Low voltage electric system modeling and simulation

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Abstract

The automotive vehicle production industry has become a huge business nowadays. The vehicle market is intense and the competition is hard. Every supplier wants to give their best product and maintenance solution to the vast amount of customers who are eagerly waiting for upgrade versions and new inventions of vehicles. So, a lot of research has been going on in the vehicle industry to provide a comfortable driving and travelling experience to the end user. These research works generally comprise a lot of experiments that require a good amount of time and money. In order to make the experiments faster, easier, and cost-effective it is a good idea to use a software based model. With this software model, the initial feasibility test can be done, and then the finally passed model from the feasibility test can be developed for further practical improvement. So, in this way combination of both the software and practical model will ultimately speed up the research work and make the process more easier and cost-effective. The goal of this thesis report is to develop a software-based model for industrial and marine vehicles.

In this thesis report, the low voltage auxiliary power transmission system of a basic marine vehicle (mainly used for cruise) is investigated. Such a vehicle generally contains an alternator, a battery, and loads (lights, air conditioning system, driving control system, emergency system, etc.)

The main parts of an auxiliary system like the alternator and battery are thoroughly investigated to develop an equivalent model of them that can be applicable in MATLAB SIMULINK software. After developing the model for each part they interlinked with each other. Then finally the results are compared with the practical output.

Acknowledgements

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Chapter 1

Introduction

1.1 Introduction

With the advancement of technology the scattered world is becoming integrated and even the most cornered and underdeveloped locations are coming into focus. So, transportation of products and people are becoming a more vital agenda. People are using vehicles more often and are spending much time in vehicles while traveling. Another application of vehicles are the heavy load vehicles which are used in industrial applications such as product carrying and lifting. So, the demand for smoothly operated and comfortable vehicles are increasing and also there are diversified demands of users. Keeping these things in mind manufacturers are investing money for research of advanced vehicles with modern, smooth and precise operation.

Every vehicle whether it is an ICE, electric or hybrid has an electric supply system which is normally a low voltage system to meet the users demand. This system produces electricity, stores the electric energy and supplies electricity to loads such as lights, ac, driving control display, electronic gadget charging facility etc. More specifically it contains an alternator to produce electricity, a battery to store the electric energy and obviously the diversified load to consume the electricity. In this report this electric system will be addressed as an auxiliary electrical system.

1.2 Background

The auxiliary electrical system of a vehicle should be designed in such a way so that the supply of electricity must meet the demands of loads in the vehicle. At the same time the loss of energy must be feasibly minimized to keep the cost reasonably low and the power supply must be smooth, uninterrupted and of good quality. In order to maintain all these requirements, a thorough and in depth investigation is needed to design and develop the electric system of vehicles based on particular application, load criteria and system operation. It is normally done by developing a test cell of a particular vehicles' auxiliary electrical system and then doing a lot of testing including trial and error. This process requires a good amount of time, work force and money which in turn reduces the efficiency of the whole design and development work. If the research and development (R and D) team can use a computer model for such testing primarily, develop the design based on the computer model simulation and then apply it on physical test cells then it will be a more sustainable solution, will greatly facilitate the design and production phase and will increase the efficiency of the whole process.

The background of this thesis evolves from this scenario and will mainly be performed for marine applications.

1.3 Aim

The aim of this thesis is to develop and provide an electric system model for vehicle auxiliary electrical power systems 12V/24V, viable with different component specific input-parameters including batteries, loads and power sources e.g alternators.

1.4 Scope

The scope of this thesis is currently available vehicle auxiliary electrical system set ups in marine applications. Also, this project is not intended to build any generic physical electric system for vehicles. This projects' extent is the investigation of the existing auxiliary electrical systems. The development phase will be confined in MATLAB simulink software. And as potential literature study, academic papers on electric vehicle simulation will be thoroughly investigated as needed.

1.5 Environmental aspects

Since the outcome of this project is going to replace the existing hardware based experiments by software based experiments therefore the use of equipment in experiments will be significantly reduced.

In existing experimental scenario, if an equipment is completely damaged during experiment then it is needed to be dumped. The dumping processes of damaged equipment cause environmental pollution.

Another important thing is reduced usage of experimental equipment will reduce demand of the equipment and is therefore need less production of the equipment. So, any production related environmental pollution will be reduced if use of equipment is reduced.

Therefore, this project is going to offer an environment friendly outcome.

Chapter 2

Theory

In this section, the theoretical background of low voltage electric system components specially for vehicle applications (auxiliary electric system) will be thoroughly discussed. It also includes the applicable equivalent circuits (that are needed for MATLAB implementation) of necessary components and the determination process of parameters.

2.1 Vehicle's auxiliary electric system

The power train of a vehicle regardless of its application must contain a traction system and an auxiliary system. The traction system is responsible for generation of traction force that enables the vehicle to move and may contain an Internal Combustion Engine (ICE) or an Electric Machine (EM), vehicle wheels or propeller, gear system etc. And the auxiliary system is responsible to provide electric power to the control system and other loads that are used for the convenience of the user while the vehicle is moving. The generalized diagram of a vehicle's power train is shown in figure 2.1 . This auxiliary system of vehicle is a low voltage system and are composed of an electric power generating device i.e. alternator, an electric power storage device i.e. battery and electric loads to consume power. The interlink between the auxiliary system and the traction system is a connecting belt or pulley arrangement that connects the ICE or EM shaft with the alternator shaft so that the alternator shaft start to rotate when the engine rotates and generate power while the vehicle is active.

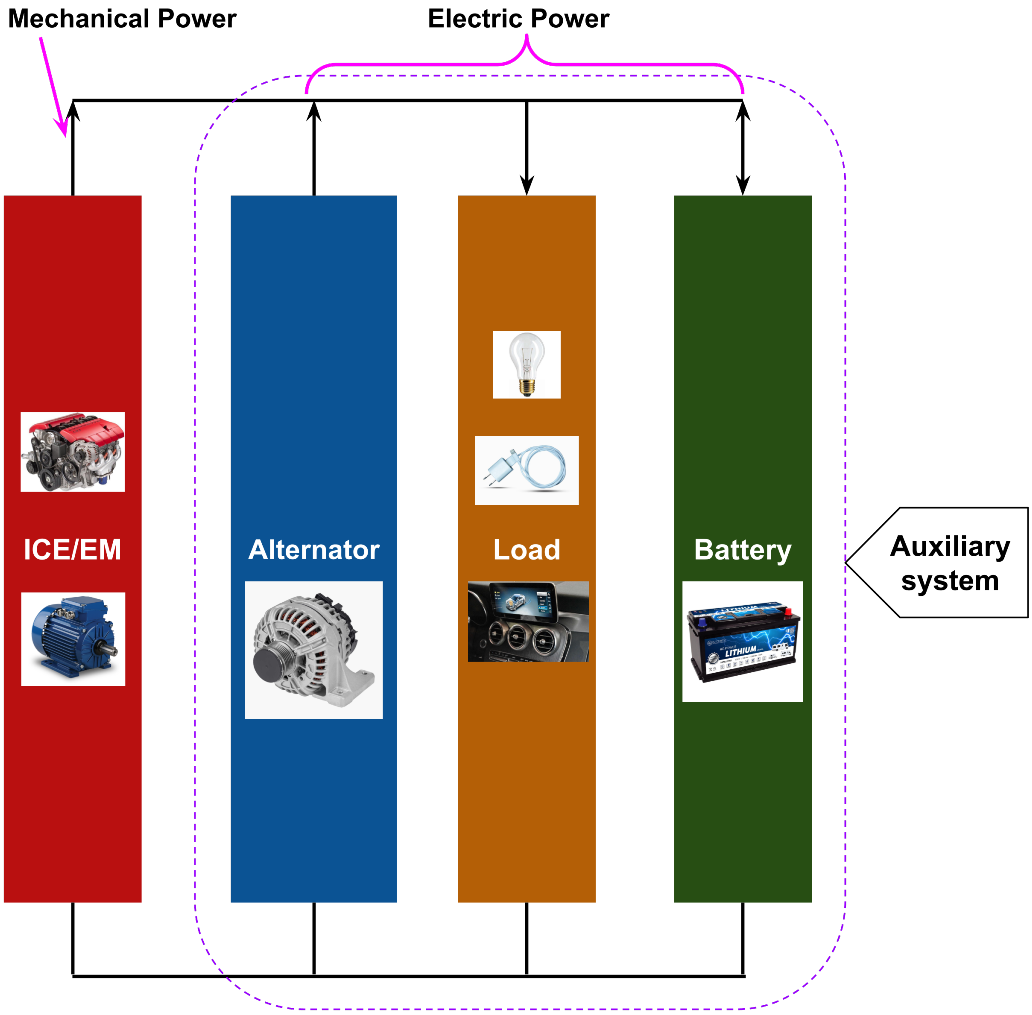

Figure 2.1: Generalized diagram of vehicle's power train

2.2 Components of vehicle's auxiliary electric system

As described earlier, an automotive vehicle's auxiliary system generally comprises of an alternator to generate power for the loads, a battery to store generated surplus electric power and supply the stored electric power (to the alternator's field winding at starting and to the loads when it is needed) and finally loads that are going to consume electric power from the system.

In this section, the basics of these auxiliary system components will be thoroughly investigated such as how they work, what is their circuit diagram, what are the components etc.

2.2.1 Alternator

An alternator is a self-rectifying AC generator that converts mechanical energy to electrical energy in the form of AC and then converts the generated AC power to DC power using a rectifier [8].

The scope of this report mainly concentrated on automotive vehicles' auxiliary electric systems, and such a system generally uses a claw pole alternator for electric power generation due to its simple structure, low cost, and high reliability [12], therefore, the basics of claw pole alternator will be discussed here.

The alternator is called a claw pole alternator because it has rotor pole shoes which have claw like structure. A claw pole alternator contains three main parts: a stator, a rotor and a rectifier as shown in figure 2.2 and figure 2.3. As other types this type of alternators also have two winding setups: stator winding setup in stator (three phase) and rotor winding setup in rotor.

Working Principle

Generally, in a generator, a magnetic field is forced to rotate at an angular speed, which means the associated magnetic flux also rotates. Therefore, the surrounding stationary windings experience a changing magnetic field that, in turn, generates electricity in the windings and is then collected as output. Same action happens in the claw pole alternator.

At first, a DC voltage is applied across the rotor field winding and the rotor core around which the windings are winded becomes an electromagnet due to electromagnetic induction. Now, if this electromagnet in the rotor can be moved at an angular speed with the rotor shaft then as described earlier electricity will be generated in the surrounding stator windings according to Faraday's law of electromagnetic induction.

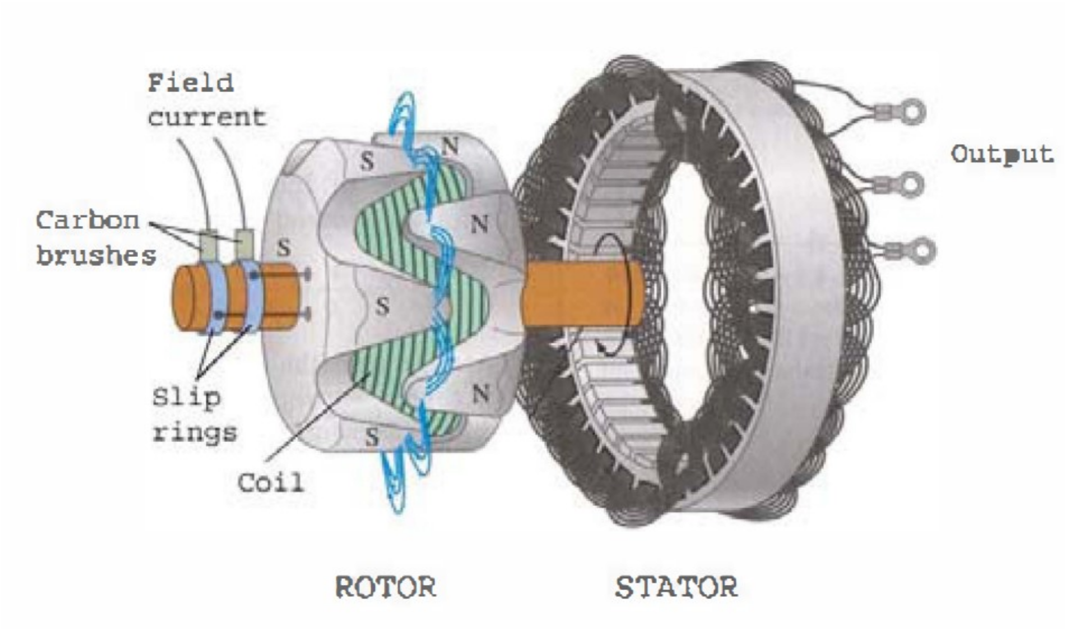

Figure 2.2: Electric Power generating parts of a claw pole alternator [11]

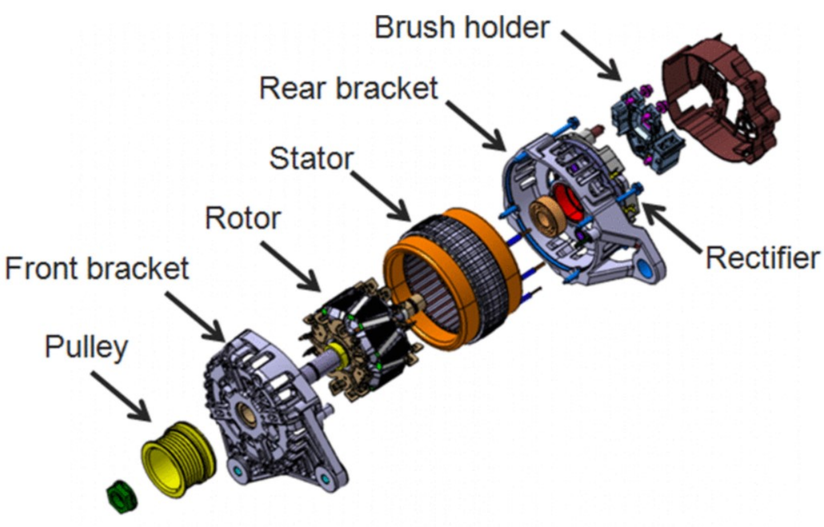

Figure 2.3: Exploded view of alternator [6]

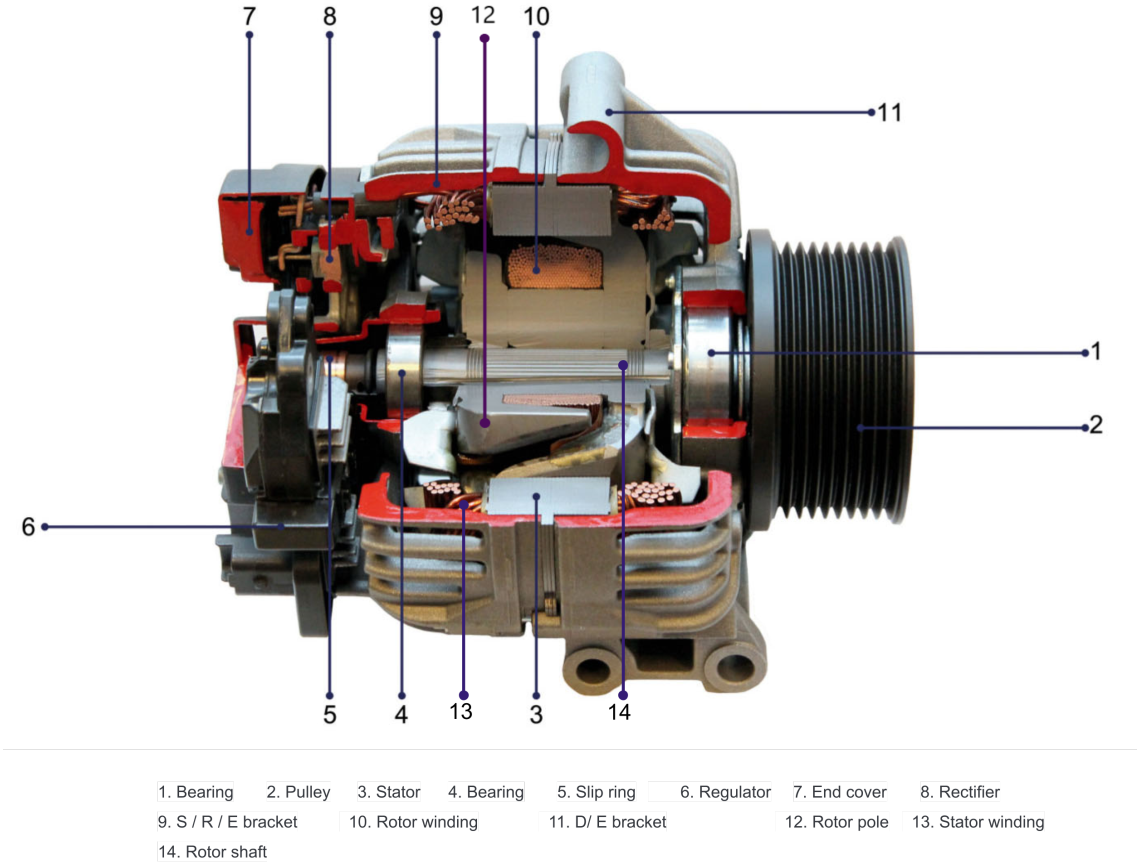

Figure 2.4: Inside view of an alternator [1]

Description of alternator parts

A brief discussion of alternator parts are given in this sections.

Stator

The stator of a claw pole alternator is the stationary part which have three phase windings. AC voltage is generated across these windings due to the electromagnetic actions between the rotor and stator. This generated voltage is then fed to a 3 phase rectifier. Stator windings are wound around the periphery of stator bars that are mainly made of a magnetic material such as iron. These bars are collectively placed in circular fashion around the rotor with small airgap between the stator and rotor to give the rotor freedom to move freely around its shaft.Firure 2.5 and 2.6 shows a disassembled stator from an alternator.

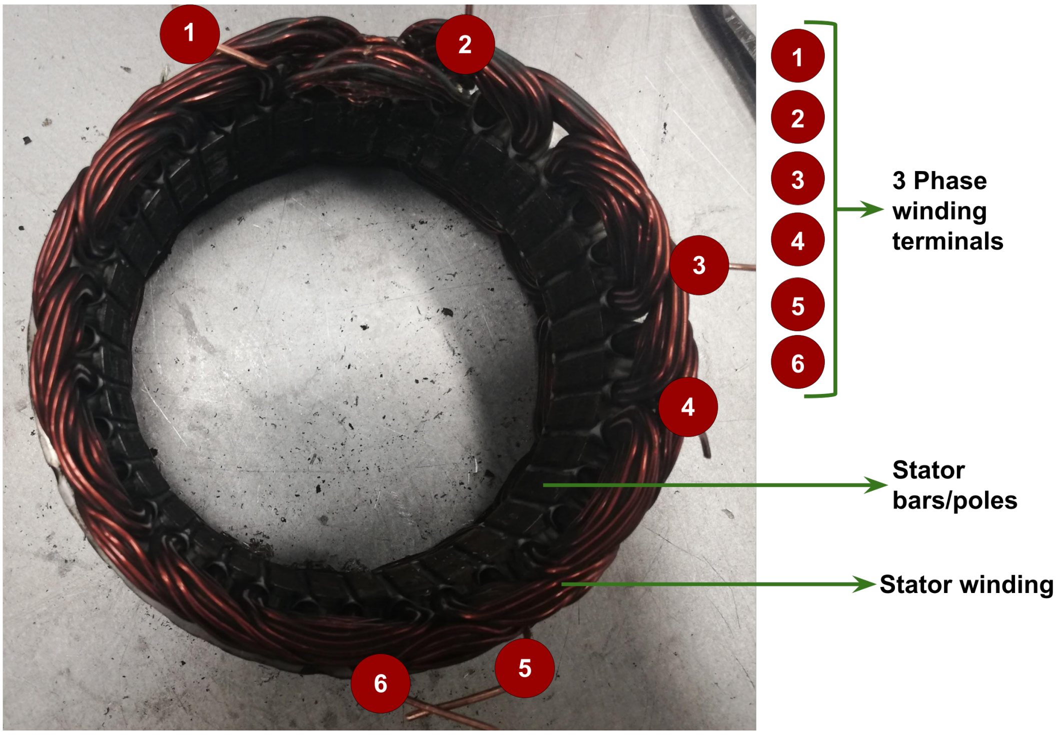

Figure 2.5: Top view of stator winding

Figure 2.6: Side view of stator winding

Claw pole Rotor

Rotor is the rotating part of an alternator. It has a shaft placed longitudinally at the center around which the rotor rotated. The rotor winding is wound around this shaft radially. This winding is generally made of solid copper wire with thin coating of lacquer or varnish as insulation [8]. This thin coating makes the rotor eligible to maximum number of turns and minimum space taken up by insulation [8]. The two ends of the winding are connected with two slip rings near one end of the shaft. These slip rings provide dc power to the winding to generate electromagnet. Two thick metal circular discs with several longitudinal trapezoidal shaped extensions which gives the thick discs a claw like shape are placed at the two ends of the shaft. These longitudinal extensions of thick discs are assembled in such a manner so that these extensions are facing each other and one extension of one disc comes after one extension of the other disc. And in such a way the two claw shaped thick discs covered the shaft winding but still there is enough space between extensions of the thick discs. A claw pole rotor and it's parts are shown in figure 2.7. The number of extensions of both discs are same and these extensions become the rotor pole when a dc current flows through the rotor winding. So the total number of pole is double of the number of extensions of a disc.

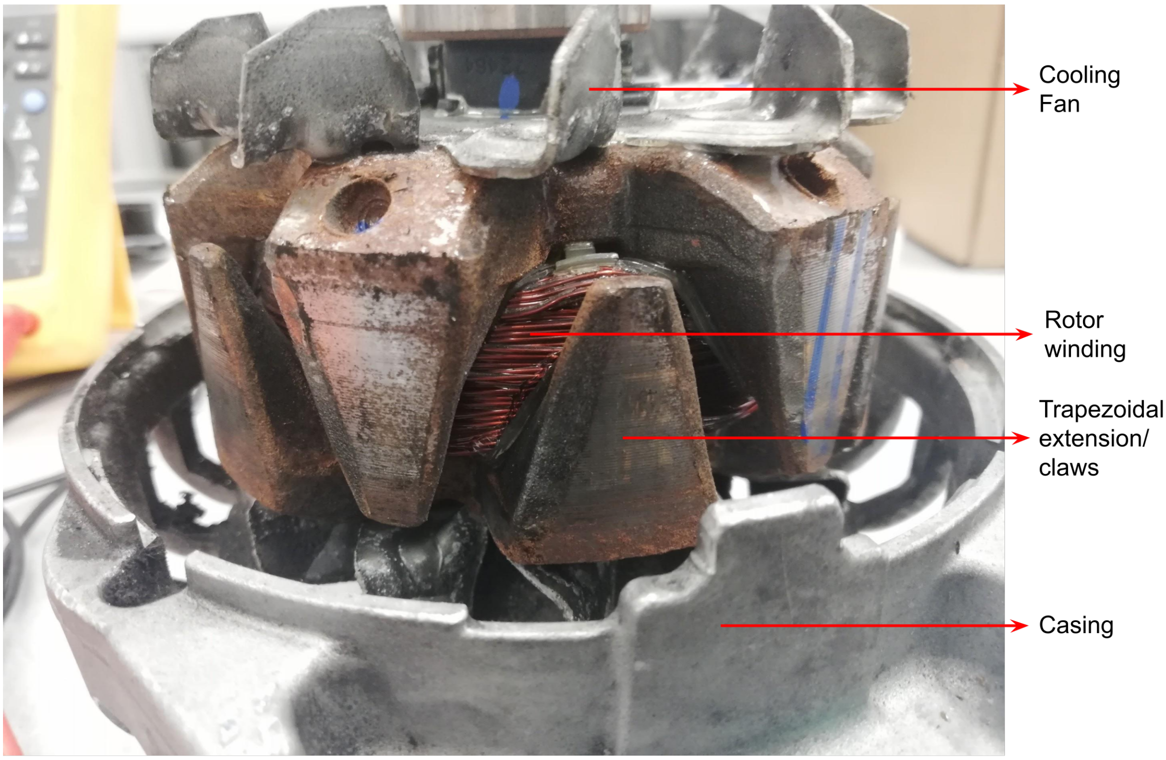

Figure 2.7: A Claw pole rotor [7]

Figure 2.8 shows the general flux distribution of claw pole rotor. When a DC voltage is applied across the rotor winding terminals then magnetic flux is generated in the winding core or rotor shaft. this magnetic flux will follow the core and then will follow the circular disc since the magnetic permeability of iron is much higher than the magnetic permeability of air. Then these flux will follow all the way to the claw shaped extensions as shown in the figure 2.8 and hence magnetic poles will be appeared here.

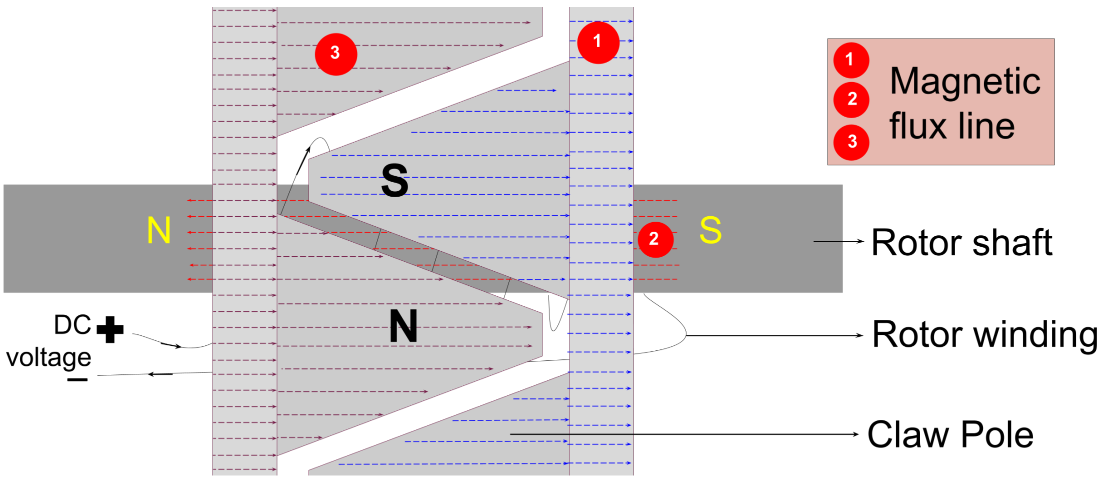

Figure 2.8: Rotor flux distribution

Rectifier

Rectifier is an electrical device that is used to convert an AC signal to a DC signal. In an automotive vehicle's alternator, a rectifier plays a vital role in converting AC power to DC power. The rectifier in alternator is fed with the generated three phase AC power from the stator, rectify this three phase AC power to DC power and then supply the output DC power to the battery and load. A three phase full bridge rectifier is used to serve the purpose.

A three phase full bridge rectifier consists of six diodes. Each two diodes are connected in series with each other in such a manner that the cathode of one diode is connected with the anode of another diode. So there will be three sets of diode series connections each set have one open anode terminal and one open cathode terminal. The open anode terminals of these three diode sets are connected together and so as the open cathode terminals. This rectifier have three input terminals and two output terminals. The connection point between two series connected diodes is a input terminal and therefore three series connected diode sets have three input terminals. The connection points of the open anode terminals and open cathode terminals are the two output terminal. Figure 2.9 shows a three phase diode bridge rectifier.

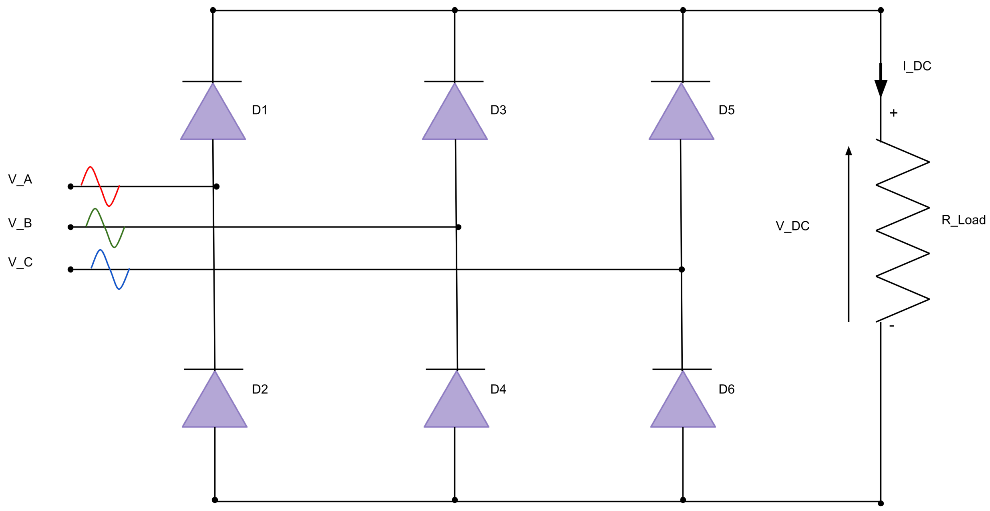

Figure 2.9: 3 phase full bridge rectifier

Diode trio

A diode trio is basically combination of three diodes that are connected between the three phase terminals of the alternator stator and switch of the field circuit to provide excitation power to the field circuit. Diode trio is used in the circuit to isolate the field circuit from the battery during vehicle operation after starting.

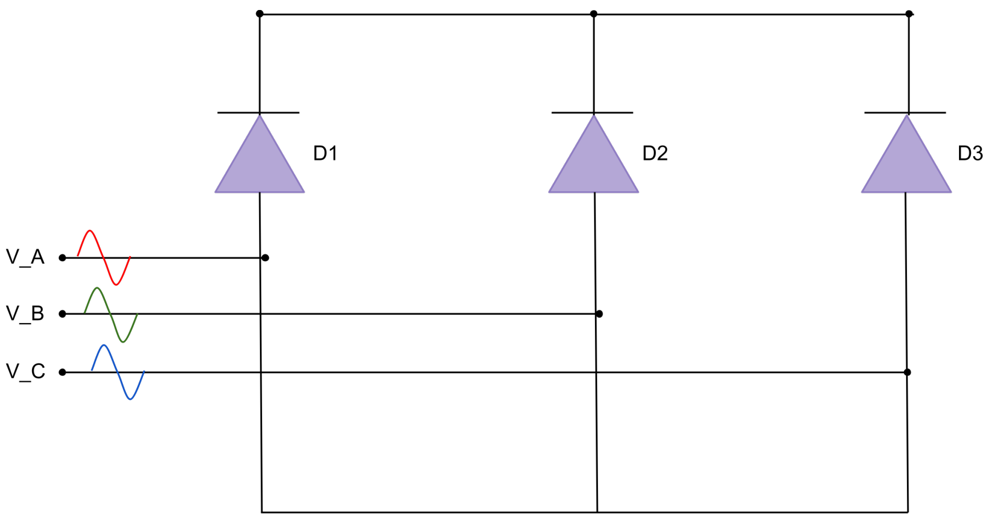

Figure 2.10: Diode trio circuit diagram

Alternator equivalent circuit diagram

Figure 2.11 shows the equivalent circuit of an alternator. Alternator field (rotor) winding terminals are B- and DF where B- is connected with the negative terminal of rectifier. The stator windings are connected with each other by delta connection. They can also be connected with each other by star connection. The three phase terminals are connected with three input terminals of the three phase full bridge rectifier. Therefore the open terminal of the alternator are DF, B+, B- and w where terminal w is taken out from one of the phase terminals.

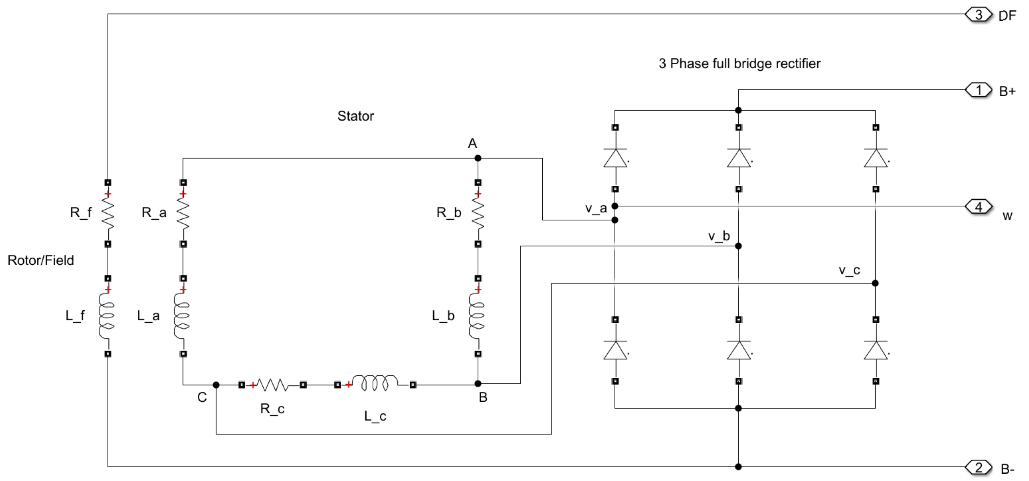

Figure 2.11: Equivalent circuit of an automotive alternator

Alternator Parameters

Parameters that shows in figure 2.12 are the important input parameters to the alternator:

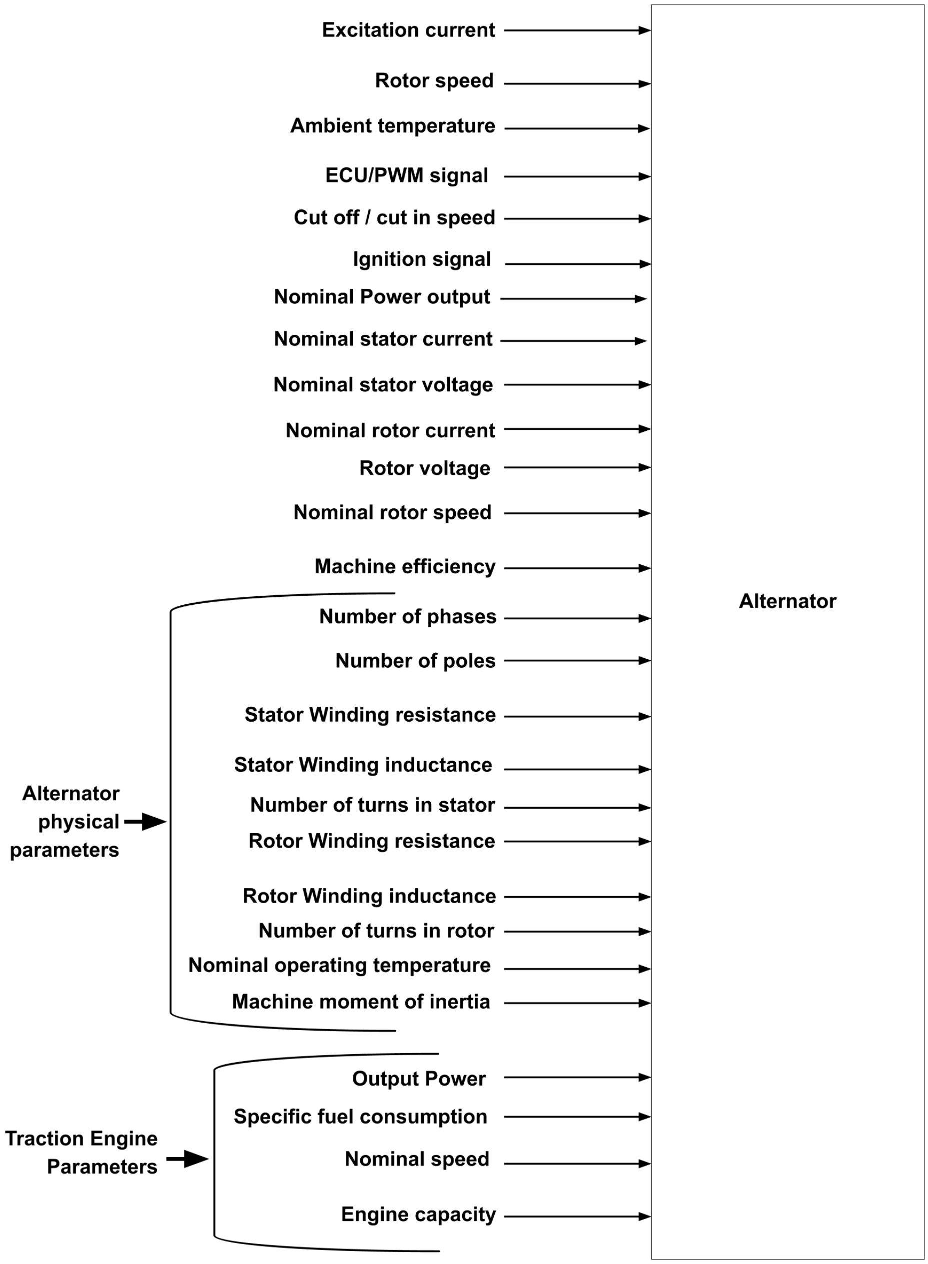

Figure 2.12: Important parameters of alternator

Excitation current: It is the field current applied to the rotor of the alternator to excite the field or create the field flux. When the rotor starts to rotate this field flux acts actively to generate voltage and current in the stator windings. The field current is applied through the battery at the time of starting the engine and as the alternator reaches the cut in speed this field current is applied from its generated current in the stator through a rectifier.

Rotor speed: This is the speed applied to the rotor shaft from the engine via pulley or connecting belt. Along with the generated flux in the field winding, this rotor speed acts as one of the most important parameters to generate voltage at the stator winding.

Excitation current: Ambient temperature is the general air temperature of the environment where the alternator is mounted or placed. Generally the ambient temperature is considered as 200C or 680F. Temperature is an important parameter for smooth alternator operation, because as temperature increases the alternator winding ohmic loss also increases.

ECU/PWM signal: it is the pulse width modulated signal which is a square signal with a specific duty cycle to control the field current in the field winding. Currently, 100

Cut off / cut in speed: It is the minimum speed of the rotor from which the alternator starts to generate enough stator voltage to provide excitation current to the field winding. So, when the alternator speed is more than the cut-off/cut-in speed, the alternator shifts from the pre-excitation mode to self-excitation mode.

Ignition signal: It is the voltage signal that is sent to the alternator regulator when the vehicle starting switch is turned on.

Maximum Power output: It is the rated power output from the stator windings of the machine that can be delivered to the load without any damage.

Maximum stator current: It is the machine-rated current for a stator phase winding at which the machine can be operated without any damage.

Maximum stator voltage: It is the machine-rated voltage for a stator phase winding at which the machine can be operated without any damage.

Maximum rotor current: It is the machine-rated current for a rotor winding at which the machine can be operated without any damage.

Rotor voltage: It is the machine rotor voltage that is needed to be applied in the rotor terminal to generate emf in the stator winding.

Maximum rotor speed: It is the machine-rated speed at which the machine can be operated without any problem.

Machine efficiency: It is the ratio of machine output power to machine input power. It is expressed in percentages. Using this value machine's input power can be determined from the measured output power and also power loss can be calculated.

Alternator physical parameters

Number of phases: It is the number of phases of the generated voltage in the stator windings.

Number of poles: It is the number of poles in the rotor.

Stator Winding resistance: It is the resistance of a stator phase winding

Stator Winding inductance: It is the inductance of a stator phase winding

Number of turns in stator: It is the number of turns in the stator winding

Rotor Winding resistance: It is the resistance of the rotor winding

Rotor Winding inductance: It is the inductance of the rotor winding

Number of turns in rotor: It is the number of turns in the rotor winding

Maximum operating temperature: It is the maximum safe operating temperature at which the machine can be operated without damage or any problem.

Machine moment of inertia: It is the tendency of the alternator rotor to resist changes in rotational speed for a given torque.

Traction Engine Parameters

Output Power: It is the output power that the engine can deliver at the rated speed

Specific fuel consumption: It is defined as the ratio of the fuel consumed per unit time to the generated output power.

Maximum speed: It is the rated speed at which the engine can produce rated power

Engine capacity: It is the maximum volumetric measurement of the fuel that an engine can hold in it, generally expressed in Liter or Cubic Centimeter (cc).

2.2.2 Regulator

A regulator acts as the brain of the alternator that is used to regulate the voltage of the connection point of alternator, battery and loads. Generally regulator is connected with the alternator via direct electrical connection. A regulator consists of an IC (ASIC - Application Specified Integrated Circuit) which mainly regulates the flow of field current to the alternator field winding in order to keep the voltage of the connection point of alternator, battery and loads at a constant value. If the voltage of this point drops then the regulator takes action to increase the field current and hence increase this connection point voltage and exactly opposite will happen when this connection point voltage goes up. The regulator has B+ terminal (positive terminal where battery positive and diode trio positive terminal are connected), GND (ground) and a phase terminal (as shown in figure 2.11) that are connected with it as input. It needs some more inputs for flawless and exact operation. It needs an ignition signal as input which tells it that the system is switched on (i.e. the engine is about to run as well as the alternator) and it becomes activated, a pwm signal that tells the regulator about which voltage value is needed to be maintained and the instantaneous voltage value of the connection point of alternator, battery and load that is needed to be controlled. It has two output terminals (positive and negative) that provides field current to the field winding via two brushes. The ASIC of the regulator decides the amount of field current the regulator needs to deliver to the field winding based on the input signals.

Figure 2.13 shows a basic alternator regulator circuit where ignition signal, PWM signal and control signal terminals are the input terminals that accept inputs from outside of the alternator. Phase voltage terminal (same as w terminal of figure 2.11) is the input terminal of the regulator that receives phase signal from inside of the alternator. B+ terminal is connected with the battery and the diode trio. And the GND terminal is connected with the system ground.

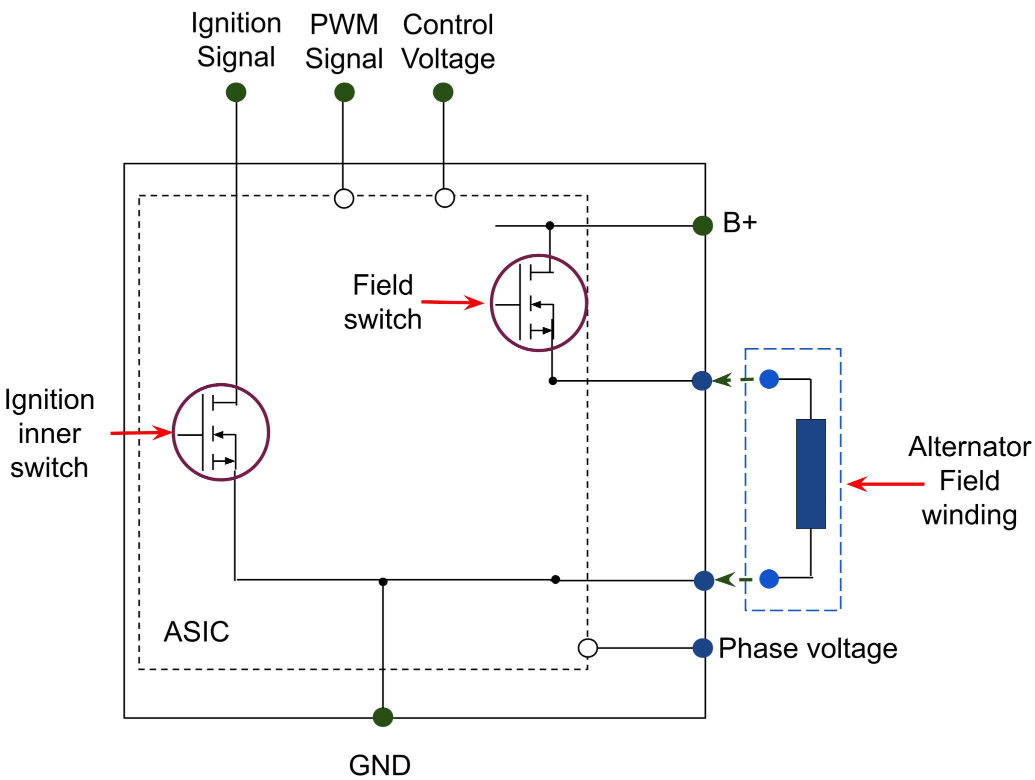

Figure 2.13: Alternator regulator circuit

2.2.3 Battery

The battery is one of the essential components of an auxiliary system of the vehicle. The most common batteries are lead-acid, AGM, and recently lithium-ion batteries. The main objective of the battery is to store the energy and provide power to the auxiliary components of the vehicle. A battery, in general, is called a battery pack, a battery pack consists of battery modules, and battery modules consists of the battery cell. The cell in the battery module is connected in series to increase the voltage level and is connected in parallel to increase the output current level.

Battery parameters[2]

The most important parameters of battery are defined as below:

Nominal Voltage: Nominal voltage defines the rated output voltage of the battery when it is fully charged.

Maximum rated current: Maximum rated current defines how much instantaneous and steady-state current the battery can draw during the operation.

SOC: State of Charge (SOC) is one of the most critical parameters of the battery that indicate the percentage of the battery's usable capacity. Unfortunately, we can't measure SOC directly; instead, it can be estimated based on voltage, current, temperature, and vibration.

Operating temperature: Operating temperature is another important parameter of the battery as it has a significant impact on battery life, health, and safety issues. The operating temperature should be well controlled to increase the battery's performance, lifetime, and safety.

Internal resistance: Internal resistance is a function of SOC and temperature of the battery cell.

Internal polarization resistance and shunt capacitance: Internal polarization resistance and shunt capacitance also are functions of SOC and temperature of the battery cell. The dynamic behavior of the battery will be represented by internal polarization resistance and shunt capacitance.

C rate: The C-rate defines the rate of the battery at which the battery is being charged or discharged within a certain period of time.

Battery technologies:

In the thesis report, two battery technologies are considered: lead-acid battery and Lithium-ion battery.

Lead-acid battery: Lead-acid battery is one of the most widely used battery technology in the automotive industry. The main reason for the vast use of lead-acid batteries is the capability of the supply high surge currents. After many years of research and development, this battery technology becomes the most reliable and robust for the auxiliary electric system of vehicles.

Lithium-ion battery[9][10]: Due to rapid electrification, the lithium-ion battery has become very attractive and famous in the automotive industry. Lithium-ion battery technology has become more promising to the automotive industry because of its high energy density, power rating, and life cycle characteristics. In addition, it can use different applications, such as an auxiliary vehicle system, by replacing the lead acid battery. Depending on the application, the following types of lithium-ion battery chemistry are Lithium Cobalt Oxide, Lithium Manganese Oxide, Lithium Nickel Manganese Cobalt Oxide, Lithium Nickel Cobalt Aluminium Oxide, and Lithium Iron Phosphate. Among the different chemistry of the lithium-ion battery, Lithium Iron Phosphate gives good electrical characteristics due to lower internal resistance.

2.2.4 Loads

Loads are the electrical equipment that are going to consume the generated electricity from the alternator and the stored electricity from the battery.There can be various types of loads that are used in the auxiliary system of an automotive vehicle. Depending on the elapsed operating time loads can be characterized into three main categories: continuous loads, prolonged loads and intermittent loads [3].

Continuous loads are needed to be operated continuously by the system during the active session of the vehicle. The ECUs that are needed to be activated throughout the active session of the vehicle for controlling vehicle's mode of operation are a good example of such load.

Prolonged loads are the loads that are generally activated by the user for a long period of time. Example of such loads are dashboard lights, radio, some side and roof lights, headlights, number plate lights etc [3].

Intermittent loads are the irregular loads that are activated by the used when needed such as ac, indicators, front and rear wipes, interior lights, electric alarm, horns, electronic devices that are needed to be charged etc [3].

2.2.5 MATLAB modelling

MATLAB is a programming and numeric computing platform that allows users to analyse data, develop algorithms and create models [4]. It is widely used in the field like engineering, physics, computational biology, automotive system designing,electronics, control systems, signal processing, data science, power system analysis and design etc.

An additional package named Simulink makes this platform capable for graphical multi-domain simulation and model-based design for dynamic and embedded systems [5].

There are add-ons in MATLAB, that enables it to develop a simulink model in a specialized area. Example of such ad-ons are simscape, powertrain block-set, HDL coder, simulink coder, simulink 3D animation, DSP system toolbox etc.

Chapter 3

System Description

3.1 Auxiliary electric system in marine applications

In this report, the auxiliary electric system of marine application is considered. Figure 3.1 is the diagram of the auxiliary electric system of a boat which contains single engine. Here, when the start switch is turned on or closed the starter battery will be connected to the starter motor which will activate the engine. The turning on or closing of the start switch will also send the ignition signal to the alternator regulator. This ignition signal will activate the regulator and will connect the alternator field circuit with the battery to excite or magnetize the rotor winding. Now, since the engine is activated it started to provide traction force to the vehicle's drive system. The alternator rotor is connected with the engine shaft via a belt. Therefore the speed of engine shaft will be transmitted to alternator rotor via this belt. At the alternator rotor, since the rotor winding is already magnetized, thus as soon as the rotor gets enough speed from the belt, it starts to generate electricity at the alternator's stator winding. This generated ac power passes through a full bridge rectifier to get the dc power output. The alternator regulator keeps track of alternator's speed by frequency evaluation of the stator's phase voltage. When the rotor speed reaches a predefined speed (cut-in speed), the generated voltage at the stator winding becomes higher than the battery voltage. Hence at this stage, the field circuit started to get excitation power from the stator circuit via the rectifier. That means the alternator field circuit is now energized from its own generated power and entered into the self-excitation mode. The sense port of the alternator regulator senses the voltage of the connection point of alternator output, battery, and loads. With this sense signal, the alternator regulator regulates the voltage at this point by altering the current in the alternator field circuit.

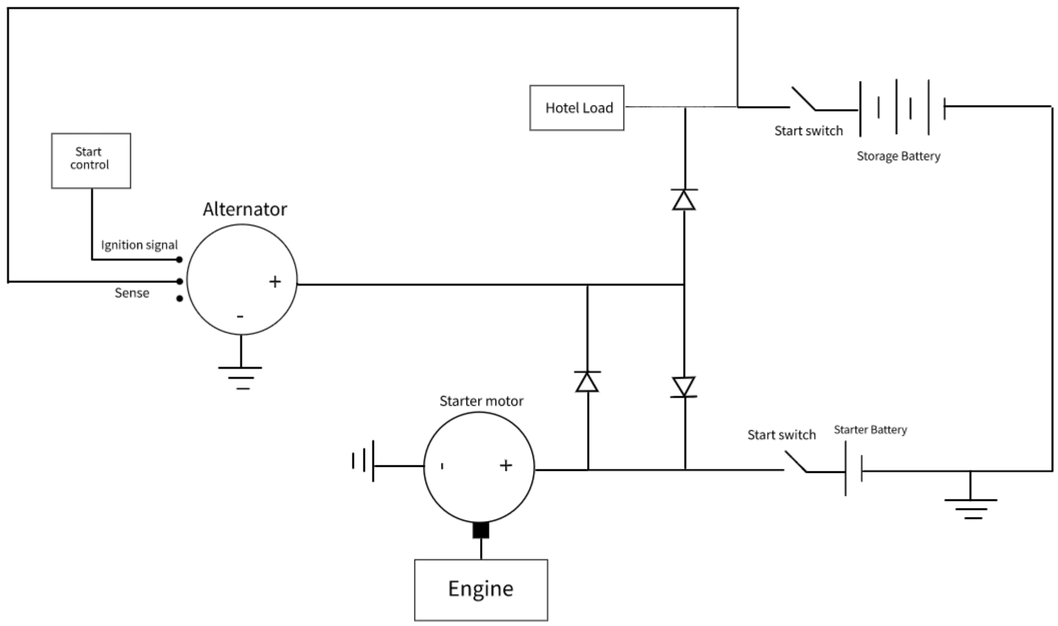

Figure 3.1: A boat's auxiliary system with single engine

The auxiliary electric system of a boat may contain several engines. Figure 3.2 shows such a system where it contains double engines. In such cases a single battery or battery pack can be used depending on the load demand.

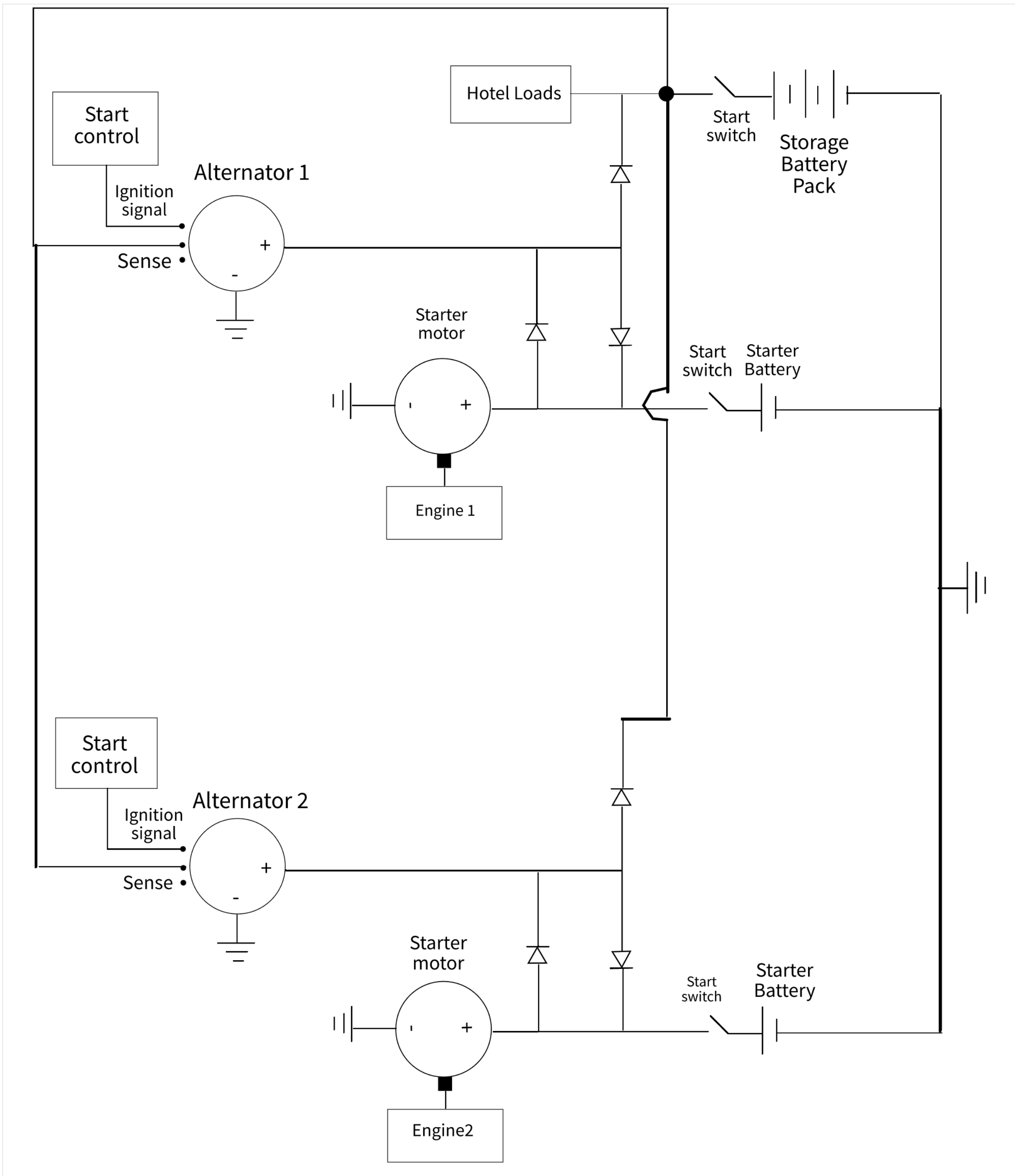

Figure 3.2: A boat's auxiliary system with double engine

3.2 System Flow charts

Figure 3.3 is the flow chart of the system engine. It shows that when the start switch is closed the engine started to generate traction force by consuming fuel. This generated traction force is transferred to the wheel via engine shaft and gear box. And since the engine shaft is connected with the alternator shaft via a pulley or belt the rotational speed of engine shaft will also rotate the alternator shaft. The engine will continue its operation until the start switch is opened.

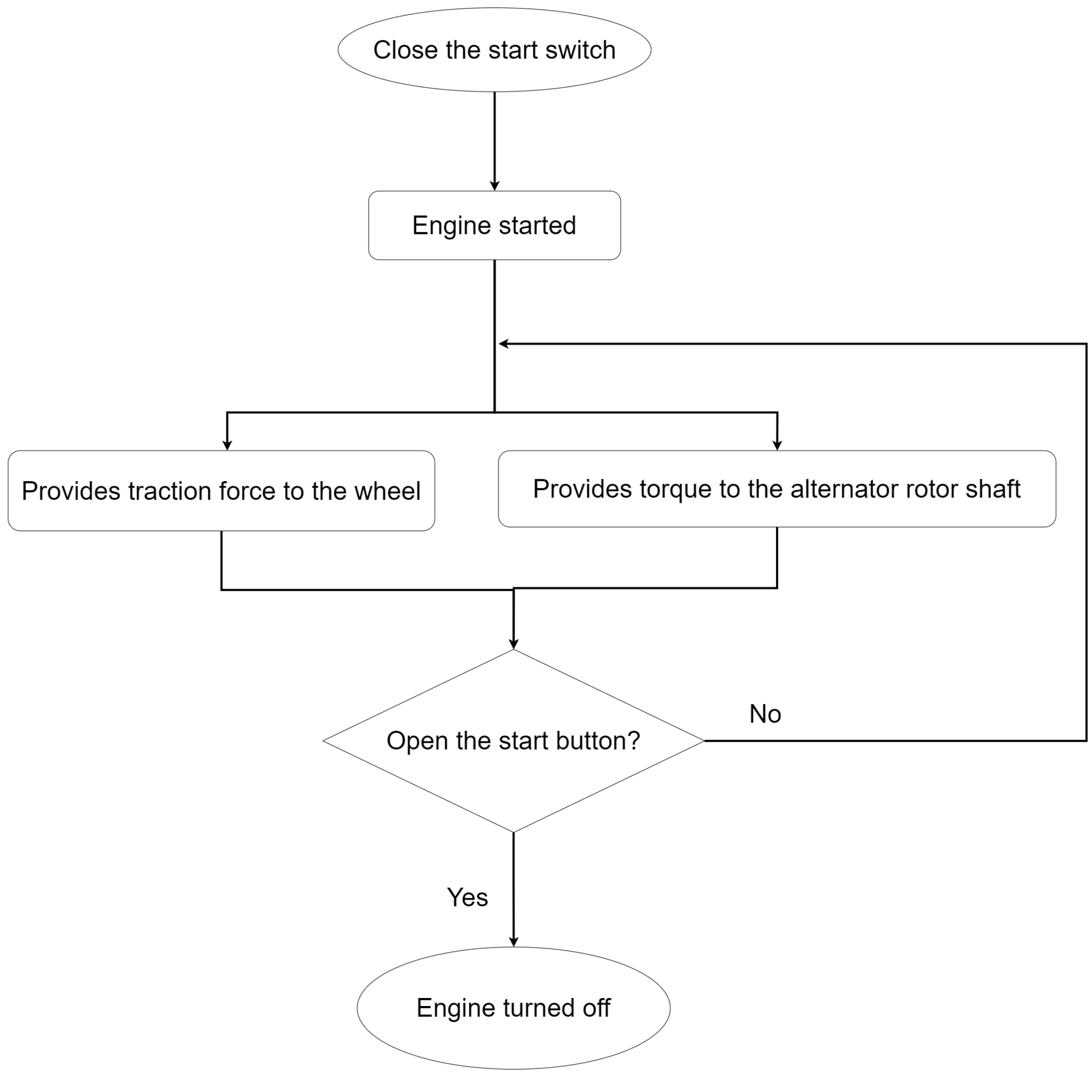

Figure 3.3: Flow chart of engine's working procedure

Figure 3.4 is the flow chart of the system alternator. It shows that when the switch is closed, the alternator's regulator gets the ignition signal and activates. To generate an initial magnetic flux, the regulator begins to supply excitation power to the alternator's field circuit. Also, with the closing of the start switch, the engine starts and begins to provide rotational force to the alternator's rotor via pulley or belt. Because the alternator's field circuit is magnetized and the rotor is rotating, a voltage will begin to be generated at the stator terminal. The regulator determines whether or not the rotor has reached cut-in speed. When the rotor reaches its cut-in speed, the field circuit begins to receive excitation power from the generated power at the stator, and thus enters into self-excitation mode. This self-excitation phase will continue until the start switch is opened. As soon as the start switch is opened, the alternator will be turned off.

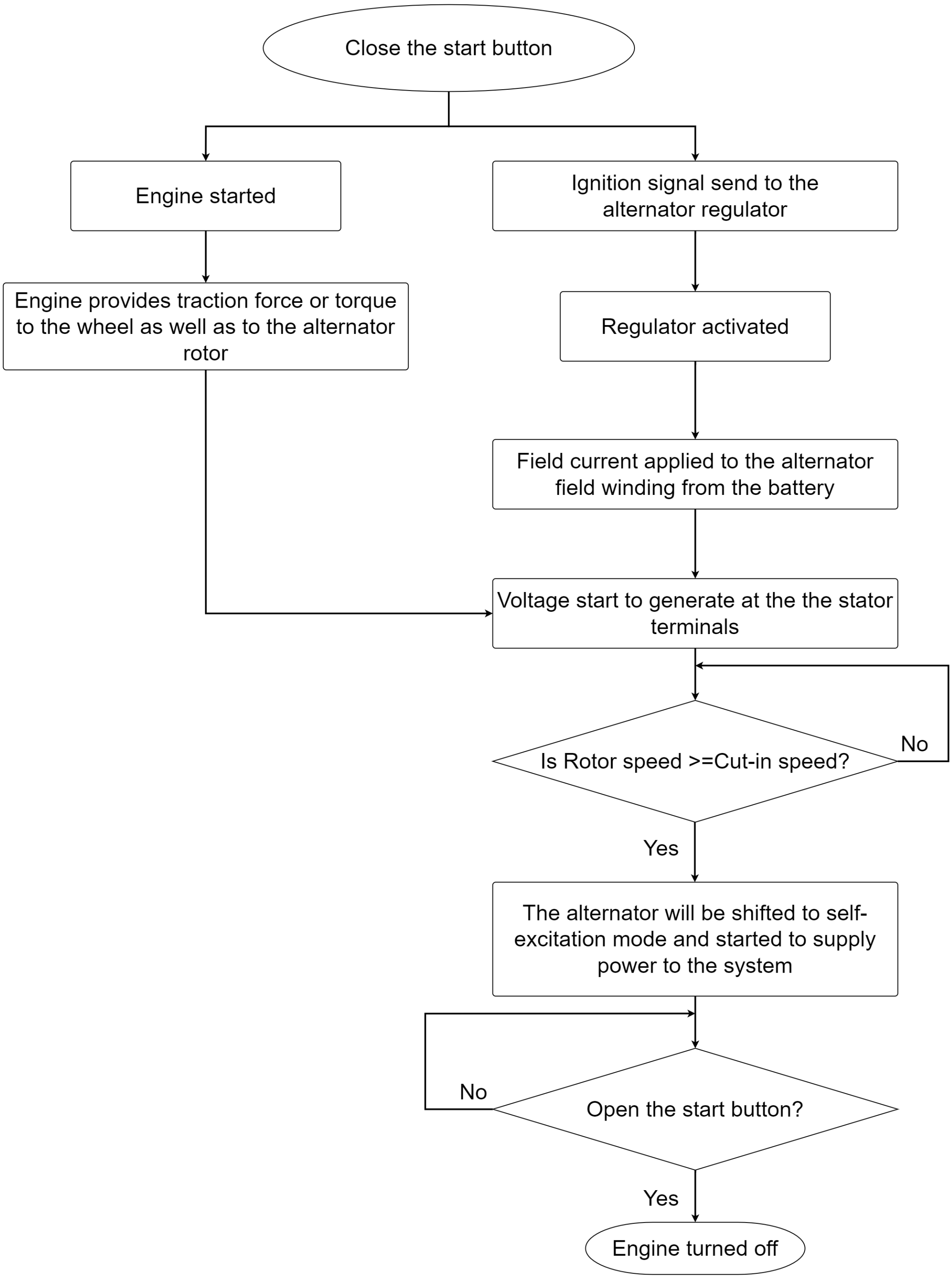

Figure 3.4: Flow chart of alternator's working procedure

Figure 3.4 is the flow chart of the alternator regulator. It shows that when the switch is closed, the alternator's regulator gets the ignition signal and activates. As soon as it activates, it turn on the start lamp and starts to provide initial excitation energy from the battery via a switch in the field circuit. This switch is initially operated at a frequency fixed duty cycle. As the alternator started to generate voltage at stator terminal the regulator starts to evaluate the rotational speed of the rotor by determining the frequency of phase voltage.

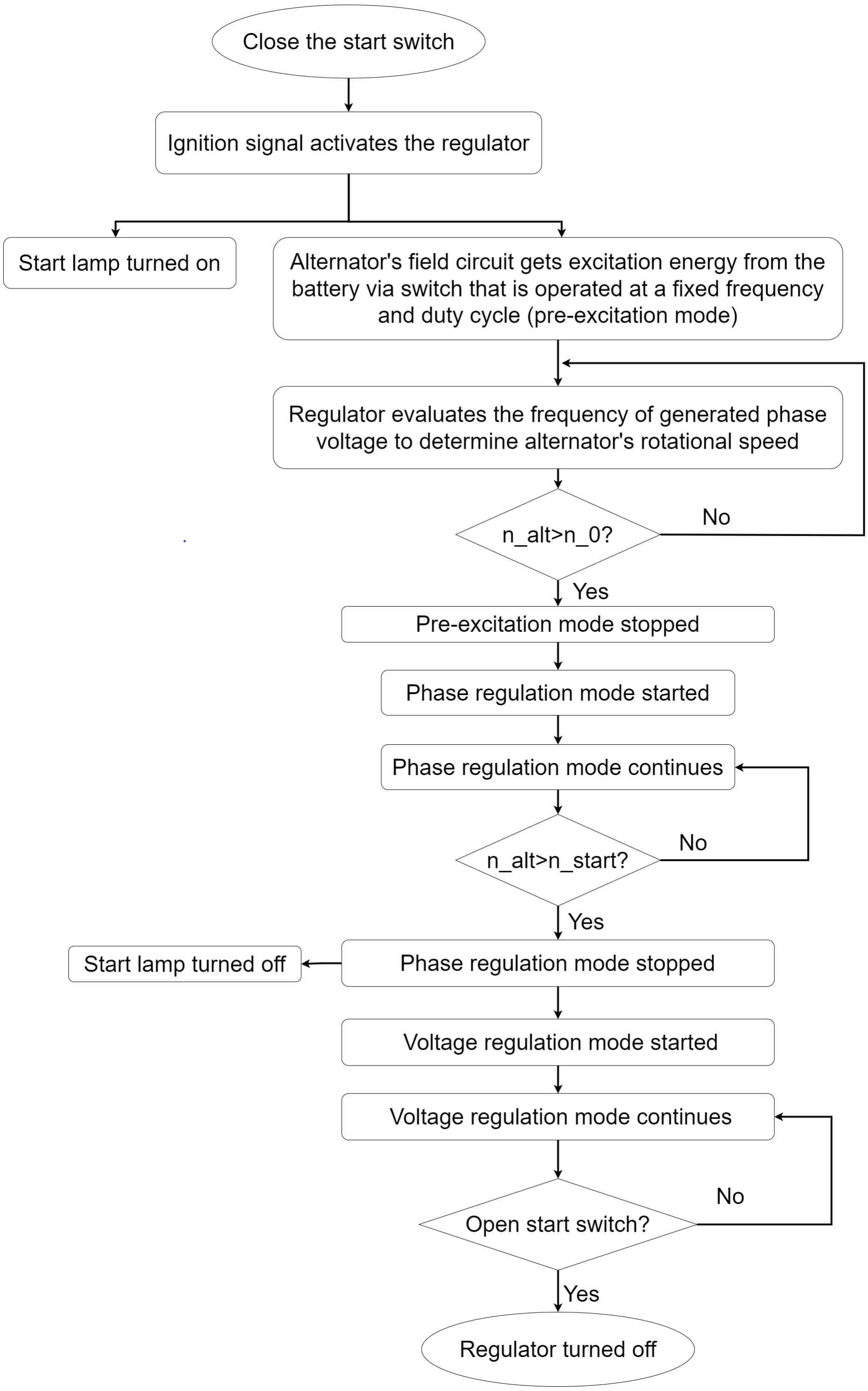

Figure 3.5: Flow chart of regulator's working procedure

Figure 3.6 is the flow chart of the system storage battery. When the start switch is closed the engine will be activated and the BCU will check whether it's SOC level is at a defined minimum level or not. If the SOC is greater than the minimum defined level, the battery will start to provide current to the alternator's field circuit and the system loads. The battery will provide current to the alternator's field circuit until the generated alternator current reaches to a minimum defined level. As the generated alternator current becomes greater than the minimum defined level the battery stops providing current to the field circuit (monitored by alternator regulator). Now if the alternator current is greater than the demanded load current and battery SOC is less than a defined maximum level then the battery will start charging i.e. the battery will be in charging mode until it reaches the maximum defined SOC level and then it will shifted to idle mode until alternator current becomes less than the demanded load current. And if the alternator current is less than the demanded load current and the battery SOC is greater than the defined minimum level then the battery will start providing current to the load until it completely discharged or until the alternator current becomes greater that the demanded load current.

The maximum and minimum level of battery SOC can be defined at any value if a BCU is used in the system. When a BCU is not used in the system then the minimum level of battery SOC is considered as absolute minimum value i.e. 0% and the maximum level of battery SOC is considered as absolute maximum value i.e. 100% as shown in the flow chart.

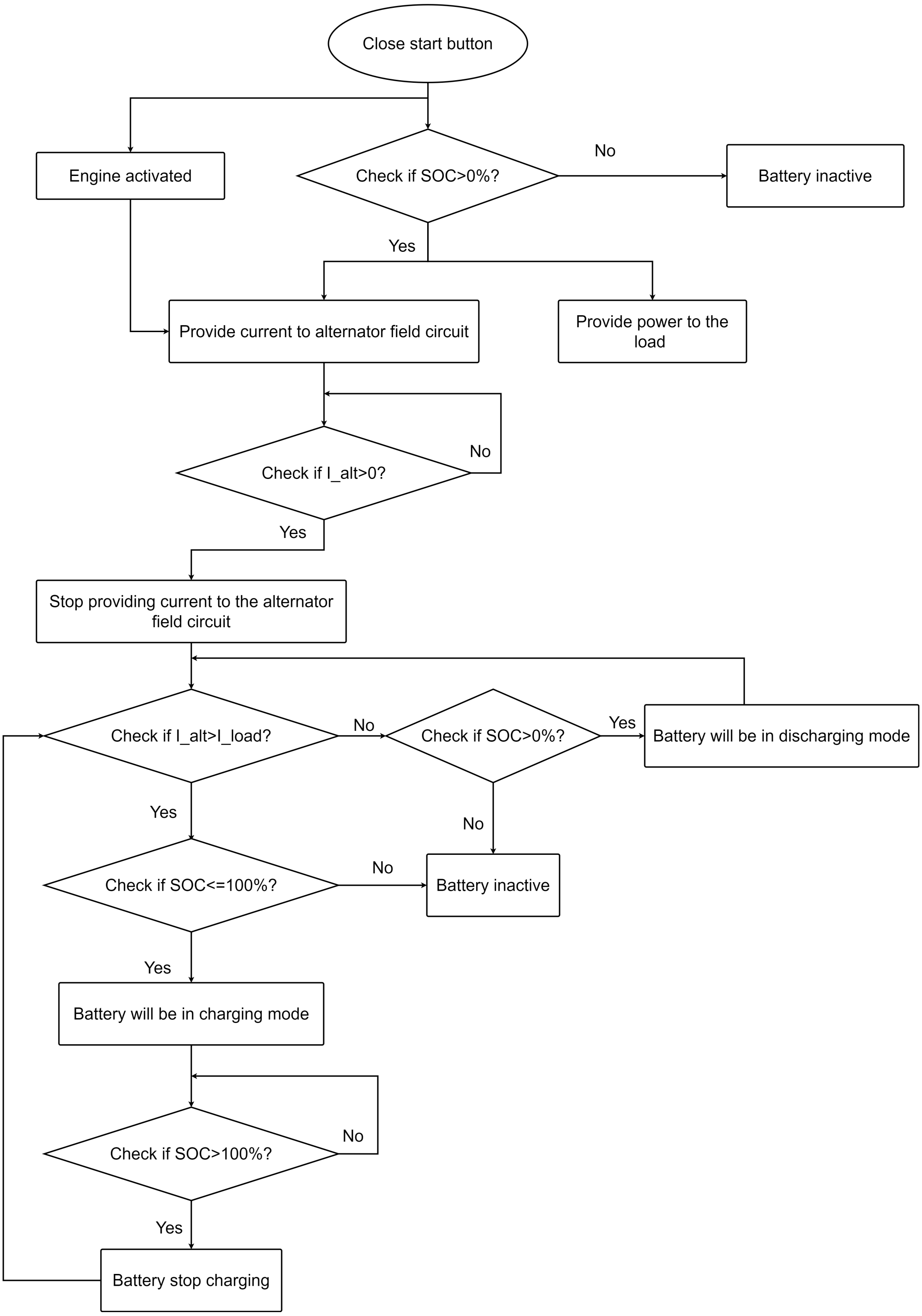

Figure 3.6: Flow chart of battery's working procedure

Chapter 4

Model Development

This part of the report is going to describe how the system components are modelled to implement in MATLAB. For a component to be implementable in MATLAB it is very important to find out the basic relatable operational equations of the device/component or an equivalent circuit or a physical circuit of the device/component that can be applied in MATLAB using available simulink tools.

4.1 Alternator

The alternator is modelled based on the operational equations. As described in section 2.2.1.1, the rotor is modeled as a coil of wire with a core which becomes an electromagnet when a dc current passes through the wire. The stator is also modelled as a coil of wire whose cores are the stator bars and an ac voltage is induced across the coil terminals when the cores/bars encounter a changing magnetic field. And finally, the generated rotor flux will pass through the stator coils. Any flux leakage is ignored in this alternator model.

4.1.1 Rotor model

If a current I is passing through a coil of wire having N number of turns and length L with a magnetic material core as shown in figure 4.1 then in the core there will be a magnetic field and the magnetic field strength or intensity can be expressed as:

$$H = \frac{IN}{L} \tag{4.1}$$

Magnetic field density is:

$$B = \mu H$$

$$or, B = \mu_0 \mu_r H \tag{4.2}$$

where,
μ = magnetic permiability of core material = $\mu_0 \mu_r$
μ_0 = magnetic permiability of air
μ_r = relative magnetic permiability of core material

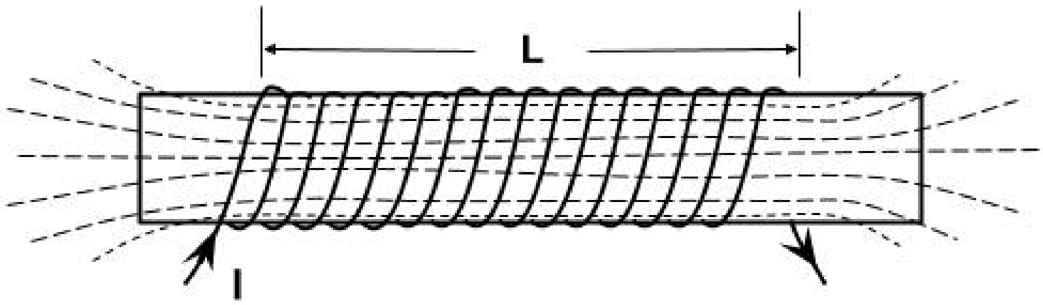

Figure 4.1: Magnetic flux in current carrying coil

Now, magnetic flux generated in rotor is:

$$\phi = BA$$

$$or, \phi = B\pi r^2 \tag{4.3}$$

where,
ϕ = magnetic flux
A = cross sectional area of core
r= radious of core

Now, putting the value of H and B from equation (4.1) and equation (4.2) in equation (4.3) ϕ becomes,

$$\phi = \mu_0 \mu_r \frac{IN}{L} \pi r^2 \tag{4.4}$$

4.1.2 Stator model

If rotor and stator of an alternator have the following parameters such as
P = number of poles in rotor
ϕ = flux per pole
n = rotor speed (in RPM)
f = frequency of the induced emf at the stator phase
Z = number of conductors (stator cores) in series per phase
N_s = number of turns per phase in stator

then in one revolution each stator conductor cuts some flux which can be expressed as:

$$d\phi = P\phi \tag{4.5}$$

Time taken to complete one revolution is

$$dt = \frac{60}{N} \tag{4.6}$$

Now, average EMF induced in one conductor can be found from dividing equation (4.5) by equation (4.6). So, Generated EMF per conductor is,

$$\frac{d\phi}{dt} = \frac{P\phi N}{60} \tag{4.7}$$

Therefore, Generated EMF per phase is,

$$EMF/phase = EMF/conductor * Z = \frac{P\phi N}{60} Z \tag{4.8}$$

Since one turn has trow conductors i.e. Z = $2N_s$
so,

$$EMF/phase = 2\phi f * 2N_s = 4\phi f N_s \tag{4.9}$$

As the rotor rotates the stator experience a changing magnetic field, therefore, the generated voltage is AC and it is sinusoidal. For sinusoidal waveform, the form factor is

$$ff = \frac{RMSValue}{AverageValue} = 1.1 \tag{4.10}$$

Now, the RMS value of EMF/phase of the generated AC waveform can be found by multiplying equation (4.9) and equation (4.10). So,

$$RMSvalueofEMF/phase, E_{ph,RMS} = 4\phi f N_s * 1.1 = 4.4\phi f N_s$$

Taking the winding factor (k_w), coil span factor (k_c) and coil distribution factor (k_d) into consideration, the RMS value of phase voltage becomes,

$$E_{ph,RMS} = 4.4 k_c k_d \phi f N_s = 4.4 k_w \phi f N_s \tag{4.11}$$

where,
$k_w = k_p k_c$

4.2 Battery

There are different kinds of modeling exits to model the battery, electrochemical models, Electric equivalent circuit models, and black-box models. In this report, an Electrical equivalent circuit model is considered. It consists of internal resistance and resistance-capacitance block, where the resistance-capacitance block will present the dynamic behavior of the battery.

Figure 4.2 shows the Thevenin's electrical equivalent circuit model of the battery:

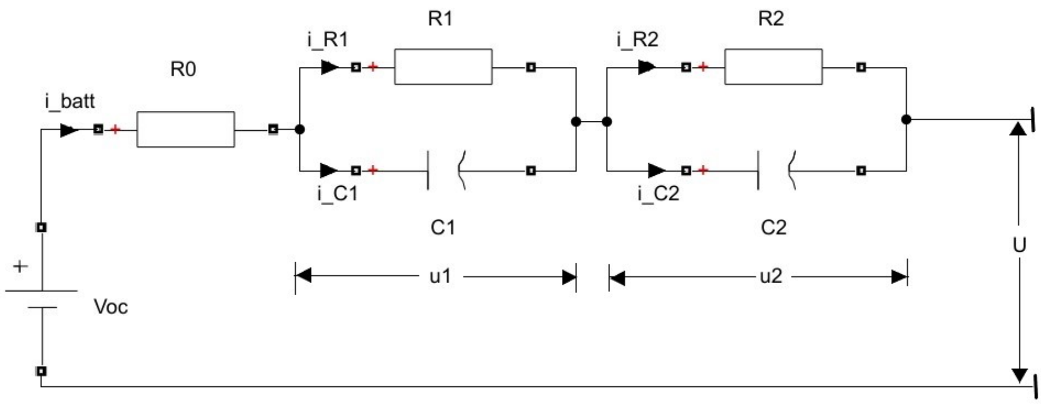

Figure 4.2: Battery electrical equivalent circuit model

The following equation expresses the voltage of the battery:

$$U = V_{oc} - R_0 i_{batt} - u_1 - u_2 \tag{4.12}$$

RC block of the battery represents the transient response of the battery voltage. For example, for the RC block of k, the voltage equation of u_k can be written in the following:

$$R_k i_{batt} = u_k + R_k C_k \frac{u_k}{dt} \tag{4.13}$$

By doing the Laplace transformation, we can find out the u_k in the following:

$$i_{batt} = \frac{u_k}{R_k} + sC_k u_k \tag{4.14}$$

$$u_k = \left(\frac{1}{s}\right)\left[\frac{1}{C_k} - \frac{u_k}{R_k C_k}\right] \tag{4.15}$$

Sate of charge calculation:
The state of the charge at time t can be written in the following equation:

$$SOC(t) = SOC(t_0) - \frac{100}{3600}\int_{t_0}^{t} \frac{i_{batt}(t)}{Q_0} dt \tag{4.16}$$

where, $SOC(t_o)$ is the initial state of charge, i_{batt} is the battery current, Q_o is the initial battery capacity.

4.2.1 Battery parameter extraction for the model

The following equation shows all the parameters that are needed to be extracted. These parameters are the functions of the state of charge and the temperature. An experimental test such that impulse test is needed to be carried out to extract the parameters for the model. As it is out of the scope of the thesis work, paper [9] is used to extract the parameters.

$$R_0 = R_0(SOC.T)$$
$$R_1 = R_1(SOC.T)$$
$$C_1 = C_(SOC.T)$$
$$E_m = E_m(SOC.T)$$

4.3 Loads

To model the loads a simple equivalent circuit is considered. Since the loads are only consuming dc power from the system, therefore, the equivalent circuit for the load is simply considered as a resistor as shown in figure 4.3.

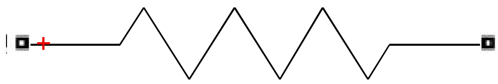

Figure 4.3: Equivalent circuit model of load

4.4 Regulator

The regulator is modeled as the combination of several functional commands and a PI controller.

The functional commands mainly determine the error signal by checking the inputs from PWM signal terminal and control voltage terminal of the regulator.

The PI controller is the main part of the regulator that decides the amount of current that is needed to be send to the alternator rotor based on the error signal(voltage difference between set voltage value and the actual voltage at the connection bus).

Chapter 5

MATLAB implementation

A MATLAB SIMULINK model of the low voltage auxiliary electric system (explained in chapter 3) is finally developed based on the idea described in chapter 4. The SIMULINK model is stated below:

5.1 Alternator model

The alternator model is actualised in simulink based on equation 4.3 and 4.11. After generating the induced emf it is implemented on three phase stator winding circuit developed with simscape blocks as shown in figure 5.1.

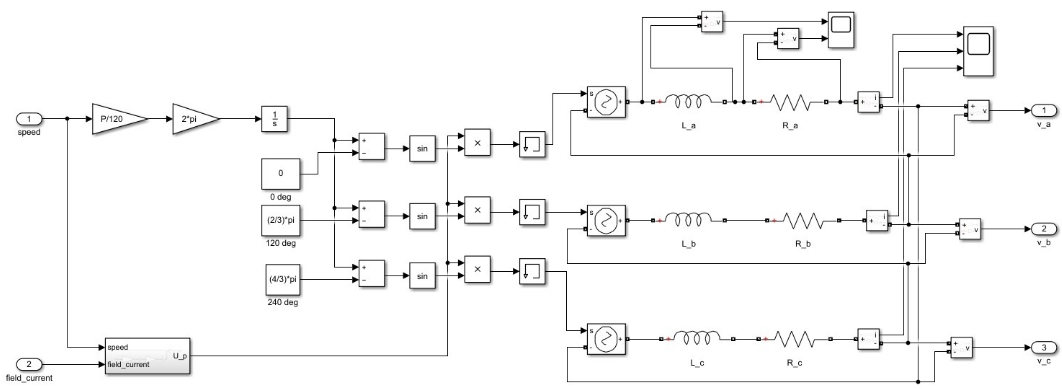

Figure 5.1: MATLAB model of alternator stator and rotor

The rectifier model is actualised in simulink with simscape blocks as shown in figure 5.2.

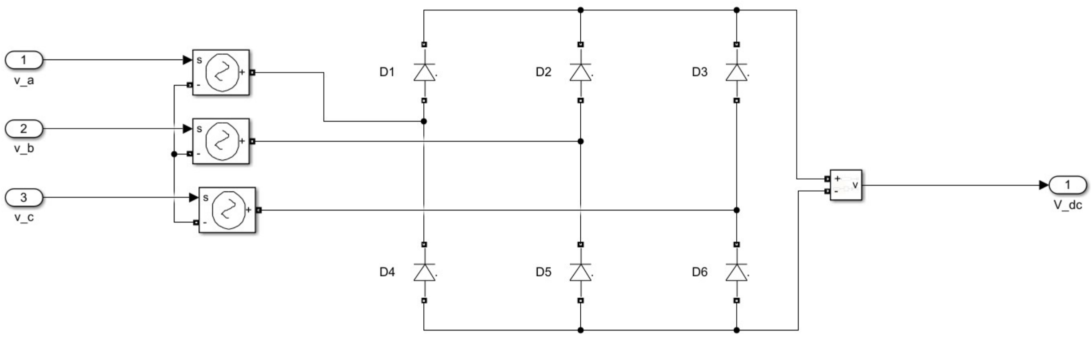

Figure 5.2: MATLAB model of rectifier

Connection between the stator-rotor subsystem and the rectifier subsystem is shown in 5.3. The stator-rotor subsystem together with the rectifier subsystem forms alternator block.

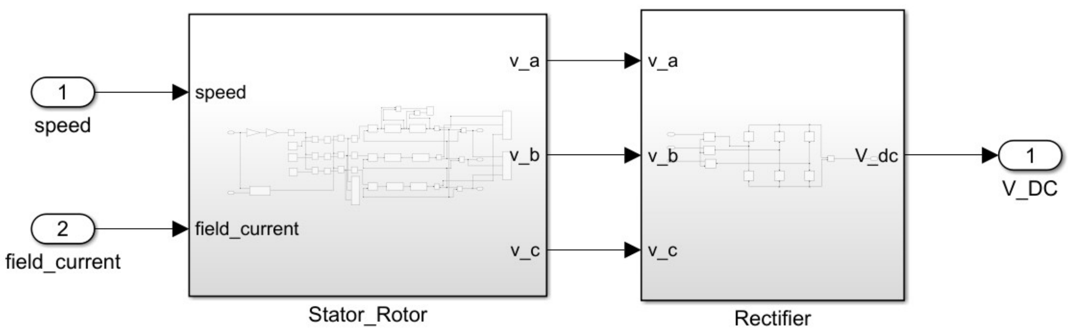

Figure 5.3: MATLAB model of alternator

5.2 Regulator model

The complete regulator model along with the alternator field circuit is shown in figure 5.4. And figure 5.5 shows the connection pattern of the PI controller and function command.

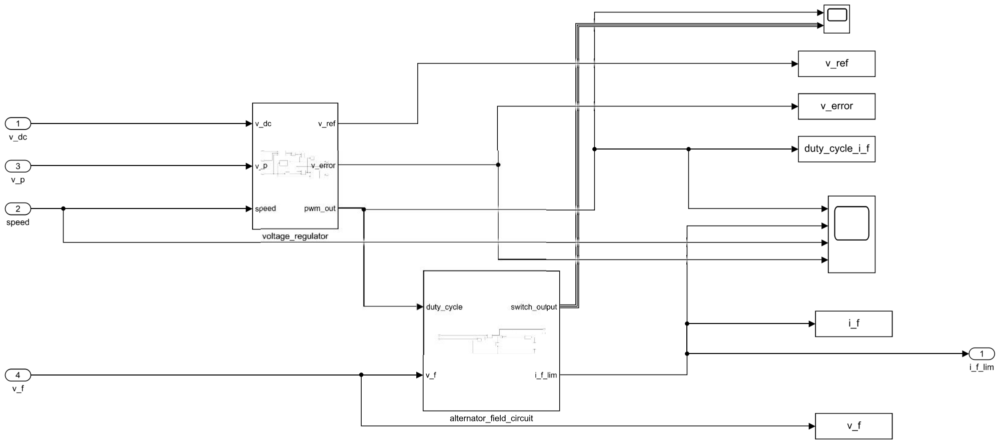

Figure 5.4: MATLAB model of regulator

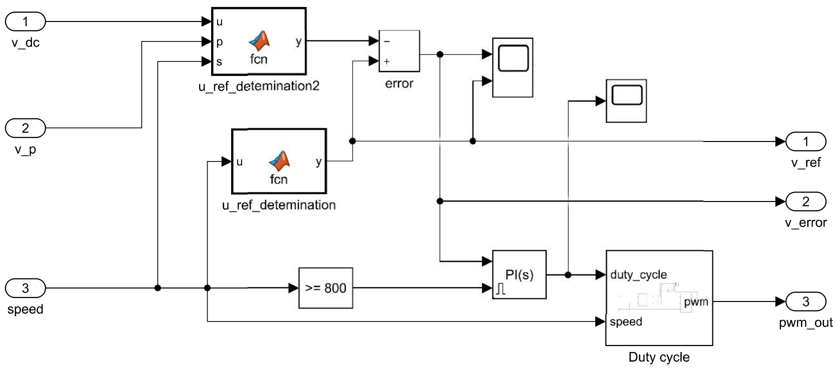

Figure 5.5: MATLAB model of PI controller in regulator

Finally figure 5.6 shows how the alternator parts are connected with each other in the MATLAB model.

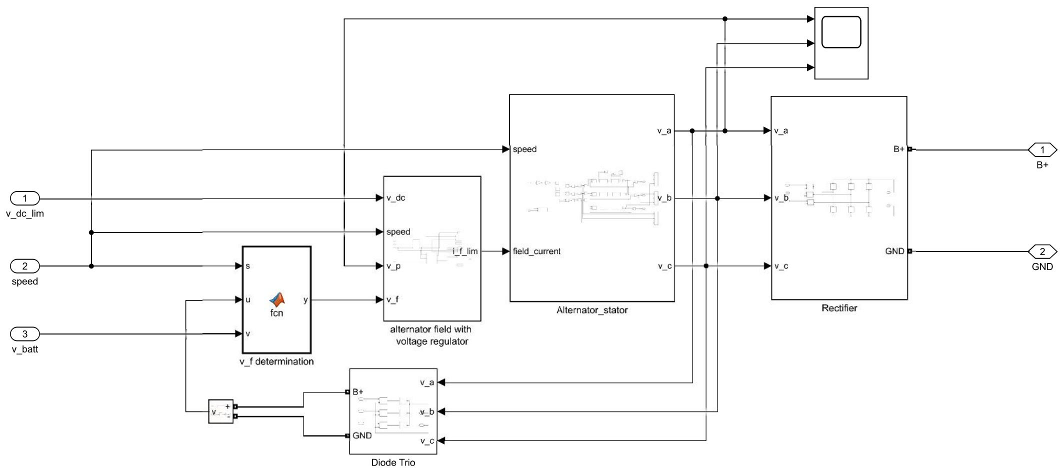

Figure 5.6: MATLAB model of alternator and regulator

5.3 Battery model[2]

The battery model is developed based on figure 4.2 as stated in section 4.2.

The value of R_0 for charging and discharging is extracted from the SOC vs R_0 graph from paper [9] and is actuated in the model as shown in figure 5.7.

The value of each R and C in figure 4.2 is evaluated from corresponding charging and discharging SOC vs R and SOC vs C graph from paper [9]. And finally using equation 4.15 the value of u from each RC is determined and the process is actualised in simulink as shown in figure 5.8.

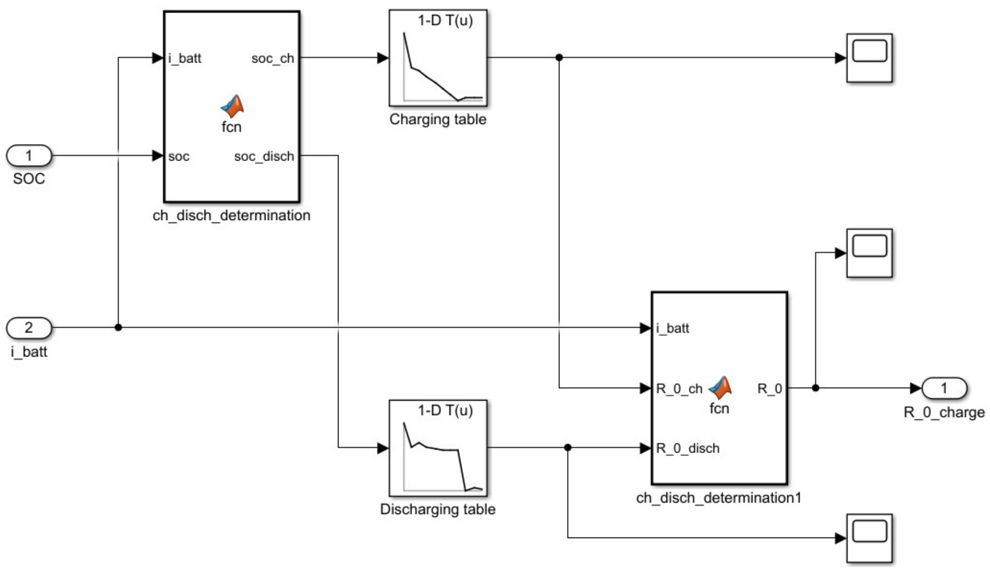

Figure 5.7: MATLAB model for R_0 determination

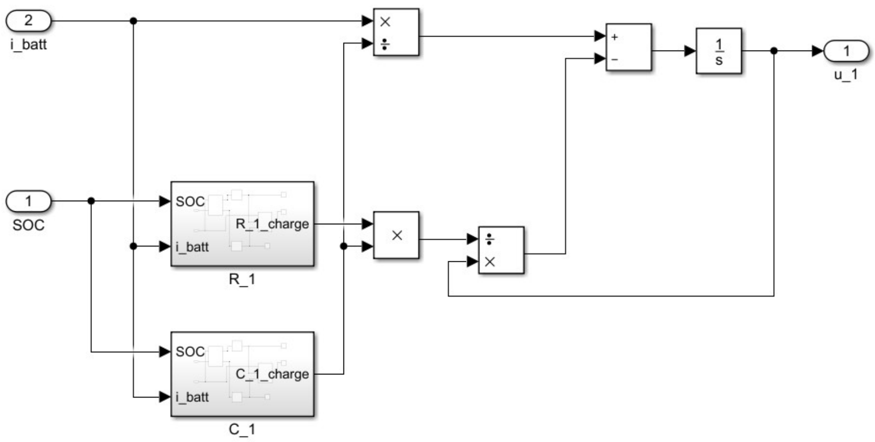

Figure 5.8: MATLAB model for RC determination

Figure 5.9 shows the battery unit developed in simulink that is developed based on equation 4.14. Figure 5.10 shows the soc determination subsystem that is actuated using equation 4.16.

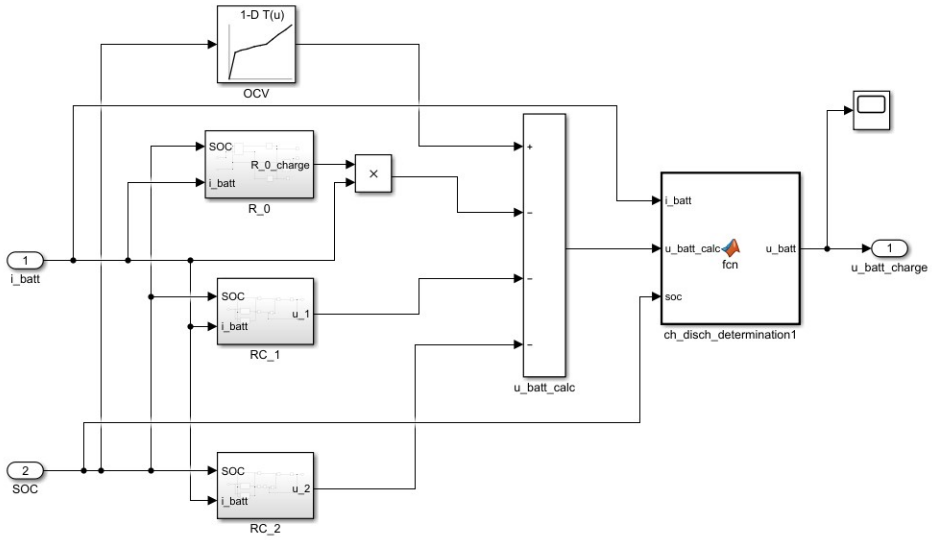

Figure 5.9: MATLAB model of battery unit

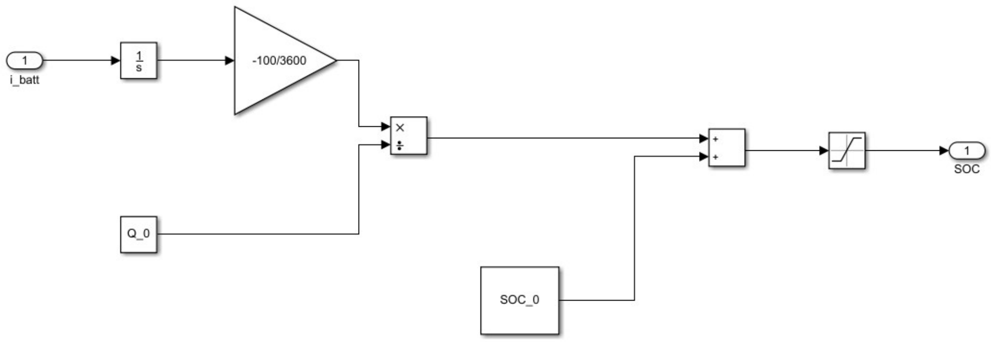

Figure 5.10: MATLAB model for SOC determination

The complete simulink model for the battery unit is shown in figure 5.11.

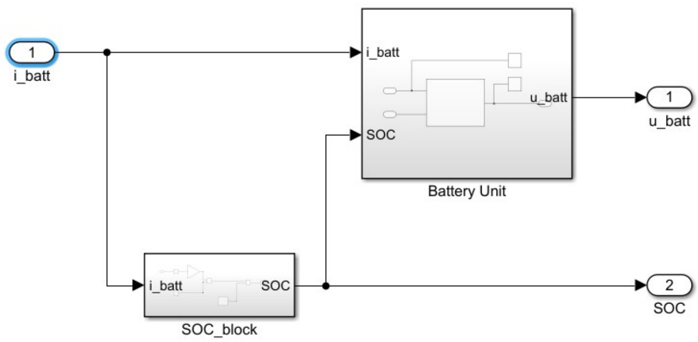

Figure 5.11: MATLAB model of complete battery

5.4 Complete system model

Detailed and complete system simulink model is shown in figure 5.13 and 5.12 respectively.

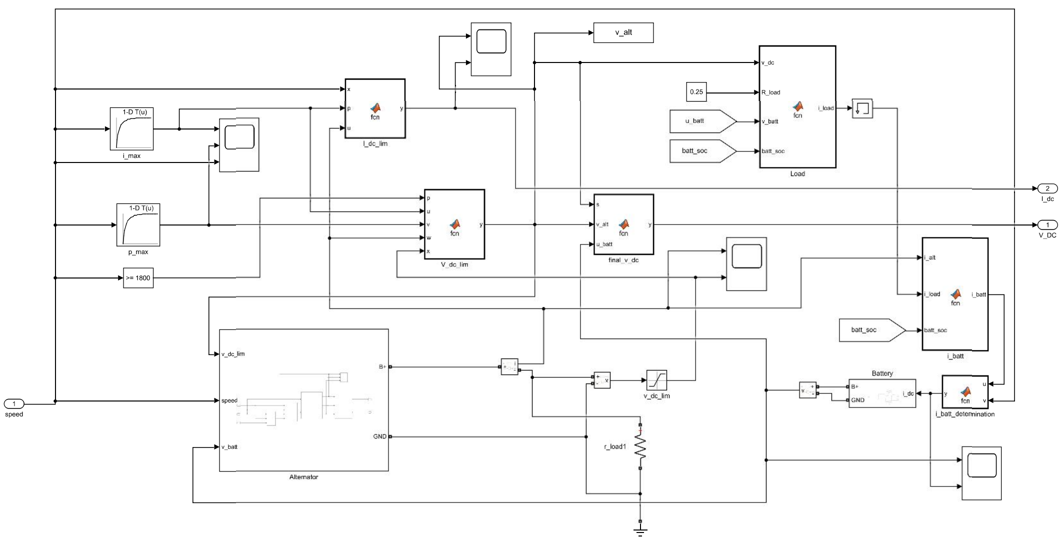

Figure 5.12: MATLAB model details of complete auxiliary system

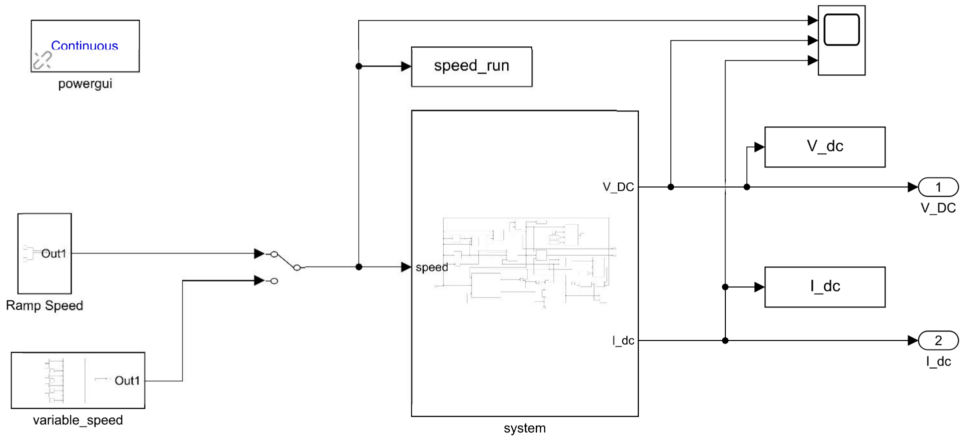

Figure 5.13: MATLAB model of complete auxiliary system

Chapter 6

Results & Validation

The developed models that are stated in chapter 5 will be verified with the results of experiments that are done in lab. The battery model will also be validate with the results stated in paper [9]. And for alternator model, it will be verified with its available specification sheet.

The parameter estimation and specification of the alternator which is used in the lab experiment to take the output signal waves are given below:

Table 1: Alternator parameter estimation and specification

Parameter Name	Symbol	Values
Sator resistance ($m\Omega$) / phase	R_s	147
Sator inductance (mH) / phase	L_s	2
Number of turns in stator / phase	N_s	14
Number of turns in rotor / phase	N_r	100
Number of poles	P	12
Number of slots (Number of conductors)	Z	36
Rotor radius (cm)	r_r	4.25
Rotor length (cm)	l	2.2
Coil span factor	K_c	0.84
Coil distribution factor	K_d	1
Coil winding factor	K_w	0.84

The specification of the battery which is used in the lab experiment to take the output signal waves are given below:

Table 2: Battery specification for Li-ion cell and module

Property	Cell	Module
Nominal Capacity(Ah)	40	40
Nominal voltage (V)	3.5	25.9
Max voltage(V)	4.2	29.4
Cutoff voltage (V)	2.7	18.9
Max charge current (A)	80	80
Cont. discharge current (A)	200	200
Peak discharge current (A)	400	400

Alternator model validation:

To validate the alternator model it is needed to be checked if the output current and voltage follows the expected behavior of an alternator and if they obey the field current and applied speed. Also it is needed to observe if output current follows the maximum current graph given in the specification sheet.

To analyze the performance of the alternator MATLAB model a very small load (resistance) is applied across the alternator output terminal. The load resistance is selected in such way so that the alternator provide maximum current at highest applied speed.

Figure 6.1 shows the alternator output dc voltage and current. From these graphs it can be seen that the voltage is increasing with increasing applied speed. And the current increases as the voltage increases until it reaches its maximum limit 120A at around 3600 rpm. After that the speed increases but the current is not increases since it is saturated at its maximum limit. At this stage the voltage is supposed to be increased with the increasing speed as the power provided by the alternator to the load increased as speed increased. But due to the action taken by the regulator the output power from the alternator reduced and hence voltage limits at 27V. The regulator perform this action by changing the field current through changing the duty cycle of the field circuit switch that is shown in figure 6.3.

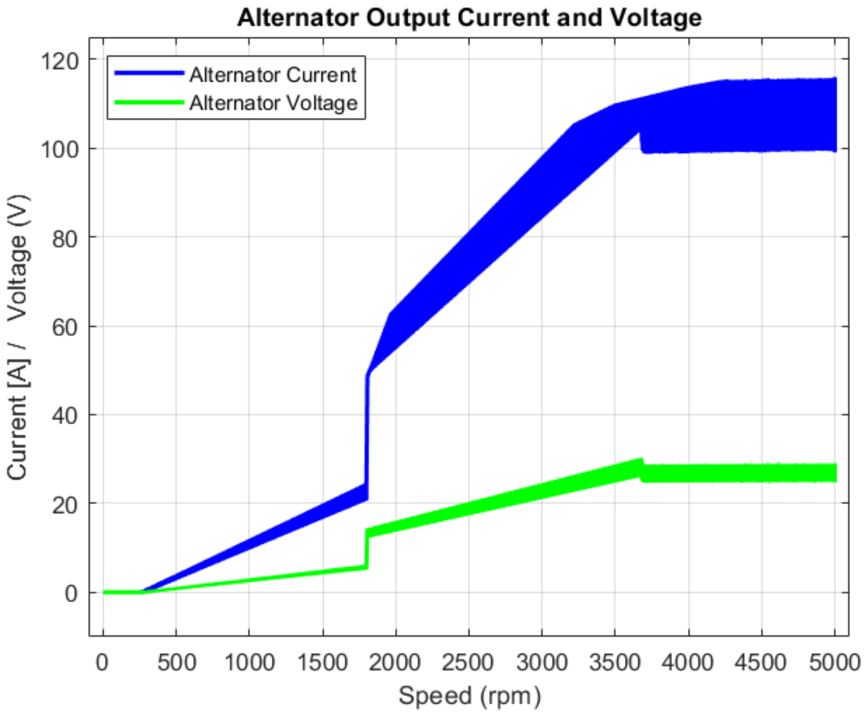

Figure 6.1: Alternator Output curves

Figure 6.2 shows the alternator field current and voltage and figure 6.3 shows the corresponding error signal and duty cycle against speed. From these figures it can be seen that during the pre-excitation phase the field switch is operated at a predefined frequency and at a predefined duty cycle. At this stage the field curcuit is getting power from the battery. When speed reaches to 800rpm the regulator started to regulate the phase voltage as it can be seen from error signal. When the speed reaches at 1800 rpm, the alternator shifted to self regulation mode i.e. the field circuit is getting power from the output of alternator. And after 1800 rpm the alternator is operated based on the load response. The output voltage is regulated at 27V which can be seen from the error signal and duty cycle graphs of the switch.

From figure 6.3 it can be seen that the duty cycle graph follow the error graph and yields the field current graph of 6.2. Therefore the voltage regulator is showing the expected output behavior.

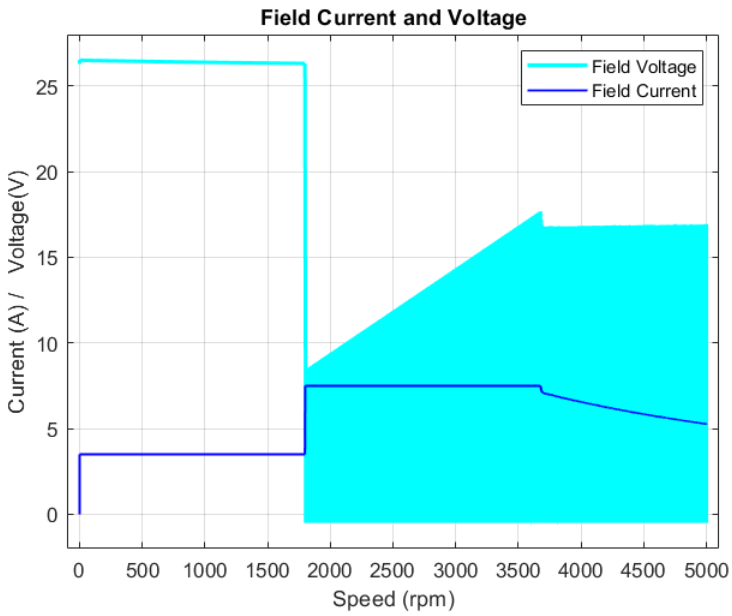

Figure 6.2: Alternator Field curves

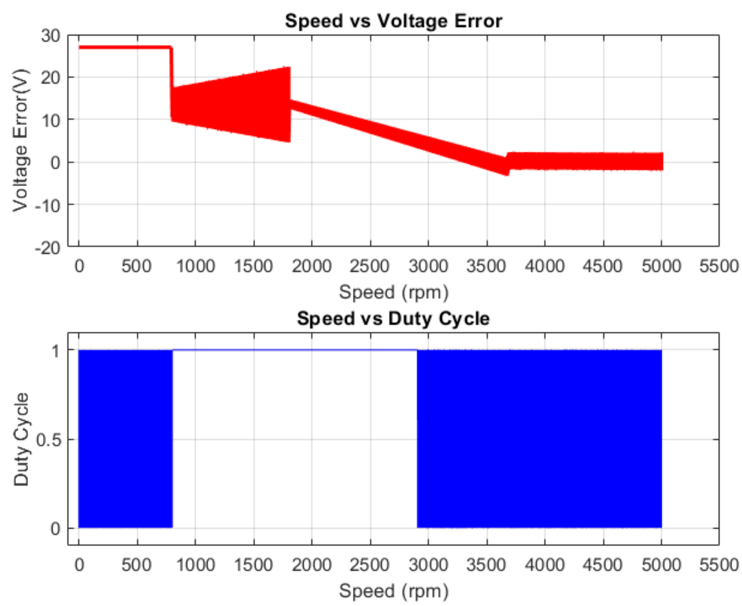

Figure 6.3: Voltage Regulator Performance Curve

The alternator output current graph from MATLAB model and the maximum current graph from the alternator specification sheet is given in figure 6.4. It is seen from the figure that both the curves shows similar shape pattern.

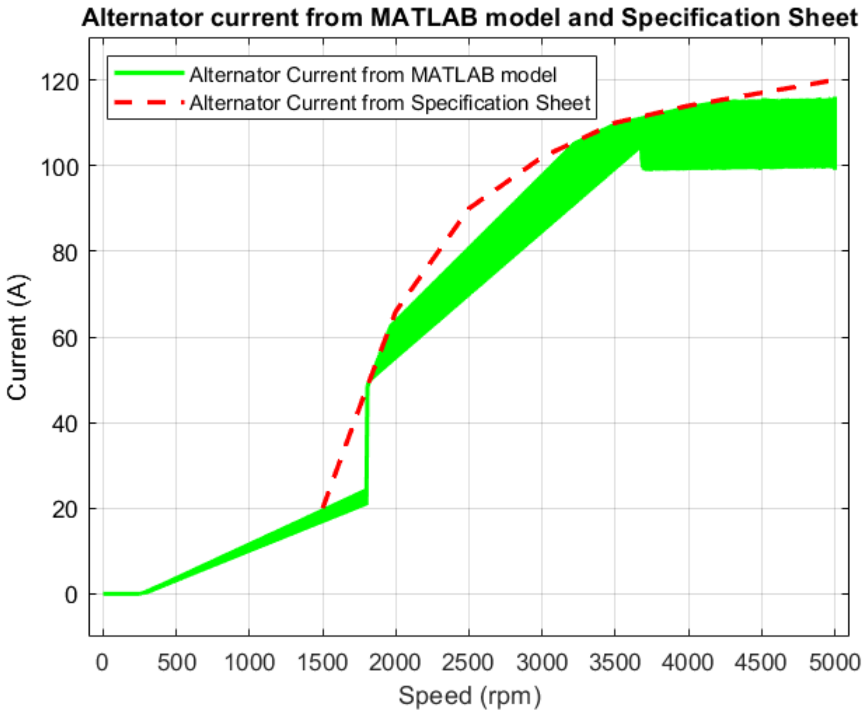

Figure 6.4: Alternator output current comparison with specification sheet

Finally from the above discussion it is realized that the alternator model along with the regulator shows expected performance characteristics.

Battery model validation with paper [9]:

It is mentioned in section 4.2 that the battery model's parameter values were extracted from paper [9] where charging and discharging pulse tests were done to extract the values. Therefore, it is logical to consider the MATLAB battery model is valid if the graph from the model matches with the relevant graphs described in the paper [9].

Figure 6.5 shows PC (Pulse Charging) simulation result graphs of charging voltage, current and SOC that was carried out at 2C rate, 10% pulse rate, and 30 min rest between two pulses. These graphs are exactly matched with the graphs described in the paper [9] for PC test.

Figure 6.6 shows PD (Pulse Discharge) simulation result graphs of discharging voltage, current and soc that was carried out at 1C rate, 10% pulse rate, and 30 min rest between two pulses. These graphs are exactly matched with the graphs described in the paper [9] for PD test.

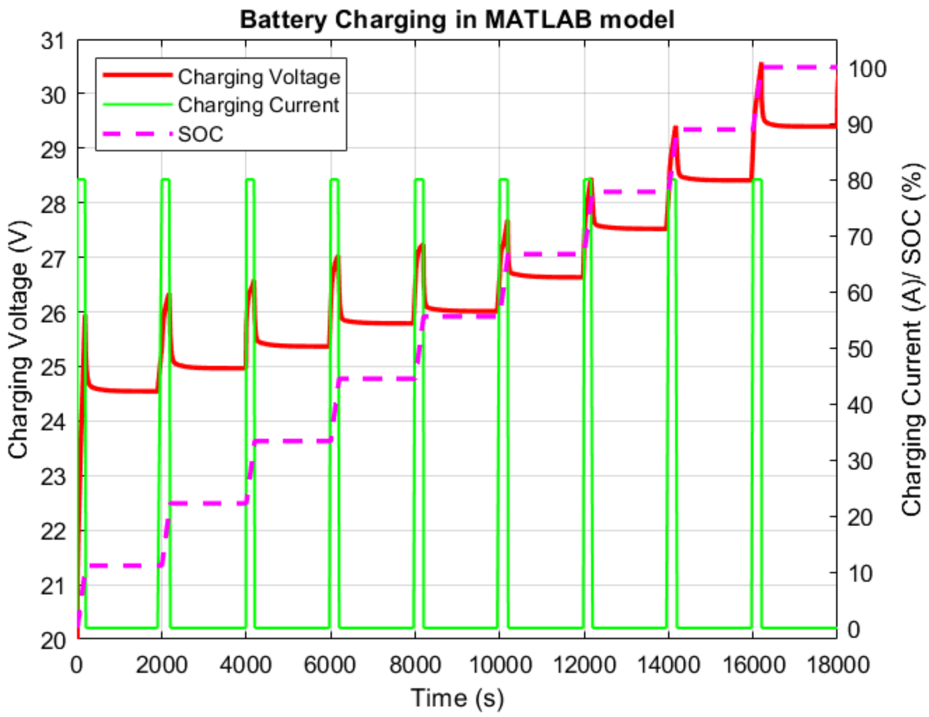

Figure 6.5: PC(Pulse charging) simulation test and simulation data extracted from the model

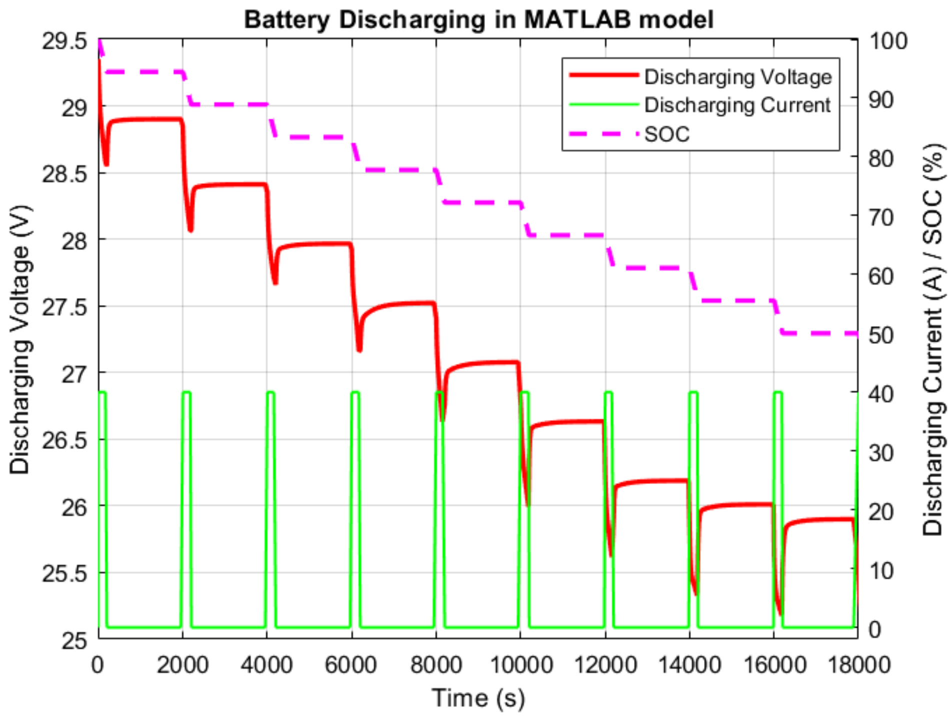

Figure 6.6: PD(pulse discharging) simulation test and simulation data extracted from the model

Battery model validation with lab experiment results:

The battery charging lab experiment was carried out with a battery having 30% SOC and it was charged until it reaches 100% SOC level.

From figure 6.7, it can be seen that during charging the shape of the battery voltage and current graphs from the simulation model follows the shapes of the battery voltage and current graphs from the lab experiment.

The battery discharging lab experiment was carried out with a battery having 100% SOC and it was discharged until it reduces to 30% SOC level.

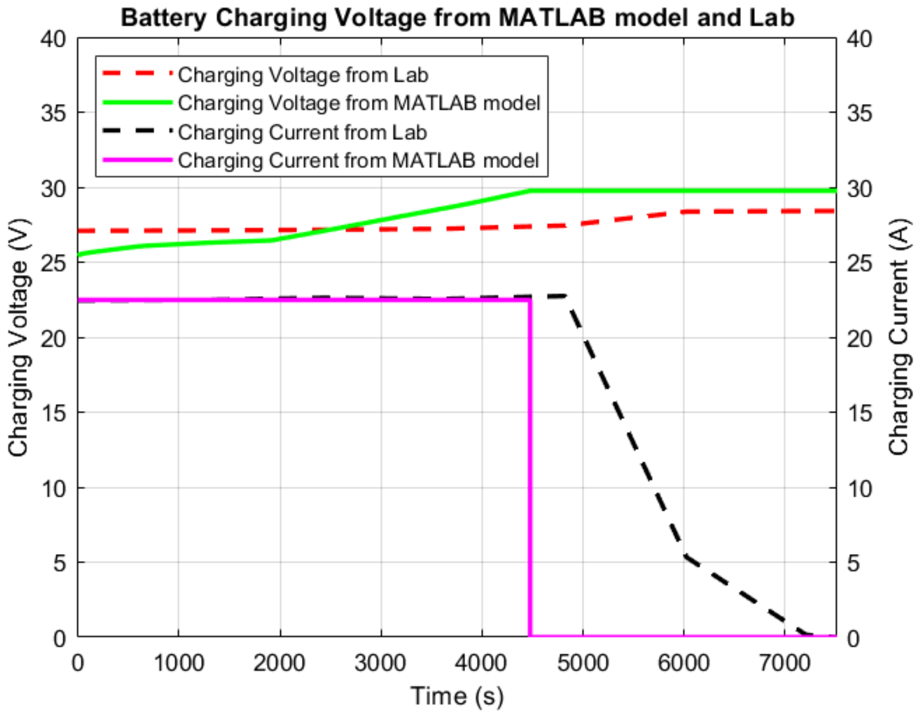

Figure 6.7: Continuous charging operation in simulation, Time vs Battery current, and time vs Battery voltage

From figure 6.8, it can be seen that during charging the shape of the battery voltage and current graphs from the simulation model follows the shape of the battery voltage and current graphs from the lab experiment.

There is difference in the charging time because the model is developed with the parameters that are collected from a different battery. Therefore the battery in the lab and the MATLAB battery model have different inner construction parameters and hence this difference appears.

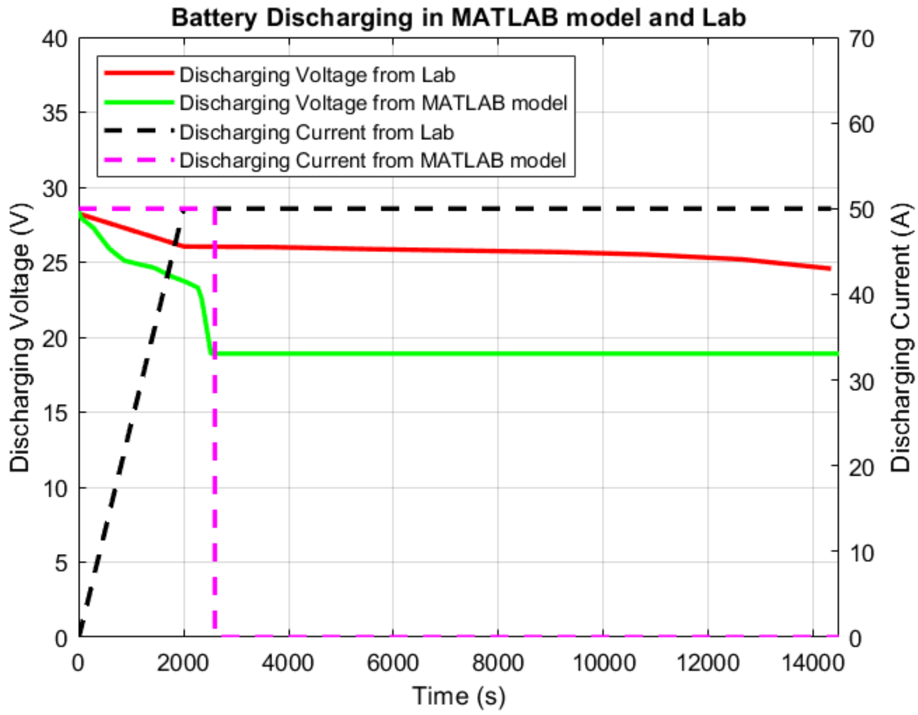

Figure 6.8: Continuous discharging operation in simulation, Time vs Battery current, and time vs Battery voltage

Complete System model validation:

To validate the system MATLAB model an experiment was performed in the lab where a 24V alternator was provided with an increasing speed with steps and a 24V 40Ah battery and a small load (low resistance) were connected in parallel with each other and with the alternator. The system graphs was taken via Dewesoft Data Acquisition (DAQ) devices and software.

Figure 6.9 shows the applied speed graph of alternator during lab experiment and the applied speed graph of alternator in the MATLAB model. In lab an increasing speed with steps was applied on rotor shaft through a long time span 1182s as compared to the MATLAB applied speed in 60s. The lab speed was increased with steps for safety of operation while MATLAB speed was a ramp function. This differences in applied speed doesn't effect much on the performance comparison except slight deviation.

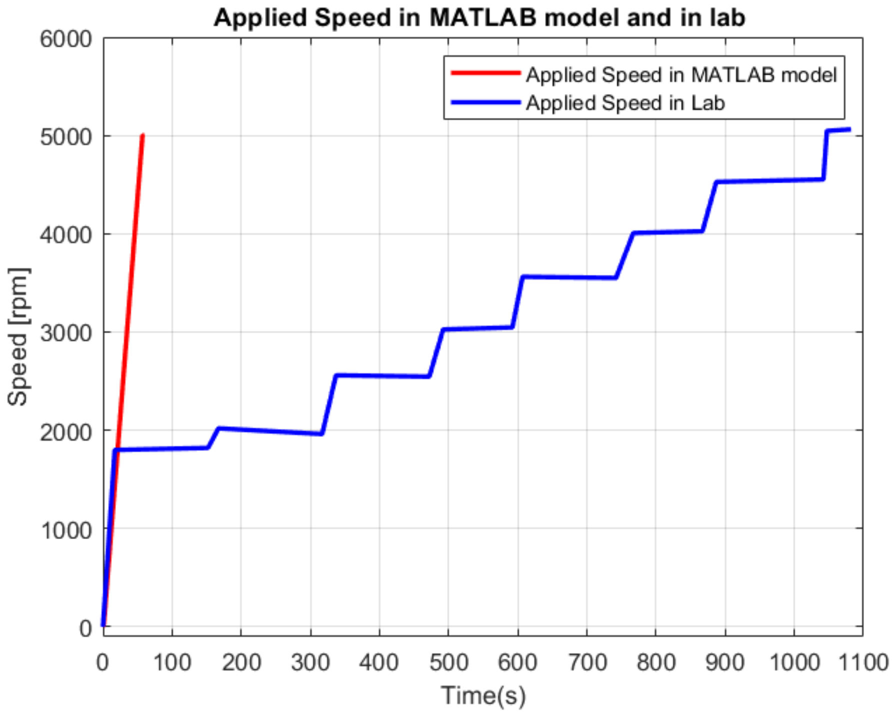

Figure 6.9: Time vs Speed curve from model

Figure 6.10 shows the voltage graphs of the system from the lab and from the developed model. From the figure graphs it can be seen that both the MATLAB graph and lab graph shapes are similar but with a deviation. This is because the practical load has inductance along with resistance and hence a capacitor was used across the load for smooth operation. Again in practical the connecting wires also have resistance that is not considered in MATLAB model.

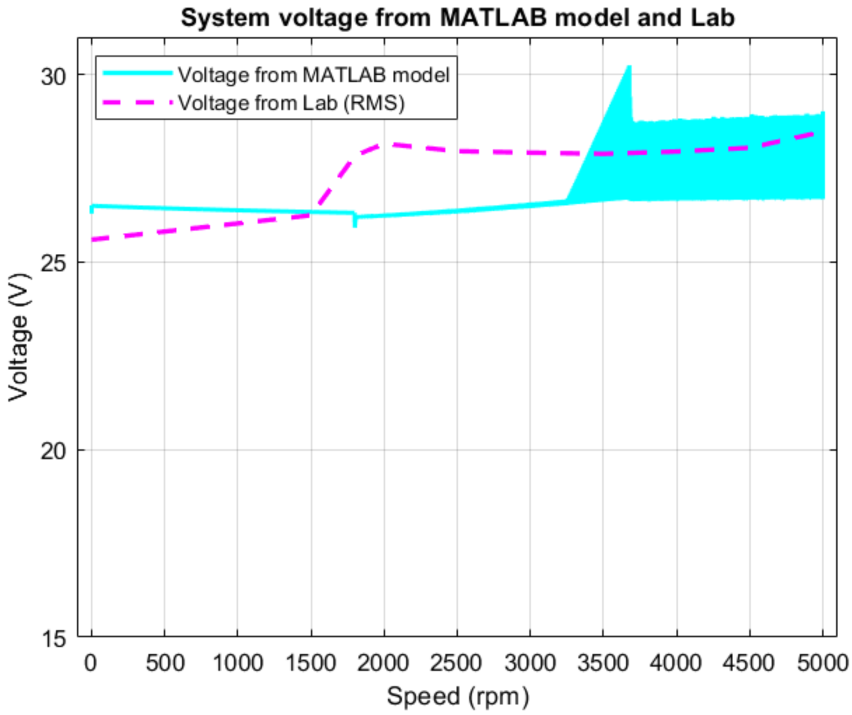

Figure 6.10: Time vs System voltage curve from model

From figure 6.11 it can be seen that the current graph from MATLAB model follows the current graph that is found with lab values but with slight deviation. The deviation is because in practical the load contains inductance along with resistor while in MATLAB only resistor is taken as load and during operation in lab a capacitor was used across the load for safety reason. Also to generate the graph the lab data was taken in RMS value.

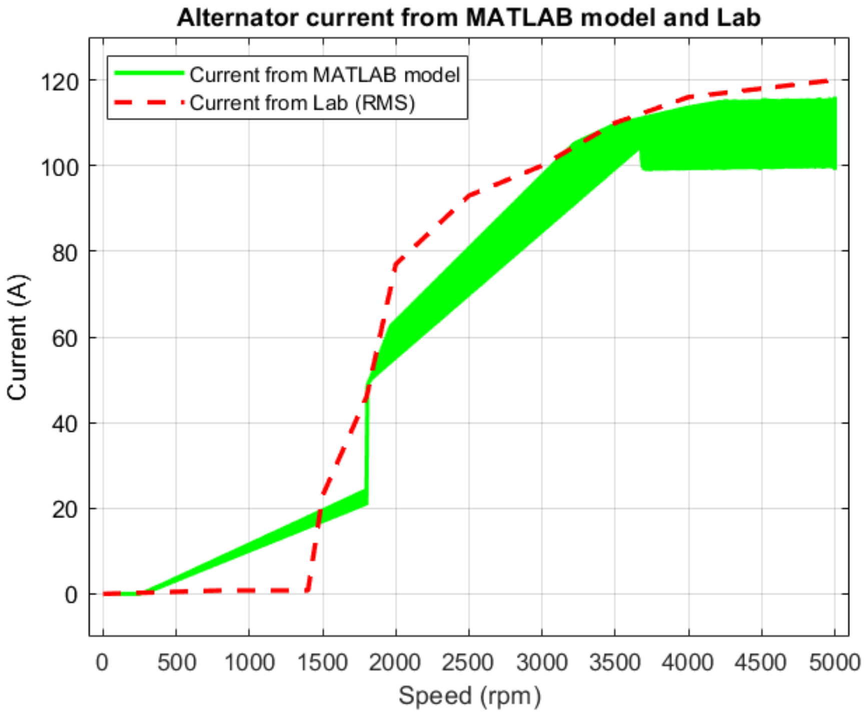

Figure 6.11: Alternator current curves from MATLAB model and from Lab

Chapter 7

Conclusion and Future work

7.1 Conclusion

For developing the model each part of the vehicle auxiliary power system was investigated.

Several alternator model was developed based on maximum power and maximum current curves that are given in the specification sheet and dq model equations. But the most conveniently applicable and controllable model was the basic equation based model. Therefore, this model is finally selected and represented in this thesis report.

In voltage regulator model, a PI controller was chosen to generate duty cycle for the PWM generator since the PI control loop regulates the increases of a signal that can react proportionally to changing conditions (proportional part), or can correct for long term deviations (integral part) from desired set point.

Several battery model was checked and finally the above described model is chosen because battery in-depth experiments was out of scope for this thesis report and the model parameter values were easily extracted from available experimental data of paper [9].

Finally after connecting the main parts of the auxiliary system model it gave the expected output curves that has been validated in the result section.

7.2 Future work

There is a great provision to perform further work in this thesis topic based on this report. Followings are some key points that may lead the future investigations:

- the system alternator can be modelled with dq model to get more accurate results
- temperature dependency of alternator can be investigated and implemented to check the power loss and alternator performance variation due to temperature increase during operation
- variation in battery performance due to alternator performance variation when temperature changes
- the MATLAB model can be customized to develop a MATLAB app for user's convenience

This idea of softwarization of the low voltage system for automotive vehicles can also be implemented in other fields, even it can be customized to implement for high voltage applications also.

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