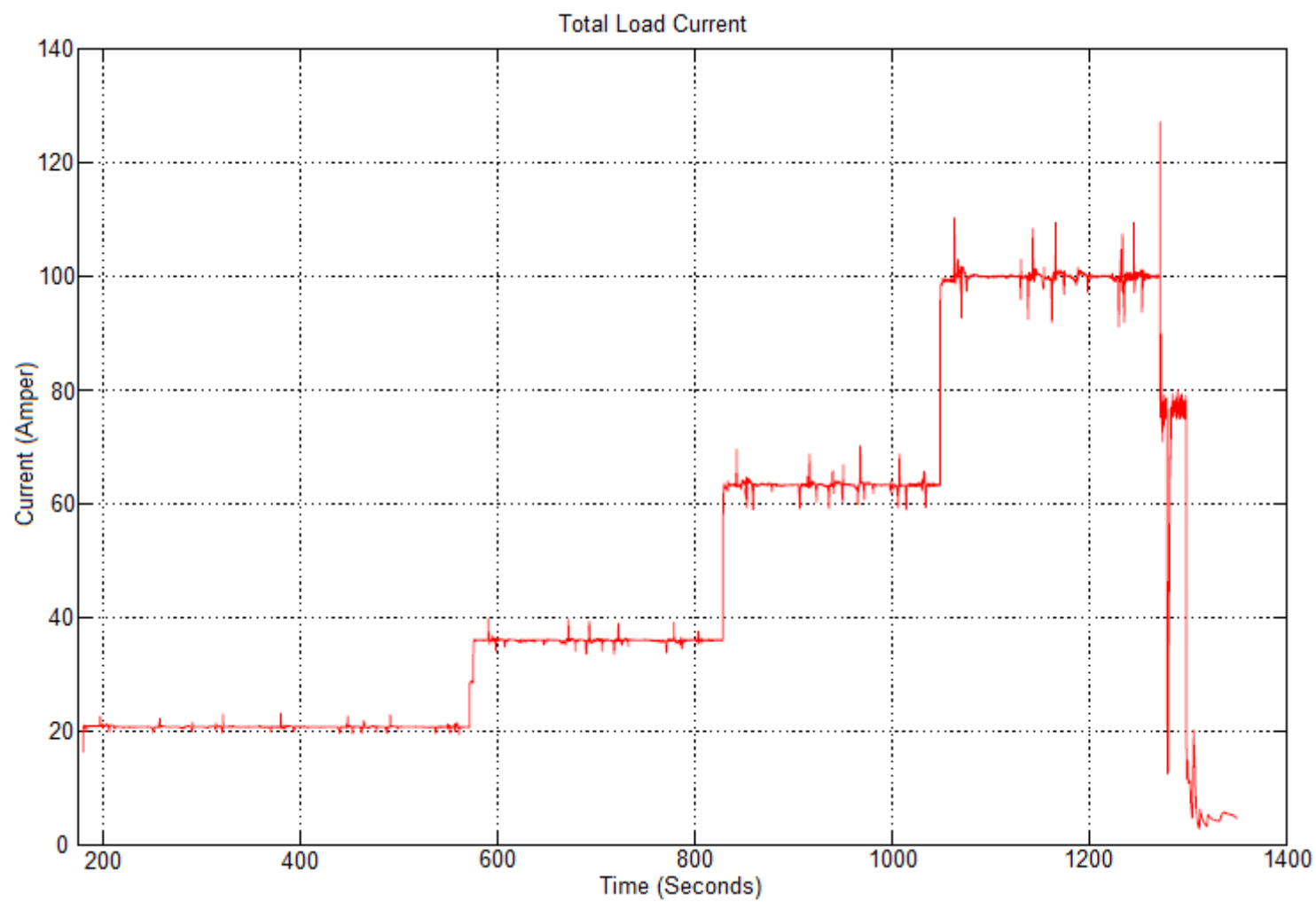
**Figure A.5 :** Excitation current in percentage



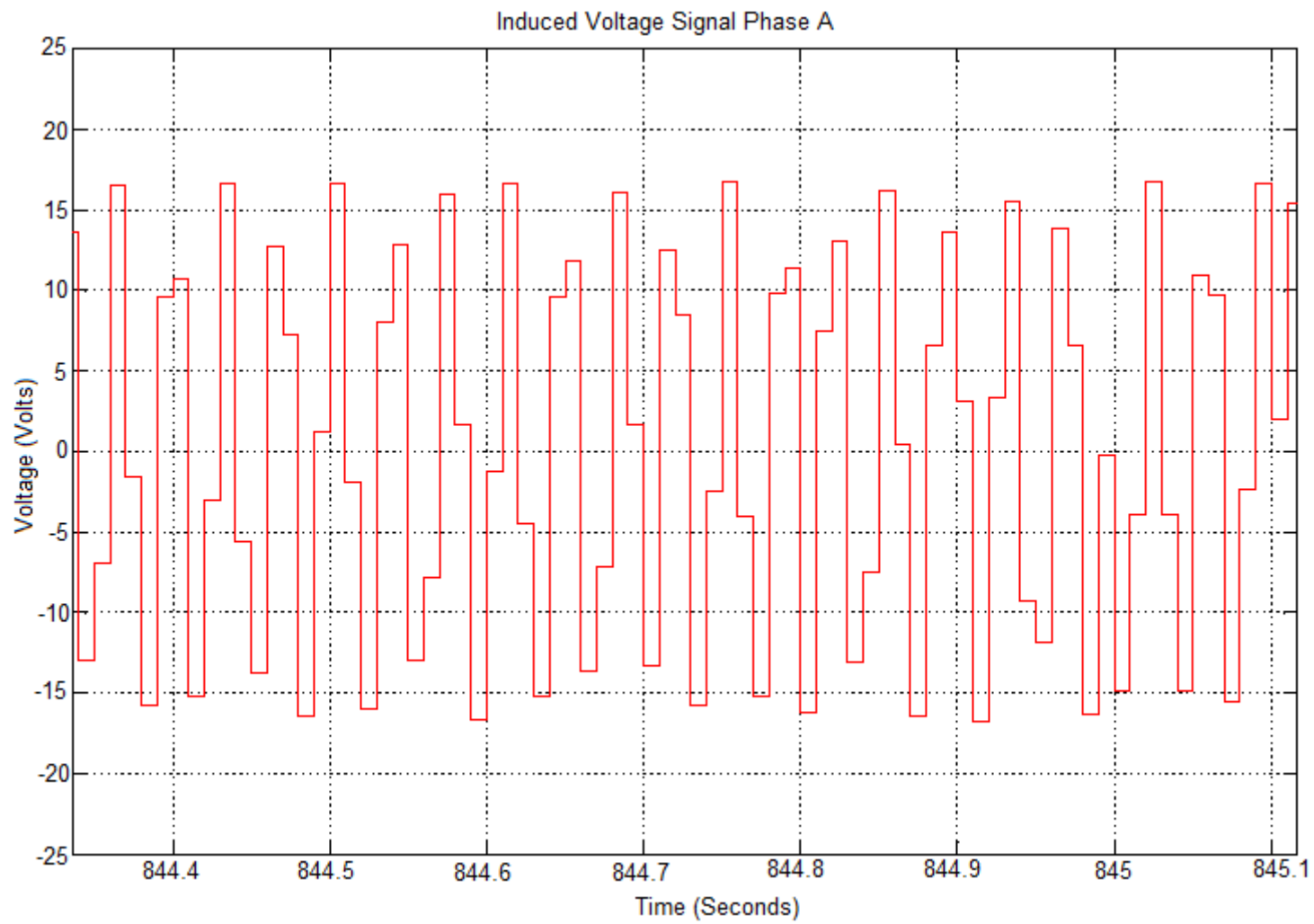
**Figure A.6 : Duty cycle in percentage**



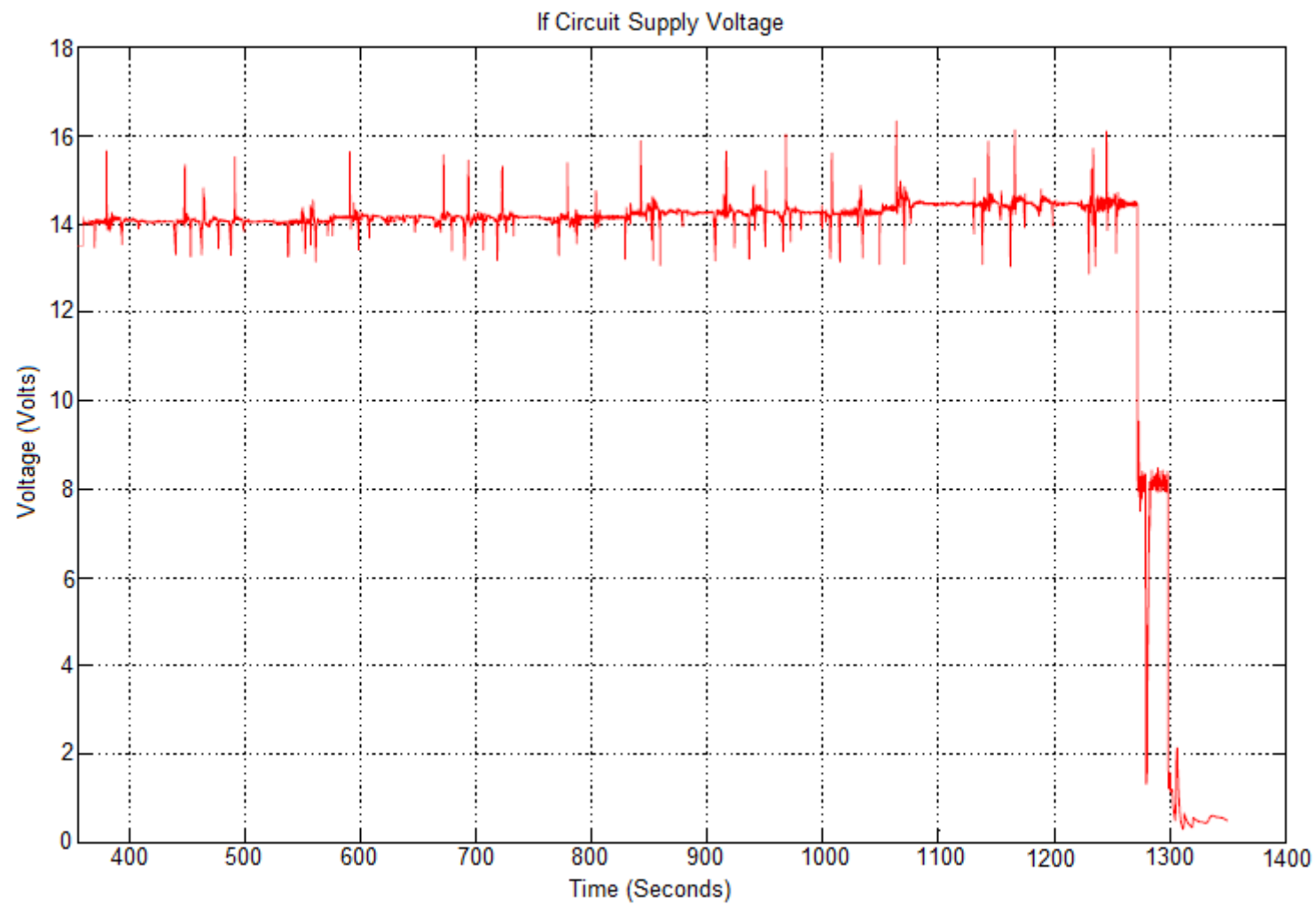
**Figure A.7 :** Total load power



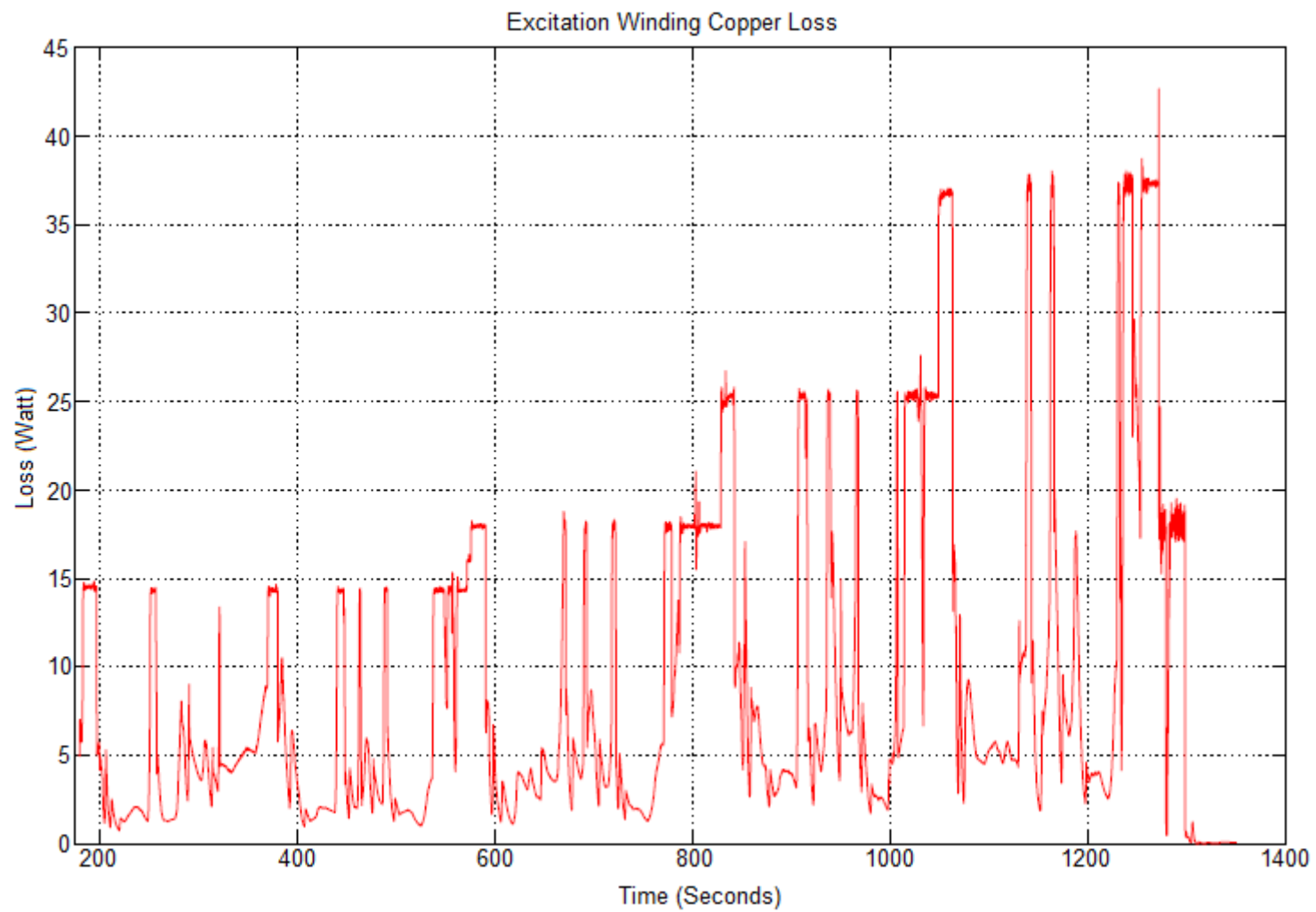
**Figure A.8 :** Total load current



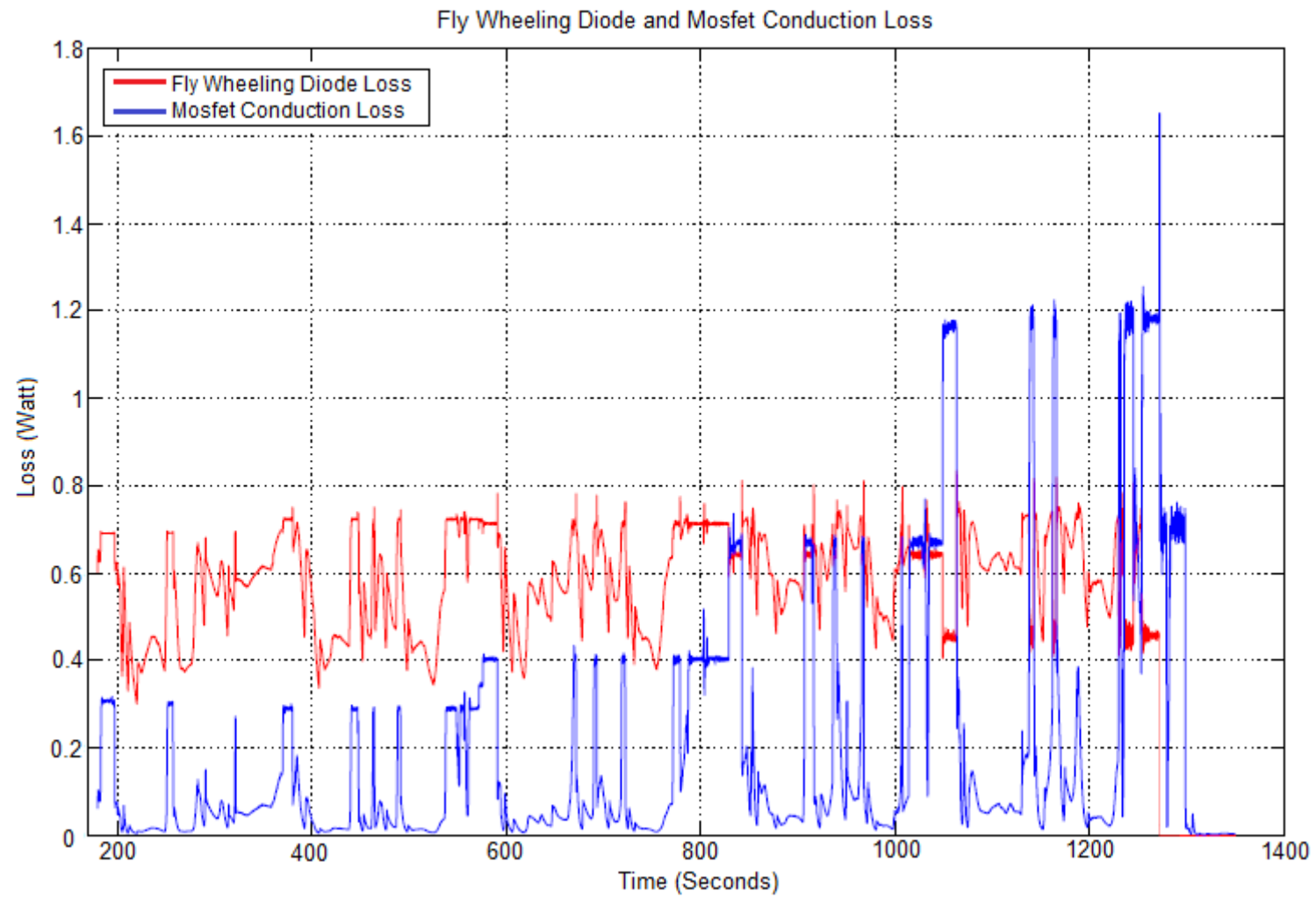
**Figure A.9 :** Induced voltage signal of phase A



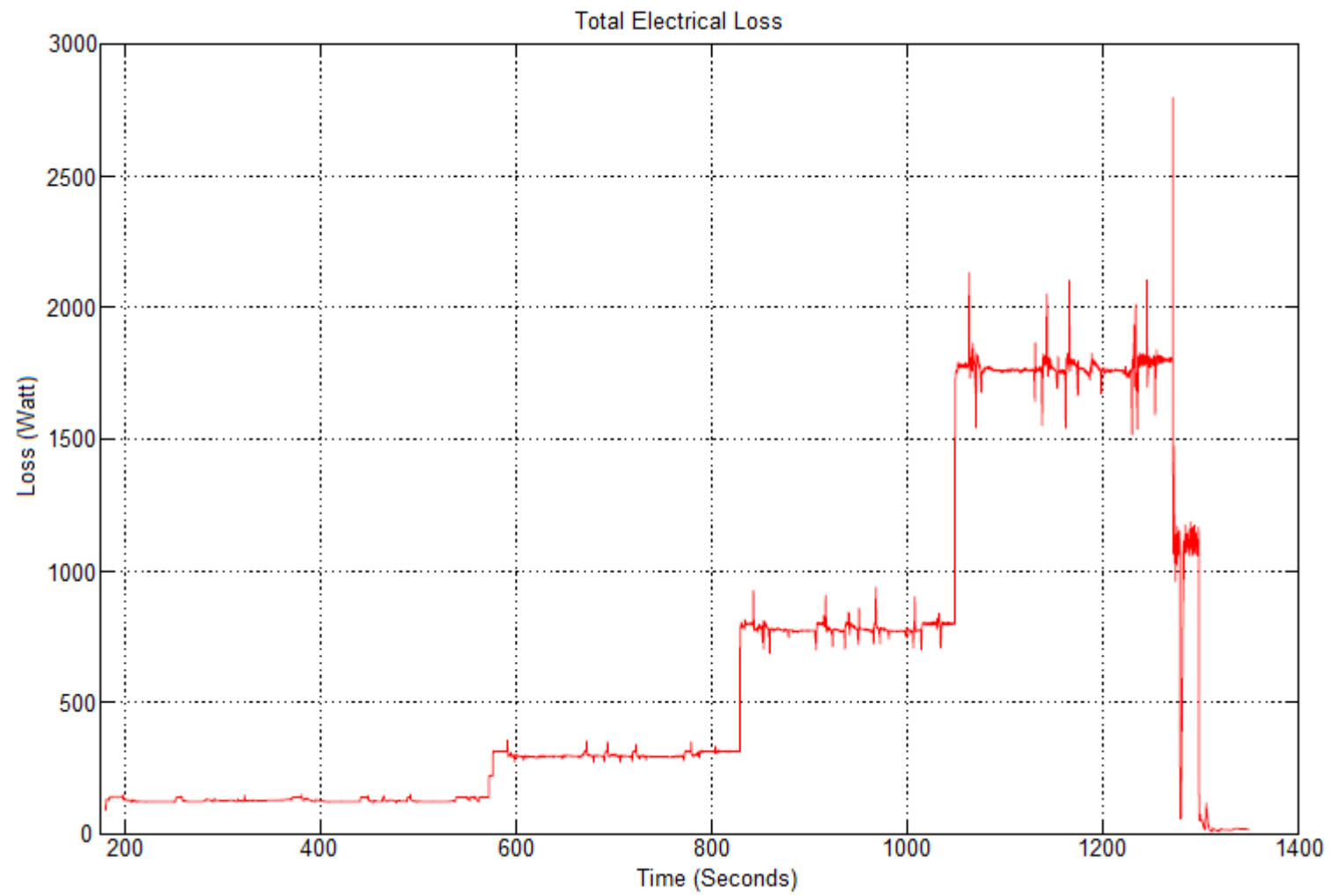
**Figure A.10 :** If circuit supply voltage



**Figure A.11 :** Excitation winding copper loss



**Figure A.12 :** Fly wheeling diode and MOSFET conduction loss comparison



**Figure A.13 :** Total electrical loss



## **CURRICULUM VITAE**

**Name Surname:** Mustafa Gökay Unutulmaz  
**Place and Date of Birth:** Üsküdar and 30/03/1987  
**E-Mail:** unutulmaz@itu.edu.tr  
**B.Sc.:** Istanbul Technical University  
Electrical Engineering  
**M.Sc.:** Istanbul Technical University  
Mechatronics Engineering

## **PUBLICATIONS/PRESENTATIONS ON THE THESIS**

- Unutulmaz M.G., Ergene L.T., Excitation Current Control of A Claw Pole Automotive Alternator. *International Conference on Electric Power and Energy Conversion Systems*, October 2-4, 2013 Istanbul, Turkey.