POLITECNICO DI TORINO

Electrification of off-road vehicles

Master's Degree Thesis in Electronic Engineering

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Abstract

This project, conducted as part of a master's degree thesis, focuses on the electrification of off-road vehicles, particularly those utilized in agricultural settings, including excavators, tractors, and loaders. The study specifically examines the conversion of a mini excavator that currently operates on an internal combustion engine (ICE) to an electric-powered system. This thesis explores the process of electrifying the ICE-operated excavator by selecting appropriate electric components, modelling the electric circuit, determining the sizing of the system based on its intended application, and conducting efficiency mapping of the electric system. In this transformation, the traditional internal combustion engine is replaced with an electric motor, battery, and inverter. The Permanent Magnet Synchronous Motor (PMSM) serves as the primary mover, interfacing with the hydraulic system for actuation. The overall efficiency of the system is influenced by the physical characteristics of the electric motor, inverter, and battery, with performance evaluations conducted under steady-state conditions. A Lithium-Ion battery is employed to supply energy to the system.

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SYMBOLS

P	Power, W
EOV	Electrification of Off-road Vehicles
Li-Ion	Lithium Ion
SOC	State of Charge
SOD	State of Discharge
DOD	Depth of Discharge
PMSM	Permanent Magnet Synchronous Motor
AC	Alternating Current
DC	Direct Current
FOC	Field Oriented Control
ICE	Internal Combustion Engine
CO2	Corbon Dioxide
EM	Electric Motor
Pdc	Battery Power, W
Pm	Electric Motor Power, W
Pabc	AC Inverter Power, W

CONTENTS

1- INTRODUCTION

Most of the vehicles used in agriculture are off road vehicles, since they are off from the main road most of their operating time cycle. One of them is Excavator, which is used for digging and damping. Since these are very big moving machines, they require a lot of energy during the operation on field.

Most of these vehicles are working on ICE (Internal Combustion Engine) and using a lot of fuel during the operation. Also, there is a lot of CO2 emission during the operation of these vehicles. So, there is a trend of making these bigger vehicles electrified to avoid fuel consumption and emission of CO2. As On road vehicles are being electrified and they are working greatly, most of the research is on going on to make of road vehicles electrified as well.

In this research, I am going to discuss about the challenges and basic steps in making these machine electrified. Also, the selection of suitable electric components, their size and efficiency of the electric system will be discussed.

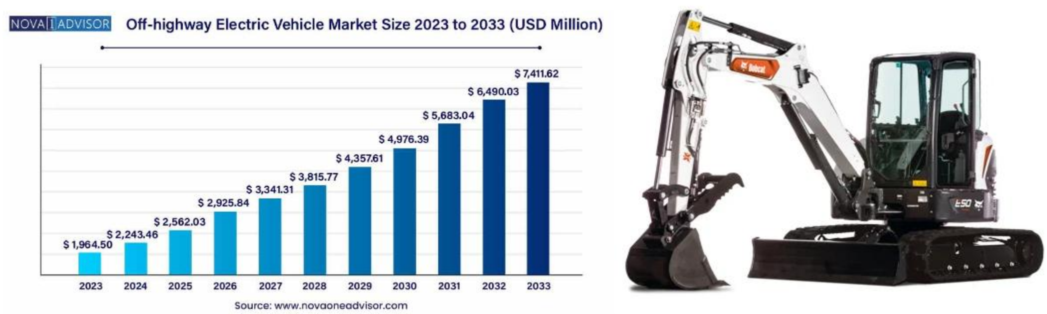


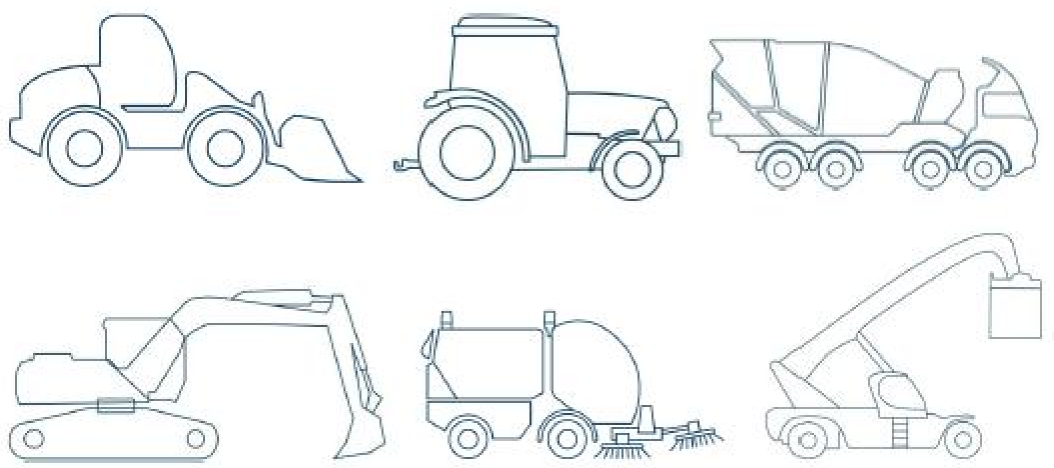
Figure 1.1: Electric Vehicle applications: (a) EV Market, (b) Excavator

1.1 OFF-ROAD VEHICLES AND THEIR USAGE

The bigger moving machine, which are mostly used in agriculture, are referred as off-road vehicle because during their operation, they are not on the roads, mostly in the fields.

As in the figure below, there are some off road vehicles and their specific application is shown. These vehicles are used to harvest the crops, they are used in digging, carrying massive equipment, transportation on massive tools and equipment, damping, loading and unloading etc.

All these vehicles mentioned below, are used in heavy duty cycle, therefore sometimes, these are also called heavy duty vehicles because most of their operation requires huge amount of energy and mostly that energy is provided by an Internal combustion engine.



1.2 WHAT IS EOV?

Electrification means the integration of electricity into your application, so electrification of off-road vehicles means, introducing electric drive and removing internal combustion engine, so now in the electrified vehicles, the prime mover would be an electric motor, controlled with an inverter and supplied by an electric battery.

The normal operation of these vehicles is carried out with the help of an ICE which is connected to gears and then to tires but in electrified vehicles, the main prime mover is Electric Motor (EM), with the help of an EM vehicle movement is governed.

In of road vehicles, ICE is replaced with electric motor, inverter and battery. Electric motor gets the power from inverter and the inverter relates to the battery.

Since these big vehicles required a huge amount of power due to their operation. These vehicles operate on heavy duty cycle, so a bigger source of energy is required to supply the main prime mover. The speed and torque control of these machine is carried out with the help of an AC power inverter, this inverter should be capable of handling high voltages and current.

By integrating electricity into these machines and making them electrified, the interference of these machine with the software control becomes easier and smoother.

1.3 IMPORTANCE OF EOV

There are so many important reasons for making these bigger vehicles electrified, few of them are listed below:

- Mechanical Failure: electric system containing motor, inverter and battery has fewer mechanical failure as compared to ICE. In the ICE there are mechanical connections, gear systems and piston movements, so there is a lot of power required to overcome loses during these movements. So, the systems containing ICE have a very less efficiency because of the frictional losses during movement in ICE. The available ICE systems have an efficiency lower than 10% which makes them very less efficient systems.
- Precise control: By integrating the electricity into these big vehicles, the torque and power control off these vehicles is too fast and smooth. Making these so making these off-road vehicles electrified bring the fast response off these machines. With the ICE installed in these big machines, the control is

mechanical so it's not so fast and quick but with the help of electricity since now we have an inverter which controls all the commands, so our machine response is quick. In the electrified off-road vehicles, all commands are controlled with the help of electronics and electrical circuits since everything is controlled electrically so we have a very quick and fast control of overall operation of the vehicle.

- Software interference: Electrified vehicles have a very good interference with software control system, since every command is electrified so software can integrate with all kinds of the commands very easily and quickly, so we can expect a very quick response of the vehicle by introducing electricity in it.
- No CO2 emission: one of the main reason of making these big off road vehicles electrified is to reduce the emission of carbon dioxide (CO2), since these big off road vehicles are using fuel to run ICE so they are producing CO2 which is not good for the environment, so by making all these big vehicles electrified we can reduce the emission of CO2 which is ecofriendly and good for the environment, but this but there's no emission of CO2 is only during the operation of the vehicle, so by introducing electricity in this vehicle we can say that these vehicles having no CO2 emission during their operation. But again, this point is very important that how the electricity is being produced, so this point is only valid during the operation of the vehicle because during the operation of the vehicle if the vehicle is electrified there would be no CO2 emission.
- Efficiency improvement: One of the main reason of making these off road vehicles electrified is improvement in efficiency, as discussed earlier these ICE operated vehicles having very less efficiency during their operation most of the vehicle's only working with 10% or lower than 10% efficiency, so by integrating electricity into these vehicles may them very efficient because our electric system is very efficient considering all the electric equipment working in the nominal condition for example if our electric motor is working in nominal condition during the whole duty cycle we can expect a 95% or more

than 95% efficiency of the motor. Similarly, if our AC power inverter is working in nominal condition, we can expect a similar efficiency around 95 to 97% and the third most important component of lactic system is battery so considering a normal operation with the normal load we can expect a 95% efficiency out of a battery.

- Reversible operation: an introduction of lactic acid in these big vehicles can bring another very important feature into it. A reversible operation is possible by making this vehicle electrified. With ICE, the reversible operation is not possible all the excessive amount of energy is leaked or metered out, but thanks to the electrified vehicles now we can reverse operation, for example if electrified vehicles are slowing down then the electric motor will be converted into the generator and can send energy back to inverter and then inverter can send that energy back to the source, so in this way we can reverse the operation and recover the energy.
- Variable speed: one of the most attractive features of making these big off-road vehicles electrified is the variable speed of the electric motor, in case of ICE we cannot achieve a variable speed because engine moves at the fix RPM but in case of electric motor because electric motor is supplied with the inverter so we can vary the speed according to the commands given by the operator. By playing with the frequency end the current supply to the inverter weekend control the torque and speed of the electric motor.

2- PROBLEM STATEMENT

In this chapter we will look the research done on the electrification of off road vehicles as we know in on road vehicles we have a lot of research and we have a very good electrified on road vehicle but in the field of off road vehicle which are mostly used in agricultural department because they are having a very heavy duty cycle application so most of them are being used in agriculture sector like excavator , tractor, loader.

Since these vehicles need a huge amount of power and torque during the operation, so for making these big vehicles electrified, there is a requirement of big battery, bigger motor, and a bigger inverter only then it would be feasible to deal the application of these big vehicles.

So making these vehicles electrified, is a big challenge due to their application and heavy duty cycle because when you are replacing ICE with an electrified solution, you need to find a space inside the vehicle to install electric motor and inverter and a bigger battery so there is always a challenge to define space for these big machines to get electric motor and inverter and battery inside these machines.

In today's market we do have electric motors which are capable of providing high torque and power but unfortunately due to their bigger size it is really difficult and a big challenge to install those motor into our big machines, so while making these make off road vehicles electrified, it is very important to choose an electric solution which is capable of dealing the heavy duty cycle of the machine and also required less space to install inside the vehicle

Below I will discuss about the existing state-of-the-art for these kinds of big machines and the research done on the electrification of these machines.

2.1 AVAILABLE STATE OF THE ART

In this section I will discuss the existing electrified solution for excavator, and this would be the starting point in explaining my own electrified solution. Below is an ECR25 electric excavator by Volvo.

Figure 2.1: Volvo Mini Excavator

The reason of selecting this electrified solution was the application and drive cycle of this vehicle because this mini ECR25 Volvo excavator is having the similar duty cycle and application as of my considered machine, this mini excavator is totally electrified. It consists of a battery which is a lithium-ion battery, an electric motor which is serving as the main prime mover is permanent magnet synchronous motor and an inverter which is three phase inverters getting the supply from battery and providing the supply to motor.

By looking to some of the specification of this electrified solution we can conclude few of the below listed things:

- This 2.5 ton capacity electric vehicle is supplied with the battery which is having a capacity of 20 kWh, since this machine during the normal operation Uses a varying power due to the nature of the application, during the operation sometime this machine needs more torque and power and other times it needs less power and torque, so can considering the nature of the application, a permanent magnet synchronous motor having the capacity of 24 horsepower is installed in the vehicle.

- After going through the details, I came to know that operating this vehicle in a crowd of people or at a busy place is normal because during the operation this vehicle works with a very low noise so you can operate this vehicle in a public place without any kind of fear of creating noise in a public place.
- Due to having a battery there is a 5-hour continuous operation is possible with this mini-VOLVO excavator.
- This state-of-the-art mini excavator with lithium-ion battery of capacity 20 kWh, an electric motor, permanent magnet synchronous motor with the capacity of 18 kilowatt and 2050 RPM continuous speed with a three-phase inverter is the best start to design A model for my considered example.

2.2 PROBLEM STATEMENT

As we know these engines based off road vehicles are very less efficient and due to their inefficient system, most of the power is lost during the operation of the vehicle. Also, since these machines use ICE as the main source of energy so during their operation these vehicles produce a lot of carbon dioxide which is creating environmental pollution so to tackle these above 2 challenges, electrification in off road vehicles is getting common in these days. But making these big off-road vehicles electrified isn't simple, the electrification of off-road vehicle is just not to replace ICE with electric system. It requires a lot of electronic control for an electric battery, an electric motor, and an inverter to power up the system, and much more space to install these devices in the vehicle.

3- ELECTRIC SYSTEM COMPONENTS

In this chapter we will discuss the electric component used in the system. For making this big off-road vehicle electrified below are the main components which are required.

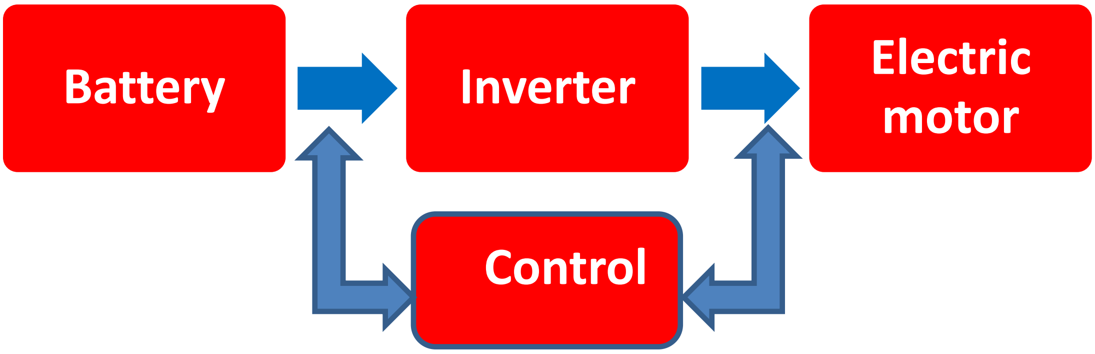


Figure 3.1:Electric Circuit for EV Electrification

As in the figure above there are main components used in the electrification of the off-road vehicles, in this chapter we will discuss the proper choice of off electric component for this typical application.

The electric battery, the electric motor and the inverter are chosen according to the requirement of the application.

3.1 ELECTRIC COMPONENTS REQUIRED FOR EOV

As we know in these big vehicles, the main source of energy is ICE, so to make these vehicles electrified this ICE will be replaced with an electric motor as a prime mover and the supply will be given by an electric battery with the help of controller and an inverter.

In these off-road vehicles, the energy source ICE is directly coupled with the hydraulic system of the machine, normally the hydraulic system consists of pumps and actuators so I CE is directly coupled with the shaft of the pump and then pump control the flow and the movement of the actuator during the operation of the vehicle. So, if ICE is being removed from the of road vehicle, a prime mover will be required which will be coupled directly with the hydraulic pump, when electrifying these off-road vehicles, the main prime mover will be an electric motor and this electric motor shaft will be coupled with the shaft of the pump.

So, when replacing ICE in off road vehicles below are the electric components required for the operation of the vehicle.

The main prime mover will be an electric motor, and this electric motor will be directly coupled with the pump shaft after machine. To power up the electric motor, a battery source will be required.

To control the torque and power required during the operation of the vehicle we need to play with the speed of the motor and for that an inverter is required.

Also, there would be some kind of electronics required to electrically connect all these devices and there would be a controlled required to control the frequency, current, voltage, power and torque.

3.2 CHOICE OF ELECTRIC COMPONENTS

As we discussed in the previous chapter, for replacing ICE from off road vehicles and making the vehicle electrified, an electric source of energy which is battery, a main prime mover which is an electric motor and a speed power and torque controller which is an inverter are required.

The selection of these above-mentioned components is very important because this selection then determines the efficiency of the overall system and also the compatibility of the electric component with the big machine. Now, I will discuss in detail all the electric components

3.3 ELECTRIC BATTERY

In this chapter we will discuss the main source of electric supply for an electric system of the vehicle. While selecting a battery there's so many important factors to consider because a battery is the most important electric component when it comes to the electrification of off-road vehicles because you cannot operate without a battery. The battery saves as the main source of energy to the inverter and eventually to the electric motor which is a prime mover and serves as a backup during operation of the vehicle.The selection of this component (battery), Depends on so many factors. The list of the main factors while selecting a battery for an electric system are below:

Energy density:

This is the energy stored in a system per unit volume. Different types of batteries has different energy density, mostly it depends on the different material used in the battery.

Power density:

This is the power per unit area, or we can say the energy transfer rate in a unit area since this factor also depends on the energy density so different material of the batteries have different power densities.

Nominal voltages:

Nominal values of any of the battery are the values which can be continuously provided by the battery these are not the maximum provided values, but these are the normal values provided continuously by any of the battery it can be voltages current power etc.

life cycle:

One of the most important factor while selecting a battery is the life cycle of a battery, a life cycle of a battery means the full discharge for bad for you for once it's called one life cycle for example if our battery is 80% charge and we drained our battery till 20% are less than 20% then we can say it is of full one life cycle but in normal application sometimes batteries are not trained fully like for example if they are charged 80% according to the application they will be trained for 20 percent 30% only which will not be counted has one complete life cycle. So normally we can get more life cycle out of a battery than the written life cycle of battery.

Energy efficiency:

The most important factor while selecting a battery is the efficiency of the battery because this is the defining factor in our electric system when it comes to the efficiency of the whole system. For example, if a battery is 95% efficient, with a one full discharge we can get only 95% out of 100% so 5% will be lost into the inefficiencies of the battery, so while selecting electric battery for the system a higher efficiency off the battery is very important for the overall system efficiency.

Self-discharge rate:

The self-discharge rate of a battery is a very important factor to consider because in our electrified system we cannot use battery with a high self-discharge rate. Any battery with a high self-discharge rate is not suitable in electrification of off-road vehicles So for electrification of off-road vehicles only the batteries with very low discharge rate will be selected. If a battery self-discharge rate is high, that battery cannot provide energy to the system for a longer period and in this big off-road vehicle we require a battery with a bigger backup.

Thermal stability:

There is another very important factor while selecting a battery is the thermal stability, because if battery is not thermally stable then it cannot work with a wide range of temperature because in our application of off road vehicle all the electrical system is very much exposed to the external temperature and the external temperature can vary from very low to very high so a battery which is not thermally stable or which cannot operate stability at high temperature is not suitable for this application, so why selecting a battery for our application we will go with the most stable battery while it comes to thermal stability. In our consideration sample, the internal system temperature, and the external atmospheric temperature both are very important to consider because during the operation since everything is moving and sometime needs very high torque and power so the internal temperature can get raised and similarly, we need to consider the external atmospheric temperature because it varies a lot.

After taking all these above factors into consideration and the research done previously on different batteries I concluded regarding the selection of battery. As per the considered example, lithium-ion batteries are the most suited batteries for the application of off-road vehicle due to their high energy density, high power density, high nominal cell voltages, higher efficiency, very low self-discharge rate and the most stable when it comes to their thermal stability. As illustrated below in the table all the characteristic of different batteries:

Battery Type	Lead Acid	Ni-Cd	Ni-MH	Zn-Br	FeCr	Li-ion
Energy Density(Wh/kg)	30-50	45-80	60-120	35-54	20-35	110-160
Power Density(W/kg)	180	150	250-1000	-	70-100	1800
Nom Voltage(V)	2	1.25	1.25	1.67	1.18	3.6
Cycle Live	200-300	1500	300-500	2000	-	500-1000
Energy Eff %	70	60-90	75	78	66	80
Self Discharge	Low	Moderate	High	Low	High	Very Low
Thermal Stability	Least Stable	Least Stable	Least Stable	Least Stable	Stable	Most Stable

Table 1: Battery Comparision

3.3.1 Lithium-Ion Battery (LiFePo4)

As discussed in the previous chapter, the lithium-ion batteries are the most suited batteries for off road high vehicles, because in off road vehicle the nature of the application is having heavy duty throughout the whole duty cycle.

Doing more research in the field of lithium and batteries there are different kinds of lithium-ion batteries available in the market. For the example of mini excavator, the most stable battery out of all available lithium-ion batteries will be chosen and selected for the proposed electrical system. After carefully analysing all kinds of lithium-ion batteries available in the market lithium iron phosphate is the most stable lithium-ion battery available. This LiFePO4 is the most stable battery among all lithium-ion batteries, because it can operate within a wide range of temperature throughout the operation of the vehicle without losing the stability, as it can be seen in the graph below:

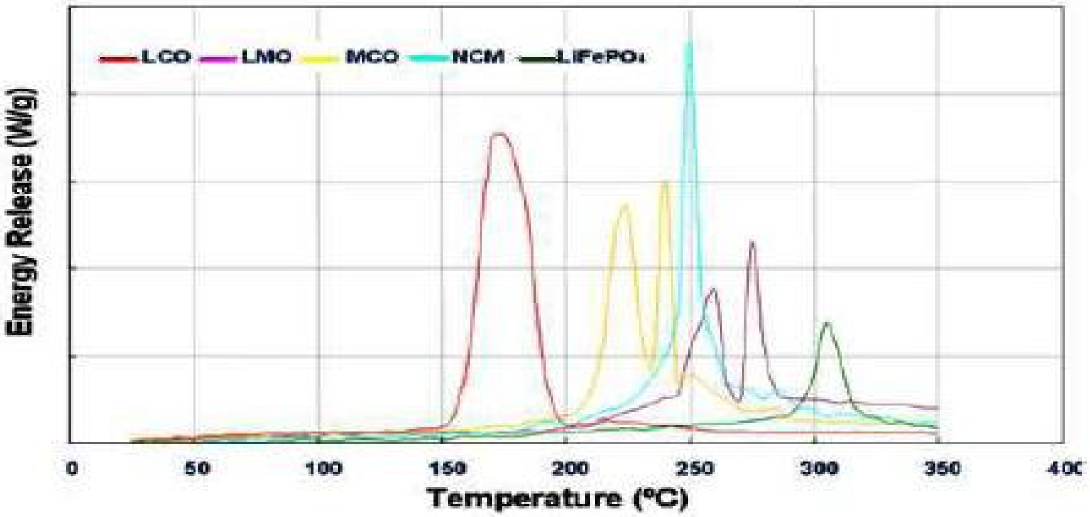


Figure 3.2:Battery performance under different temperature

3.3.2 SOC AND DOD OF LI-ION BATTERY

In any of the battery state of the charge and depth of discharge, are the two main key factors while choosing a battery for the application.

SoC states how much charge remaining in the battery and DoD represents the percentage of discharge from a fully charged state battery for example if a battery is 70% charge it's mean SoC is 70% but on the other hand if your battery is discharged 60% from the full the duty of the battery is 60%. For both SoC and DoD the value varies between 0% to 100%. Normally the lithium-ion batteries are used in heavy duty cycle application it is avoided to go for 100% DoD. If during the operation a battery is going from 0% to 100% DoD it will complete one life cycle which is not recommended while using these batteries in off road heavy vehicles.

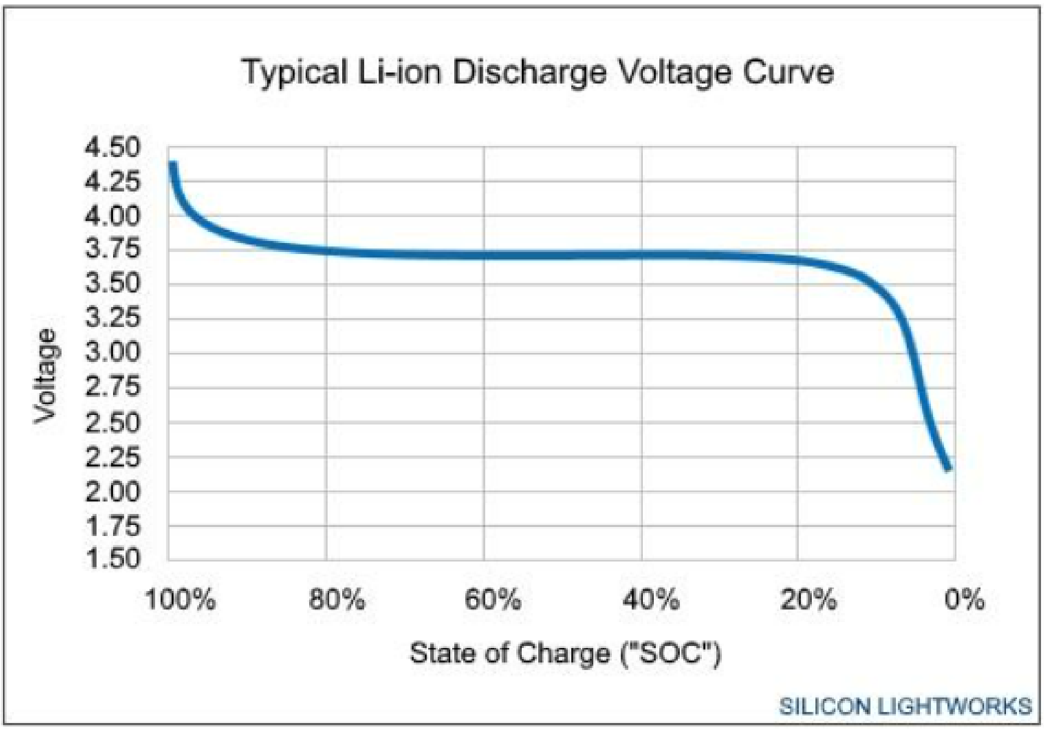


Figure 3.3:Lithium Ion Discharge rate curve

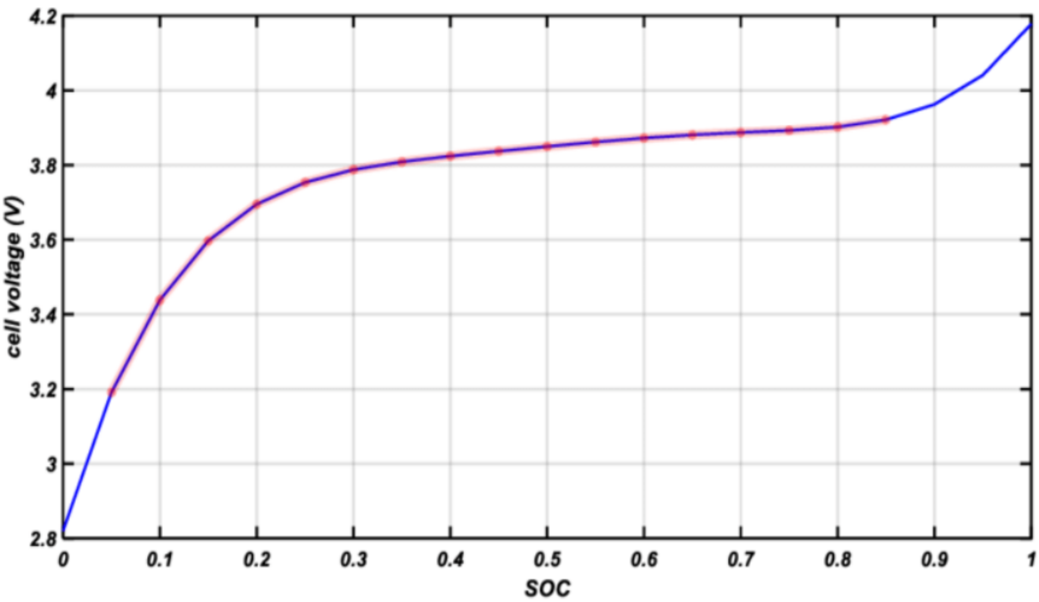


Figure 3.4:Lithium Ion SOC

3.4 ELECTRIC MOTOR (EM)

In the electrification of off-road vehicles, the second most important electrical component is the electric motor which also serves as the prime mover of the system. This selected motor will be directly coupled with the pump in the system and then the pump will take care of the actuation in the system.

Before the electrification of this off-road vehicle, ICE was directly connected to the pump for the actuation, when making this off-road vehicle electrified now the prime mover is electric motor which is getting supplied by the battery and is directly coupled with the pump in the system.

Since this electric motor now is serving as the main prime mover and its very important component so while choosing an electric motor we need to consider some important feature of electric motor in mind for example the type of the motor, the control strategies for the motor, maximum and continuous values of torque and power and nominal operating condition of the motor.

For the consider example of mini excavator since this is a heavy-duty application, so motor which is capable of providing high torque and power and maintaining the high speed is required for the application.

3.4.1 PERMANENT MAGNET SYNCHRONOUS MOTOR

By doing research on the existing types of the motor, it is the permanent magnet synchronous motor which can provide high torque and power at the same time it can maintain a high RPM. Also, this permanent magnet synchronous motor is highly suitable for heavy duty application of off road vehicles.

The choice of permanent magnet synchronous motor is due to the following few factors:

- Permanent magnet synchronous motor can provide higher energy efficiency, higher power dynasty and higher starting torque.

- By installing permanent magnet synchronous motor into electrified solution, the precise control can be achieved and also permanent magnet synchronous motor has low maintenance costs
- With permanent magnet synchronous motor even with Heavy duty cycle high efficiency can be achieved around 95 to 97% efficiency.
- With permanent magnet synchronous motor while working in the nominal operating region of the motor maximum torque and power can be achieved.
- Permanent magnet synchronous motor is more compact, most suitable and compatible with off road application.

3.5 POWER INVERTER

This is one of the most important electric components in electrification of off-road vehicles. The is the power flow controlling device from Battery to Motor and in reverse case, motor to battery. These AC power inverters consists of switches which are normally made of semiconductor materials like silicon, the most common inverters are made of IGBT or MOSFET according to the application on the inverter.

3.5.1 THREE PHASE AC POWER INVERTER

An AC Power Inverter converts DC power supplied by Battery to AC power for a PMSM which then moves and acts as the main prime mover.
This AC Power inverters is a smart compact device consisting of switches which help to convert DC sources to AC source and then can be fed to AC operating systems.
There are different kinds of ac power inverter in the market with different specifications and applications. While selecting an ac power inverter, we need to consider few factors which are listed below:

- Communication Protocols: Since these ac power inverters are controlling devices in the electric system, so the communication between devices and inside the inverter is important to consider. Normally this AC inverters come with J1939 communication protocols.

- Overload Capacity: The capacity to deal with high peaks of power (current and voltages) at higher frequency is very important to keep in mind while selecting an inverter, because in the considered example of application, there might be high peaks of power during the duty cycle of the operation of off-road vehicle.
- Current and Voltages Ratings: The Power rantings of an inverter are very important while selecting an inverter for considered application, since these ratings vary a lot, so while selecting an ac power inverter, nominal power, voltages and current and maximum power, voltages and current needs to be considered.
- DC voltage level: Since the ac power inverter will be supplied by a battery, so it is important to specify input dc voltage level for an inverter before selecting for specific application.

4- ELECTRIC SYSTEM MODELLING

In the previous chapter it was discussed about the electrical component used in a system, now in this chapter I will be discussing about the electrical system modeling. It will be the whole electrical system containing battery inverter electric motor and the control between electric motor and inverter. In the below figure, there is a Simulink based electrical model developed to analyze the parameters of the electric component and the efficiency of the whole system.

4.1 SIMULINK BASED ELECTRIC MODEL

In this section we will discuss the Simulink based model for the considered Example of electrification of off-road vehicles. The reason of choosing Simulink for modeling electric system Was to analyze the system by the physical parameter of the different component used in electrification. Since in Simulink, there are built in models for different electric components that can be used and customize according to the application of your interest. For example, in our application, we are using a permanent magnet synchronous motor and thanks to Simulink there's already built in model of a permanent magnet synchronous motor that can be used and customized according to the application.In this section it will be discussed about the required torque and required power during the duty cycle of this mini excavator. From modelling the electric circuit of the above machine, the power consumption during the whole duty cycle will be considered and analyzed. Since this mini excavator is a machine with higher consumption of power during the operation so while modeling the electric circuit for the above machine, all the components used in modelling the circuit, should be capable of providing high power and should be capable to sustain the sudden high required torque and power.

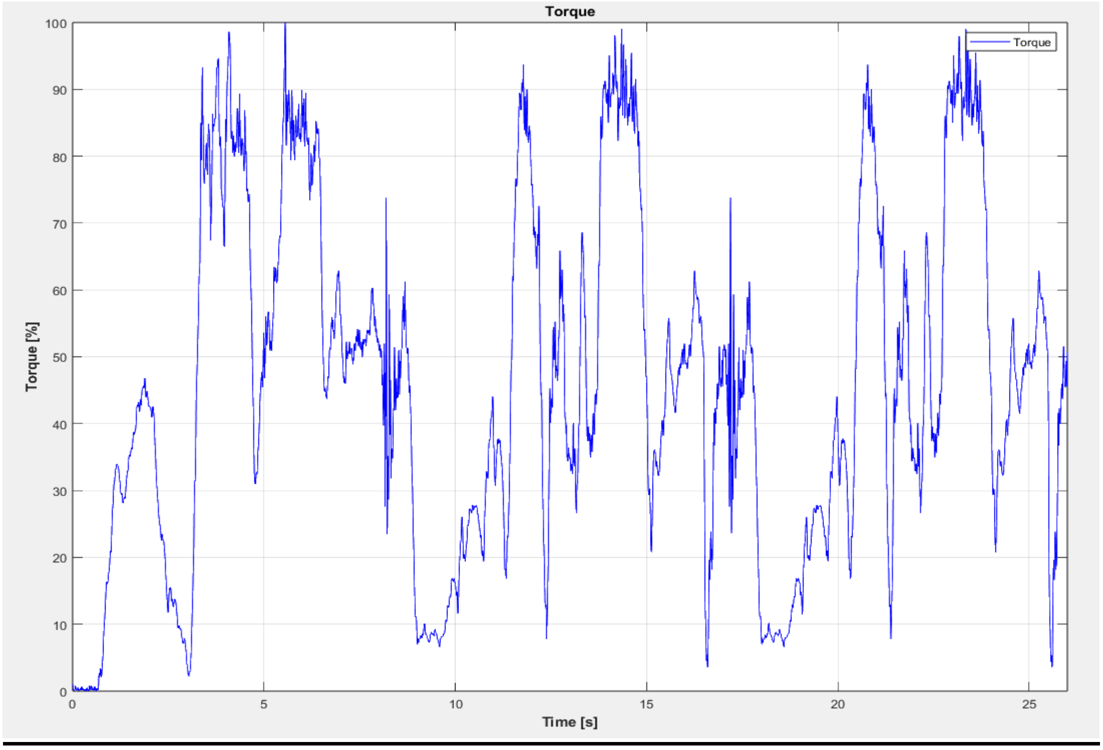


Figure 4.1:Nominal data for the Electric pump Torque

In the above graph, there is torque required during the operation of the vehicle. The graph values are normalized, and this is not the actual data from the manufacturer, but this is verified with the data from the manufacturer. During the duty cycle of the considered machine, there is dynamic torque required during the whole duty cycle.

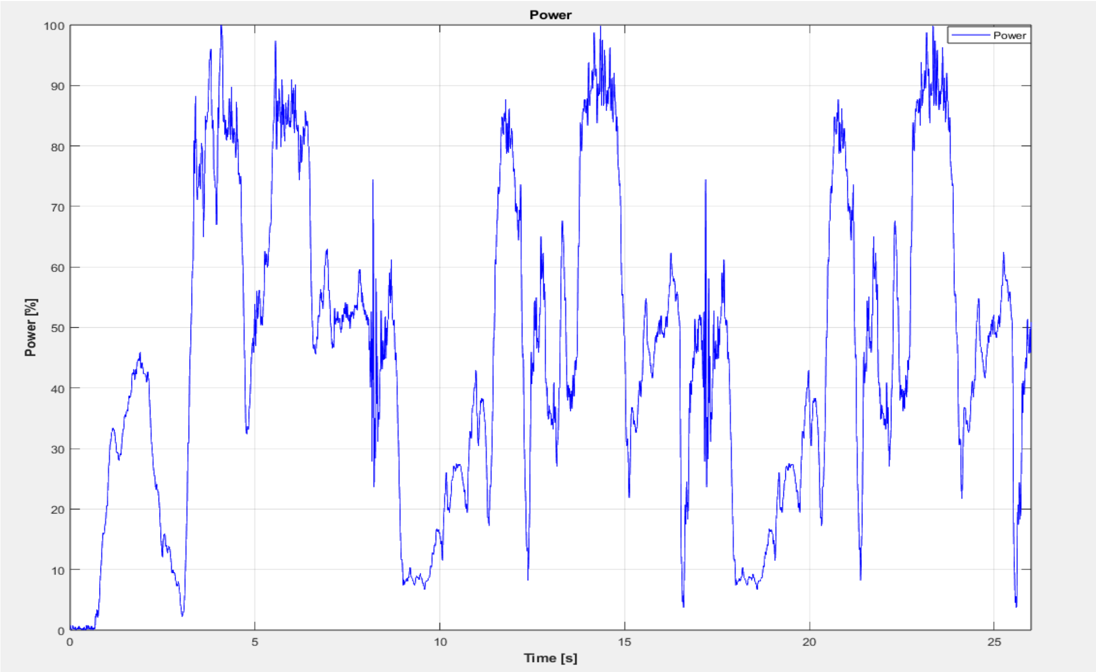


Figure 4.2:Nominal data for the Electric pump Power

In the graph above, a varying power required during the duty cycle is shown in normalized form. This is not the actual data of the machine. But this is the normalized data corresponding to the actual data. By looking at the power consumption graph, during the operation of the machine dynamic power is it required which means sometimes less power is required and the other times, it requires high power which makes the machine complex machine to model. It would be easy to model a machine with constant consumption of power but since the above machine requires dynamic power during the operation it makes the machine hard to model and there would be efficiency loss involved in it.

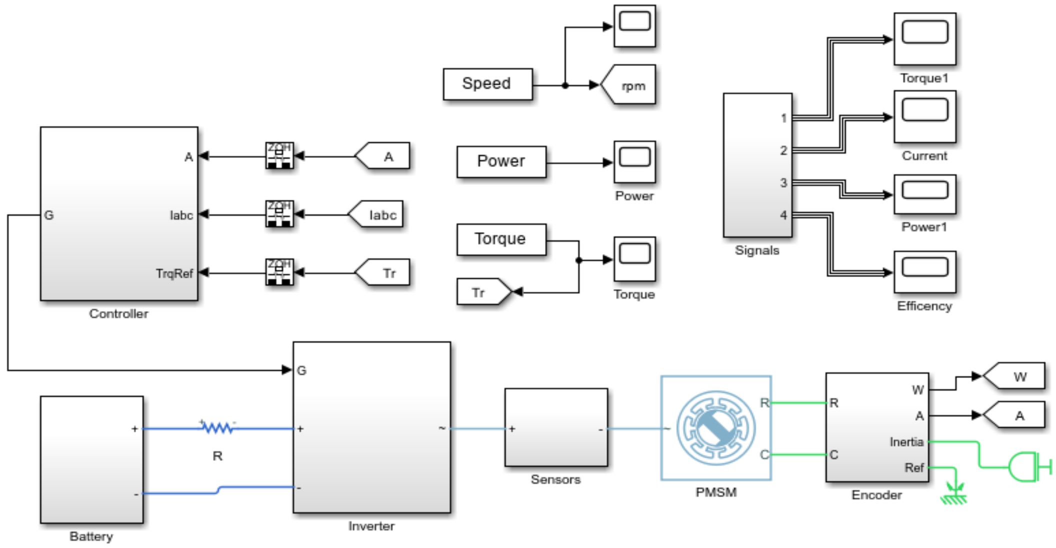


Figure 4.3:Proposed Electric Circuit

In the figure above, there's an electric circuit designed for analyzing the electrification model proposed for mini excavator. The above figure shows different blocks from Simulink since the electrification model for off road vehicle is proposed by creating a model in Simulink. This above Simulink model can provide the required parameter set to analyze the electrification system for mini excavator and is able to provide the efficiency of the whole system. Apart from providing the efficiency of the system and physical parameter-based analyzation, the above model can also control the required supplied parameter to the electric motor. To analyse the different components and block shown in the above model, I will take into more detail of each separate component and block use from already built in Simulink model.

4.1.1 Modelling for Battery

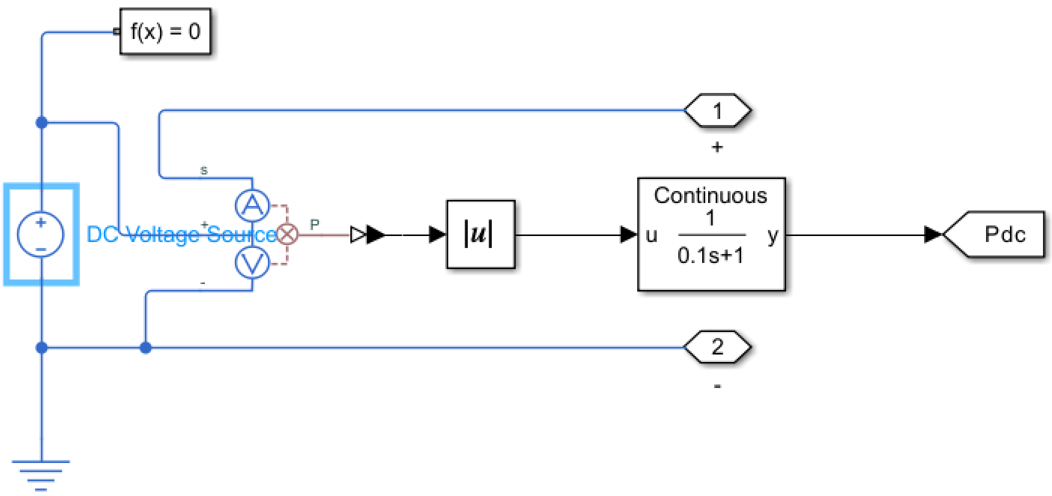


Figure 4.4:Battery Modelling

The figure above shows the internal blog for a battery, as discussed earlier battery is the most important part when it comes to the electrification of off-road vehicle. In the figure above, there is a constant source of DC voltage supply, the output of the DC source is being measured with the power sensing block which is available in Simulink electrical library. To get the absolute value there's absolute value measuring block is used, before getting the output power there's a filter used to remove the noise from the signal, in the figure above Pdc is the output power coming from the battery.

4.1.2 Modelling for AC Power Inverter

In the figure above the internal structure of a DC to AC inverter is shown. An AC power inverter is another key component when it comes to the electrification of many excavators. This is an intermediate electrical component which gets power from battery (DC power) and supplies an AC power to the permanent magnet synchronous motor connected at the output of the inverter. An AC power inverter has three input controlling parameters and three output signals. Two of the input signals at the battery are positive and negative signals and one is the gate pulses signal which is given to the gates of all the switches in this case IGBT to control the duty cycle after signal. At the output of the inverter there's a three-phase signal for three different currents, 120° apart from each other. All the control in the inverter is carried out through the gate pulses at the gate of each IGBT.

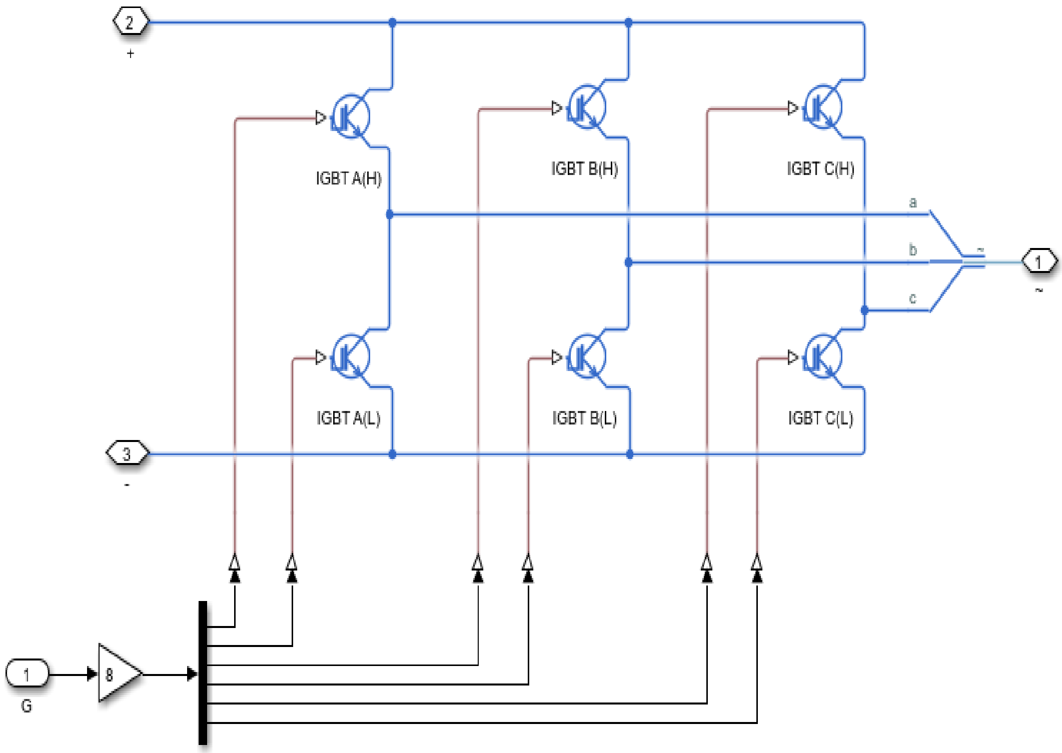
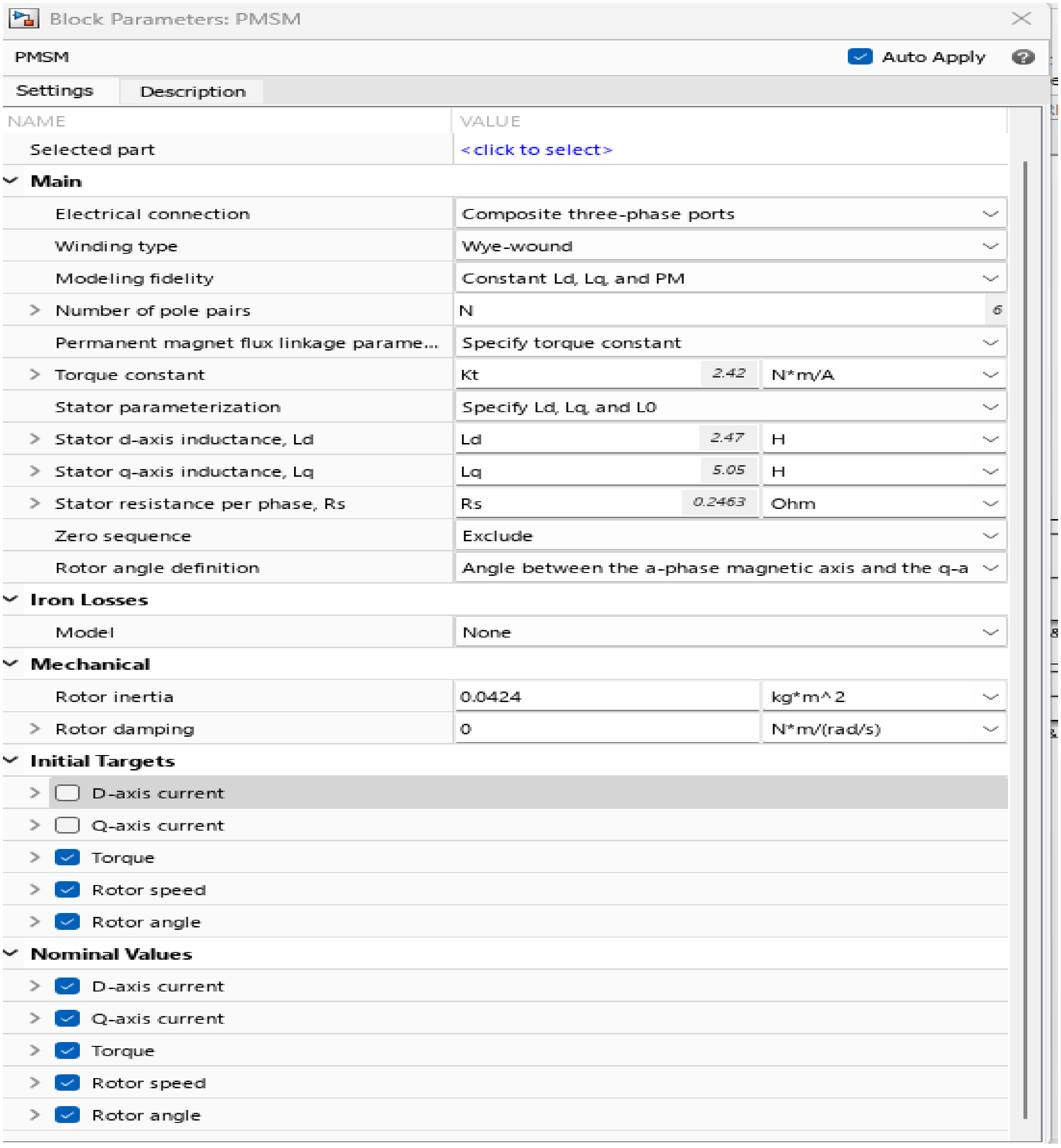


Figure 4.5:AC Inverter Modelling

4.1.3 MODELLING FOR ELECTRIC MOTOR (PMSM)



The above block in Simulink corresponds to the permanent magnet synchronous motor inside the block, all the physical parameters of the motor can be customized according to the selected motor.

As can be seen in the figure above, we can customize different physical parameters of permanent magnet synchronous motor with the help of this above block. For example, we can set the type of the load at the output of the permanent magnet synchronous motor, the electrical connection type, number of the poles in the motor Torque parameter and whining inductances and reactance. Also, the above block gives the freedom to insert mechanical parameters like rotor inertia and rotor damping.

With the help of the above block, all the physical electrical and mechanical parameters of a permanent magnet synchronous motor can be addressed and customized. It helps to customize the motor according to the application.

4.2 CONTROLLER FOR THE ELECTRIC SYSTEM

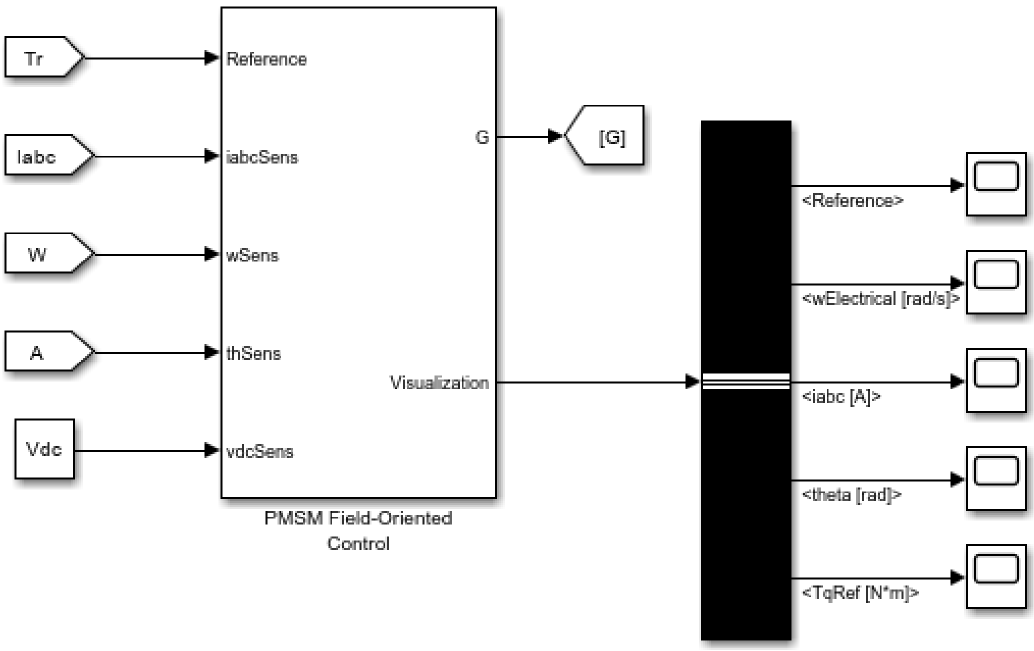


Figure 4.6:Proposed controller

In the above figure, the block represents field-oriented control for permanent magnet synchronous motor, this is a built-in block in Simulink which can be customized

4.2.1 CONTROLLING METHOD FOR PMSM

As can be seen from the block it has some input controlling parameters and an output signal. The input signal to the block, I'm mostly the controlling signal for permanent magnet synchronous motor, as in the figure it can be seen there's a reference signal which can be torque or speed of the motor according to the controlling strategy used or selected inside the block, Iabc is the current signal fed to the FOC and this is also a controlling parameter for controlling the speed and the torque of the permanent magnet synchronous motor. Then W and A and the signals purely related to the rotor of the motor, and these signals are speed and angle of the rotor of the motor respectively. Controlling the speed and torque of the permanent magnet synchronous motor through FOC method, requires rotor speed and angle with the three-phase current fed to the motor, a controlling reference parameter And DC source supply, and it produces get signals and all the reference selected signal at the output.

4.2.2 FIELD ORIENTED CONTROL METHOD

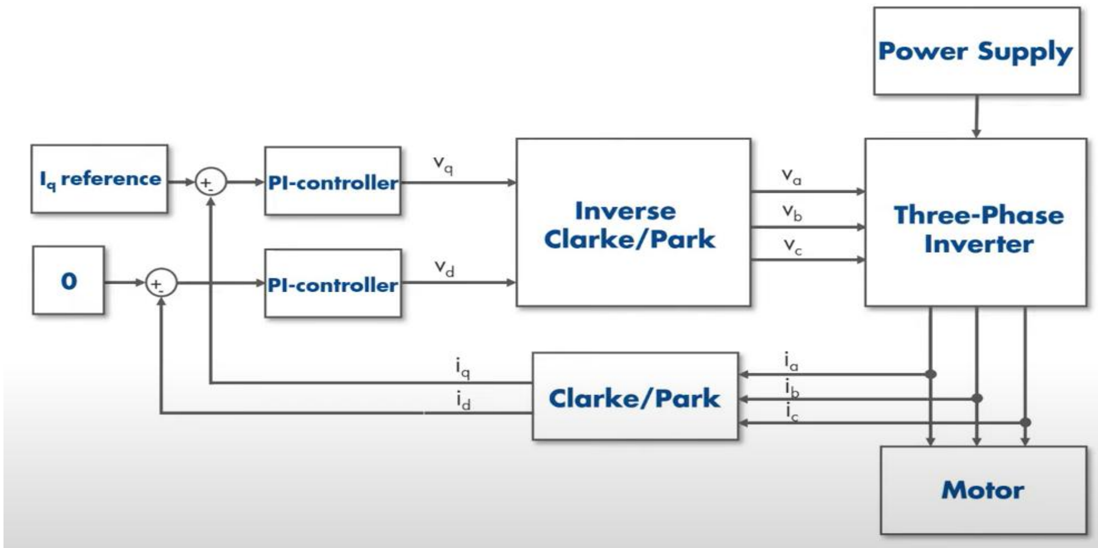


Figure 4.7: FOC Method

In the figure above, there's a conceptual representation of FOC method. The FOC method, also known as vector control method, is used to control permanent magnet synchronous motor. The main concept of the method is to convert three phase axis frames to two frame axes. The FOC takes three phase currents and converts them into direct and quadrature axis frame. This method of controlling permanent magnet synchronous motor is to maximize the torque of the motor during the operation, and to do so one of the axes which is align to rotor axis also called the direct axis, set to zero.

The other axis, which is called quadrature axis is set to move according to the variation in the three phase currents. Then that generated signal fed to the Pi controllers and the output of the PI controller will be the voltages which are quadratic and direct axis voltage, Then the signal again fed to the block already building to see my name with the name inverse Clark and park transform after applying inverse of Clarke/Park transform, the signal friend to the three phase inverter which controls the speed of the motor and the talk required for the application.

Why FOC:

Since there are so many controlling methods for permanent magnet synchronous motor, why use FOC method for our typical application.

There are so many advantages for selecting the FOC method. Some of the benefits of selecting the FOC method, are listed below.

Better Performance: This FOC method gives better performance with PMSM operation due the compatibility of the method with the type of the motor.

Better Dynamic Behaviour: Since the considered example is having dynamic parameters and dynamic controlling signals, so a method which is more suitable with dynamic signals is used to control the PMSM.

Smooth and Fast: This method proves to be a fast and smoothly dealing method with sharp and sudden changes in the controlling parameters.

Maximum Torque achievable: This method works on the basics of making torque of the motor maximum, so this is a good method to go with when it comes to maximizing the torque of the motor during the operation.

High Efficiency and Precise Control: And this method is one of the most efficient methods in controlling PMSM.

4.2.3 EFFICIENCY MEASURING SYSTEM

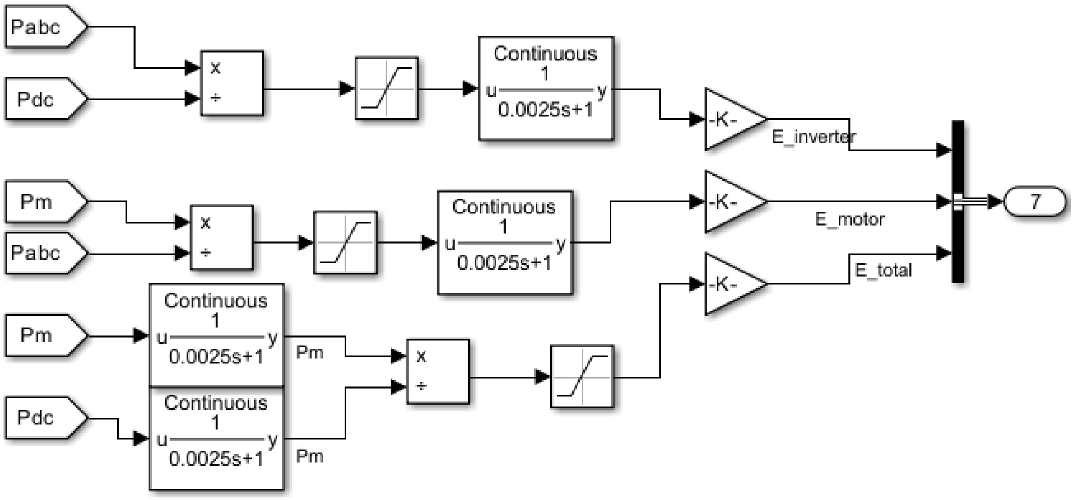


Figure 4.8: Efficiency Measuring

In the figure above, the strategy to measure the efficiency of the whole system can be seen. In the figure above most of the blocks used are the built in Simulink blocks to control, analyze, Calculate And to make the signal filtered from the noise.
Pabc, Pdc and Pm are inverter output power, battery output power and motor output power.

5- ELECTRIC COMPONENT SIZING

For the sizing of the electrical components, Battery, Electric Motor, and Inverter, need to consider the power of the considered system as shown in the above figure.

Bobcat E50	
Net Power	49.8hp
Operating Weight	10677lb
Bucket Digging force	8977lb
Arm Digging Force	6744lb
Hydraulic System Pressure	3045psi
Lift Radius	118in
Hydraulic System Pump Flow Cap.	20gal/min

Figure 5.1:Considered Excavator Specification

5.1 SIZING

For sizing electric system for this big off-road vehicle, it is required to consider the dynamic load requirement during the whole duty cycle, since these off-road vehicles work on ICE, so a huge amount of power can be delivered to the machine by internal combustion engine. But when we talk about the electrification of these off-road vehicles, it is very important to consider the size, the power, and the capacity of all the components used in making this mini excavator an electrified version. Now in the electrified version of these off-road vehicles, the load power during the operation is totally dependent on the electrical components installed in the machine. If a high voltage/high kWh battery, a high-power electric motor and a high-power inverter is installed in the mini excavator, it would be capable of providing high power required during the operation.

Also, it is required to consider the duty cycle off this mini excavator because normally all these off-road big vehicles require a heavy-duty cycle during the operation. Normally a huge amount of power is required during the operation of off-road vehicles. Therefore, for making these off-road vehicles electrified, high Capacity and high-power electric components are required.

There is another challenge while sizing the electric component for this mini excavator, is the space inside the machine to install all electrical component Because previously an internal combustion engine was installed in the machine and since these machines were designed considering only engine in mind, so the internal structure of these machines is having less space according to the ICE. So, to install all the electrical component batteries, electric motor, and an inverter plus a small control for controlling all the electrical connections and circuits, it is a challenge to create space for installing the above-mentioned components.

5.1.1 BATTERY SIZING

There are some of the main factors while selecting and sizing a battery for the considered example. Below is the list of the factors which are being considered while sizing a battery for this mini excavator application.

Load Characteristics: While deciding a battery for the application the load characteristics are very important. In the off-road vehicles, mostly the duty cycle during the operation requires varying dynamic load, since these off-road vehicles requires a lot of load fluctuation during the operation so selecting the electrical components which are suitable with dynamic load, are very important.

Peak Power Demand: Since the battery is being selected for an application which requires a huge amount of power during the operation, so while selecting and sizing a battery for the electric system, the peak power which can be provided by the battery should be kept in mind also the power required during the normal operation is very important for a longer operation with the battery.

Voltage Compatibility: In the container mini excavator application, since this bigger machine requires a lot of power and torque so a bigger motor and a bigger inverter is required so to power up the inverter and electric motor a bigger voltage battery is required which can provide high power for continuous interval.

SOC and SOD: In selecting and sizing a battery, state of charge state of discharge and depth of discharge are very important and key factors to consider. A battery with a fast state of discharge is not recommendable and a battery with low state of charge is also not suitable for mobile applications.

Temperature: The temperature is the key factor, effecting the performance of a battery, So I battery which is suitable for wide range of temperature, is selected

Life Cycle: Since battery is the main source of energy to the electric system and governs the whole operation, so a battery with higher life cycle is selected so that it can work for longer period, one of the main challenges of making these big off-road vehicles electrified is to keep them running for longer period with a huge amount of backup power source.

Efficiency: This is the main factor while selecting a battery, a battery with low efficiency is not suitable for this operation, only a battery with higher efficiency is suitable because if a battery is not higher efficient, most of the power will be lost during the operation before even reaching main prime mover, so a high efficiency battery around 95% or more is suitable for this application

Cost and Maintenance: While selecting a battery, cost and maintenance in future are very important, because if the battery is very expensive than most of the big machine where a bigger battery is required cannot put battery and make their machine electrified. Similarly, if it has a high cost of maintenance, it will be avoided.

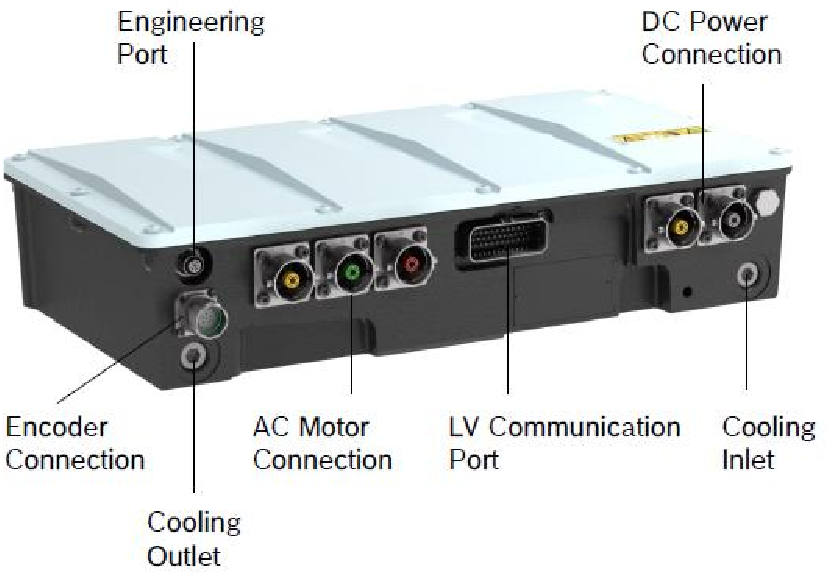
So, considering all the above factors in mind, the most suitable battery selection for the above type of application is Lithium-ion battery, due to its long lasting ability, higher SOC and very stable among the available batteries.I have selected Lithium iron phosphate ($LiFePO_4$) which is most suitable for mini excavator application due to its characteristics and wide temperature range.

Figure 5.2: Selected Battery

5.1.2 Sizing of an AC Power Inverter

The AC Power Inverter in making off-road vehicles electrified, is very important because this inverter works as a bridge in between Battery and Electric Motor.

The following is the selected AC Power Inverter because of its suitability and compatibility with the application of off-road vehicles.



EDS1 Inverter Connection Interfaces

- Pulse-width modulation inverter for motor and generator operation
- Operating voltage 270 to 800 V
- High overload factor up to 2.5
- High efficiency over operating range (up to 98%)
- Protection class up to IP6K7, IP6K9K
- Ambient temperature −40 to +85 °C
- Liquid cooled with inlet temperature up to 65 °C

Figure 5.3: Selected AC Inverter

5.1.3 SIZING OF ELECTRIC MOTOR

Since Electric Motor is the main prime mover in the application considered, so while selecting an electric motor, the following main factors should be considered.

Speed Requirements:

While selecting an electric motor, rpm during the operation is very important to consider because it the electric motor is not working under the nominal condition while it comes to speed, then it cannot work with high efficiency, to avoid working electric motor in not working in nominal condition,

Torque Requirement:

Electric motor is the main prime mover in this application and the torque associated with the electric motor is very important to consider, since for these big off-road vehicles, due to the nature of their application and duty cycle, high torque is required during the operation. So, a motor capable of providing high torque in nominal condition would be selected.

Power Requirements:

Since the use of the main prime mover (electric motor) is mostly during the whole operation, and the nature of the duty cycle demands high power, a motor capable of providing high power is selected.

The efficiency of the electric motor during the operation cycle is a key factor, so a motor with high efficiency during the nominal operation condition is selected.

I have selected a motor from Bosch (Elion Motor EMS1 series). Due to its compatibility and suitability with the application.

TECHNICAL DATA

eLION Motor EMS1	
Axial radius:	100, 130, 160, 200 mm
Nom. voltage:	270 ... 800 V_{DC}
Nom. power:	up to 229 kW
Max. power:	up to 530 kW
Nom. torque:	up to 1,430 Nm
Max. torque:	up to 2,520 Nm
Max. speed:	up to 12,000 rpm
Cooling:	50:50 Water-Glycol Mixture
Coolant flow rate (@ 65 °C)	nom. 20 L/min
Data sheet:	RE96709

Figure 5.4: Electric Motor Technical Data

6- EFFICIENCY OF THE SYSTEM

The main purpose of making off road vehicle electrified is to increase their efficiency, because the hydraulic system with ICE is very inefficient, so all the efforts making off road bigger vehicle electrified is to increase the overall efficiency of the system when we replace ICE with electric system the efficiency of the overall system increases a lot for example in the consider application of mini excavator with the ICE, the overall efficiency of the system was less than 10% majorly because of the ICE inefficiencies. So, when we remove ICE from the system and introduce an electric system instead of it the overall efficiency of the system increases up to 32% which is way better than the baseline system efficiency which was less than 10%.

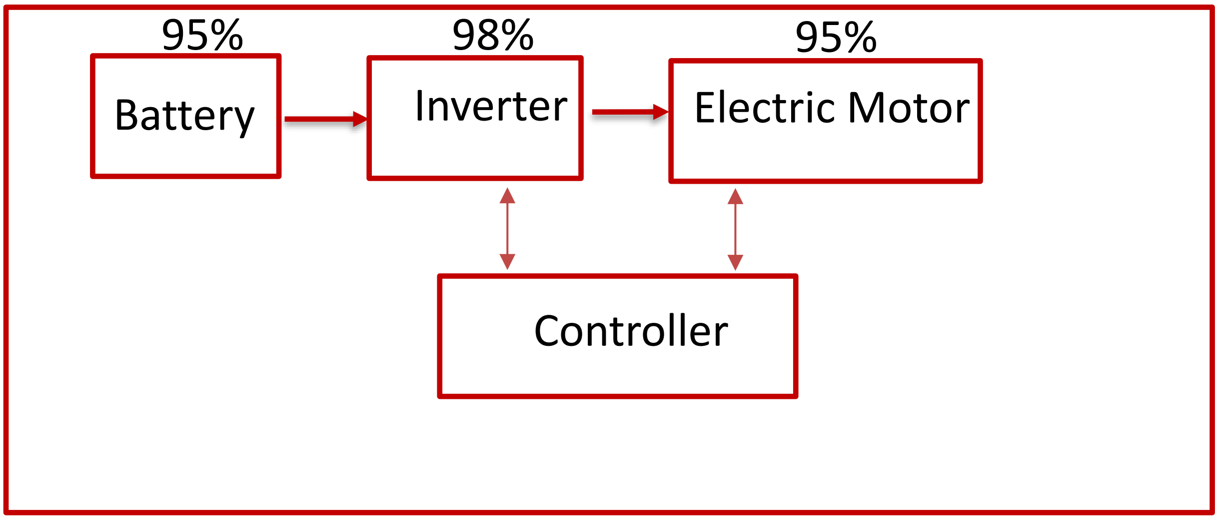
The main motivation to convert these big off-road vehicles from ICE to electrified solution, is to increase their overall efficiency. So, the research done on the electrification of this mini excavator, and it was seen that introducing electrical system into these big vehicles increases the overall efficiency of the system a lot.

Also, there's another motivation for making these big off-road vehicles electrified is to make them fast and to make their control easy because when you introduce electronic control the response of the system gets much faster than the baseline machine.

It is obvious that by making these off-road vehicles electrified increases the overall efficiency of the system and makes the systems response faster and control much easier but to make these big off-road vehicles electrified is not simple. There are challenges to deal with when it comes to electrification of off-road vehicles. It is not simple just to replace ICE with battery inverter and motor, it is required to modify the internal structure of the system to introduce the new system and to make the installation possible. Also removing ICE and installing battery, an inverter and an electric motor, there's a challenge of internal space of the machine where the new equipment can be installed. Because previously there was only one IC engine but now instead of IC engine, there are quite big and heavy electrical equipment which need to be installed so much space would be required.

6.1 Physical Parameter based Efficiency

In this section, the physical parameter-based efficiency of the electric motor an inverter and a battery will be discussed. Considering all the electrical components working in the nominal condition during the whole operation the below efficiency numbers from all the electric components can be considered.



So, if the whole electric system is working under the nominal condition during the whole duty cycle, 83 to 85% efficiency have the whole electric system can be considered. But this efficiency can be achieved only if all the equipment during the whole operation is working under nominal conditions.

We have three major electrical components in the above figure which governs the overall efficiency of the system when it comes to the electrical side of the overall machine system. As we know in these off road big vehicles we have hydraulic system which is very complex and also not a high efficient system so when the overall system efficiency will be discussed it would be the combination of the electrical system side and the hydraulic system side in the below sections only the electrical side of the hole machine will be discussed and as we know, we have three major electrical components, battery, inverter and an electric motor. For high efficiency from electrical side, it is required to operate under nominal condition.

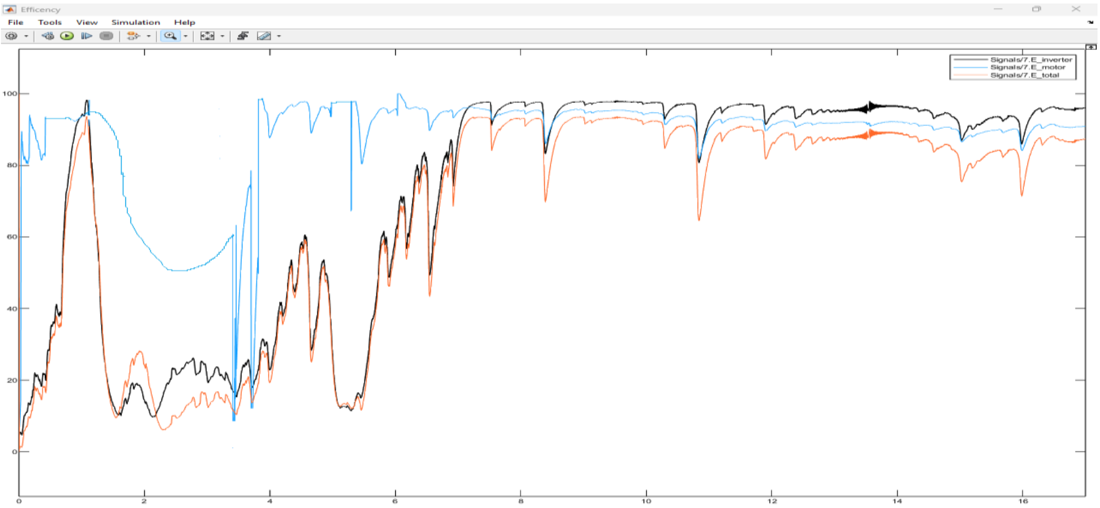


Figure 6.1: Efficiency Curves

In the above figure, these are the efficiency curves based on the physical parameter of the electrical components.The above efficiencies are calculated with the help of the above figure where Pabc, Pdc and Pm are the powers of inverter, battery, and motor.

In the figure above (efficiency figure), it can be seen there are three different colors graph, the black graph shows the efficiency of the inverter, the blue color graph shows the efficiency of the electric motor and red color graph shows the overall total system efficiency, these efficiencies a calculated based on the physical parameter after electric motor used, the inverter and the battery used.

From the efficiency figure graph, it can be easily seen that by setting the physical parameter according to the selected component and normalizing the nominal and maximum values from the manufacturer battery inverter and motor.

These physical based parameters at the normalized parameter taken from the actual data provided by the manufacturer. All the efficiency graphs, torque and power graphs are plotted against the normalized data. As per the selected electrical components, the efficiency graphs in the figure of efficiency as per expectation, since the selected electrical components are working under the nominal values, so it was expected higher efficiency from all of the electrical components and as in the graph of efficiency it can be seen during the whole duty cycle accept the start of the cycle with this spike, the efficiency gross are in the range of 85 to 95%.

6.2 MAP BASED EFFICIENCY

In the previous section, physical parameter-based efficiency was discussed which was based on the physical parameter of a battery, inverter, and electric motor. Considering battery as a constant source of supply and considering a fix officially out of inverter since we are working under the nominal condition so fix efficiency out of inverter can be considered, so in this section motor map-based efficiency will be discussed. Map-based efficiency for general motor which has the same capabilities and parameters as the manufacturer motor (Bosch Elion EMS1). To get the map efficiency of a general motor, all the parameters and the base values from manufacturer motor are normalized and then fed into Amesim software. Amesim has given a map officially over the different values off speed and torque by setting the required power.
The figure above is the efficiency map for a general motor setting the torque speed and power as per the requirements. The parameters of the motor are selected and calculated from the considered example of mini excavator.
The different color in the above figure shows the different efficiency levels during the different operating points. If a motor works under the nominal condition, maximum efficiency can be considered out of that motor. For example, in the above figure the red color shows the higher efficiency region where you can expect 85 to 95% efficiency.

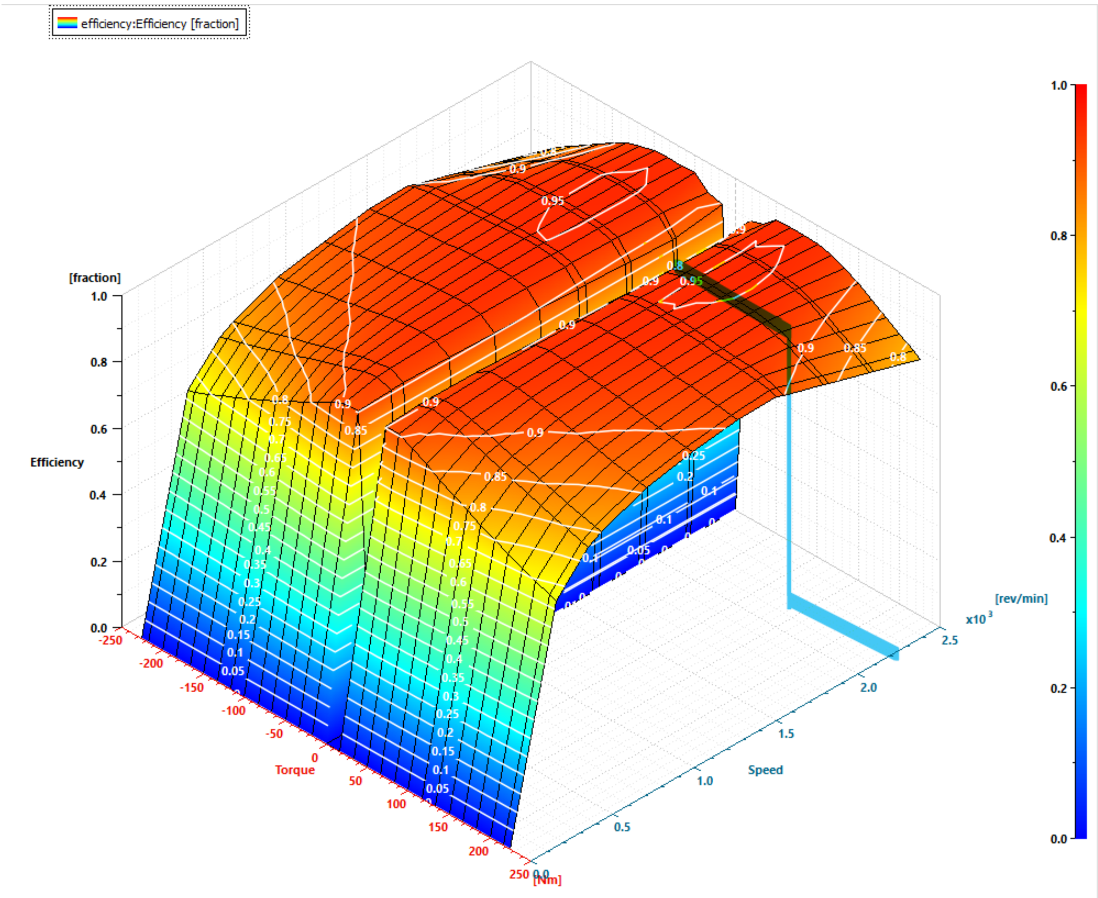


Figure 6.2:Map Based Efficiency

The above figure shows the mapping efficiency of an electric motor in Simulink. This map also shows both sides positive and negative talk sides and gives the efficiency what are the different operating points of torque and speed, the yellow part after graph shows the higher efficiency region. The point on the yellow graph is one of the operating points during the duty cycle of considered mini excavator which shows above 95% efficiency after electric motor.Considering the nominal operating condition for our electric system, it is easy to conclude that our motor efficiency will be around 90 to 95% during the whole duty cycle.

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Considering the nominal operating condition for our electric system, it is easy to conclude that our motor efficiency will be around 90 to 95% during the whole duty cycle.

In the above figure, a general motor efficiency map can be seen with the different values of efficiencies at different operating points, there's a considered duty cycle at 2200 RPM with a dynamic torque and from the graph it can be seen that even though having a dynamic torque, the efficiency of the system is lying in the range from 90 to 95% Which is a good efficiency for an electric motor during the whole duty cycle of the considered mini excavator.

7- CONCLUSION

In the above research for the electrification off off-road vehicles, the following and the outcomes:

Selection of Electric Components: Since the research was to convert engine based off-road vehicle to electrified version, ICE will be removed with the electric components. So, suitable and compatible electrical components were selected. In the electrical component selection, a battery, an inverter, and an electric motor were selected. During the selection of above-mentioned components, the comparison between available different types of electrical components, was carried out and the most suited and compatible to the considered example, were selected.

Electric System Modelling: After the selection of the electrical components which are going to be used in the electrification of the off-road vehicle, electrical system modelling was carried out through Simulink, with the electric circuit was built to analyze the overall system behavior and to get the efficiency of the system individually end for the whole system.

Sizing of the electric components: since these big off-road vehicles requires a lot of power during the operation so when removed ICE and installing the electric component to make the system electrified, the size of the electric components is very important to consider. All the electric components were sized according to the requirement of the system.

Efficiency of the system: the efficiency of the system was determined and explained. Both the physical parameter-based efficiency and the map-based efficiency were discussed.

The concept of making these big off-road vehicles electrified is fascinating and attractive but it brings a lot of challenges and efforts to make this happen. In today's market, there are few examples of already electrified off road vehicles which are working perfectly but still there are challenges to increase the efficiency which already increased a lot from the baseline ICE models. Also, there's a problem of space inside the vehicles because these vehicles were not designed for electrification and their hydraulic system is also not that capable. So, to make a better electrified version of these offered vehicles it is required to reconsider the hydraulic systems installed into these vehicles and the space inside the vehicle should be considered while designing the vehicle for electrification in mind. The considered efficiency of the vehicle has some limitations of operating region which was considered under nominal during whole duty cycle, torque and power required during the operation of the vehicle, working voltages levels, operation time and backup and external temperature.

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