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Modelling 600V Traction System for a Hybrid Electric Vehicle

Master's thesis in Electric Power Engineering

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Abstract

Today's automotive technology requires compact solutions for electrical distribution systems without sacrificing essential characteristics intended for their actual functioning. These solutions are essential for heavy-duty electric vehicles and hybrid construction machinery for which high operating voltages of the electrical system are essential. This work focuses on modelling and simulations of the Traction Voltage System (TVS) for the voltage level of 600V, which is supposed to be implemented in a hybrid construction equipment (wheel loader) developed at Volvo CE. In the thesis, the Matlab/Simscape model of the TVS was designed, including a battery, power electronic components (converters) and an electrical machine. The electrical connections between the components are implemented utilizing a specially designed busbar. The busbar parameters may affect the system's performance, and therefore its design and electrical parameters (capacitance, frequency-dependent resistance and inductance) were examined utilizing computer simulations using Comsol Multiphysics software. The obtained electrical characteristics were integrated into the Matlab/Simscape model of the traction voltage system, and simulations were performed for the conditions corresponding to its regular operation. The obtained voltage and current patterns in different components of the TVS were analyzed. FFT analysis was performed, and the results were compared with the real-time measurement results, particularly for the TVS currents distributed through the busbar. The work resulted in the working models of the system, which can be further used for power quality analysis of the TVS and its optimization.

Keywords: Traction voltage system, laminated busbar, finite element analysis, electrical drive system, MATLAB/Simscape, COMSOL-Multiphysics

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1

Introduction

1.1 Electrical distribution in hybrid electric construction machinery

Construction/Earth-moving machine is typically a heavy-duty vehicle designed for construction works involving earthworks. A wheel loader is a heavy machine frequently used in the construction industry. Recently, hybrid solutions are being implemented in various kinds of machines by the manufacturers of the construction machinery industry. Unlike the regular automotive vehicles, the hybrid system of the construction machinery has to fit the unique working style in order to have higher efficiency. The TVS is part of the electrical distribution system, which comprises electrical and mechanical components to propel the machine by transferring energy.

1.2 Power quality issues in a distribution system

The traction system in heavy-duty off-road vehicles is not advanced when compared to light passenger vehicles. So it is necessary to analyse and understand the vehicle performance contributed by each of the subsystems. The Volvo Construction Equipment (VCE) has planned to analyse the power quality of the traction voltage system with all the connected subsystems.

An essential consideration in the design of traction voltage systems is power quality. It generally describes the quality of the system voltage. However, the power is proportional to both the voltage and the current. Hence, the power quality analysis necessarily includes the voltage and current together. The stability and performance of the machine are adversely affected by the harmonics due to the common dc-bus connection with high-frequency switching inverters.

Moreover, the busbars used in the dc-bus connection can create electromagnetic noise and interference with the performance of nearby devices since it carries a significant amount of current with harmonics at relatively high frequencies. Therefore, the complete characteristics of the busbar have to be analysed, including the electromagnetic and electrostatic characteristics, to find the electrical equivalent model of the busbar. In order to study the electrical behaviour and make the power distribution system more stable, the simulation of the traction voltage system needs to be done.

1.3 Aim

The objective of the thesis work is to model and simulate the traction voltage system with all the connected components such as the busbar, PEC and electric drive system models for the Volvo hybrid construction equipment-wheel loader. The power quality of the TVS needs to be studied with all the connected loads. The comparison has to be studied for simulated and measured results.

1.4 Scope of the thesis

In this work, the 600V traction system should be modelled and simulated with all the connected components in MATLAB. The busbar model for the 600V traction system should be developed using COMSOL-Multiphysics. The thermal analysis is to be excluded for this project. The electrical characteristics and the parameters are to be analysed to obtain an equivalent model. The obtained model of the busbar is to be provided as an input to the MATLAB/Simscape model of the whole traction voltage system of the wheel loader. The analysis is to be performed for the most familiar combination of materials such as copper (conductors) and polyethylene terephthalate (PET) (dielectric).

The Simscape model of the TVS is to be developed with all the discrete elements of the actual components. The design parameters of the components in the simscape model has to be considered from the available specification from VCE. The ideal values have to be considered for the parameters if the data are unavailable. The power quality analysis of the TVS has to be done. The FFT analysis has to be done for the load current which is flowing through the DC-busbars.

The power quality analysis has to be studied with the help of real-time measurements from the test rig of the TVS setup. The measurement data provided are considered for the FFT studies.

2

Theory

2.1 Traction voltage system

Energy conservation and the reduction of emission are essential aspects of electric and hybrid powertrain technologies. In order to implement the fully electric powertrain with these machinery, certain features are needed considering the heavy load, unique functions and the period of operation. So hybrid technology can be utilised initially in transforming and leading the industry to a fully electric road map [1].

The subsystems of hybrid electric TVS are connected with the help of a junction box that contains the busbar with suitable connectors. A traction motor is connected to the Hybrid-electric voltage Junction Box (HJB) via Power Electronic Converters (PEC), an electronic control unit is used to monitor the current flowing to or from the electrical components.

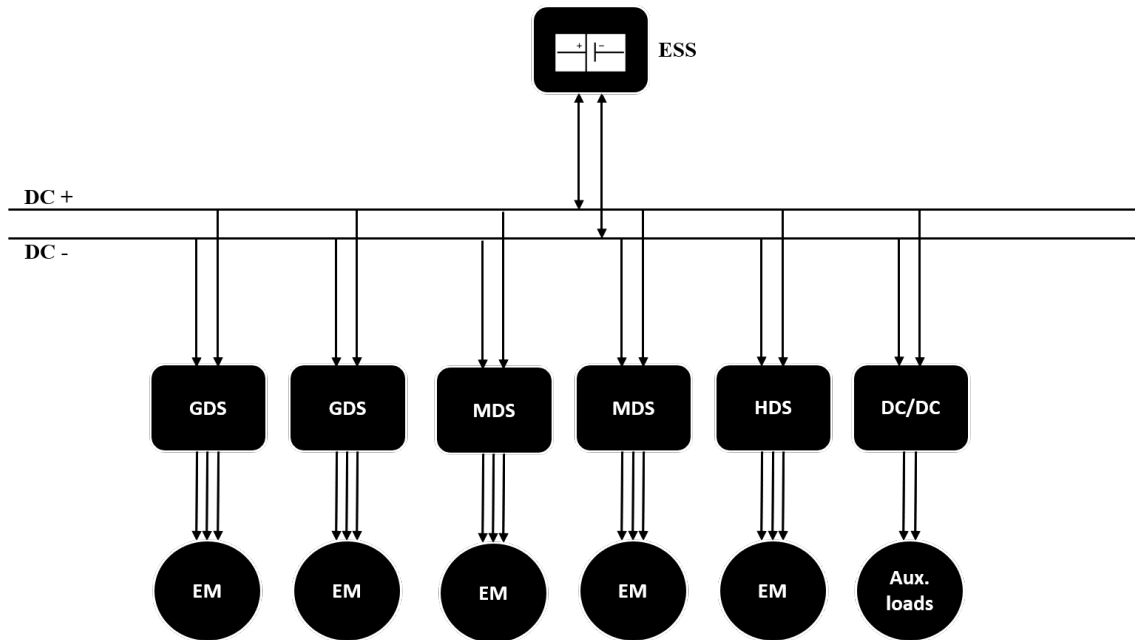


Figure 2.1: TVS of Wheel Loader

The traction voltage system has been energised with the help of a 600V battery pack and distributed into five drive systems such as two generator drive systems

(GDS), two motor drive systems (MDS) and one hydraulic drive system (HDS), as shown in figure 2.1. These drive systems are used to drive the electric machines, which drives the respective loads via gearbox assemblies. The energy distribution is being done through the DC busbar via five pole-pole connection terminals. The DC-DC converter is used to drive auxiliary loads like a fan, pump, headlights, etc.

2.1.1 Laminated busbar

The recent techniques are being implemented in the automotive industry to have electric and hybrid vehicles functioning smoothly. One such method is to use busbars in electrical distribution over the conventional cables. However, the conventional busbar system has some disadvantages such as more significant space requirement, insulation failure leading to short circuits of the system, etc. It is necessary to use heavy gauge cables if the system current exceeds several hundred amperes. These wires are heavier and stiff to bend or fit into a confined location, e.g. HJB. It also possesses more stray inductance, and a low capacitance leads to transient spikes in the system from which the connected subsystems are greatly affected [2].

The laminated busbar can overcome the above-said problems with its unique structure and design. It maintains a low stray inductance and a high capacitance effect as the structure contain the conduction materials sandwiched with the insulation in a suitable and required manner. The chances of having sparking, heating effect and wiring problems are minimal compared to the traditional busbar if we design the busbar with suitable materials. Laminated busbars can fulfil the demands of the applications, which requires low stray inductance, less weight, low space requirement, and a safe operation [3] and [4].

Laminated busbar systems offer better electrical and mechanical performance and improve reliability and reduce installation costs. It would be much easier to troubleshoot the connections when having field issues [5]. Figure 2.2 shows the actual busbar of the traction voltage system in the Volvo wheel loader.



Figure 2.2: Busbar in TVS of wheel loader

2.1.2 Energy storage system - Batteries

The wheel loader is equipped with a 600 V battery with a 50 Ah capacity. The subsystems which are connected to the battery are drawing current in the range of several hundred amperes. Dealing with this high power requires this massive size of battery which also creates transient peak voltages [3].

2.1.3 Load subsystems

2.1.3.1 Electric drive system

The electric drive system is used to produce propulsive and braking torque to the vehicle. The electric drive system comprises the electric machine (PMSM) and electric motor drive (converter) [6]. It is connected to the battery via an HJB, as shown in figure 2.3

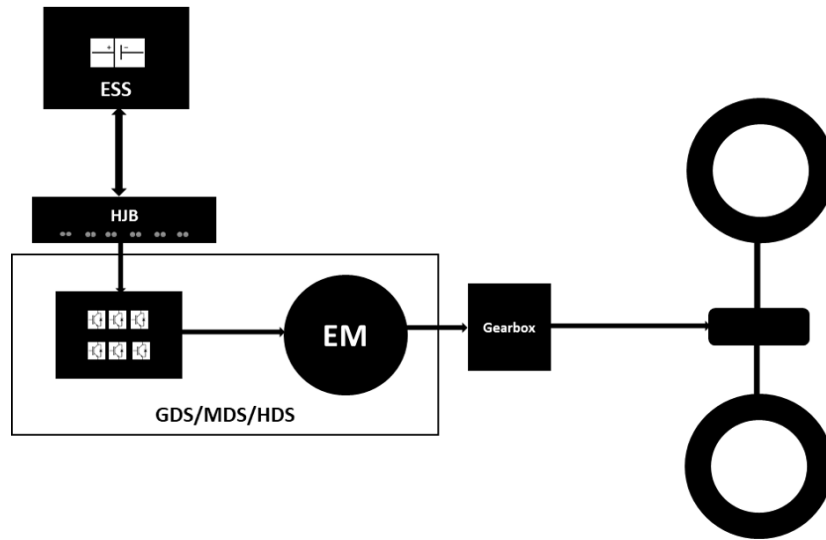


Figure 2.3: Electrical drive system

Power conversion in an EV/HEV usually takes place in several stages, primarily using IGBT devices. The critical need for the IGBT devices, i.e. to have a low inductance power path, is significantly achieved by the laminated busbars.

Inverters: The electric vehicles use one or more traction inverters to convert the DC voltage/current provided by the traction battery to the AC voltage/current to drive the traction motors. Voltage boosting, switch protection and regenerative braking are the other functions performed by an inverter [7]. The wheel loader has five inverters for each of the machine subsystems.

DC-link capacitance: The traction inverters are connected to a large and bulky DC link capacitor in their input. It is to provide a smooth ripple current and stabilise DC bus voltage [8]. However, these capacitors occupy almost 50% of the whole package and contribute 20% of the inverter cost. They are always over-designed to have a more significant safety margin during the fast transient operations [7].

DC-DC converters: Typically, the dc-dc converters are employed to power the auxiliary loads other than the functional loads of the construction machine. Typical auxiliary loads include power headlights, wiper/washer motor, fans, pumps, interior lights and other miscellaneous systems. These converters step down the higher voltages (200 V - 800 V) to lower dc voltages (12 V - 48 V) [9].

2.1.3.2 Permanent magnet synchronous machine(PMSM)

PMSM consumes ac power is used to drive the mechanical loads. There are 5 PMSMs used in the system to drive the vehicle with different propulsion systems such as generator drive system (GDS), motor drive system (MDS) and hydraulic drive system (HDS). PMSM can provide a high torque-to-current ratio, high power-to-weight ratio, high efficiency and robustness. Due to these potentials, PMSMs are used in electric vehicle applications such as variable speed AC drives [10].

2.2 Design considerations for busbar

The extensive study on the design considerations for busbar has been done with the published paper [4]. The below factors have been taken into considerations and compared against the actual busbar of the wheel loader.

2.2.0.1 Shape of the busbar

The design complexity of the busbar depends on both mechanical and electrical parameters as stated in [4]. The number of ports decides the shape and structure of the busbar mechanically. As shown in figure 2.2, the input and output ports determine the dimensions of the busbar. Electrically, the thickness of the busbar is determined by its average and rms current amplitude and the low/high-frequency components. The current distribution can be improved by determining the correct thickness. The busbar has very few sharp edges in order to reduce the eddy currents. However, the bends can also impact the eddy current, increasing the voltage drop consequently the losses. A sufficient radius has to be maintained to reduce the inductance effect in the corner and the bends.

2.2.0.2 Insulation

The electrical insulation depends on the operating voltage to which the busbar is subjected. The dielectric strength is the crucial factor that depends on the type of material used. The common materials are Mylar (PET), epoxy-glass, Kapton, Ultem, polyimide or a combination of materials are used for the insulation. The dielectric strength is inversely proportional to the thickness. If the capacitance is designed to be higher, which in turn decreases the busbar impedance, consequently reduces the noises in high frequencies.

Three types of insulation can be employed at the edges to protect the busbar from contamination as stated in [4] called edge, sealed edge and epoxy filled edges.

- Open edge is the least wanted since it is most susceptible to contamination. Primarily used in clean and dry environments
- The second type is a closed one on the edges. The concerned busbar model is similar to this, which is shown in figure 2.4. The protection against contamination is good compared to the open type.

- The epoxy is filled with the open type configuration, making the busbar more immune to the harsh environment and subsequent contamination.



Figure 2.4: Sealed edge insulation in the busbar

2.2.0.3 Conductors

In order to achieve electrical performance and mechanical stiffness criteria, the material choice for the busbar conductor is crucial. Copper, aluminium, and copper alloys are the most commonly utilized materials. In order to remove excess heat from the busbars, system ventilation may be required. Busbars can also be used as a heat sink to remove heat from components.

2.2.0.4 Non-copper conductors

When compared to copper, non-copper conductor materials (such as aluminium) have both advantages and disadvantages. Aluminium has a density that is 33% lower than copper, but it has a 60% poorer electrical and thermal conductivity, depending on the alloy used. As a result, an aluminium design should weigh 66% less than a copper design of the same thickness. Aluminium is also suitable for mass production, but the influence of doubling the conductor thickness on manufacturability, on the other hand, must be taken into account.

To minimize high-frequency harmonics, other conductors, such as nickel, can be applied to the surface of the copper conductors. This combination will dampen the high-frequency noise pushed to the surface by the skin effect and travels through the nickel. The low-frequency current will flow through the less-resistive copper.

2.2.0.5 Conductor thickness and current density

The maximum current density determines the thickness of the busbar. The input and the output terminal connections can decide the thickness if it is not for the mechanical requirement. The input terminals can be split into two or more terminals

to enhance the current distribution without compromising the conductor thickness. Depending on the conductor thickness, it may be advisable to increase the dielectric material thickness to reduce the impact of the swarf while pressing the sheets together. A general rule of thumb for bus bar design is that current density should not exceed 5 A/mm² [4].

2.2.1 Equivalent circuit

An equivalent circuit of any electrical component is essential for analysing its performance and finding out if the design needs modification based on the simulation outcome. The busbar used in the TVS has two parallel plates of conductor, which is separated by dielectric insulation, and it has a non-uniform structure with input and output terminals as shown in below figure 2.5. R_P , L_P are the resistance and stray inductance of the positive plate and R_N , L_N are for the negative plate for a single load. The equivalent circuit is being elaborated for all the five loads connected to it with the respective resistance and the stray inductance and capacitance in parallel (C_P) between the two plates.

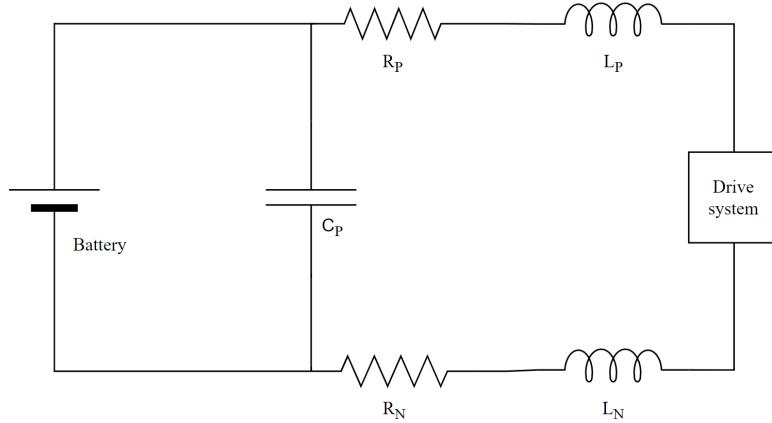


Figure 2.5: Equivalent circuit of busbar for a single load drive system

The impedance of the busbar, especially its inductance, is vital during the operation of converters as it creates an overshoot of voltage across the semiconductor devices during the switching transition. In order to withstand this overshoot voltage, the IGBTs' capacity is over-engineered, which makes the whole system cost higher. Repeated voltage spikes also create higher heating which reduces the life expectancy of the devices [11].

2.2.2 Parallel plate capacitance

The capacitance of the busbar arrangement is determined by the dielectric material used. It depends on the system's physical dimensions, such as the area and the

thickness of the insulation. It can be computed using the below expression (2.1).

$$C = \varepsilon \frac{A}{d} = \varepsilon_0 \varepsilon_r \frac{A}{d} \quad (2.1)$$

where ε_0 = permittivity of free space, ε_r = relative permittivity/dielectric constant, A = area of the conducting plate in m^2 , d = dielectric thickness in m.

Since the laminated busbar has a complex structure, the easy way is to calculate the capacitance from the electrostatic analysis from the expression (2.2)

$$W_e = \frac{1}{2} CV^2 \quad (2.2)$$

where W_e = total electric energy stored in J, V = voltage in V, C = capacitance in F.

As capacitance increases, characteristic impedance decreases. Noise is reduced more effectively when the impedance is low. As a result, the maximal capacitance between conductor levels is preferred. It is possible to accomplish this by

- maintaining the dielectric as thin as possible under acceptable manufacturing and design procedures.
- using a dielectric material with a high relative permittivity [5].

2.2.3 Stray inductance

Keeping the low inductance results in a low characteristic impedance and better noise reduction. The following strategies can obtain the lowest possible inductance:

- Minimize the dielectric thickness
- Maximize the conductor width
- Increase the frequency [5]

L can be determined from the total magnetic energy stored using the below equation (2.3).

$$W_m = \frac{1}{2} LI^2 \quad (2.3)$$

where W_m = total magnetic energy stored in J, I = current in A, L = inductance in F.

2.2.4 Resistance

In general, the resistance is governed by the conductor material and its form. When the frequency increases, so do the resistance value, resulting in a higher ohmic

loss on both negative and positive plates. However, the overall ohmic loss on the busbar is just a few watts, which is insignificant compared to the inverter power loss. Power loss on a busbar is affected by resistance. As a result, low bus bar resistance is recommended. For high frequencies, skin depth has been taken into account for calculating ac resistance using the equation (2.4) [5].

$$R_{ac} = \frac{2 * \rho * l}{\delta * w} \quad (2.4)$$

where R_{ac} = AC resistance in Ω , ρ = resistivity of the copper in $\Omega.m$, l = length of the conductor in m, δ = skin depth in m, w = width of the conductor in m.

2.2.5 Impedance

The impedance should be kept as low as feasible in the design of the laminated busbars. It will minimize all types of EMI transmission to the load. The decisive variables in noise elimination include increasing capacitance and decreasing inductance. Impedance can be calculated by using below equations (2.5) & (2.6).

$$Z = \frac{V}{I} \quad (2.5)$$

$$Z = R + jX_L \quad (2.6)$$

where R = real part of impedance in Ω , X_L = imaginary part of impedance in Ω . Finally, the inductance can be found from the below equation (2.7).

$$X_L = 2 * \pi * f * L \quad (2.7)$$

where f = frequency in Hz, L = inductance in H

2.3 Skin effect

The 'skin effect' will arise as a result of the high-frequency switching of the converter. It is a phenomenon in which high-frequency current in a conductor does not flow evenly over its cross-section area but instead squeezes into increasingly shallower areas near the conductor's surface called 'skin depth'. It causes overheating on the busbars, resulting in increased system losses.

The skin effect is an inductive mechanism related to the rate of change of magnetic fields in the conductor. So, it gets more strong at higher frequencies. Because of skin

effect phenomena, inductance and resistance are dependent on frequency. The below equation (2.8) calculates the skin depth of the regular conductor without having any complex structures. For the actual busbar, the skin depth can be visualised by the comsol magnetic field study.

$$\delta = \sqrt{\frac{\rho}{\pi * f * \mu}} \quad (2.8)$$

where δ = skin depth in m, ρ = resistivity of the conductor in $\Omega.m$, f = frequency in Hz, $\mu = \mu_0 * \mu_r$ and μ_r = relative permittivity of the conductor, μ_0 = permittivity of the free space = $4 * \pi * 10^{-7}$

3

Modelling and Simulation

3.1 Importance of modelling:

Creating a prototype takes a long time because of all the different specialized tasks that must be completed. It may conflict with the timelines on occasion. Performing the test after the prototype is complete is challenging, especially when the worst-case scenario must be explored. Replicating high-temperature, complicated, or high-current electrical conditions can be difficult. Large structures cannot be accommodated in a typical environmental assembly. Because of this, the test may be expensive and necessitate a significant amount of preparation time. As a result, a simulation is an effective tool for speeding up development.

3.2 COMSOL Modelling

3.2.1 Geometry

The geometry of the busbar is created by taking the actual measurements from the physical busbar prototype, as the precise CAD model of the busbar is not available. 2D geometry is created based on the measurements in the table 3.1 with COMSOL, and it has been extruded to form the 3D geometry. The complexity of the geometry is to be reduced by simplifying the busbar structure without impacting the analysis as below.

- Small bolts and screws as shown in figure 2.2 have not been considered as it has a negligible amount of power loss.
- Sealing insulation sheet as shown in figure 2.2 covering the whole busbar is not considered.
- The precision of curvatures near the poles as shown in figure 2.2 have higher dimension tolerances as it was measured with a vernier calliper.
- The insulation thickness between the positive and negative plate has been calculated from the total thickness and the thickness of the individual plates since the busbar prototype cannot be subjected to destructive measurement.

3.2.2 Materials

As stated earlier, copper and PET have been considered as the materials for conductor and insulator respectively as the specification of the prototype is not

Dimensions of the busbar	Measured value
Length	562.5 mm
Breadth	50 mm
Distance between two poles	17 mm
Radius of each pole	5.5 mm
Total busbar thickness	6.75 mm
Positive/Negative plate thickness	3 mm
Insulation thickness	0.75 mm

Table 3.1: Busbar geometrical measurements

Properties	Material	
	Copper	PET
Electrical conductivity (σ)	5.998e7 S/m	1e-3 S/m
Relative permittivity (ϵ_r)	6	3.1

Table 3.2: Material properties

available. The material properties are shown in the table 3.2 as referred in [12] and [13].

3.2.3 Physics interfaces

The COMSOL studies include the below-listed physics interfaces for the analysis to be made to find the electrical equivalent of the busbar.

3.2.3.1 Electrostatics

The Electrostatics (es) interface computes the electric field, and potential distributions in the dielectrics [14]. In this analysis, the busbars are considered parallel plate capacitors with a dielectric insulation layer in between them. The positive plate has a potential of 600 V, and the negative plate has the ground potential, i.e. 0 V. This potential can be assigned to the respective plates by using the terminal feature. Figure 3.1 shows the parallel plate setup of the busbar with a snapshot from the COMSOL geometry.

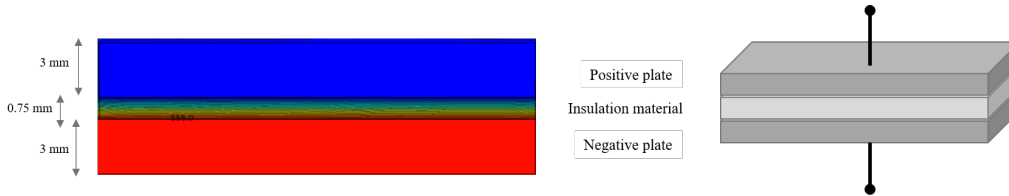


Figure 3.1: COMSOL geometry side view and the parallel plate setup

From this electrostatic analysis, the total electrical energy stored in the capacitor, which is formed by the parallel plate setup of the busbar, is obtained, and the value of the capacitance can easily be calculated using the equation (2.2).

3.2.3.2 Electric circuit

The Electrical Circuit (cir) interface is used to model currents and voltages in the circuit, including voltage and current sources, resistors, capacitors, inductors and semiconductor devices [14]. Models created with the electrical circuit interface can include connections to working models. Each busbar terminal's load subsystem is considered a resistive load in this interface to make the simulation less complex. Instead, the voltage input is considered AC to introduce the critical parameter, i.e. frequency of the operating loads connected to the busbar. This approach is helpful to perform the electromagnetic physics study to calculate the stray inductance.

3.2.3.3 Electric current

The Electric Currents (ec) interface is used to create the virtual terminals on the model to connect it with the electric circuit interface [14]. The created terminals can easily be an interface to the electric circuit by selecting the appropriate terminals from the list in the circuit interface.

3.2.3.4 Magnetic field

The Magnetic Fields (mf) interface computes magnetic field and induced current distributions in and around the conductors, or coils [14]. Each conductor is defined using the coil feature and considered a solid conductor excited by the external voltage source 600 V AC, and corresponding load sections are from the electric circuit interface. The coil feature computes the lumped parameters, which is of interest, i.e. impedance and inductance.

3.2.4 Meshing

Finely tuned meshing needs to be done to see the impact of skin depth in magnetic field analysis. Free tetrahedral is chosen for the entire geometry with the maximum element size specified globally. The calculated skin depth for the actual switching frequency is 0.7 mm , which should be the maximum element size. However, compiling will take much longer, and a vast memory is required; we may need a supercomputer to solve these problems. So the meshing element is restricted to 3 mm due to the above-stated problem, and the analysis has been done.

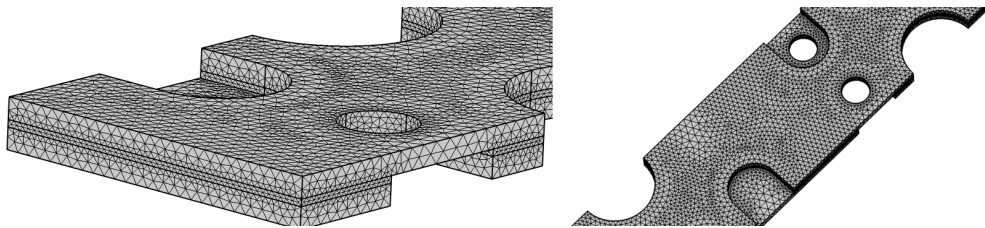


Figure 3.2: Busbar mesh in different views

The figure 3.3 shows the complete modelling tree in COMSOL.

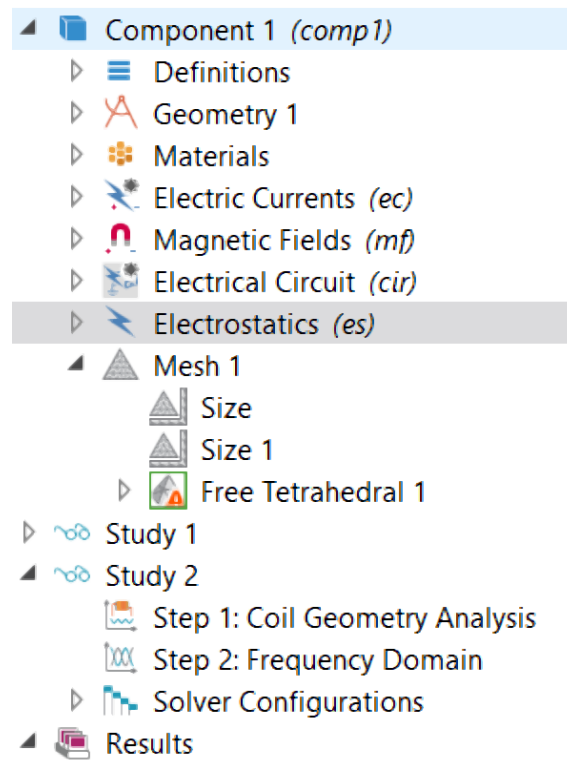


Figure 3.3: COMSOL modelling tree - Busbar

3.2.5 COMSOL study

The electrostatics (es) physics is resolved with the stationary study since the busbars are energized with a constant voltage source that is not changing over time. The study-step parametric sweep is used to find the capacitance for a range of insulation thicknesses.

The coil feature in magnetic field (mf) physics especially requires coil geometry analysis study, which is used to compute the current flow of a coil feature in 3D models. It is a preprocessing step that must be solved before solving the main study step frequency domain.

The magnetic field (mf) and electrical circuit (cir) physics are solved with frequency-domain study with a range of frequency (100 Hz - 1 MHz) since we use an AC voltage source for inductance analysis.

Solver steps: The above physics is simulated with corresponding below study steps.

- Step 1: Stationary study
- Step 2: Coil Geometry Analysis and
- Step 3: Frequency Domain for a range of 100 Hz - 1 MHz .

3.3 MATLAB simulation

The obtained busbar electrical mode from the comsol has to be integrated into a Simscape model in which the distribution system is modelled. Simscape is a part of Simulink, and it is a physical modelling representation in the Simulink environment. Significantly, the simscape electrical libraries for modelling and simulating electrical and electronic systems can parameterize our models using MATLAB variables and expressions for electrical systems in the Simulink.

3.3.1 Simscape model - TVS

The below figure 3.4 represents the Simscape model of the traction voltage system. It contains all the subsystems, including the busbar equivalent model. The TVS has been modelled based on the input from the COMSOL analysis and as per the specifications in section 3.3.2. The cable is used to connect the drive systems with the busbar. The DC-link capacitor reduces the ripple and maintains the stable voltage as per the actual inverter model.

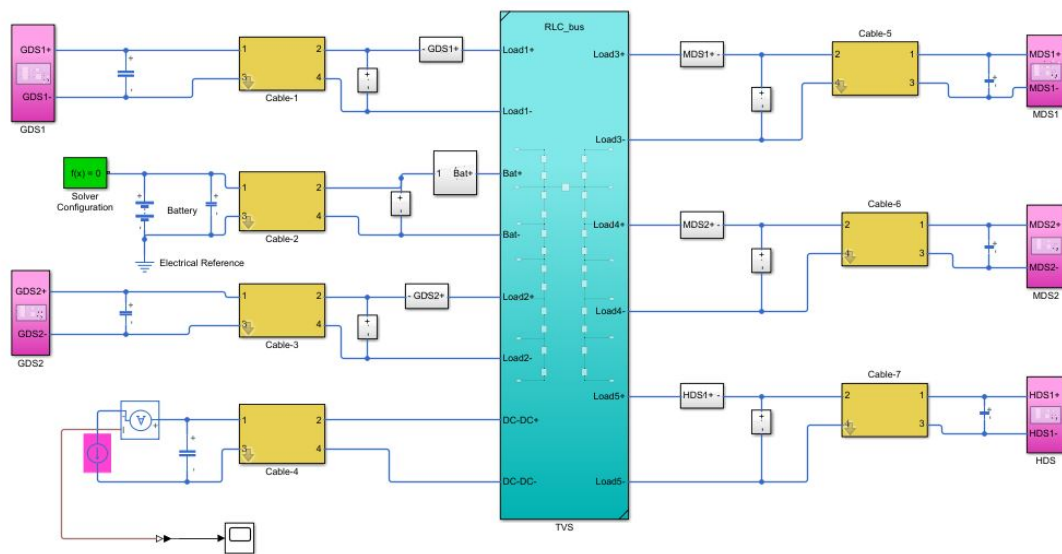


Figure 3.4: MATLAB/Simscape model - TVS

The drive systems comprise of converter and PMSM. The sinusoidal PWM technique is used where the reference signal is a sine-wave, and the carrier signal is a triangular wave to generate pulses for the switches in the converter. The inverter has been modelled considering the actual switching frequency of the inverter 8 kHz , and the model is shown in figure 3.5.

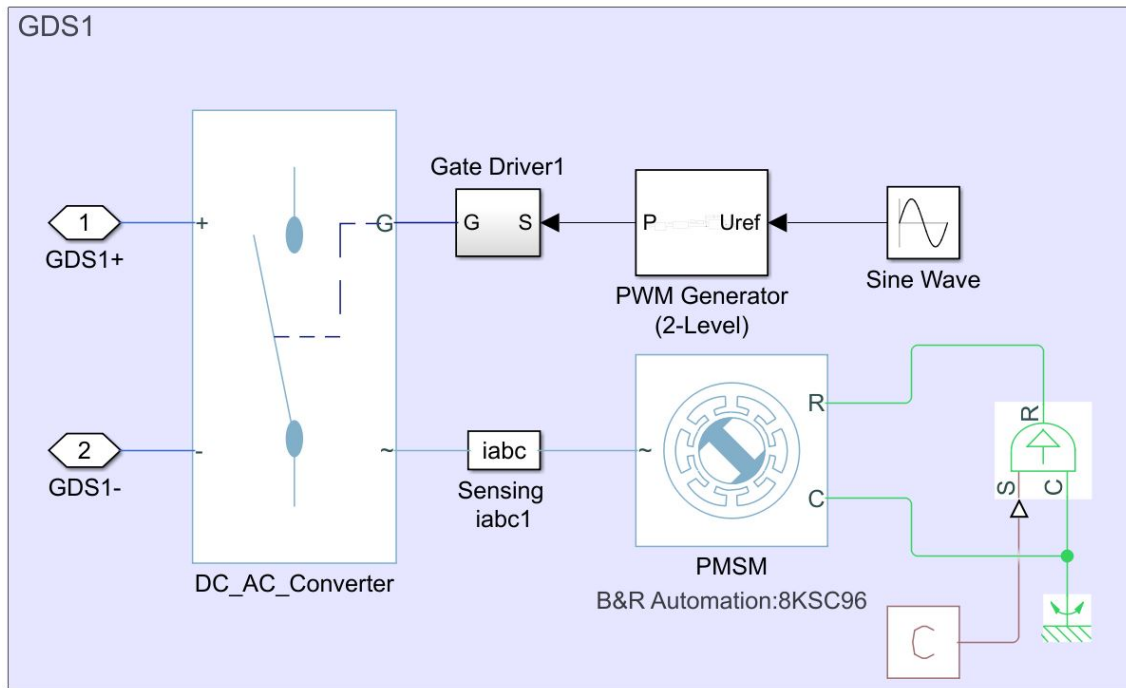


Figure 3.5: MATLAB/Simscape model - Electric drive system

The electric machine-PMSM is modelled with the known machine parameters as per table 3.4. The controller for the machine is assumed to be an open-loop as the information on the controller is not available. The ideal IGBT switches are considered for the converter model, and it is mentioned in table 3.5. The constant current source is used for the auxiliary load that consumes power through the busbar.

3.3.2 Parameters specification for the simscape model

Parameters	Values
Voltage	600 V
Internal resistance	1.3 m Ω
Capacity	50 Ah

Table 3.3: Battery parameters

PMSM parameters	Values
Number of stator poles	4
D-axis inductance	0.741 mH
Q-axis inductance	1.23 mH
Stator resistance	30.1 m Ω
Back emf	83.5 mV/rpm
Nominal DC voltage	600 V
Nominal AC voltage	400 V
Nominal speed	1500 rpm
Maximum fundamental frequency	600 – 650 Hz
Winding type	Star
Rotor inertia	0.06 kgm ²

Table 3.4: PMSM parameters

Converter parameters	Values
Switching device	IGBT
Forward voltage	0.8 V
Switching frequency	8 kHz
Threshold voltage	0.5 V
DC link capacitance	1 mF

Table 3.5: Converter parameters

Cable parameters	Values
Resistance	0.8 m Ω
Inductance	1 μ H
Capacitance	5 nF
Cross-sectional area	50 mm ² /4 mm ² (DC-DC converter)
Resistivity	1.333 $\times 10^{-8}$ Ω /m
Length	3 m
DC link capacitance	1.25 mF

Table 3.6: Cable parameters

3.4 Real time measurements

The actual measurement data of the load currents are provided by VCE which are obtained from the test rig of the TVS setup. A fresh set of measurements from the actual complete machine was not performed. The current from the busbar to the PEC of each drive system is measured using a rogowski coil.

4

Results

4.1 COMSOL Modelling results

The findings of the impedance analysis of the busbar modelling of electrostatic and magnetic field interfaces are presented in this section.

4.1.1 Busbar parameters

The electrical characteristics of the busbars are studied with the help of the below described parasitic elements.

4.1.2 Capacitance

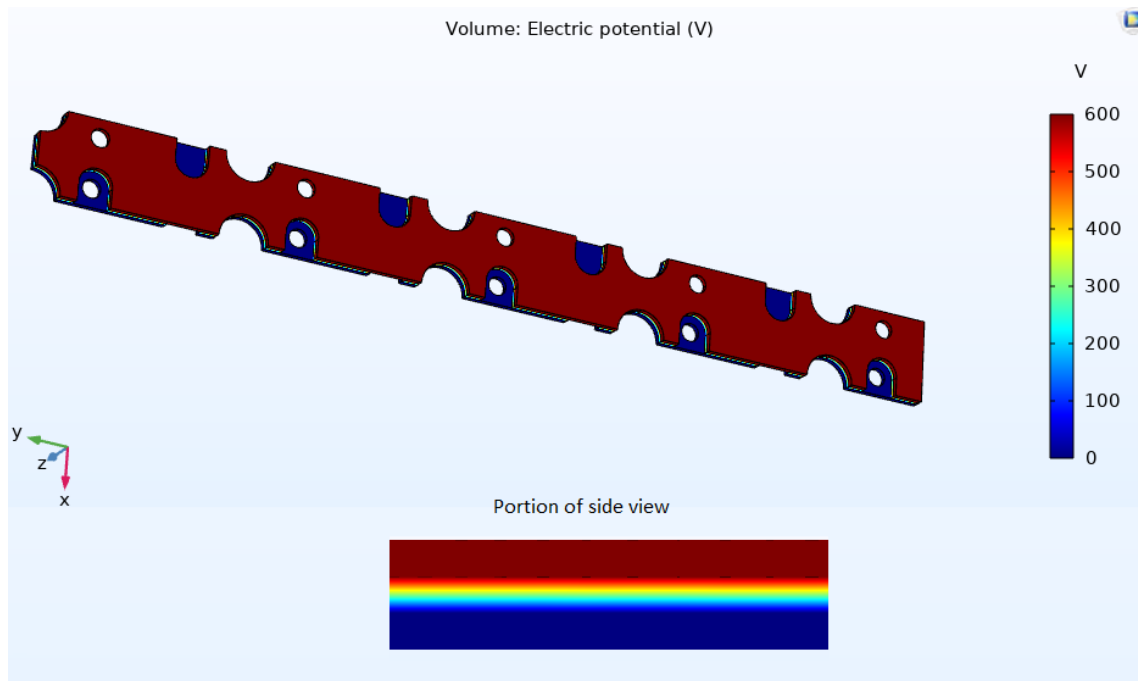


Figure 4.1: Electric potential

The capacitance analysis is done by assigning the higher potential to the positive plate and the lower (ground) potential to the negative plate, which is illustrated in figure 4.1. The magnified side view gives a clear illustration of the electric potential together with the insulation.

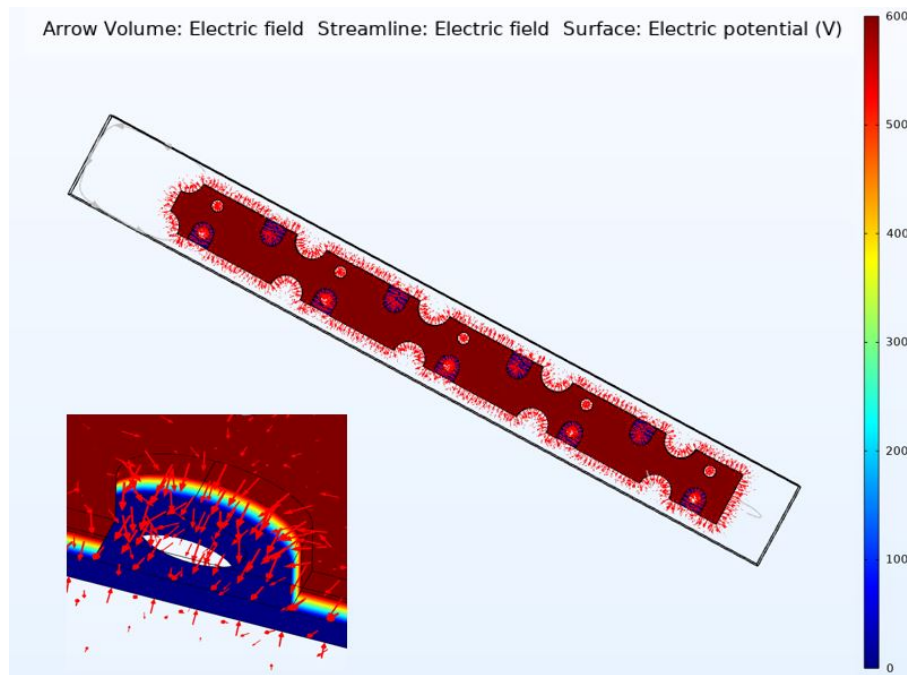


Figure 4.2: The electric field strength surrounding of the positive busbars

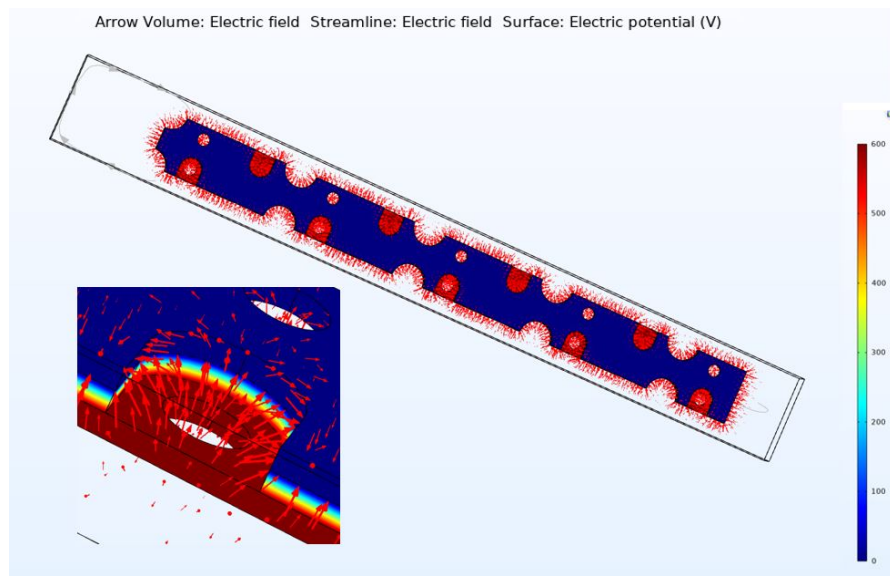


Figure 4.3: The electric field strength surrounding of the negative busbars

The electric field is plotted in figure 4.2 & 4.3 . The field varies depending upon the busbar structure, but some strong variations are seen at the edges and curved surfaces of the busbar plates. The plots' magnified view illustrates that the electric field's direction is towards the negative busbar from the positive busbar.

The contour plot in figure 4.4 illustrates the electrical potential over the conductors, insulator and air medium. The fringing fields are observed because the electric field extends the area of the overlap since the outer sealing (insulation) is not considered.

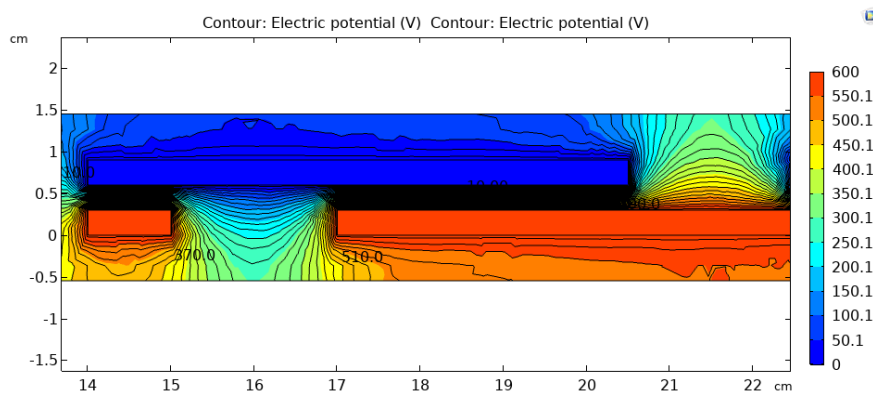


Figure 4.4: Side view - Electric potential contour

The Maxwell capacitance is calculated from the COMSOL simulation of the total electrical energy stored. The figure 4.5 shows the capacitance from the COMSOL simulation and the analytical results for the different insulation thicknesses. Since the busbar structure is analogous to parallel plate capacitors, the analytical calculation has been done using the equation (2.1). The capacitance decreases when the insulation thickness increases. The simulated value almost matches the analytical method of calculation as per table 4.1.

Method	Capacitance
Simulated	0.695 nF
Analytical	0.664 nF

Table 4.1: Stray capacitance

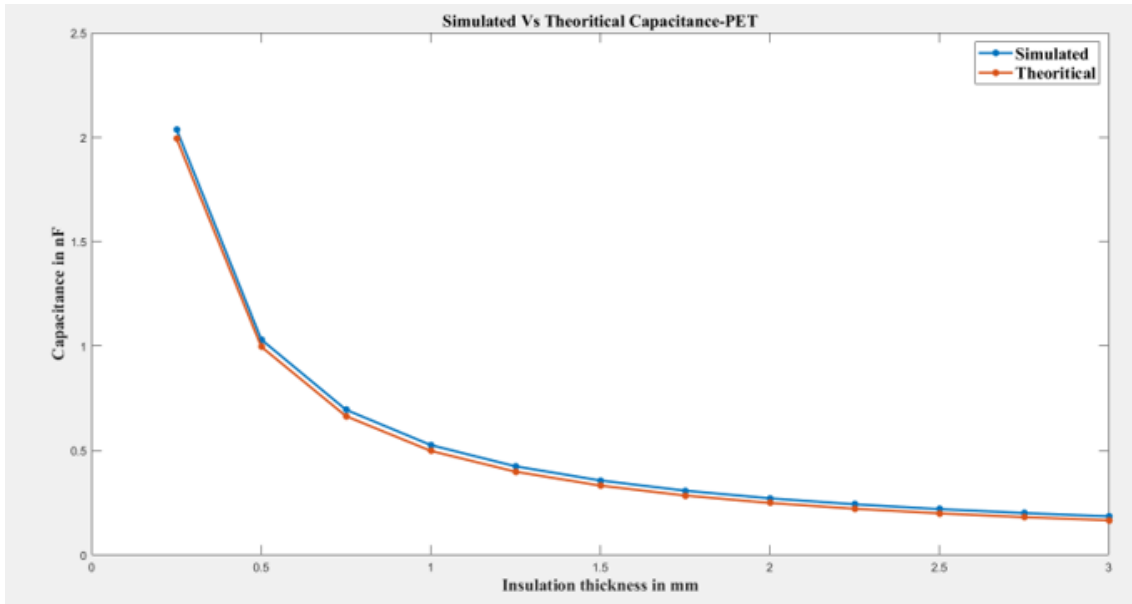


Figure 4.5: Simulated Vs theoretical capacitance

4.1.3 Skin depth and Resistance

The total dc resistance calculated from the voltage drops in each of the load terminals is $0.176 \text{ m}\Omega$, which is the summation of all stray resistances of the load sections, and the respective load resistance is shown in figure 4.10. However, skin depth plays a vital role in determining the effective resistance in high frequencies. Skin depth is nothing but the actual surface, which has the current conduction when it operates under high frequencies. The current density is not uniform if the frequency varies significantly in higher values, as shown in figure 4.6. The skin depth and the AC resistance are shown in the figure 4.7. When the frequency increases, skin depth decreases which means current conduction decreases, increasing the resistance.

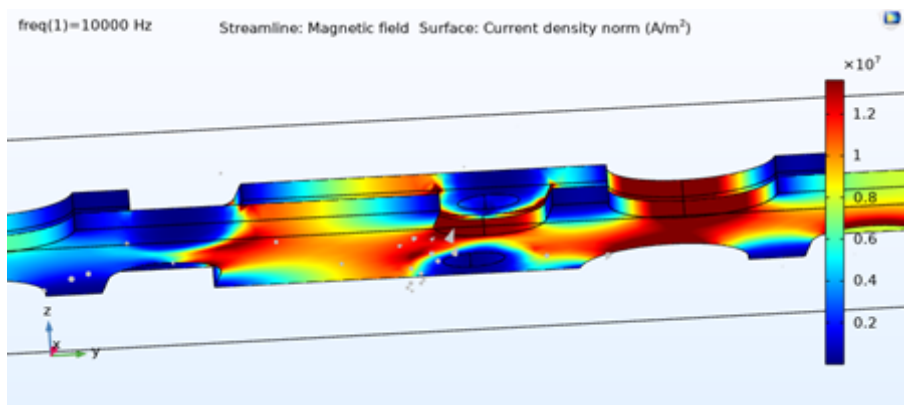


Figure 4.6: Non-uniform current distribution in high frequencies

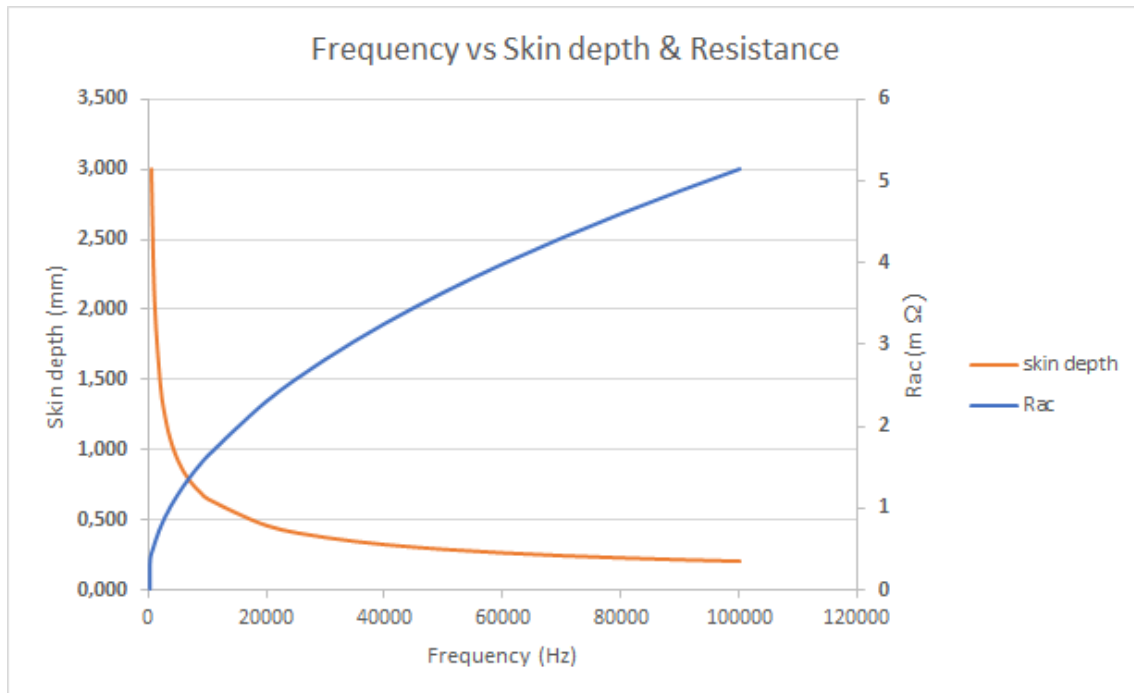


Figure 4.7: Frequency vs skin depth and resistance

4.1.4 Inductance

Figure 4.8 shows the magnetic field around the busbar conductors, which carries the electric current. The electric current produces the magnetic field, which is perpendicular to the busbar conductors. The current density is observed more in the battery terminals because various load terminals draw all the currents from those terminals.

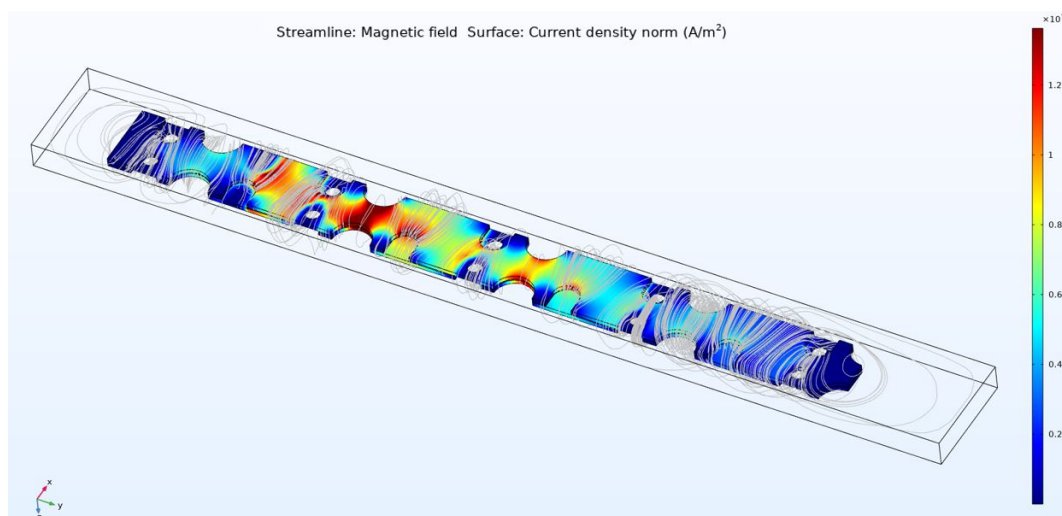


Figure 4.8: Magnetic field and current density of busbar

4. Results

Maxwell's inductance is calculated based on the expression (2.3) which uses the total magnetic energy and the current through the conductor obtained from the COMSOL magnetic field analysis. The stray inductance is calculated for the range of frequencies to see the variation in different frequencies. The mutual inductance of the busbar is nullified because of the arrangement of the positive and negative conductor plates. Figure 4.9 clearly shows the inductance decreases when the frequency increases. The total inductance of the busbar is 149 nH , and the inductance of each load section is calculated based on the length of the sections, and it can be found from the figure 4.10

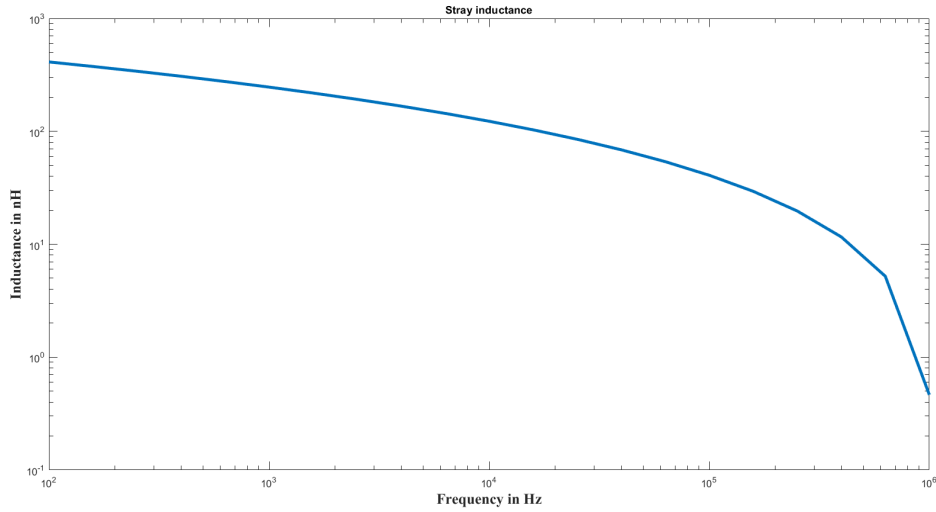


Figure 4.9: Inductance simulated from COMSOL

4.1.4.1 Equivalent circuit of the busbar

The figure 4.10 shows the electrical equivalent representation of the busbar, including all the drive systems. The values of the stray parameters are from the above results and are specified for each load section. The total values of the stray parameters of the whole busbar are obtained as shown in the table 4.2.

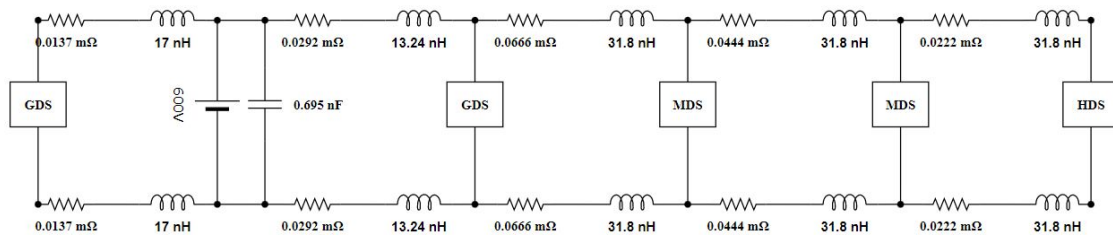


Figure 4.10: Equivalent circuit - Busbar

Busbar parmeters	Values
Resistance	0.176 m Ω
Inductance	149 nH
Capacitance	0.695 nF

Table 4.2: Equivalent circuit parameters for busbars

4.2 MATLAB/Simscape results

This section presents the results of the working model of the TVS and its power quality analysis with all the connected electric drive systems.

4.2.1 TVS power analysis

The voltage in one of the load terminals of the busbar is shown in the figure 4.11. The ripples are observed due to the higher frequency switching operation of the power electronic converters in the load section.

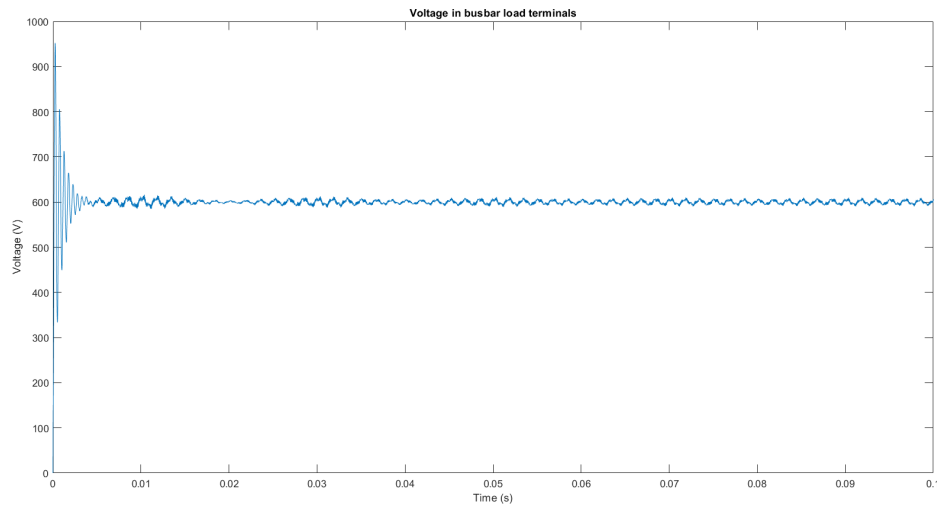


Figure 4.11: Busbar volatge

Even though the loads are identical, the different peak voltages are observed at different load terminals due to the particular sectional stray parameters for each of the load sections as shown in figure 4.12.

4. Results

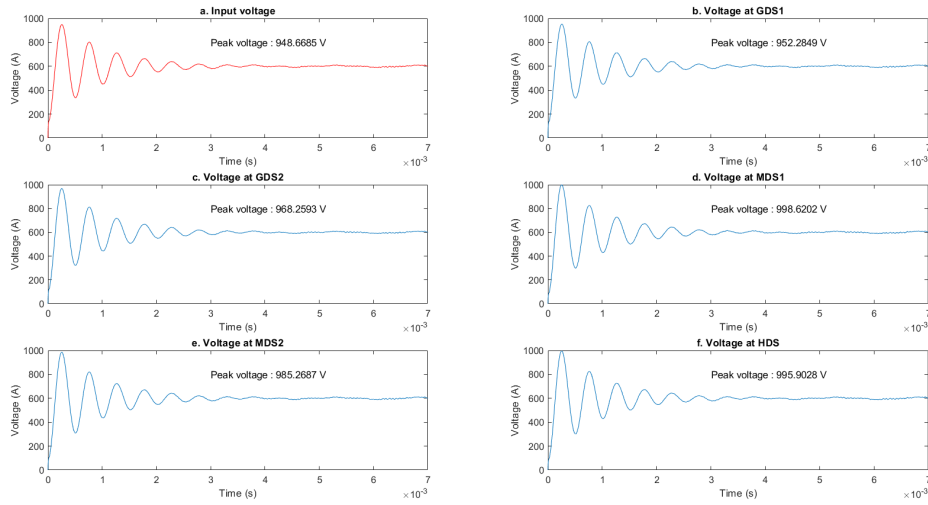


Figure 4.12: Peak voltages at different laod terminals

Figure 4.13a represents the total current drawn by all the load systems in the TVS. The distortion is observed in the current waveforms since power electronics converters operate in the higher frequency (8 kHz) connected to the common DC busbar. An initial peak surge of 18.5 kA is observed due to the stray inductance of the distribution system. The total rms current drawn is around 1 kA for all five load systems. As the loads considered to be similar, the Simscape model is equipped with the identical PMSM load.

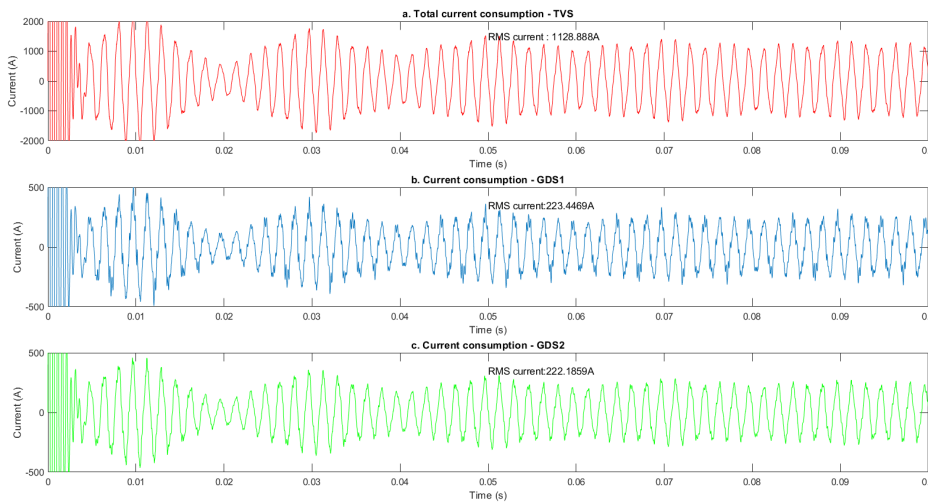


Figure 4.13: Current consumption of the TVS

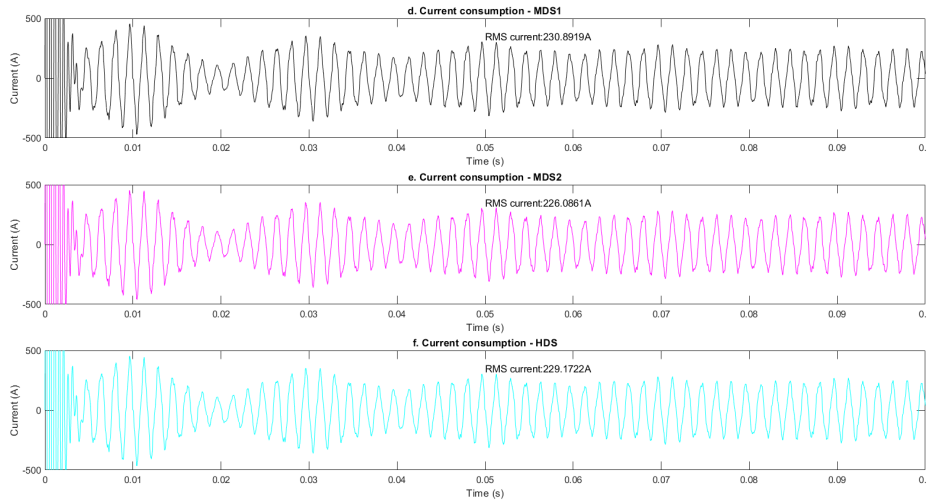


Figure 4.14: Current consumption of the TVS

Figures from 4.13b to 4.14f shows the individual load currents of the each subsystem. The load characteristics slightly vary because each load system has varied stray impedance properties based on the positions of the load terminals in the bus bar. The rms load currents are within the range of 195 A for the simulation time of 1 second. Since the DC-DC converter is assumed to be a current source in the model, it draws 20 A constant current.

4.2.2 PMSM power consumption plots

The power consumption plot for the PMSM at a stable operation is shown in figure 4.16 . All the PMSM's have a similar rating, so the power plots are almost identical. Figure 4.15 shows the PMSM load currents of one of the subsystems. The electric machine is considered an open-loop system, and the model is designed accordingly, so the output current cannot be controlled, unlike the actual system conditions. As the electric machine data are insufficient to design the controller, it is not included in the simulation.

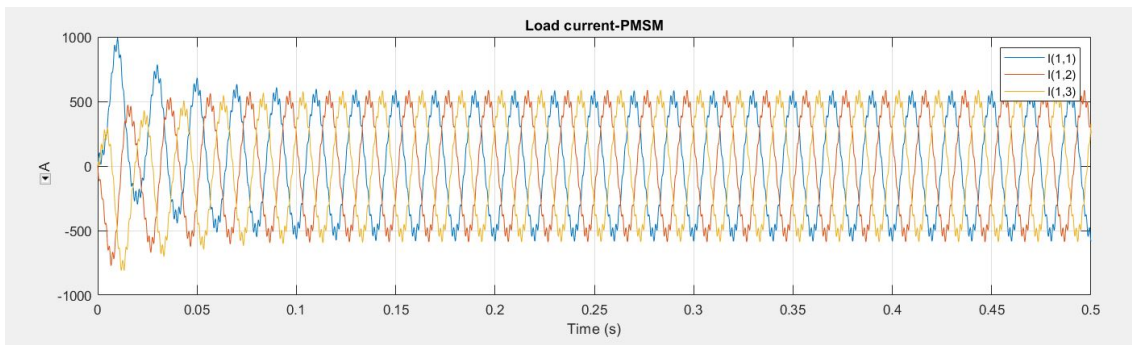


Figure 4.15: Load current-PMSM

4. Results

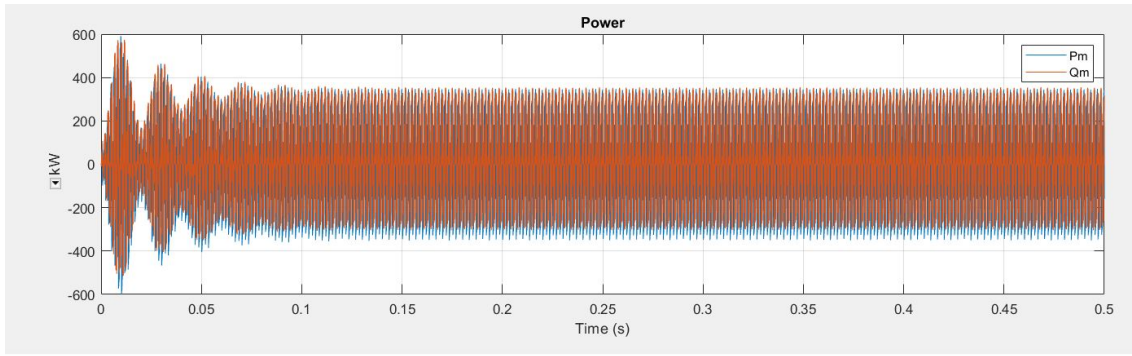


Figure 4.16: Power consumption-PMSM

4.2.3 FFT analysis

FFT analysis is done for the GDS current, which is our main interest, and the region of machine stability can be found using this analysis. Figure 4.17, 4.18 & 4.19 shows the harmonic spectra of the TVS current. The base frequency is considered to be 650 Hz. The lower order harmonics (3^{rd} order) are observed from the FFT analysis.

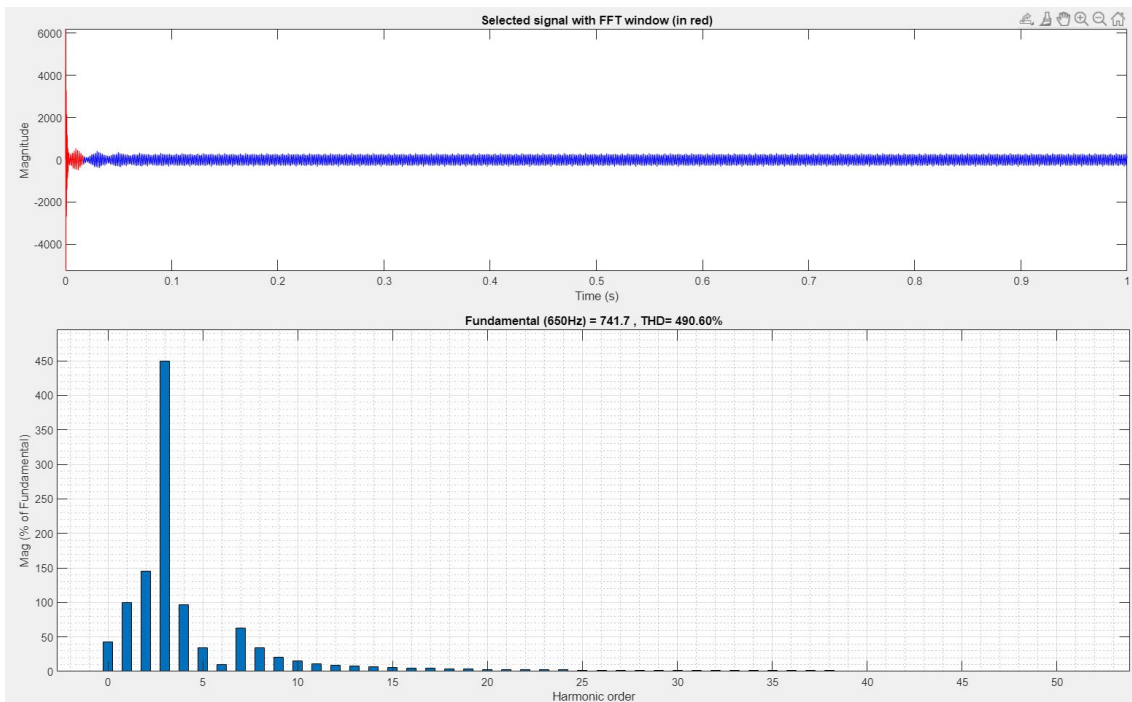


Figure 4.17: FFT analysis-GDS

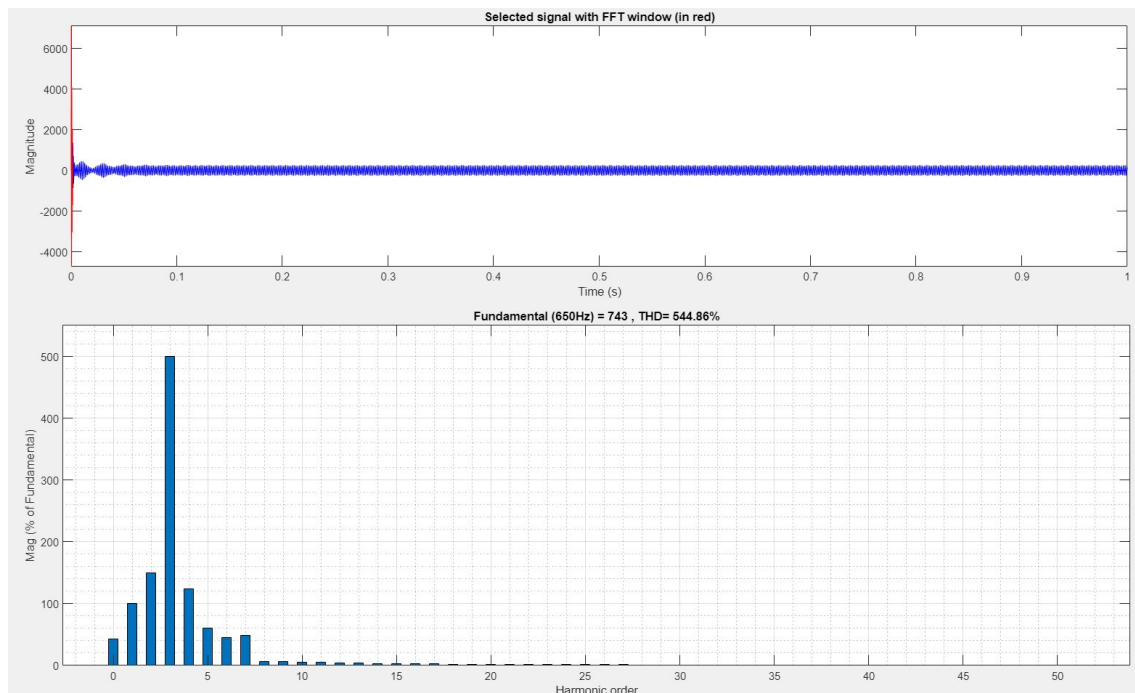


Figure 4.18: FFT analysis-MDS

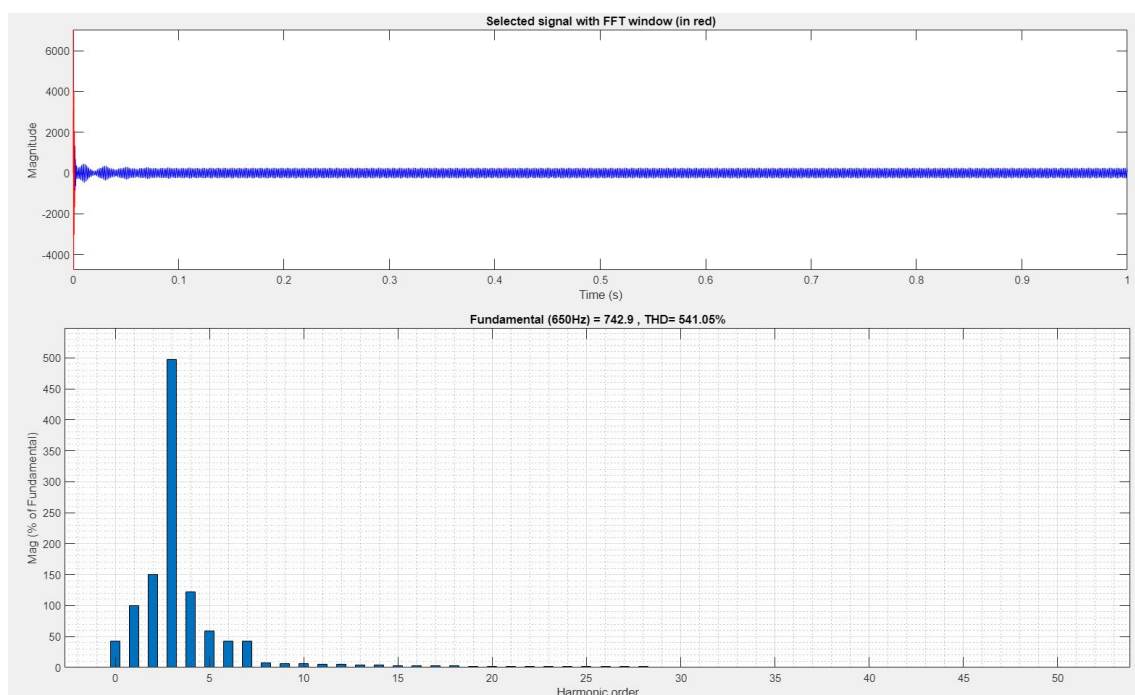


Figure 4.19: FFT analysis-HDS

4.3 Real time measurement results

4.3.1 FFT analysis

The Figures 4.20, 4.21 & 4.22 represents the harmonic spectra of measured DC current of GDS, MDS and HDS respectively based on the real-time measurement data available. The THD is more than the simulated results since the real loads such as boom and bucket operations are not considered in the simulation. The peak surge is observed initially in the simulated results, but the measured values show a different observation as these two measurement setups are not identical.

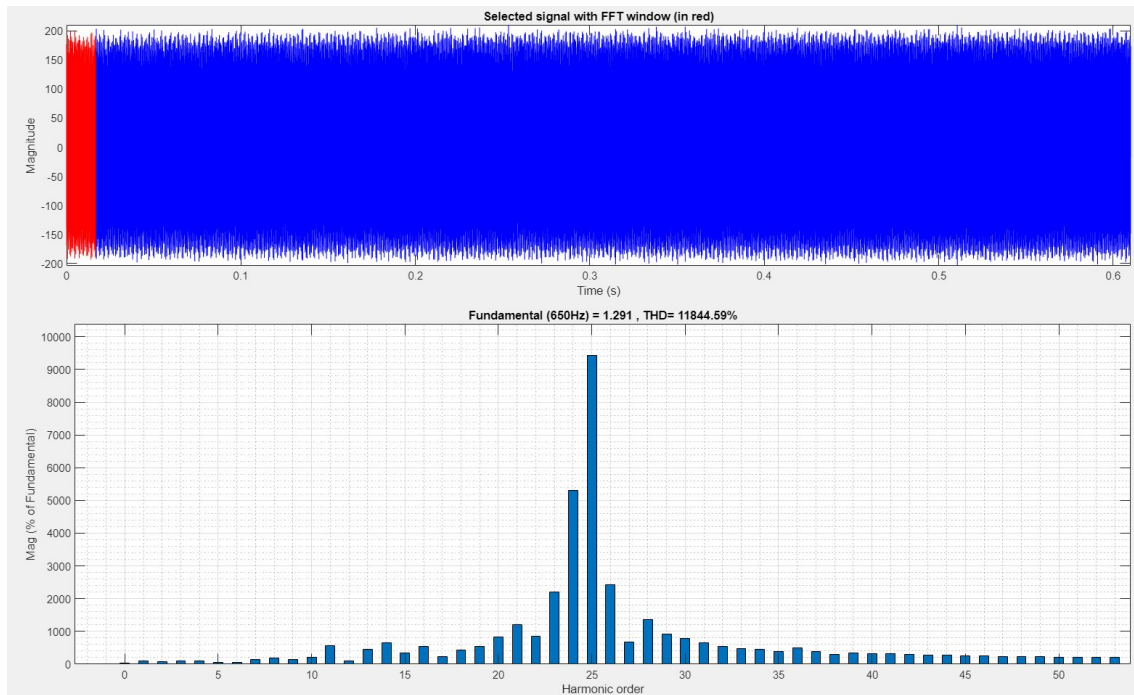


Figure 4.20: FFT analysis-GDS

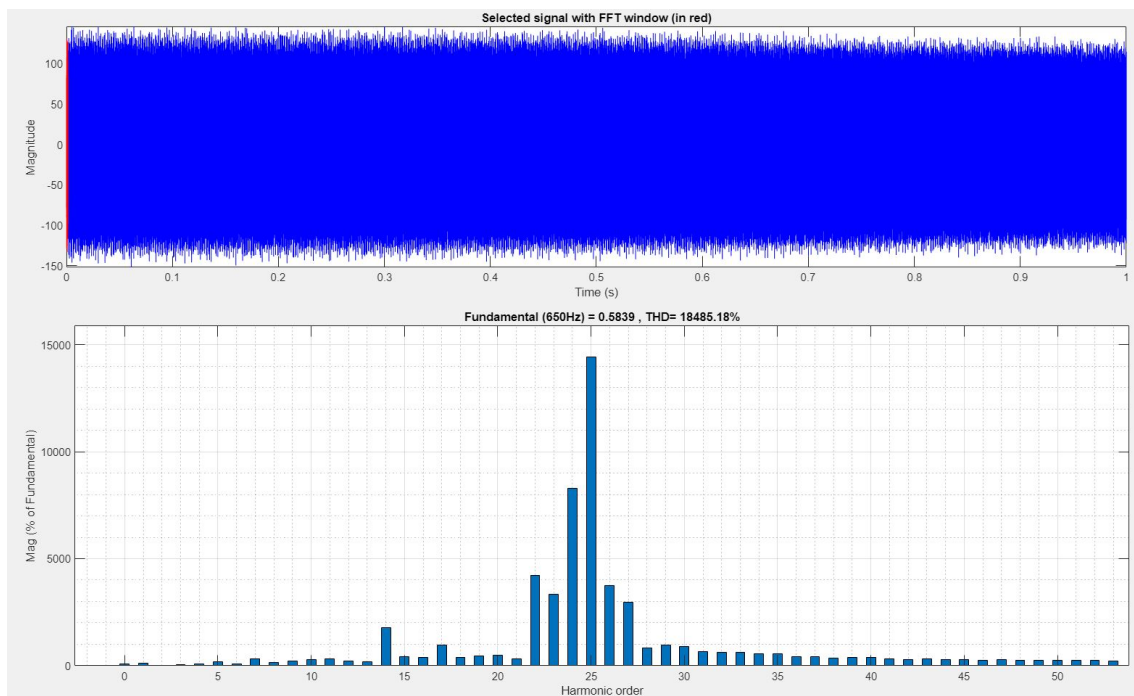


Figure 4.21: FFT analysis-MDS

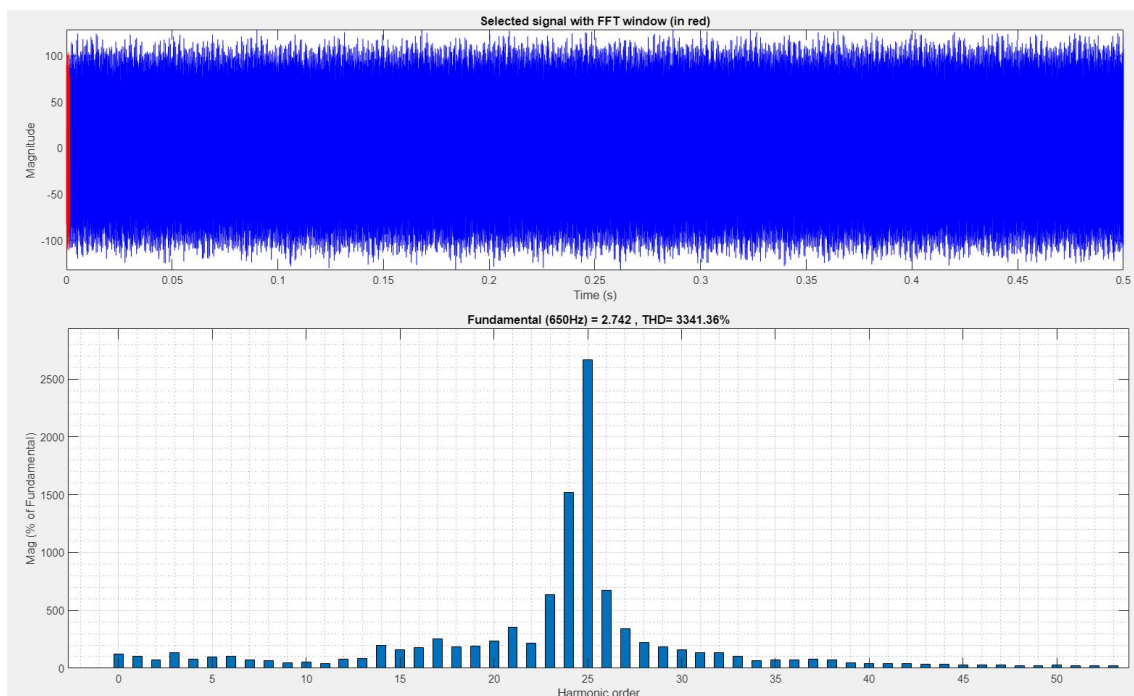


Figure 4.22: FFT analysis-HDS

5

Conclusion

In this thesis work, the 600 V traction system was designed and simulated using MATLAB/Simscape. The models of the subsystems, such as electric drive systems including PEC and PMSM, battery and cables, were configured in Simscape. The busbar electrical model was created using COMSOL-Multiphysics. The stray parameters of the busbar were analysed over a range of frequencies, including the system's operating frequency. The power quality of the load systems was studied and correlated with the obtained stray parameters. The FFT analysis was performed on the simulated and measured current waveforms of the load systems. The comparison between the simulated and measured results was not made since the test condition, and the specification of some of the subsystems are not similar.

6

Future work

The possible combination of materials (e.g. Aluminium and polyimide) have to be considered and analysed for the busbar. The PMSM modelling could be improved by considering its actual controller design to mimic the real load scenario. The FFT analysis can be elaborated, and the harmonic filtering techniques can be studied to improve the system performance. New measurement data to be acquired from the traction system to compare the simulated data precisely. Thermal analysis can be performed.

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