

STUDY ON INTERACTIONS BETWEEN MECHANICAL AND ELECTRICAL SYSTEMS IN ELECTRIC VEHICLES

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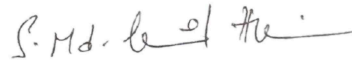
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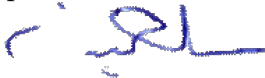
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LIST OF SYMBOLS

A	Exponential Voltage
α	Angular Acceleration
a	Amplitude (subscript)
B	Exponential Charge Capacity
c	Damping Factor
C	Capacitance
ch	Charging (subscript)
d	Vehicle Width
δ	PWM Signal Width Ratio
Δ	Differential Gear (subscript)
D	Diode
d	Direct Axis (subscript)
dis	Discharging (subscript)
D	Duty Cycle Expressed as Percentage
e	Electrical (subscript)
em	Electromagnetic (subscript)

f	Frequency
G	Gearbox Ratio for Number of Teeth (o/i)
i	Current
L	Inductance
I	Inertia
i	Input (subscript)
i	Integral (subscript)
j	Square Root of -1
k	Stiffness Factor
K	Control Constant
K	Polarization Constant
m	Magnetization (subscript)
m	Mechanical (subscript)
ml	Mechanical Loads (subscript)
ml_l	Mechanical Loads - Left Front Wheel (subscript)
ml_r	Mechanical Loads - Right Front Wheel (subscript)
m	Modulation Ratio
m	Electric Motor (subscript)
N	Winding Turns
N	Neutral
n	Nominal (subscript)

1	Final Moment of Time (subscript)
o	Output (subscript)
p	Pole Pairs
p	Primary Winding (subscript)
p	Proportional (subscript)
ψ	Magnetic Flux of Permanent Magnet
Q	Battery Capacity
q	Quadrature Axis (subscript)
r	Wheel Radius
R	Steering Radius From Origin to Nearest Wheel
R_d	Steering Constant
$*$	Reference (superscript)
R	Resistance
res	Resonance (subscript)
rw	Rotating of Wheel Around Center (superscript)
s	EMS Switching Signal Vector
s	Secondary Winding (subscript)
s	Driveline Shaft (subscript)
$s1$	Driveline Shaft Segment 1 (subscript)
$s2$	Driveline Shaft Segment 2 (subscript)
s	Source (subscript)

S	Switch
sw	Inverter Gate Switching Signal (subscript)
t	Terminal (subscript)
θ	Angular Displacement
t	Time
τ	Torque
v	Voltage
ω	Angular Velocity
wh	Spinning Wheel (superscript)
Z	Impedance
0	Initial Moment of Time (subscript)

LIST OF ABBREVIATIONS

AOSC	Active Oscillation Suppression Control
BA	Body Acceleration
BEV	Battery Electric Vehicle
BMS	Battery Management System
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
DMF	Dual Mass Flywheel
DS	Driveline Shaft
EM	Electric Motor
EMS	Energy Management System
ESD	Energy Storage Device
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FEM	Finite Element Method
FOC	Field-Oriented Control
FWISDEV	Four-Wheel Independent Steering and Driving Electric Vehicle

HEV	Hybrid Electric Vehicle
IEDS	Integrated Electric Drive System
Li-Ion	lithium-ion
MCU	Motor Control Unit
MLL	Multi-level Loading
MMF	Magneto-Motive Force
NVH	Noise, Vibration and Harshness
PHEV	Plug-in Hybrid Electric Vehicle
PMSM	Permanent Magnet Synchronous Motor
POC	Prescribed Output Constraint
PS/AS	Passive/Active Suspension
PWM	Pulse Width Modulation
SLME	Single-level Multi-edge Switching Loading
SMS	Super-capacitor Management System
SOC	State of Charge
SRM	Switched Reluctance Motor
SVPWM	Space Vector Pulse Width Modulation
SWS	Suspension Working Space
WRDL	Wheel Relative Dynamic Load

THESIS ABSTRACT

NAME: SULTAN BAWAZEER

TITLE OF STUDY: Study on Interactions Between Mechanical and Electrical Systems in Electric Vehicles

MAJOR FIELD: Electrical Engineering

DATE OF DEGREE: November 2025

The increased electrification of many systems in electric vehicles (EV)s is primarily aimed to reduce fossil fuel emissions backed by advancement in power system technologies. One critical problem that arises is the interaction between the current and new electrical systems introduced in EVs with the existing mechanical systems, which originates from their varying dynamic response durations and patterns. Although various strategies and architectures of EVs individual systems to reduce noise, vibration and harshness (NVH) effects were proposed in the literature, limited work was conducted on comprehensive EV models. Therefore, a complete MATLAB/Simulink model for EVs was developed to study system transients and dynamics of eight common operating actions in a typical driving journey along with brief verification of some mitigation strategies proposed in the literature. It was concluded that some systems

are consistently impacted by these operating actions while other systems were more resistant to them. This work promotes further investigation to study optimizing the full architecture of EVs to minimize NVH effects and improve driving experience.

ملخص الرسالة

الاسم: سلطان باوزير

عنوان الدراسة: دراسة تفاعلات الأنظمة الميكانيكية والكهربائية في السيارات الكهربائية

التخصص: قسم الهندسة الكهربائية

تاريخ الدرجة العلمية: جمادى الأولى 1447هـ

تزايد كهربائية العديد من النظم في السيارات الكهربائية (EV)s يهدف بشكل أساسي إلى تقليل انبعاثات الوقود الأحفوري، بدعم من تقدم تقنيات أنظمة الطاقة. من المشاكل الحيوية التي بدأت في الظهور هي التفاعل بين الأنظمة الكهربائية الحالية والجديدة المقدمة في السيارات الكهربائية مع النظم الميكانيكية القائمة، والتي تنشأ من اختلافات في مدة استجابة وأنماط ديناميكية هذه الأنظمة. وعلى الرغم من اقتراح استراتيجيات وهياكل متعددة للأنظمة الفردية في السيارات الكهربائية لتقليل تأثيرات الضوضاء والاهتزاز والخشونة (NVH) في الأدبيات، إلا أن العمل المنجز في نماذج شاملة للسيارات الكهربائية كان محدودًا. لذلك، تم تطوير نموذج كامل باستخدام MATLAB/Simulink للسيارات الكهربائية لدراسة الانتقالات الديناميكية خلال ثمانية إجراءات تشغيلية شائعة في رحلة قيادة نموذجية مع دراسة مبسطة عن بعض استراتيجيات التخفيف المقترحة في الأدبيات. وقد تم الاستنتاج أن بعض الأنظمة تتأثر بشكل مستمر بهذه الإجراءات التشغيلية، بينما كانت أنظمة أخرى أكثر مقاومة لها. يعزز هذا العمل مزيدًا من الدراسة حول تحسين الهيكل الكامل للسيارات الكهربائية لتقليل NVH وتحسين تجربة القيادة.

CHAPTER 1

INTRODUCTION

1.1 Background and Context

The substantial growth in population of EVs over the past decade was due to the advancement of EV technologies [1], [2], batteries [3]–[6], charging facilities [7], [8], and public charging services [9], [10]. Considering their significance in reducing greenhouse gas emissions, multiple plans have been implemented by governments to ban fossil fuel vehicles [10]–[16]. EVs are classified into four main types; BEVs, PHEVs, HEVs and FCEVs [17], [18].

A considerable demand of EVs for automotive market share continues to elevate [19]–[21]. Recent advancements of technology in EMs [22]–[26], power electronics [27]–[31], and ESDs [32]–[36] were major drivers for this movement. Although of their presence in market, cost competitiveness is still an issue as large-scale market penetration necessities affordable costs as in conventional vehicles. In addition, absence of charging infrastructure adds to the cost issue [7], [37] along with mileage

limitations [38], [39] and reliability issues [40].

Various policies and incentives were established by governments to encourage adoption of EVs [16], [41], [42], with additional purchasing incentives focused on manufacturing EVs [16]. One example is the existing financial incentives in Flanders, Belgium for private car buyers with more ongoing incentives to accelerate maturity of electrified fleets [43].

1.2 Motivations

Despite the swift expansion of EVs in recent years and their contribution to the decrease in greenhouse gas emissions, NVH remains a significant hurdle in EVs. NVH negatively impacts EVs via reduced driving experience, passengers comfort and efficiency of the driveline system. The proposed use of light weight materials [44] and different types and geometries for EMs [45] have introduced new forms of NVH. It is crucial to emphasize that NVH are also dependent on the complete driveline system [45]. Therefore, development of advanced designs for EVs components require careful consideration of their implications on NVH.

1.3 Problem Statement

The literature review reveals that numerous investigations have been carried out to formulate and enhance control tactics for external NVH disruptions and torsional oscillations primarily induced by the individual mechanical systems and EMs of EVs.

Nonetheless, there exists a void in research concerning the examination of internal dynamic interplays between all the systems within EVs.

1.4 Research Questions

1. How different mechanical and electrical operating actions in EVs can affect vehicle dynamics and stability?
2. Which operating action causes the most severe impact on vehicle dynamics and stability?
3. To what extent can EV system controllers mitigate vehicle dynamics and improve efficiency?
4. What advanced control strategies can be developed to smooth the interaction between mechanical and electrical systems in EVs?
5. What are the key challenges and opportunities in the integration of mechanical and electrical systems in EVs?
6. How can the electromechanical architecture of EVs be optimized to improve the overall performance and efficiency?

1.5 Objectives

The aims of this research are to:

1. construct an all-encompassing MATLAB/Simulink model for an EV that integrates all mechanical and electrical systems.
2. assess the dynamic behavior and interplay among the mechanical and electrical systems under diverse operational conditions.
3. study some sophisticated control tactics to enhance performance and reduce the effects of interactions between the mechanical and electrical systems.
4. demonstrate effectiveness of the studied control tactics through simulation studies.

1.6 Thesis Contributions

This work provides a comprehensive view of how EVs systems interact collectively during various operating actions during a typical driving journey, helping to identify systems that most affected by this integration. This is in contrast with work conducted in the literature where focus was placed on the individual systems and optimization of their dynamic responses against NVH. It also tests some mitigation strategies for NVH proposed for electric aircraft systems on EVs.

1.7 Thesis Organization

This work is composed of six sections organized as follows: Chapter 1 starts with an introduction to this work covering background and context, motivations, problem statement, research questions, objectives and contributions. Chapter 2 delves

into literature review where an overview of publications in this field is followed by a detailed review of all narrow topics related to this work. In Chapter 3, a problem formulation and foundational knowledge of the mechanical and electrical systems are developed and reviewed. Chapter 4 translates problem formulations of Chapter 3 into MATLAB/Simulink models backed with simulation studies to verify accuracy and applicability of the models. A full model is constituted in Chapter 5 by integrating all the models covered in Chapter 4 and simulation studies are conducted during a series of operating actions to the full model. In addition, analysis of the output results are carried with two mitigation strategies tested on some operating actions to evaluate their effectiveness. Finally, conclusion and future work are presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Reference to Figure 2.1, EVs attracted interest in academic and industrial fields since 1917. However, publications in this field was minimal during that period until 1991. A sharp increase in number of conference papers published can be observed in 2003. In addition, a gradual increase can be seen in 2008 for journal articles. This can be reasoned due to some political and economical issues during these periods which led to increased attention to EVs as an attempt to reduce dependency on fossil fuel. Table 2.1 shows summary of number of research publications per item type. For this work, publications that covered NVH in EVs were segregated by topic in Table 2.2.

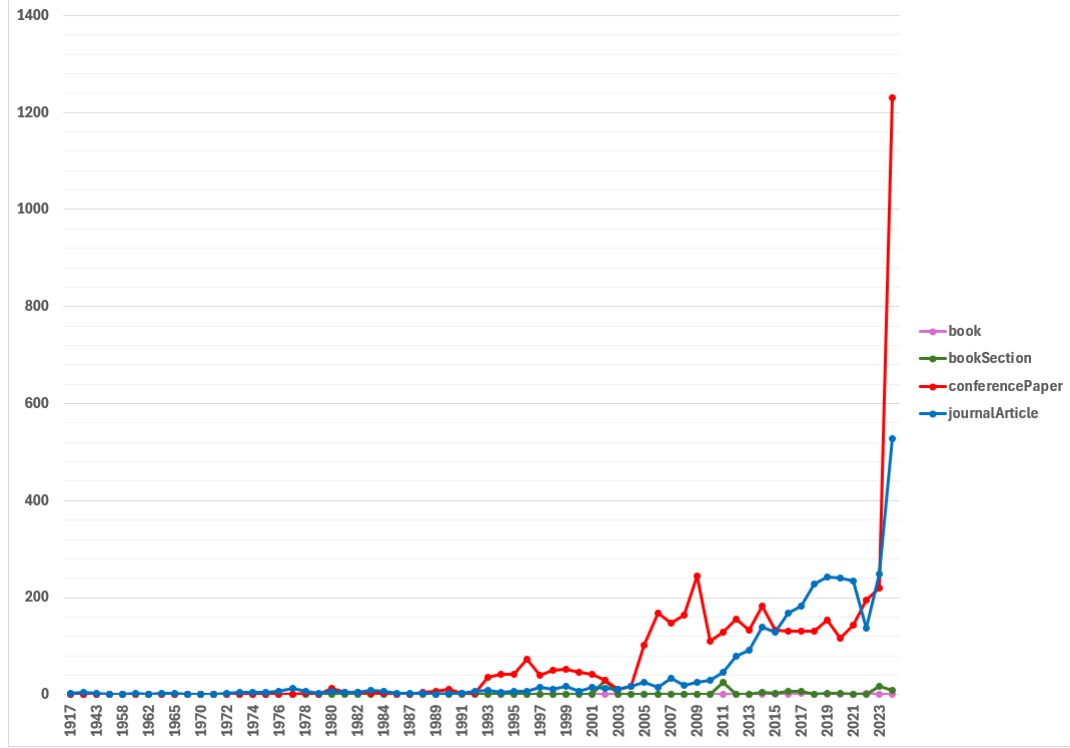


Figure 2.1: Growth of Sample Research Publications in EVs

Table 2.1: Count of Sample Research Publications Per Item Type

Item Type	Count
Book	6
Book Section	109
Conference Paper	4669
Journal Article	3098
Total	7882

Table 2.2: Summary of Literature Review for The Subject Topic

Research Topic	Count	References
Analysis, modeling and computation of NVH in EVs	5	[44]–[48]
Torsional vibrations in EVs	5	[49]–[53]
Control strategies to mitigate driveline fluctuations from EMs	5	[52], [54]–[57]
Vibro-acoustics in EVs	4	[58]–[61]
Design of PMSMs for reduction of electrical harmonics in EVs	3	[62]–[64]
Vertical vibrations in EVs	2	[65], [66]
Optimization of EVs performance under NVH factors	2	[46], [67]

2.2 Analysis, Modeling and Computation of NVH in EVs

Behavior of NVH issues in EVs were explored in [44] through a comparison against gasoline-powered vehicles. The study noted that although there is a substantial disparity in noise levels, this disparity lessens as the speed increases. In addition, analysis, modeling, and computation of certain NVH sources were performed in [45]–[48]. Two EMs were compared in terms of electromagnetic and NVH performance in [45]. A comprehensive methodology was offered in [46] for the examination and improvement of NVH in a newly combined motor and two-speed gearbox system in a systematic way. FEM model was constructed, taking into account both electromagnetic and mechanical excitations. Sequentially, order interference analysis, modal analysis, vibration

analysis, and acoustic noise analysis were executed. A multiphysics examination was introduced to forecast the acoustic radiation characteristics of a SRM in [47]. This examination involves a series of simulations, linked in both directions and one direction. Each stage in the simulation sequence permits system inputs or alterations, including geometry, changes in materials, or control strategies. Consequently, it can serve as a potent instrument to anticipate the acoustic performance of the motor at an initial design phase, proving especially beneficial in sectors where noise output is significant, like the automotive industry. A variety of techniques was illustrated for determining the values of electromagnetic force and torque in EVs in [48]. The deformation of motor geometry was investigated by moving mesh nodes instead of recreating and meshing a fresh geometry. A dependable method was discovered for these calculations can be achieved by making certain that elements in crucial areas maintain the same form and orientation through the use of mapped meshes.

2.3 Torsional Vibrations in EVs

Torsional vibrations, generated by changing torsional forces either between the rotor and the load or within various sections of the rotor along the axial direction, can markedly diminish the dependability and longevity of the motor system [49]. The study of torsional vibrations in PMSMs has been discussed in [49], [50]. A novel segmented rotor motor was suggested for EVs in [49] to counteract torsional vibrations induced by structural disparities along the motor's axial direction. The suggested rotor design aligns with the same phase of the stator magnetic field, exhibits reduced

torque ripple, and superior torque smoothness under both light and heavy loads when compared to the rotor step-skewing motor. Furthermore, it does not necessitate an increase in material usage and remains unaffected by the motor's axial length. Additionally, an exhaustive examination of the tangential electromagnetic force and torsional vibration in interior PMSMs featuring a multi-segmented rotor step-skewing was showcased in [50]. The initial research focuses on the spatial dispersion and the torsional design in the axial direction of the tangential force when the rotor is skewed. An excitation index was formulated to illustrate the interplay between the tangential force and the torsional modal, signifying the contribution of the torsional modal to the vibration response.

Research was conducted on the torsional vibrations in driveline and entire power transmission systems in [51]–[53]. undamped free torsion vibration system model was formulated, and a lumped mass model was created through appropriate simplification in [51]. The mass and stiffness matrices were derived through relevant computations. A sensitivity analysis was performed on the natural characteristics of the power transmission system to identify the system parameters that have the highest sensitivity to the natural frequency and vibration mode. This analysis serves as a theoretical foundation for dynamic modifications and optimizations. A model that couples electromechanical elements, encompassing an IEDS, final drive, differential, half-axle, and wheels of the EV was constructed in [52]. This model integrates both the dynamics of the motor and the driveline. The dynamic characteristics of the IEDS, during instances of swift acceleration and impact loading, are simulated and examined. Following this,

a preemptive damping control approach was proposed to alleviate the torsional vibration of the driveline during the commencement of the vehicle. A research was carried out to understand the traits of torsional vibration in a power-split hybrid powertrain fitted with a DMF in [53]. A comprehensive dynamic model for the hybrid powertrain was formulated to forecast the torsional vibration traits of this driveline, and the precision of the dynamic model was confirmed through mathematical methods. The research suggested that DMF can significantly diminish torsional vibration of the hybrid powertrain when contrasted with a powertrain that has a standard flywheel.

2.4 Control Strategies to Mitigate Driveline Fluctuations From EMs

[52], [54]–[56] introduced control approaches to lessen driveline fluctuations triggered by torque alterations from EMs in EVs. A computational model of torsional vibration that takes into account nonlinear backlash was devised in [54], based on the operational principle of a series-parallel HEV. Subsequently, a feedforward and feedback control system was presented and integrated into a hybrid controller to diminish the launch vibration. To supply feedback signal to the hybrid controller, a robust sliding mode observer was engineered to enhance response traits by estimating and neutralizing unknown disturbances instigated by nonlinear backlash. Moreover, the control performance amidst system uncertainty was examined, and the findings indicate that the suggested control strategy outperforms the feedforward control approach, thereby

guaranteeing improved ride comfort during situations with abrupt torque shifts such as launch and speed variations. An AOSC strategy for the EV powertrain that takes into account both the uncertain backlash and the POC was introduced in [55], ensuring finite-time stability and predetermined tracking performance, thereby enhancing the drivability of the vehicle. A PID-based anti-jerk controller was designed for EVs, considering backlash as a hindrance to improve speed tracking performance and vehicle control in [56]. The vehicle’s movement is prone to jerk initially due to the motor’s rapid response, inadequate damping in the drive shaft, and the flexibility of different parts. To mitigate this, a Kalman filter was employed to precisely predict the system’s states, with the motor speed serving as the measurement state, which was subsequently used to compute the shaft torque. A real-time vibration reduction approach for EVs was suggested by [57]. By utilizing a high-performance FOCed EM drive, a slight offset in rotation speed can be introduced to the traction motor, significantly reducing resonant vibration with minimal effect on vehicle speed. The effectiveness of this proposed approach was confirmed through simulation studies.

2.5 Vibro-acoustics in EVs

Examination and characterization of vibro-acoustics in electric machines for EVs were covered in [58], [59]. The influence of harmonic currents on the harmonics of electromagnetic force was explored in [58]. Following this, a multi-physics model was formulated to forecast the vibroacoustic behavior of a PMSM powertrain. An analysis was conducted on the vibro-acoustic characteristics of the electric powertrain,

taking into account both electromagnetic and gear meshing forces, which was then emphasized by a vibro-acoustic examination. The acoustic characteristics of four commercially available cars using sound-pressure spectrograms was investigated in [59], gathered during test drives. The findings reveal that electrical machines in vehicles, particularly those with a large number of pole pairs, are primarily affected by mode-0 borne noise, which can significantly impact the vehicle's overall acoustic performance. Additionally, a novel method was presented to reduce vibro-acoustics, by devising a new strategy to produce current waveforms with the least RMS value in certain situations in [60]. This pioneering technique has been applied to a high-efficiency SRM with 18/12 stator and rotor poles, and its efficiency has been comparatively analyzed using FEM. The creation of vibro-acoustic meta-materials to alleviate NVH in power electronic components of EVs was undertaken in [61]. This project encompassed the numerical prediction of the stop band, the development of resonator designs, their fabrication, and the empirical validation of the vibro-acoustic meta-material when applied to the intended structure.

2.6 Design of PMSMs for Reduction of Electrical Harmonics in EVs

Different designs of PMSMs were proposed for reduction of electrical harmonics part of NVH in [62]–[64]. A unique six-phase fractional-slot per-pole-per-phase was introduced, featuring a slot-pole combination of 18-slot/8-pole in [62]. This design was

characterized by a high winding factor and the elimination of all odd order space harmonics. The optimized motor design, with its new winding configuration, was experimentally validated, demonstrating high efficiency across a broad speed range and increased suitability for EV applications. The use of a dual three-phase or six-phase 24-slot/10-pole machine, driven by a six-phase inverter, was proposed for EV applications in [63]. This design effectively eliminated all sub-harmonics, significantly reduced the main slot harmonics, particularly the seventh, and greatly enhances MMF distribution. A strategy for minimizing stator MMF harmonics in a nine-phase 18-slot/14-pole interior PMSM with concentrated windings was presented in [64]. This was accomplished by utilizing multiple three-phase windings and choosing suitable phase shifts in both spatial and temporal dimensions. The suggested winding layout eradicates all the MMF sub-harmonics and a number of high order MMF harmonics. The proposed machine design maintains the benefits of the concentrated windings and demonstrates a high winding factor, minimal torque ripple, reduced production cost, high torque density, and superior efficiency across a wide range of torques and speeds.

2.7 Vertical Vibrations in EVs

The analysis and management of vertical vibrations in EVs were discussed in [65], [66]. The research in [65] examined the vertical dynamics of EVs equipped with suspended in-wheel motors, utilizing dynamic simulation on quarter-car models. The factors being evaluated encompass the grip of the tire, the comfortability of the ride, and the vibration of the motor. An examination of sensitivity was conducted on the factors

associated with the motor's mass and the characteristics of the motor's suspension. Following this, comprehensive optimizations are carried out on the motor suspension to explore potential avenues for improving the performance of the vehicle. The study in [66] was based on the structural characteristics of the suspension system in the FWISDEV that was designed. Both PS/AS models were developed and the impact of excessive un-sprung mass on the vehicle's performance was examined. It was found that an increase in un-sprung mass has minimal effect on the SWS and BA, but it significantly affects WRDL.

2.8 Optimization of EVs Performance Under NVH Factors

Optimizing of EVs performance subjected to NVH factors was worked on in [46], [67]. A mechanism and a method were devised for optimizing the generation of NVH issues in EVs in [67], which were thoroughly analyzed and clarified. An examination and enhancement of road noise, wind noise, and the noise from the air conditioning system in purely EVs led to an improvement in NVH performance. A modal analysis of the tires was carried out and the characteristics of the road noise were optimized.

2.9 Research Gaps

After comprehensive review of the literature, research gaps were framed into questions listed in Section 1.4.

CHAPTER 3

PROBLEM FORMULATION

3.1 Model Structure

Various architectures of EVs were exhibited in [68] and capitalizing on them, a MATLAB/Simulink model is developed for EVs with a proposed structure shown in Table 3.1 while Figure 3.1 illustrates the connections between the model systems:

Table 3.1: EVs Systems Segregated by Domains

Mechanical Systems		Electrical Systems		Control Systems	
1	DS	1	Battery	1	MCU
2	Single Speed Gearbox	2	Super-capacitor	2	EMS
3	Differential Gearbox	3	Three Phase PMSM	3	BMS
4	Mechanical Loads	4	DC/DC Converter	4	SMS
5	Braking	5	2x DC/AC Converter		
		6	Three Phase Transformer		
		7	Three Phase AC Loads		
		8	DC Loads		
		9	2x LCL Filters		

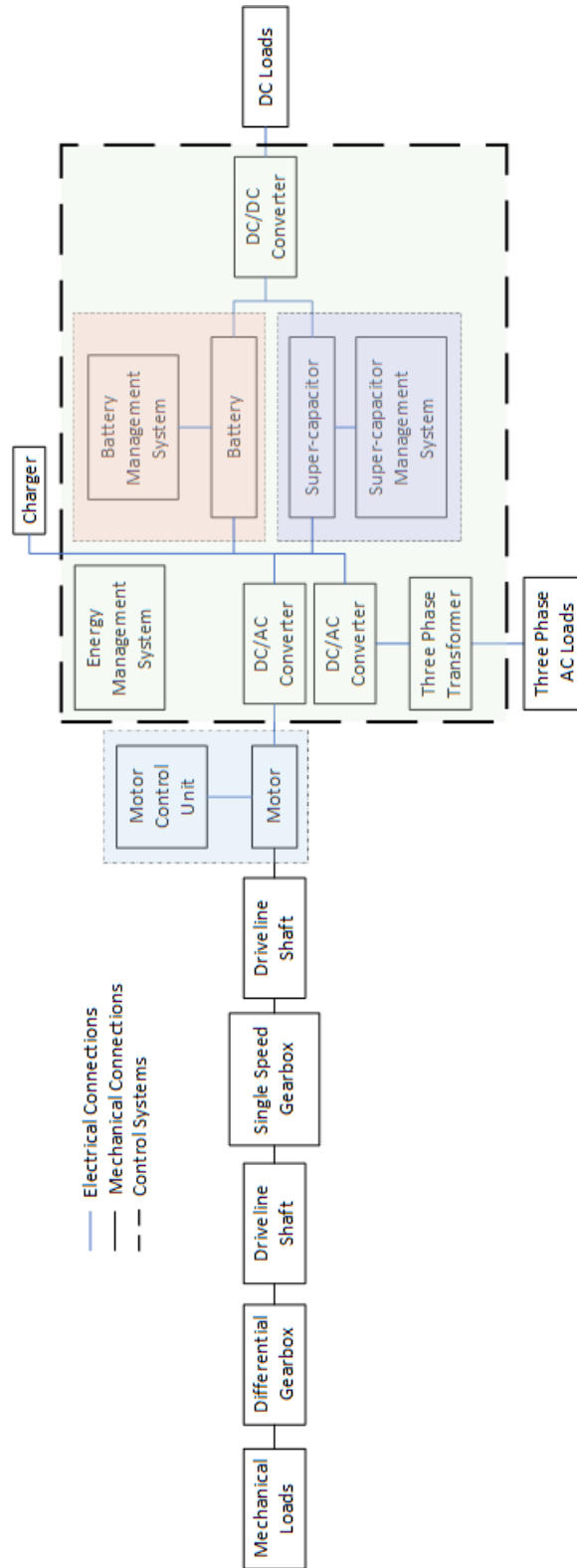


Figure 3.1: Proposed Diagram of EV

Simulation studies will be conducted on the dynamic response of EVs under various operating actions as shown in Table 3.2:

Table 3.2: The Operating Actions Segregated by Channels

Mechanical Channel		Electrical Channel	
1	Speed variation	1	Removal/addition of three phase AC load
2	Regenerative braking	2	Removal/addition of DC load
3	Conventional braking	3	AC fault in three phase transformer
		4	AC fault in three phase PMSM
		5	DC fault

3.2 Problem Description

For a defined speed profile as an input, below parameters are plotted and measured during the operating actions as shown in Table 3.3:

Table 3.3: Recorded Parameters During The Operating Actions

#	System	Parameter	Unit	#	System	Parameter	Unit
1	Battery	SOC	%	11	PMSM	ω_m	rad/s
2		i	A	12		τ_{em}	Nm
3		v_o	V	13	Three Phase Sinusoidal PWM Inverters	v_t	V
4	Super-capacitor	SOC	%	14		v_o	V
5		i	A	15	Three Phase Transformer	v_p	V
6		v_o	V	16		v_s	V
7	DC/DC Converter	v_i	V	17	DS	ω_m	rad/s
8		v_o	V	18		ω_{mll}	rad/s
9		i_L	A	19		ω_{mlr}	rad/s
10	EMS	s	-	20		$\Delta\theta$	rad

Flowchart shown in Figure 3.2 describes the sequence of actions for all the operating actions to be studied noting that t_0 and t_1 are initial and final time moments.

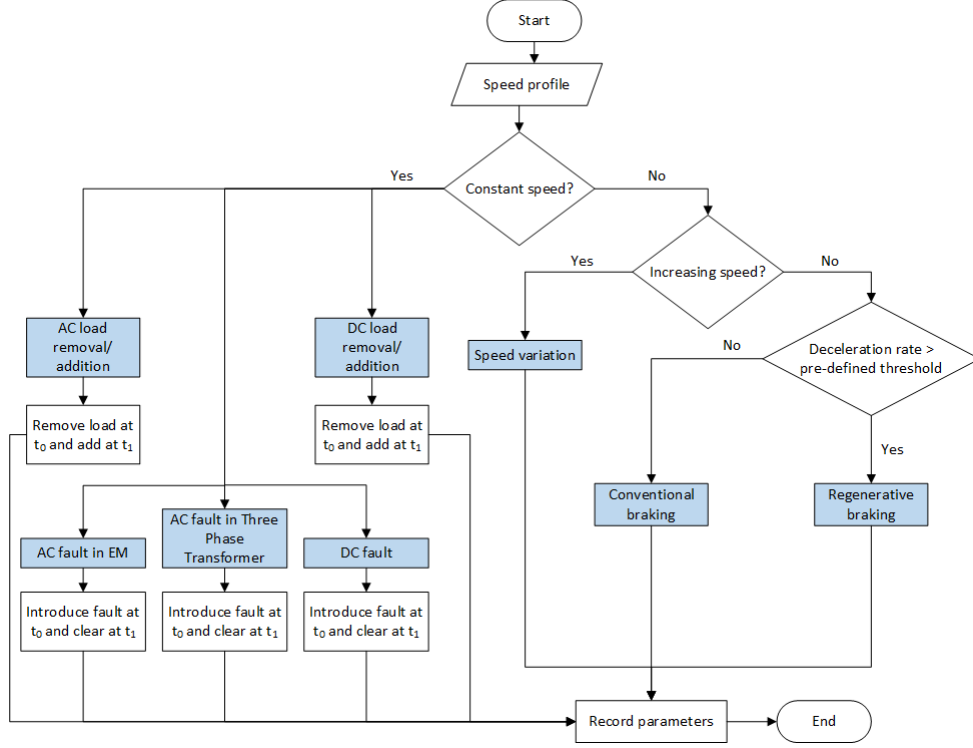


Figure 3.2: Flowchart of EV Operating Actions

This work will investigate two electrical mitigation techniques for aircraft applications proposed in [69], [70] and designed to minimize disruptions: MLL and SLME. These methods will be evaluated through the operating actions involving the disconnection and connection of AC and DC loads. Basic PI controllers were engineered to maintain specific parameters at set target levels. The tuning of control systems parameters was explored to determine the best operating conditions for EVs to reduce mechanical vibrations and electrical transients.

τ_{em} is the input from three phase PMSM model to DS model. Also, regenerative braking is the default braking mode as mentioned in Sub-section 3.3.2 for all operating actions unless stated otherwise. All switching devices e.g., breakers, switches, diodes and MOSFETs have infinite $C_{snubber}$, $R_{snubber} = 10^6 \Omega$, $R_{on} = 10^{-6} \Omega$ and $L_{on} =$

$10^{-6} H$. Simulation settings in MATLAB/Simulink were set to discrete mode with fixed step of $0.5 \mu s$.

3.3 Mechanical Systems

3.3.1 Driveline Shaft

The basic transmission diagram of power from the three phase PMSM to DS is shown in Figure 3.3.

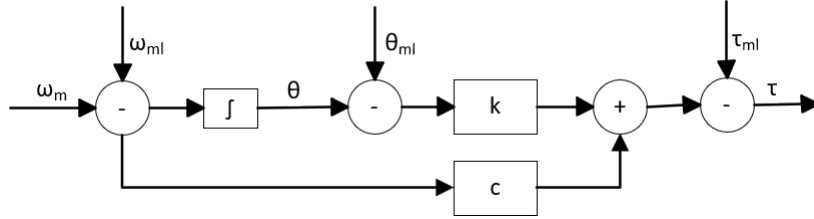


Figure 3.3: Control Diagram Between Three Phase PMSM and DS

Where τ transmitted from the three phase PMSM to mechanical loads is given by:

$$\tau = c (\omega_m - \omega_s) + k (\theta_m - \theta_s) - \tau_{ml} \quad (3.1)$$

[71], [72] presented in an extended manner the design and mathematical modeling of a dynamic EVs transmission system. [72] incorporated differential gear and wheels in their model and utilized it to compare between two real-world EVs data. [71] considered opposing torque caused by road slope in its model. The proposed model is based on two DSs that are be split by a single speed gearbox. Their model is shown in Figure 3.4:

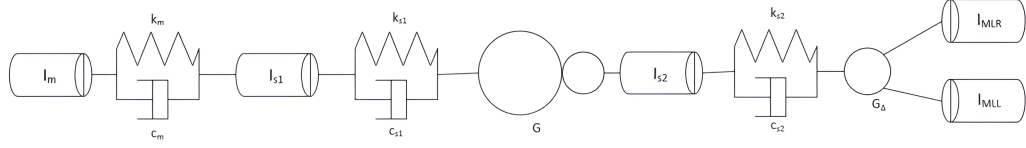


Figure 3.4: Control Diagram of DSs

The single speed gearbox is used to improve dynamic performance and extend EV range [73]. It has a ratio of number of teeth given by:

$$G = \frac{\omega_i}{\omega_o} = \frac{\tau_o}{\tau_i} \quad (3.2)$$

The twist angle $\Delta\theta = \theta_{s1} - G\theta_{s2}$. G_Δ represents the differential gearbox that distribute torque proportionally between both wheels I_{mlr} and I_{mll} . It is worth noting that further reduction in EV weight and control improvement can be achieved using electronic differentials instead of conventional mechanical differential transmission and control system [74].

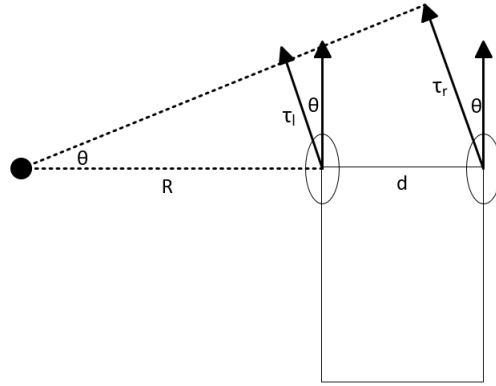


Figure 3.5: Vehicle Diagram During Steering Around a Center

During steering and based on Figure 3.5:

$$\theta_{mll}^{rw} = \theta_{mlr}^{rw}$$

$$R\theta_{mll}^{rw} = r\theta_{mll}^{wh}$$

$$(R + d)\theta_{mlr}^{rw} = r\theta_{mlr}^{wh}$$

$$R\alpha_{mll}^{rw} = r\alpha_{mll}^{wh}$$

$$(R + d)\alpha_{mlr}^{rw} = r\alpha_{mlr}^{wh}$$

Assuming I_{mll} and I_{mlr} are equal and since α_{mll}^{rw} and α_{mlr}^{rw} are the same:

$$R\tau_{mll}^{rw} = r\tau_{mll}^{wh}$$

$$(R + d)\tau_{mlr}^{rw} = r\tau_{mlr}^{wh}$$

$$\frac{R}{R+d} = \frac{\tau_{mll}^{wh}}{\tau_{mlr}^{wh}}$$

$$\tau_m = \frac{1}{G}(\tau_{mll}^{wh} + \tau_{mlr}^{wh})$$

$$\tau_m = \frac{1}{G}\tau_{mll}^{wh}(1 + \frac{1}{R_d})$$

$$\tau_m = \frac{1}{G}\tau_{mlr}^{wh}(1 + R_d)$$

R_d is calculated as:

$$R_d = \frac{R}{R + d} \quad (3.3)$$

The state space representation of Figure 3.4 is derived through equations (3.4)-(3.21) as shown below:

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) \quad (3.4)$$

$$y(t) = C(t)x(t) \quad (3.5)$$

$$u = \begin{bmatrix} \omega_m \end{bmatrix} \quad (3.6)$$

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \quad (3.7)$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix} \quad (3.8)$$

$$\dot{x} = \begin{bmatrix} \omega_m & \dot{\omega}_{s1} & \omega_{s1} & \dot{\omega}_{s2} & \omega_{s2} & \dot{\omega}_{mlr} & \omega_{mlr} & \dot{\omega}_{mll} & \omega_{mll} \end{bmatrix}^T \quad (3.9)$$

$$x = \begin{bmatrix} \theta_m & \omega_{s1} & \theta_{s1} & \omega_{s2} & \theta_{s2} & \omega_{mlr} & \theta_{mlr} & \omega_{mll} & \theta_{mll} \end{bmatrix}^T \quad (3.10)$$

$$\omega_m = \omega_m \quad (3.11)$$

$$\omega_{s1} = \omega_{s1} \quad (3.12)$$

$$\omega_{s2} = \omega_{s2} \quad (3.13)$$

$$\omega_{mlr} = \omega_{mlr} \quad (3.14)$$

$$\omega_{mll} = \omega_{mll} \quad (3.15)$$

$$\begin{aligned} \dot{\omega}_{s1} = & \left(\frac{1}{I_{s1}} \right) \left[c_m(\omega_m - \omega_{s1}) + k_m(\theta_m - \theta_{s1}) - c_{s1}(\omega_{s1} - G\omega_{s2}) - k_{s1}(\theta_{s1} - G\theta_{s2}) \right. \\ & + \frac{1}{G}c_{s2}\left(\omega_{s2} - \frac{1}{1 + \frac{1}{R_d}}\omega_{mll} - \frac{1}{R_d + 1}\omega_{mlr}\right) \\ & \left. + \frac{1}{G}k_{s2}\left(\theta_{s2} - \frac{1}{1 + \frac{1}{R_d}}\theta_{mll} - \frac{1}{R_d + 1}\theta_{mlr}\right) \right] \end{aligned} \quad (3.16)$$

$$\begin{aligned}
\dot{\omega}_{s2} = & \left(\frac{1}{I_{s2}}\right) [c_{s1}(\omega_{s1} - G\omega_{s2}) + k_{s1}(\theta_{s1} - G\theta_{s2}) \\
& - \frac{1}{G}c_{s2}(\omega_{s2} - \frac{1}{1+\frac{1}{R_d}}\omega_{mll} - \frac{1}{R_d+1}\omega_{mlr}) \\
& - \frac{1}{G}k_{s2}(\theta_{s2} - \frac{1}{1+\frac{1}{R_d}}\theta_{mll} - \frac{1}{R_d+1}\theta_{mlr})]
\end{aligned} \tag{3.17}$$

$$\begin{aligned}
\dot{\omega}_{mlr} = & \left(\frac{1}{I_{mlr}}\right)\left(\frac{1}{R_d+1}\right) [c_{s2}(\omega_{s2} - \frac{1}{1+\frac{1}{R_d}}\omega_{mll} - \frac{1}{R_d+1}\omega_{mlr}) \\
& + k_{s2}(\theta_{s2} - \frac{1}{1+\frac{1}{R_d}}\theta_{mll} - \frac{1}{R_d+1}\theta_{mlr})]
\end{aligned} \tag{3.18}$$

$$\begin{aligned}
\dot{\omega}_{mll} = & \left(\frac{1}{I_{mll}}\right)\left(\frac{1}{1+\frac{1}{R_d}}\right) [c_{s2}(\omega_{s2} - \frac{1}{1+\frac{1}{R_d}}\omega_{mll} - \frac{1}{R_d+1}\omega_{mlr}) \\
& + k_{s2}(\theta_{s2} - \frac{1}{1+\frac{1}{R_d}}\theta_{mll} - \frac{1}{R_d+1}\theta_{mlr})]
\end{aligned} \tag{3.19}$$

$$A = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{k_{s1}}{I_{s1}} & -\frac{c_{s1}+c_{s1}}{I_{s1}} & -\frac{k_{s1}+k_{s1}}{I_{s1}} & \frac{\frac{c_{s2}}{G}+Gc_{s1}}{I_{s1}} & \frac{\frac{k_{s2}}{G}+Gk_{s1}}{I_{s1}} & -\frac{\frac{c_{s2}}{G}}{(1+R_d)I_{s1}} & -\frac{\frac{k_{s2}}{G}}{(1+R_d)I_{s1}} & -\frac{\frac{c_{s2}}{G}}{(1+\frac{1}{R_d})I_{s1}} & -\frac{\frac{k_{s2}}{G}}{(1+\frac{1}{R_d})I_{s1}} \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{c_{s1}}{I_{s2}} & \frac{k_{s1}}{I_{s2}} & -\frac{(\frac{c_{s2}}{G}+Gc_{s1})}{I_{s2}} & -\frac{(\frac{k_{s2}}{G}+Gk_{s1})}{I_{s2}} & \frac{\frac{c_{s2}}{G}}{(R_d+1)I_{s2}} & \frac{\frac{k_{s2}}{G}}{(R_d+1)I_{s2}} & \frac{\frac{c_{s2}}{G}}{(1+\frac{1}{R_d})I_{s2}} & \frac{\frac{k_{s2}}{G}}{(1+\frac{1}{R_d})I_{s2}} \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{\frac{c_{s2}}{G}}{(R_d+1)I_{mlr}} & \frac{\frac{k_{s2}}{G}}{(R_d+1)I_{mlr}} & -\frac{\frac{c_{s2}}{G}}{(R_d+1)^2I_{mlr}} & -\frac{\frac{k_{s2}}{G}}{(R_d+1)^2I_{mlr}} & -\frac{\frac{c_{s2}}{G}}{(R_d+1)(1+\frac{1}{R_d})I_{mlr}} & -\frac{\frac{k_{s2}}{G}}{(R_d+1)(1+\frac{1}{R_d})I_{mlr}} \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{\frac{c_{s2}}{G}}{(1+\frac{1}{R_d})I_{mll}} & \frac{\frac{k_{s2}}{G}}{(1+\frac{1}{R_d})I_{mll}} & -\frac{\frac{c_{s2}}{G}}{(1+\frac{1}{R_d})(R_d+1)I_{mll}} & -\frac{\frac{k_{s2}}{G}}{(1+\frac{1}{R_d})(R_d+1)I_{mll}} & -\frac{\frac{c_{s2}}{G}}{(1+\frac{1}{R_d})^2I_{mll}} & -\frac{\frac{k_{s2}}{G}}{(1+\frac{1}{R_d})^2I_{mll}} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{bmatrix} \tag{3.20}$$

Mechanical loads, such as wheels and other mechanical attachments, are depicted as load torque.

3.3.2 Braking

Two types of braking are covered; conventional and regenerative. Conventional braking works by applying resistive force mechanically against wheels to reduce speed while regenerative braking takes advantage of EM inertia to charge back ESDs during speed reduction when ω_m is higher than ω_e of inverter feeding the EM. Regenerative braking is the default braking mode when the EMs speed slows.

3.4 Electrical Systems

3.4.1 DC/DC Converter

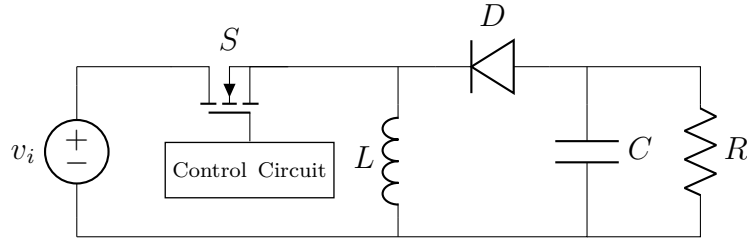


Figure 3.6: Schematic of Buck-Boost Converter

The DC/DC converter selected is an inverting buck-boost type shown in Figure 3.6 with voltage relationship given by:

$$\frac{v_o}{v_i} = \frac{-D}{100 - D} \quad (3.21)$$

Where the converter will act as buck when $D < 50\%$ and boost when $D > 50\%$.

DC/DC converter primary function is supply power to DC loads such as electronics.

The four basic topologies of DC/DC converters are buck-boost, Cuk, Zeta and SEPIC [75]. These types were covered in [75] with their advantages and disadvantages listed. For this work, buck-boost converter was adopted due to simple configuration and fewer number of components.

By referring to basic formulas of L and C :

$$v = L \cdot \frac{di}{dt} \quad (3.22)$$

$$i = C \cdot \frac{dv}{dt} \quad (3.23)$$

Two formulas can be derived for selecting the converter parameters:

$$L = \frac{v_i D}{\Delta i_L f_{sw}} \quad (3.24)$$

$$C = \frac{-v_o D}{\Delta v_o R f_{sw}} \quad (3.25)$$

and the minimum L set as the boundary between CCM and DCM is [76]:

$$L_{min} = \frac{(1 - D)^2 R}{2 f_{sw}} \quad (3.26)$$

DCM shall be avoided in order to reduce current spikes from the diode and switching of solid state devices [75].

3.4.2 Three Phase Transformer

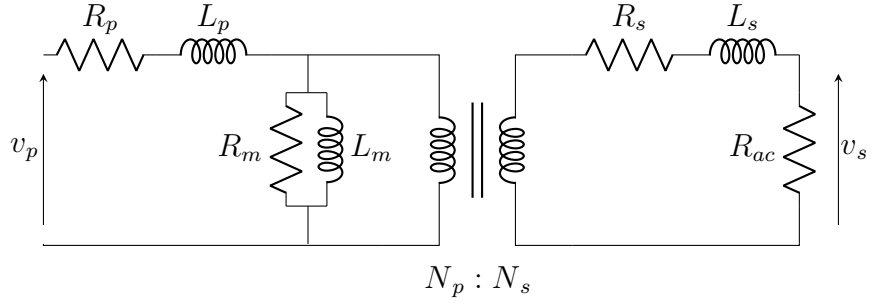


Figure 3.7: Schematic of Three Phase Transformer

The three phase transformer selected is a three-limb core with grounded Y connection for both primary and secondary windings as shown in Figure 3.7.

$$\frac{v_o}{v_i} = \frac{N_s}{N_p} \quad (3.27)$$

$$\frac{Z_s}{Z_p} = \left(\frac{N_s}{N_p} \right)^2 \quad (3.28)$$

A separate three phase inverter is used for each of three phase PMSM and three phase transformer along with their own LCL filters.

3.4.3 Three Phase Sinusoidal PWM Inverter

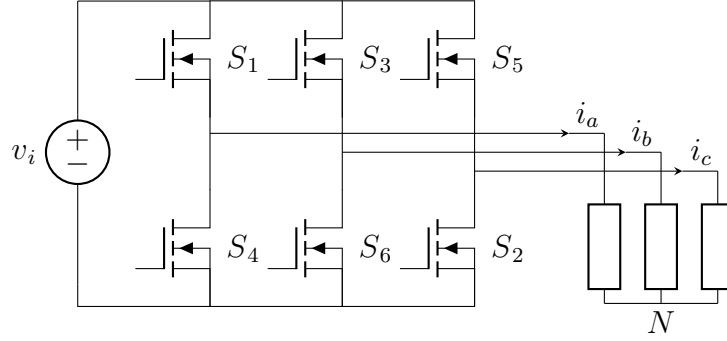


Figure 3.8: Schematic of Three Phase Sinusoidal PWM Inverter

Three phase sinusoidal PWM inverter shown in Figure 3.8 is a power electronic circuit designed to convert DC voltage to three phase AC voltages. A comparator circuit used for gates signaling consisting of two signals controls output of the inverter. Two important ratios for f and v are utilized to control amplitude and frequency of the inverter output are given below [76]:

$$m_f = \frac{f_{carrier}}{f^*} \quad (3.29)$$

$$m_a = \frac{v^*}{v_{carrier}} \quad (3.30)$$

Lower m_f results in higher inverter output frequency while higher m_a results in smaller output amplitude. A closed loop voltage control is designed by adjusting v^* in m_a . Feedback v is expressed in $d-q$ frame, subtracted from $v^* = 1$ of inverter output in $d-q$ frame as well and passed to a PI controller to adjust inverter gate signals.

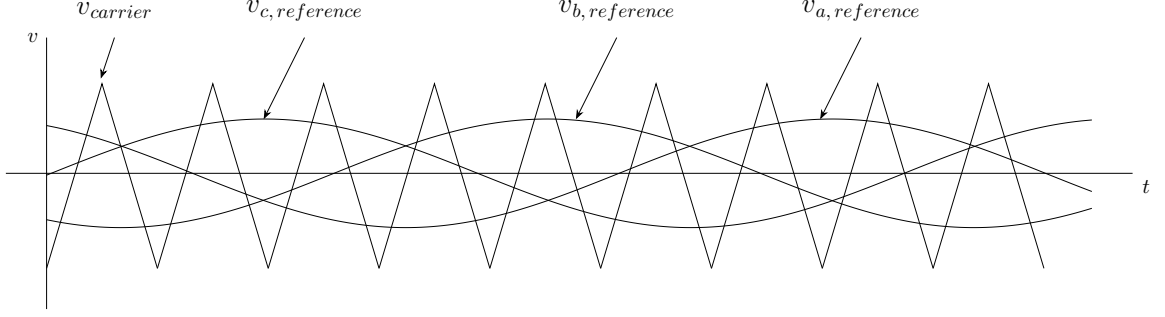


Figure 3.9: Plot of Carrier and Reference Signals in Three Phase Sinusoidal PWM Inverter

From figures 3.8 and 3.9, output of each phase is v_i if $v^* > v_{carrier}$ and zero otherwise. Signals for S_1 , S_3 and S_5 are ON when their corresponding $v^* > v_{carrier}$ while S_2 , S_4 and S_6 are the inverse of the formers respectively.

3.4.4 LCL Filter

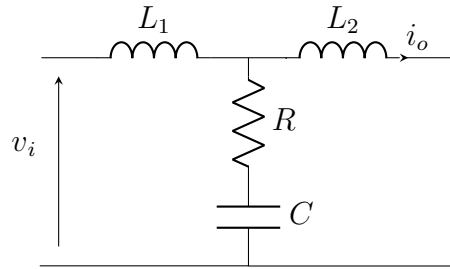


Figure 3.10: Schematic of LCL Filter

Due to their robust harmonic attenuation capabilities and reduced weight of their passive components [77], LCL filters shown in Figure 3.10 are widely used in power grids [77], which was incorporated for EV chargers connected power grids in [78]. The LCL filter transfer function and resonant frequency are given in [79] for Figure 3.10

as:

$$\frac{i_o}{v_i} = \frac{j\omega CR + 1}{-j\omega^3 L_1 L_2 C - \omega^2 CR(L_1 + L_2) + j\omega(L_1 + L_2)} \quad (3.31)$$

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \quad (3.32)$$

Based on [80], LCL filter parameters are recommended based on empirical analysis to satisfy below inequalities as follow:

$$f_o \leq \frac{1}{10} \cdot f_{res} \quad (3.33)$$

$$L_1 \leq \frac{0.05 \cdot v_i \cdot \delta}{\Delta i_o f_{sw}} \quad (3.34)$$

$$\frac{1}{10} \cdot L_1 \leq L_2 \leq \frac{1}{5} \cdot L_1 \quad (3.35)$$

$$\frac{1}{10} \cdot \omega_{sw} \cdot L_2 \leq \frac{1}{\omega_{sw} \cdot C} \leq \frac{1}{5} \omega_{sw} \cdot L_2 \quad (3.36)$$

$$R = \frac{1}{3 \cdot \omega_{res} \cdot C} \quad (3.37)$$

These equations were derived in [80] in order to reach parameters that compromise between component weights and acceptable current ripples.

3.4.5 Three Phase PMSM

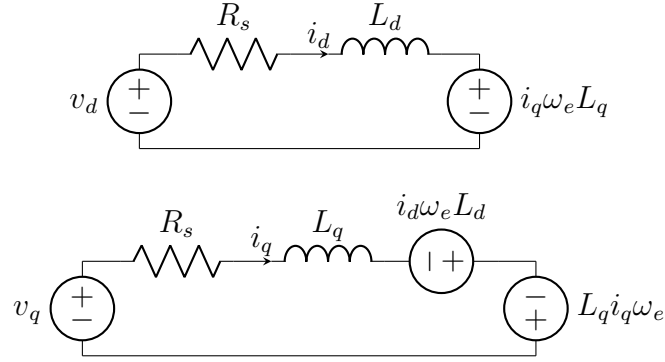


Figure 3.11: Schematic of PMSM Equivalent Circuits in d and q Frame

Due to their high torque and power density, PMSM are the most popular and widely utilized EMs in EVs [81]. PMSM equivalent circuits in Figure 3.11 are governed by below equations in d-q frame [82]:

$$v_d = L_d \frac{di_d}{dt} + R_s i_d - L_q i_q \omega_e \quad (3.38)$$

$$v_q = L_q \frac{di_q}{dt} + R_s i_q + L_d i_d \omega_e + \psi \omega_e \quad (3.39)$$

$$\omega_e = p \cdot \omega_m \quad (3.40)$$

$$\tau_{em} = \frac{3}{2} \cdot p \cdot (\psi i_q + (L_d - L_q) i_d i_q) \quad (3.41)$$

MCU primary component is FOC. FOC decouples and adjusts values of i_d and i_q to obtain desired torque given it is a function of both by modifying v_d and v_q to get new inverter gate signals using sinusoidal SVPWM. From the torque equation, i_q controls flux torque while i_d controls reluctance torque. Speed is controlled indirectly by the FOC during adjustments of gate signals frequency.

3.4.6 Battery

Although uses of Li-Ion batteries in EVs are continuously increasing, various types of batteries exist [5]. This battery has multiple benefits ranging from lower weight, simple components, higher loading ratings, high loading and unloading periods and reduced memory effect [5]. Li-Ion battery was modeled Li-Ion battery as an RC equivalent circuit in [83]–[85]. Five different models of Li-Ion were analyzed in [86] in which are all RC equivalent circuit based: Shepard, Nonlinear, Partnership for a New Generation of Vehicles, 3rd Order RC Model With One-State Hysteresis and Three RC Network Model. For this work, Li-Ion v vs. SOC curve is segmented into three equations corresponding to different periods in the curve.

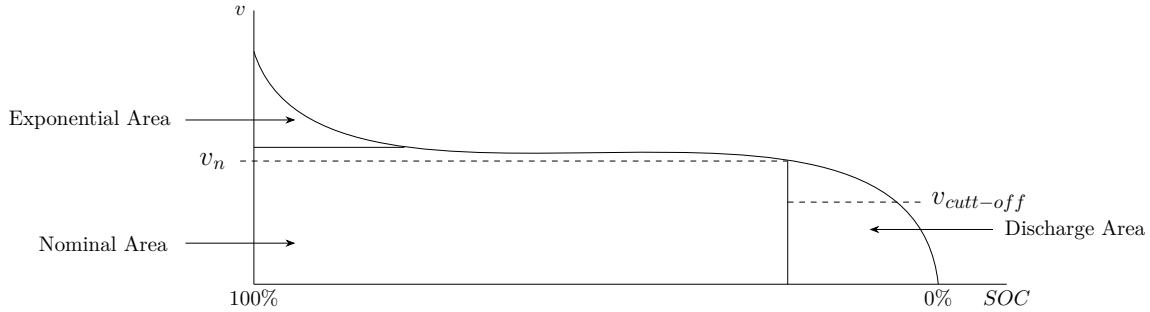


Figure 3.12: Curve of v and SOC for Li-Ion Battery

Reference to [87] and Figure 3.12, the superimposed v equations during charging and discharging are:

$$v_{ch} = v_{dis} = v_n - K \frac{1}{SOC} \cdot Q \cdot (1 - SOC) + A \cdot e^{-B \cdot Q \cdot (1 - SOC)} \quad (3.42)$$

Subsequent parameters such as $v_{cut-off}$ and fully charged v are calculated based on the common ratios observed in Li-Ion battery datasheets. BMS is designed to

maintain SOC between a lower and upper bounds.

3.4.7 Super-capacitor

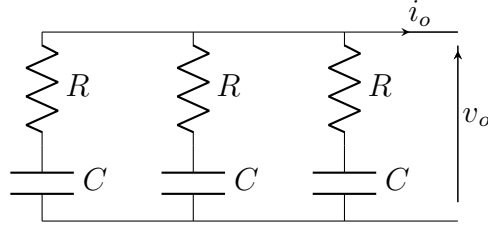


Figure 3.13: Schematic of Super-capacitor Circuit

Super-capacitors, with their high power density and rapid charge-discharge capabilities, are well-suited to handle high power bursts, complementing the energy density and storage capacity of batteries [88]. A literature review was conducted focusing on super-capacitor circuit models while also proposing a simplified equivalent circuit with experimental method used for parameter identification in [89]. Although of their usefulness for many applications, RC equivalent circuits fail to reveal all dynamic responses of super-capacitors [90].

The model for this work consists of multiple RC branches connected in parallel as shown in Figure 3.13. Similar to BMS, SMS works to maintain SOC between a specified upper and lower limits.

3.4.8 Energy Management System

Efficient power distribution in EVs relies heavily on executing successful approaches for energy management. It plays a central role in both meeting the EV power requirements and optimizing its power system. EMS dictates how each energy source responds to

power demands, which facilitating efficient power distribution [91]. Several control schemes have been implemented for EMS shown in Figure 3.14 [91]:

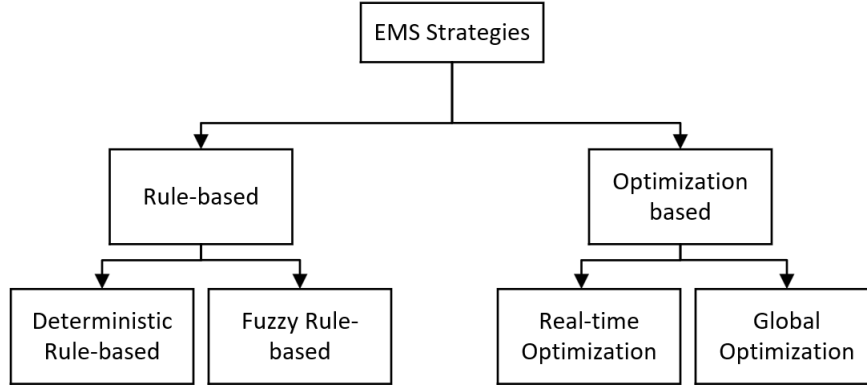


Figure 3.14: Control Strategies of EMS for EVs

EMS is specifically emphasized due to its role in overseeing the utilization and charge/discharge cycles of the ESDs. The EMS for this work is composed of several switches located at various points of the full model, and uses a rules-based decision-making controller to link and unlink certain components in the system.

CHAPTER 4

METHODOLOGY

4.1 Simulink Modeling of Mechanical Systems

4.1.1 Driveline Shaft

The Simulink model for this system is shown in Figure 4.1 below:

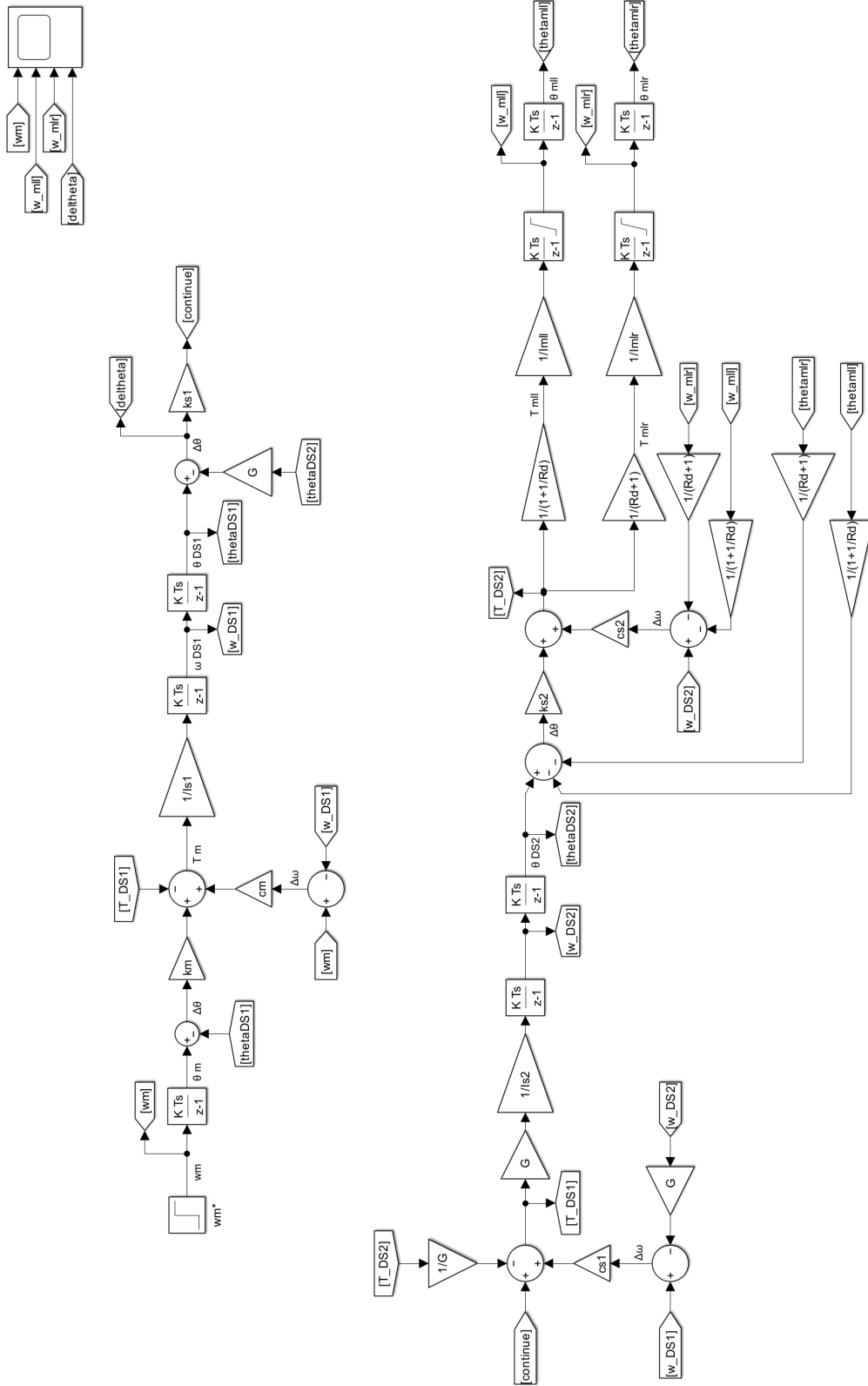


Figure 4.1: Simulink Model of DS

Table 4.1: Driveline Parameters

#	Parameter	Unit	Value	#	Parameter	Unit	Value
1	I_{s1}	$kg.m^2$	10^{-3}	8	c_m	$N \cdot s/rad$	5
2	I_{s2}	$kg.m^2$	10^{-3}	9	c_{s1}	$N \cdot s/rad$	25
3	I_{mlr}	$kg.m^2$	5×10^{-5}	10	c_{s2}	$N \cdot s/rad$	30
4	I_{mll}	$kg.m^2$	5×10^{-5}	11	G	-	2
5	k_m	N/rad	50×10^3	12	d	m	1.84
6	k_{s1}	N/rad	30×10^3	13	R	m	20
7	k_{s2}	N/rad	45×10^3	14	R_d	-	0.9158

Values of DS parameters shown in Table 4.1 are substituted in equation 3.20, resulting in seven eigenvalues of matrix A which are $10^5 \{-3.19, -0.71, -0.02 \pm 0.05j, -0.02, -0.01, 0.0\}$. These poles indicate stable system with non-positive real poles.

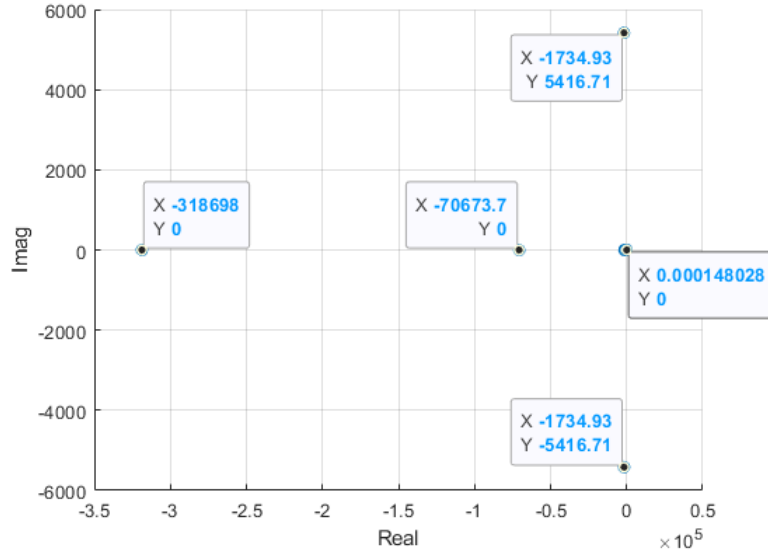


Figure 4.2: Eigenvalues of DS State Space Matrix

For ω_m of $5000 \text{ rpm} \equiv 523.6 \text{ rad/s}$:

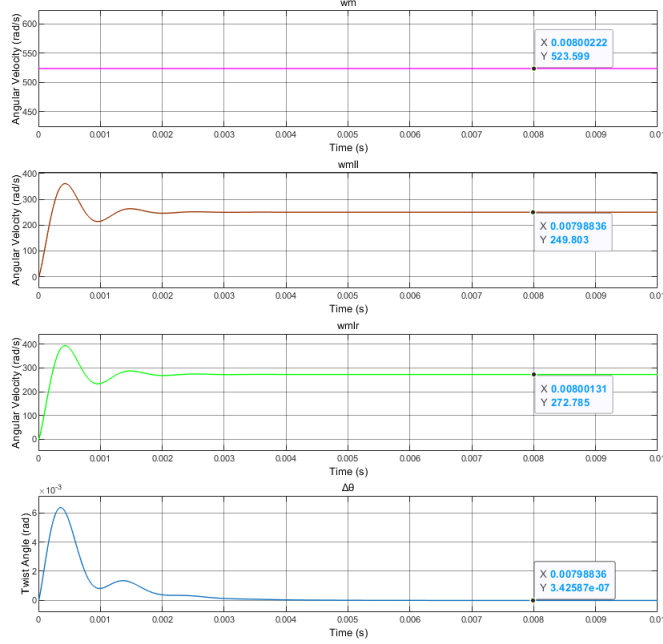


Figure 4.3: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle

It can be observed that all velocities and twist angle stabilize at 0.003s. Also, $\Delta\theta$ is positive indicating that I_{s1} is ahead of I_{s2} . However, this is not always the case as what will be observed in full system plots.

4.1.2 Braking

The Simulink model for this system is shown below:

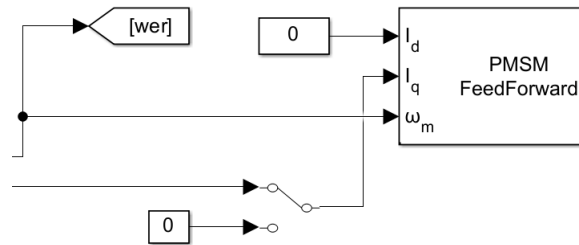


Figure 4.4: Simulink Model of Braking

In order to model conventional braking, three phase PMSM τ_{em} will be stopped by

setting i_q^* to zero and applying external mechanical force to decrease speed. However, regenerative braking works when ω_m is higher than ω_e and thus negative τ_{em} will be produced supplying power back to the ESDs. At $\frac{d\omega^*}{dt} = 0$, regenerative braking is enabled by default.

4.2 Simulink Modeling of Electrical Systems

4.2.1 DC/DC Converter

The Simulink model for this system is shown below in Figure 4.5 with the system parameters given in Table 4.2:

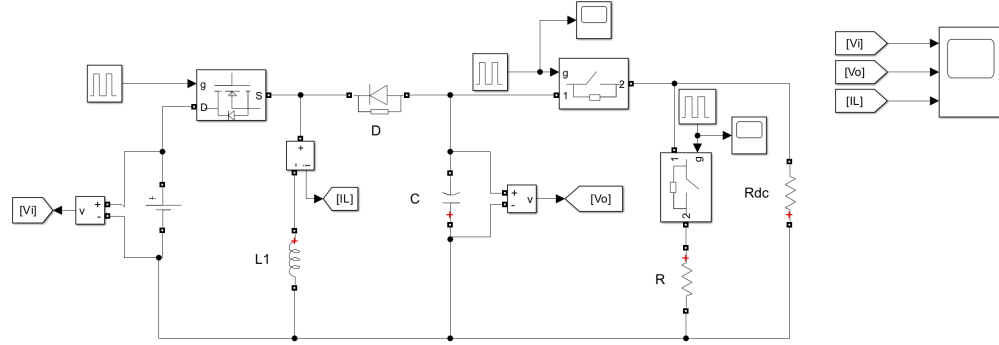


Figure 4.5: Simulink Model of DC/DC Converter

Table 4.2: DC/DC Converter Parameters

#	Parameter	Unit	Value	#	Parameter	Unit	Value
1	v_i	V	400	5	Δi_L	A	0.1
2	v_o	V	-12	6	Δv_o	V	0.05
3	D	%	2.912	7	R_{dc}	Ω	10
4	L	H	$3.4 \cdot 10^{-3}$	8	C	F	$69.87 \cdot 10^{-6}$

A switch is placed with $R = 10^{-3} \Omega$ to induce a fault during the operating actions.

Ripples of v_o and i_L can be shown in Figure 4.6 clearly with their ripples determined from L and C values selected.

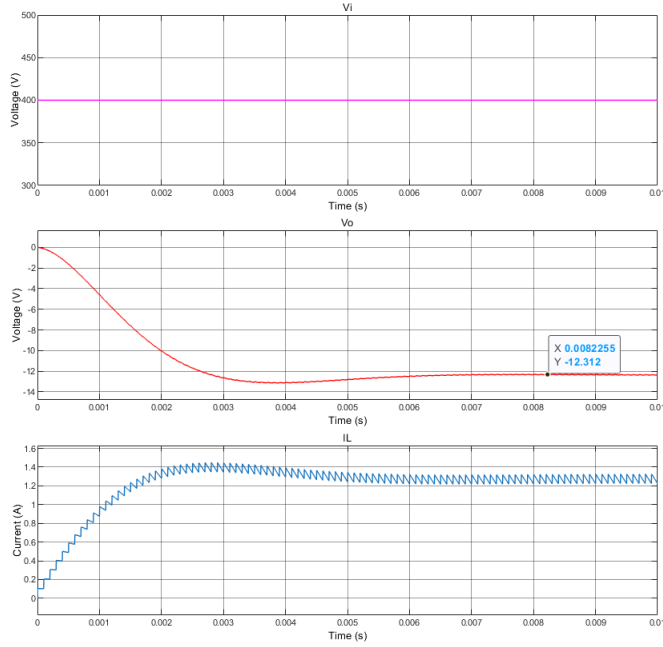


Figure 4.6: Input, Output Voltages and Inductor Current for DC/DC Converter

4.2.2 Three Phase Transformer

The Simulink model for this system is shown below in Figure 4.7 with system parameters given in Table 4.3:

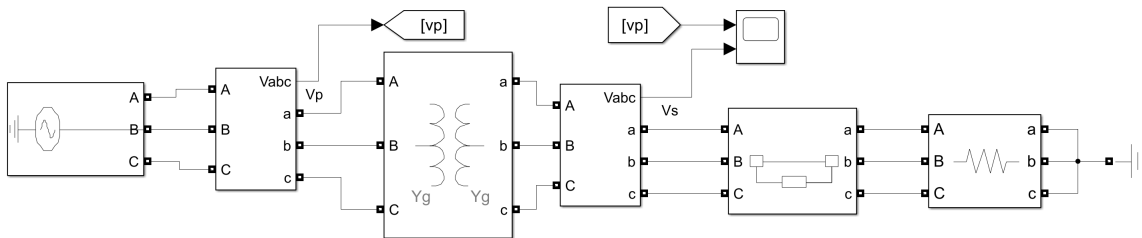


Figure 4.7: Simulink Model of Three Phase Transformer

Table 4.3: Three Phase Transformer Parameters

#	Parameter	Unit	Value	#	Parameter	Unit	Value
1	v_p	V	400	6	R_p	Ω	0.1
2	v_s	V	300	7	R_s	Ω	0.056
3	f	Hz	60	8	L_p	H	10^{-3}
4	R_m	Ω	$1.08 \cdot 10^4$	9	L_s	H	$5.63 \cdot 10^{-4}$
5	L_m	H	2866	10	R_{ac}	Ω	10

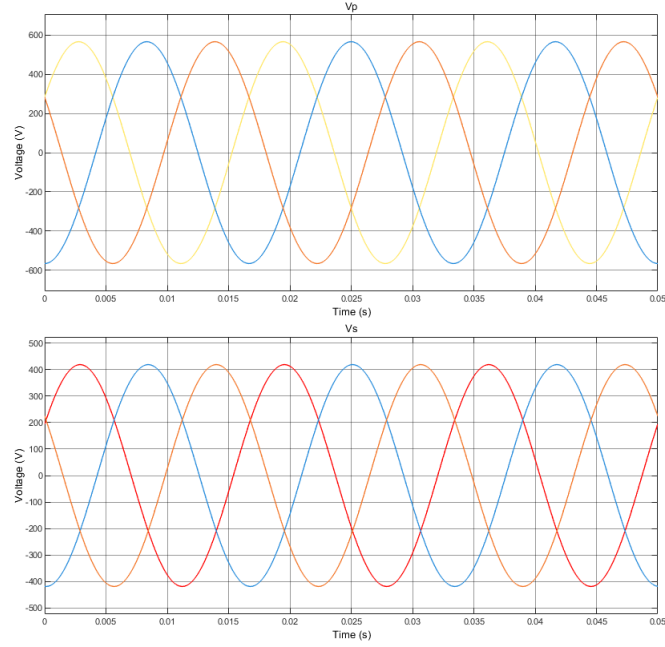


Figure 4.8: Primary and Secondary Voltages for Three Phase Transformer

4.2.3 Three Phase Sinusoidal PWM Inverter

The Simulink model for this system is shown below in Figure 4.9 with all system parameters given in Table 4.4:

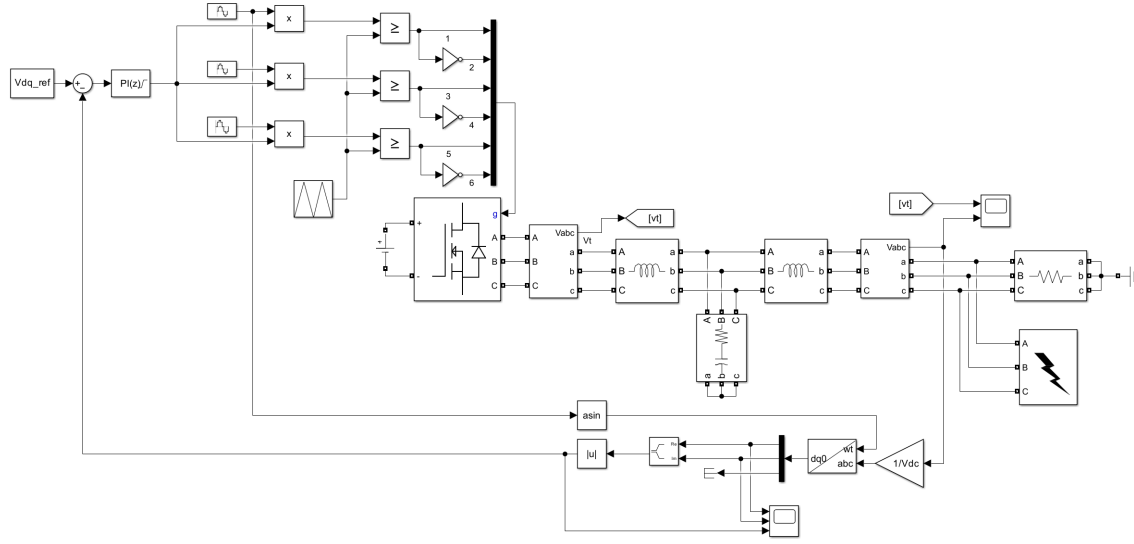


Figure 4.9: Simulink Model of Three Phase Sinusoidal PWM Inverter

Table 4.4: Three Phase Sinusoidal PWM Inverter Parameters

#	Parameter	Unit	Value	#	Parameter	Unit	Value
1	f^*	Hz	60	5	v^*	V	1
2	$f_{carrier}$	Hz	$15 \cdot 10^3$	6	$v_{carrier}$	V	1
3	m_f	-	250	7	m_a	-	1
4	K_p	-	10	8	K_i	-	1

To demonstrate effectiveness of the closed loop voltage controller, a three phase to ground fault with ground $R = 10^{-3} \Omega$ is introduced between 0.03s and 0.04s as shown in Figure 4.10. The controller adjusts values of v^* to correct both v_t and v_o .

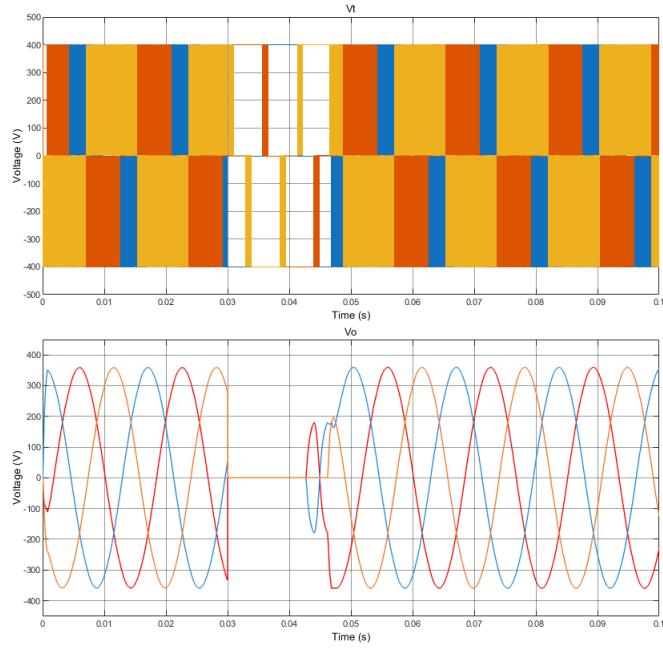


Figure 4.10: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter

4.2.4 LCL Filter

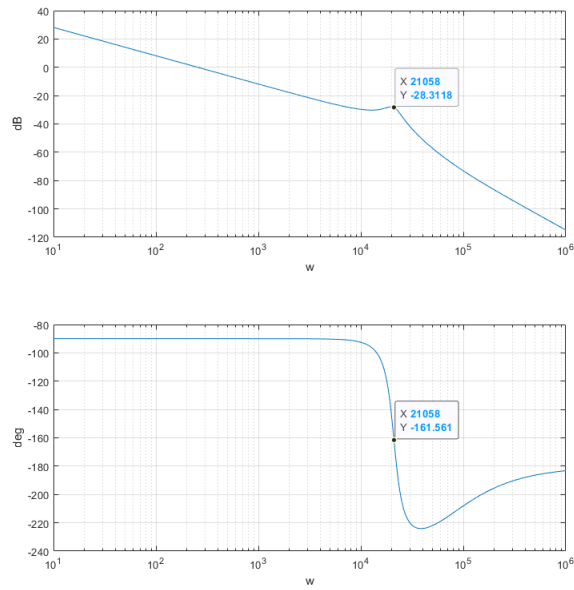


Figure 4.11: Amplitude and Phase Response of LCL Filter

To satisfy all equations in Sub-section 3.4.4, parameters were selected as in Table 4.5 resulting in $f_{res} = 210.58 \cdot 10^3 Hz$ and amplitude and phase responses shown in Figure 4.11.

Table 4.5: LCL Filter Parameters

#	Parameter	Unit	Value	#	Parameter	Unit	Value
1	L_1	H	$3.35 \cdot 10^{-3}$	4	R	Ω	3.36
2	L_2	H	$0.56 \cdot 10^{-3}$	5	Δi_o	A	0.02
3	C	F	$4.7 \cdot 10^{-6}$	6	δ	-	0.1

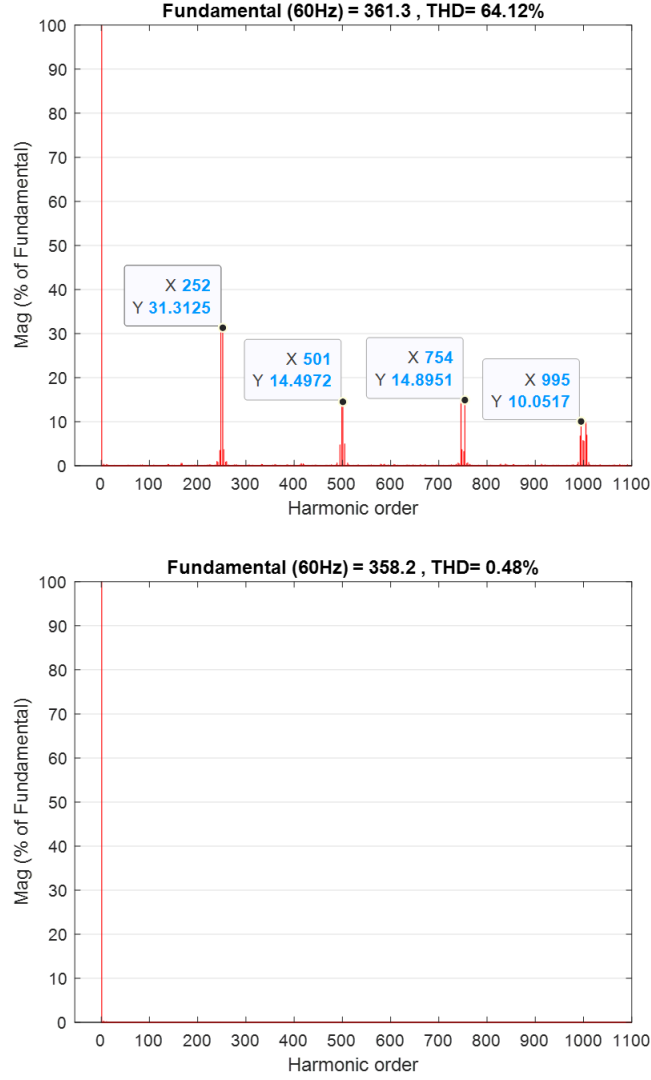


Figure 4.12: Total Harmonic Distortion of Three Phase Sinusoidal PWM Inverter Before and After LCL Filter

In Figure 4.12, high amplitude harmonics can be seen around multiples of m_f before filtering. On the other hand, a significant reduction is shown for all harmonics after filtering. Noting that harmonic order of 1 has 100% magnitude of the fundamental frequency for both cases.

4.2.5 Three Phase PMSM

The Simulink model for this system is shown below in Figure 4.13 with system parameters given in Table 4.6:

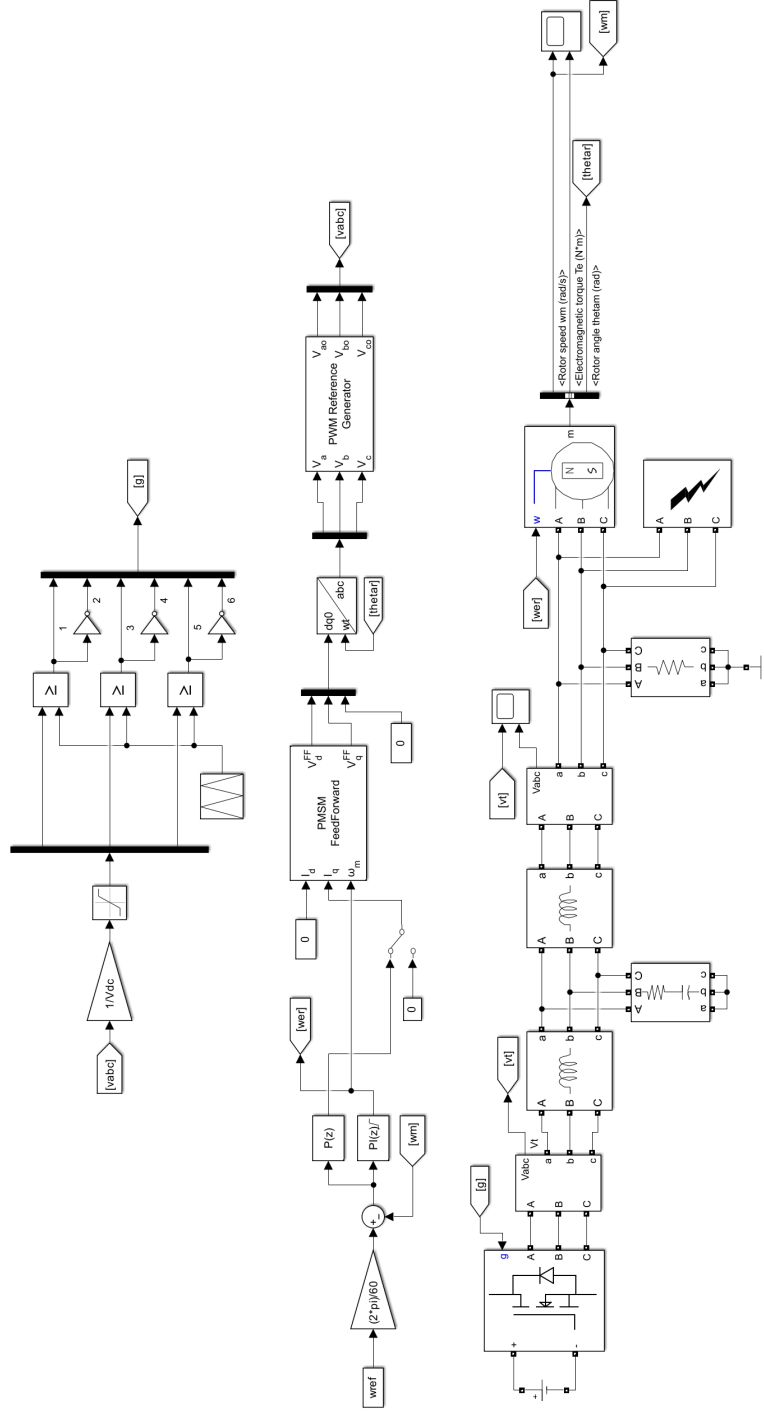


Figure 4.13: Simulink Model of Three Phase PMSM

Table 4.6: Three Phase PMSM Parameters

#	Parameter	Unit	Value	#	Parameter	Unit	Value
1	ω_m	<i>rpm</i>	3600	7	R_{stator}	Ω	0.0485
2	f_e	<i>Hz</i>	60	8	I_m	<i>kg.m²</i>	0.005
3	p	-	1	9	ψ	<i>Wb</i>	0.5
4	L_d	<i>H</i>	0.01	10	K_p	-	10
5	L_q	<i>H</i>	0.02	11	K_i	-	1000
6	K_p for i_q	-	100				

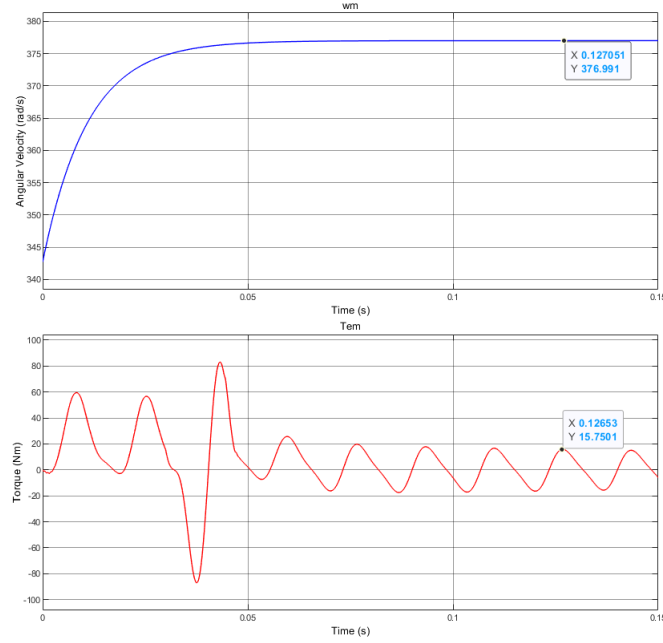


Figure 4.14: Angular Velocity and Electromagnetic Torque of Three Phase PMSM

In order to reach and maintain ω_m desired value, it can be shown that average τ_{em} in Figure 4.14 is 23.3 Nm and zero when ω_m reaches its steady state value of $3600\text{ rpm} \equiv 377\text{ rad/s}$. τ_{em} is calculated as a function of i_q while setting i_d to zero to remove reluctant torque as explained in Sub-section 3.4.5. A three phase to ground fault with ground $R = 10^{-3}\Omega$ was introduced between 0.03s and 0.04s to test the FOC controller effectiveness in correcting both ω_m and τ_{em} . Its effect can be shown as large

fluctuation in τ_{em} of 83.1 Nm in Figure 4.14. Steady state τ_{em} oscillates around zero with an amplitude of 15.7 Nm .

PMSM has an intrinsic nature of regenerative braking unless modification to FOC controller is adjusted by setting i_q^* to zero for conventional braking.

4.2.6 Battery

The Simulink model for this system is shown below in Figure 4.15 with all system parameters given in Table 4.7:

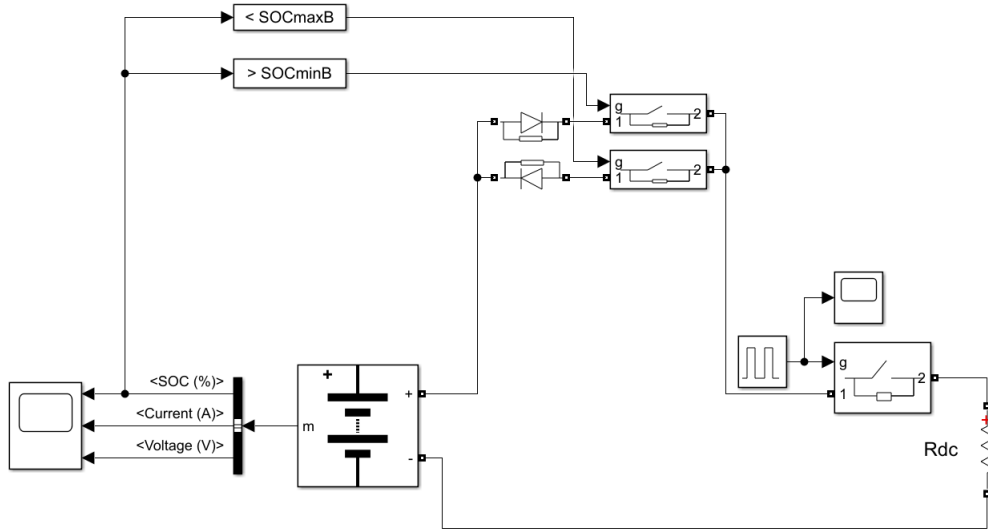


Figure 4.15: Simulink Model of Battery

Table 4.7: Li-Ion Battery Parameters

#	Parameter	Unit	Value	#	Parameter	Unit	Value
1	Nominal v_o	V	400	5	Current SOC	%	70
2	Q	Ah	100	6	SOC_{min}	%	20
3	R_{dc}	Ω	10	7	SOC_{max}	%	80
4	External charging v_{dc}	V	440				

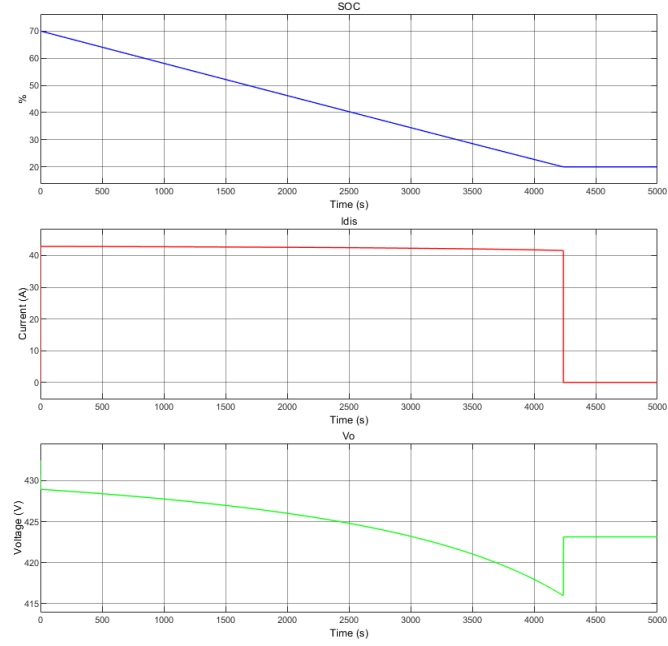


Figure 4.16: State of Charge, Discharge Current and Voltage of Li-Ion Battery

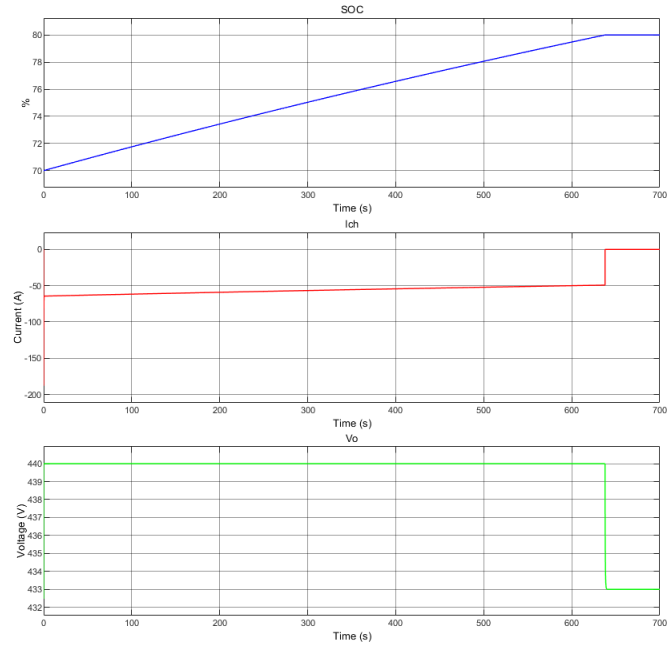


Figure 4.17: State of Charge, Charge Current and Voltage of Li-Ion Battery

BMS is modeled by two switches and diodes. Forward diode is enabled only when $SOC < SOC_{max}$ and reversed diode is enabled only when $SOC > SOC_{min}$. When

one or both of the conditions are satisfied, the switches will be ON allowing current flow.

The discharge area shown in Figure 3.12 can be observed in v_o in Figure 4.16. Also, although battery was operated in the nominal area i.e., v_o is constant, there was a slight linear increase in i_{ch} .

By comparing Figure 4.16 to work presented in literature, a good consistency is observed between discharge area in Figure 4.16 and Fig. 3 in [86] for constant current profile. However, one limitation of the model used for this work is the hysteresis nature of v_o during both charging and discharging cycles as indicated in Fig. 14 in [83] when compared with figures 4.16 and 4.17.

4.2.7 Super-capacitor

The Simulink model for this system is shown below in Figure 4.18 with system parameters given in Table 4.8:

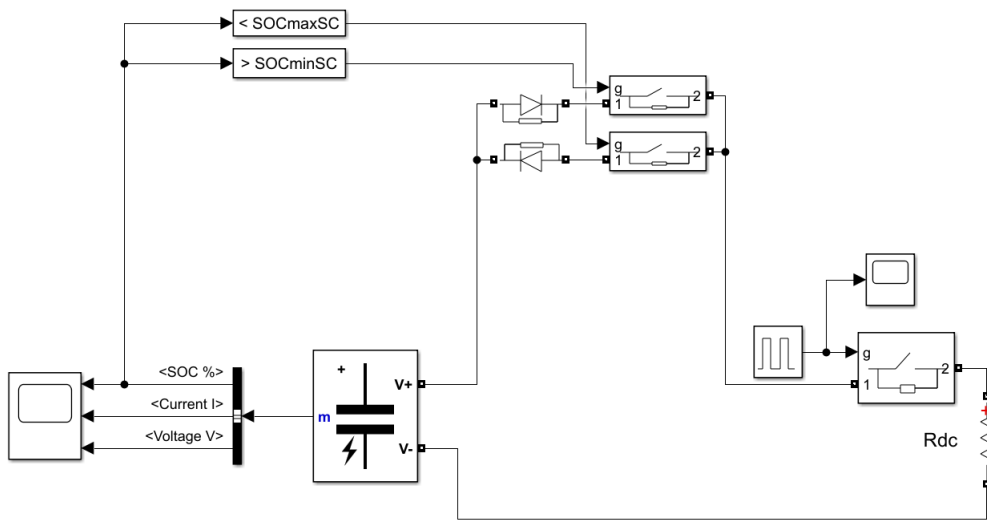


Figure 4.18: Simulink Model of Super-capacitor

Table 4.8: Super-capacitor Parameters

#	Parameter	Unit	Value	#	Parameter	Unit	Value
1	Initial v_o	V	250	6	R_{series}	Ω	1
2	Rated v_o	V	400	7	Super-capacitor rated C	F	10
3	SOC_{min}	%	20	8	# of C 's in a branch	-	10
4	SOC_{max}	%	80	9	R_{dc}	Ω	10
5	RC branches	-	3	10	External charging v_{dc}	V	350

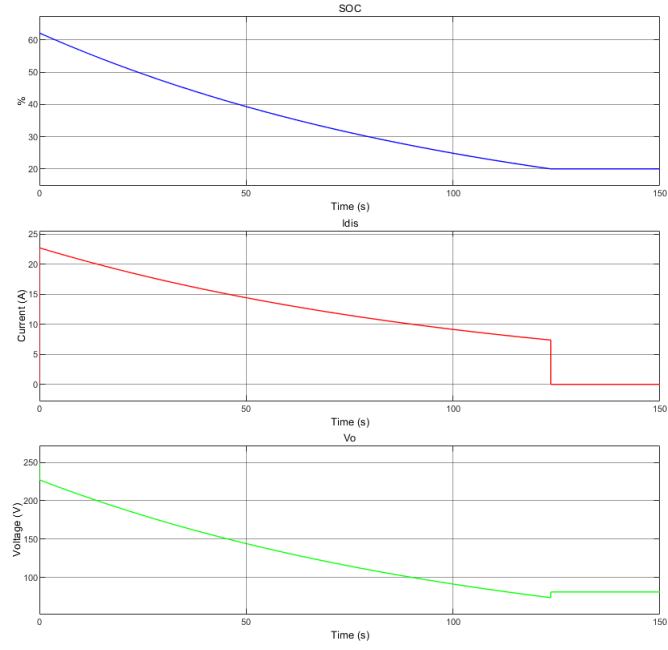


Figure 4.19: State of Charge, Discharge Current and Voltage of Super-capacitor

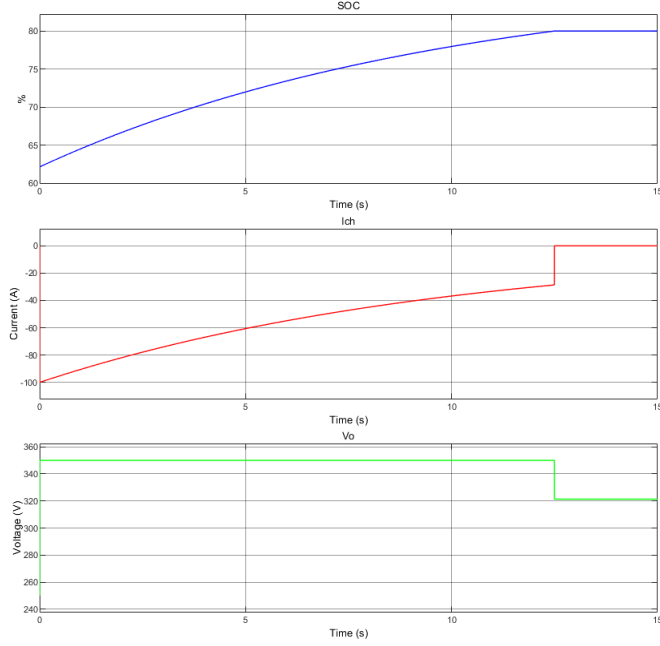


Figure 4.20: State of Charge, Charge Current and Voltage of Super-capacitor

Compared to batteries, dynamic response to charging and discharging in super-capacitors is generally relatively faster as shown in figures 4.19 and 4.20 when both are connected to $R_{dc} = 10 \Omega$. In addition, SOC exhibits a non-linear behavior compared to it for the Li-Ion battery model with its decay rate determined by the super-capacitor time constant.

4.2.8 Energy Management System

The Simulink model for this system is shown below:

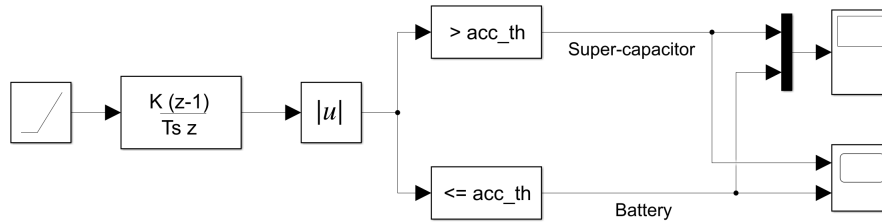


Figure 4.21: Simulink Model of EMS

Depending on the speed profile, EMS will connect either battery or super-capacitor to other systems based on acceleration rates as given below:

$$s = \begin{cases} \text{Battery} & \text{if } \left| \frac{d\omega}{dt} \right| \leq \alpha_{max} = 2000 \text{ rpm/s} \\ \text{Super-capacitor} & \text{if } \left| \frac{d\omega}{dt} \right| > \alpha_{max} = 2000 \text{ rpm/s} \end{cases} \quad (4.1)$$

4.3 Full System

For ω^* of $3600 \text{ rpm} \equiv 377 \text{ rad/s}$ and other parameters from the individual systems:

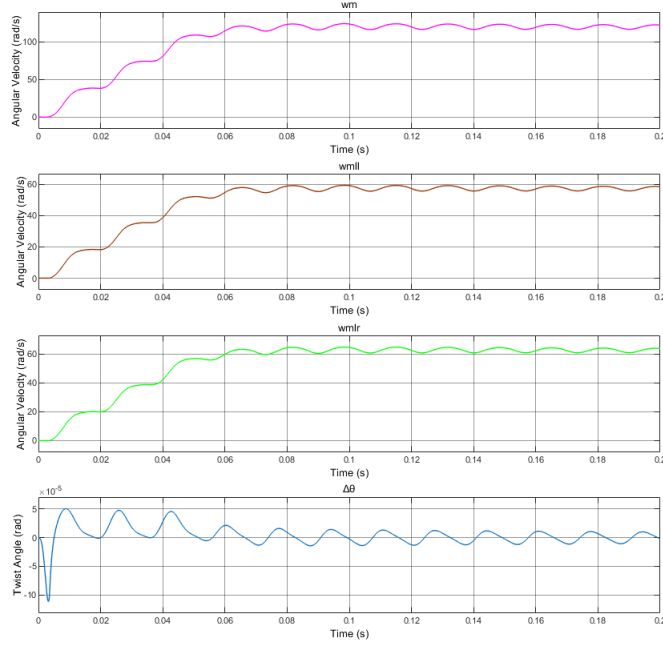


Figure 4.22: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle During Constant Reference Speed

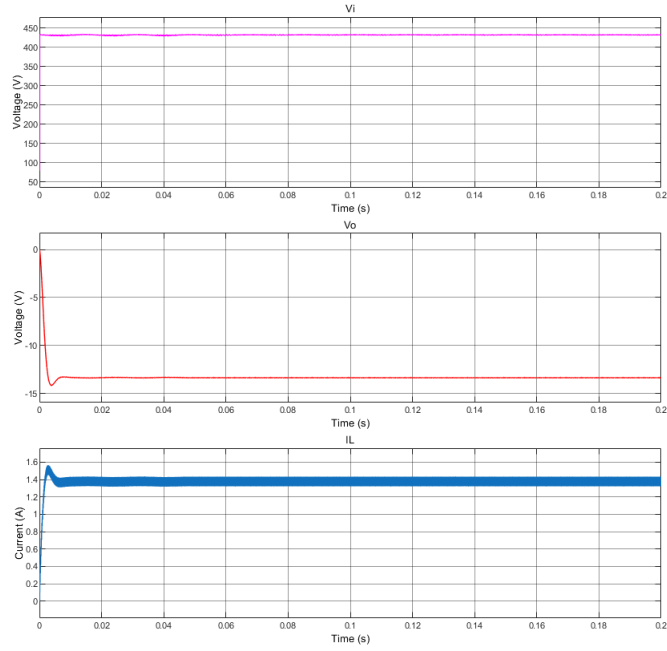


Figure 4.23: Input, Output Voltages and Inductor Current for DC/DC Converter During Constant Reference Speed

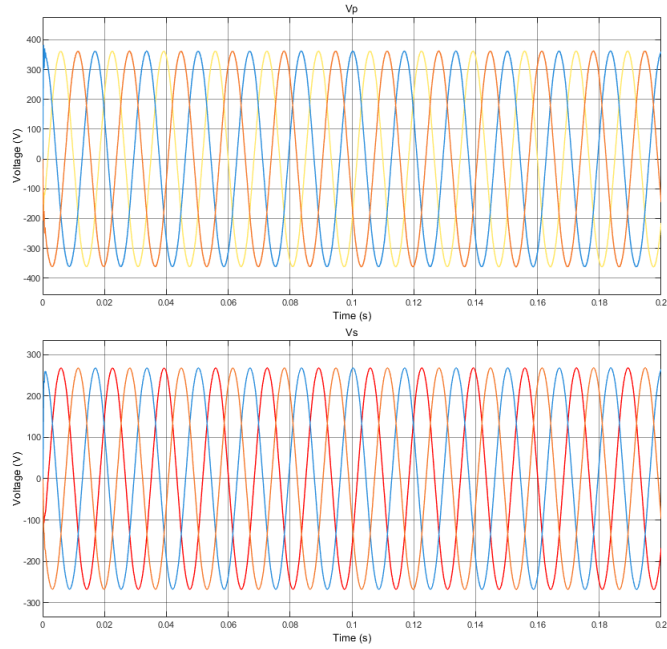


Figure 4.24: Primary and Secondary Voltages for Three Phase Transformer During Constant Reference Speed

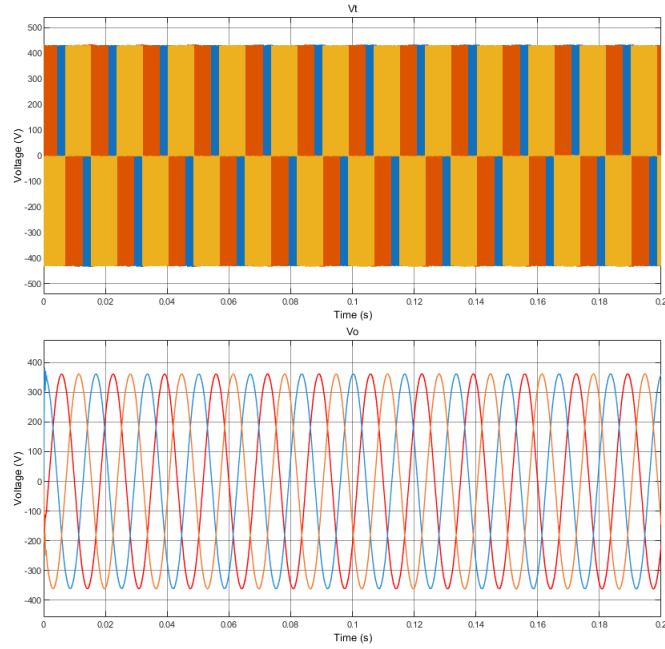


Figure 4.25: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase Transformer During Constant Reference Speed

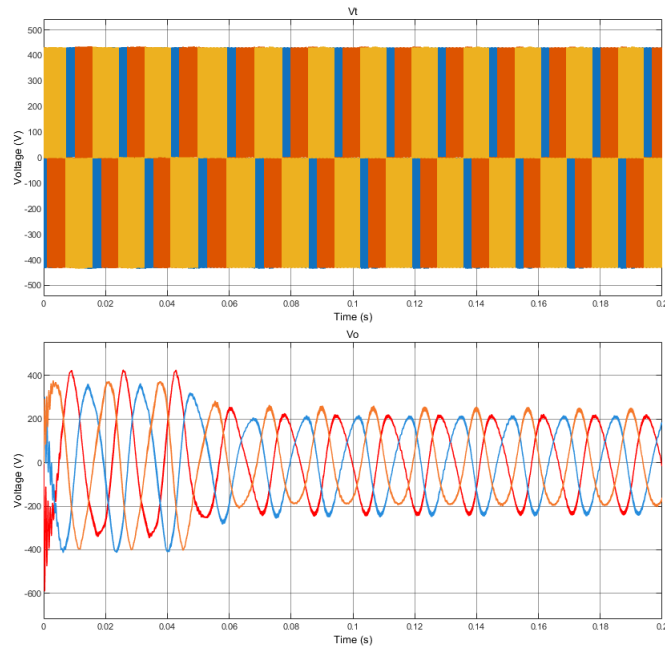


Figure 4.26: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase PMSM During Constant Reference Speed

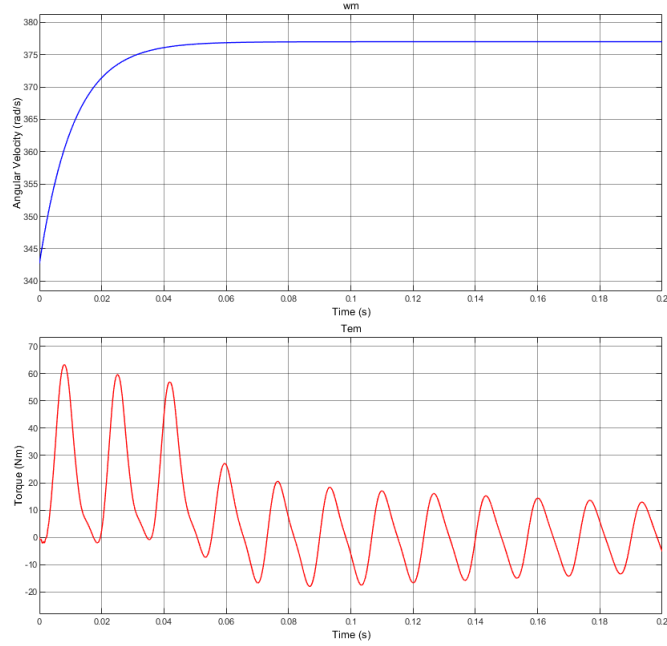


Figure 4.27: Angular Velocity and Electromagnetic Torque of Three Phase PMSM During Constant Reference Speed

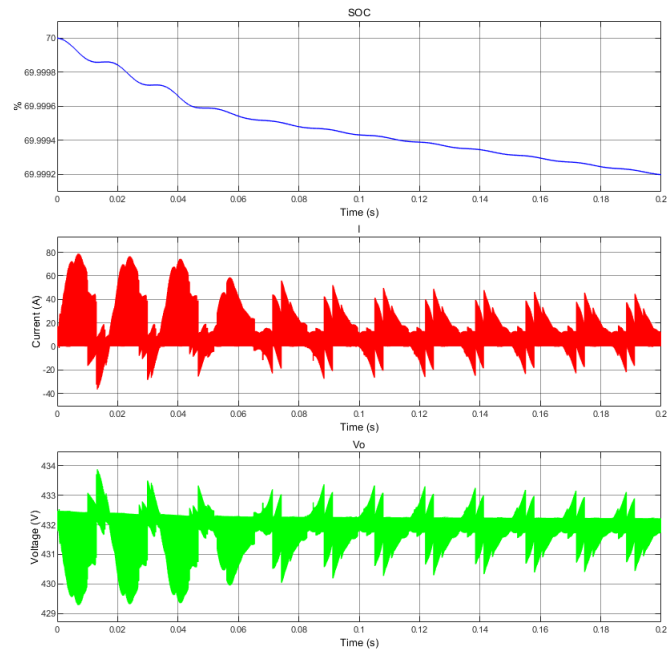


Figure 4.28: State of Charge, Current and Voltage of Li-Ion Battery During Constant Reference Speed

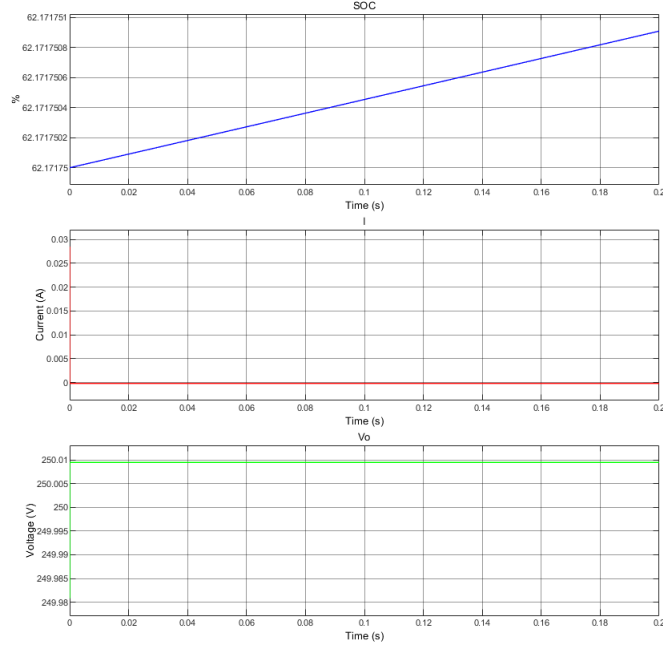


Figure 4.29: State of Charge, Current and Voltage of Super-capacitor During Constant Reference Speed

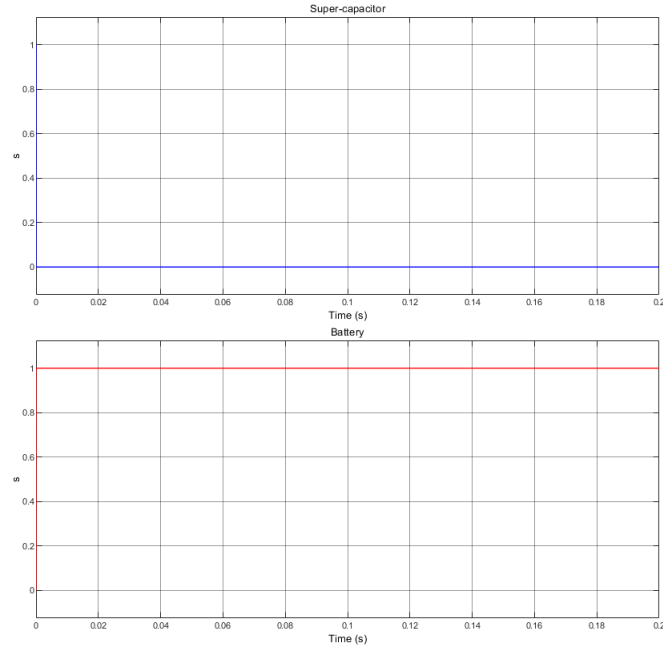


Figure 4.30: Signals of EMS During Constant Reference Speed

Reference to Figure 4.22, although $\omega^* = 377 \text{ rad/s}$, steady state ω_m is 120.2 rad/s due to the fact that portion of three phase PMSM τ_{em} is used to counteract the EM

inertia as this torque is the input to the DS. Both ω_{mll} and ω_{mlr} have steady state values of 57.4rad/s and 62.6rad/s with similar pulsating pattern as ω_m with amplitudes of 1.6rad/s , 1.8rad/s and 3.2rad/s respectively. This pulsating pattern is caused by the three phase PMSM FOC fluctuating torque periodically to maintain ω_m of the EM, in addition the nature of rotor design (salient in this work) and number of stator poles. Also, during system transient phase $\Delta\theta$ starts with I_{s1} reversed in direction between 0s and 5ms by $-1.1 \cdot 10^{-4}\text{rad}$ before being ahead of I_{s2} and afterwards $\Delta\theta$ oscillates making both segments of DS move ahead of each other alternatively at amplitude of $1.1 \cdot 10^{-5}\text{rad}$.

v_i of DC/DC converter exhibited a light sharp fluctuations between $433V$ and $430.5V$. Although nominal v_o of battery is $400V$, steady state v_i of the DC/DC converter is $431.7V$ which represents voltage during exponential area of the battery shown in Figure 3.12 since the initial *SOC* was set to 70% in Table 4.7. v_o experienced an initial trough of $-14.18V$ with a transient fluctuation decaying to $-13.37V$ in contrary to the set v_o of $-12V$ shown in Table 4.2, which is also reasoned due to the increased battery v_o . In addition, i_L had an initial peak of $1.56A$ with a transient fluctuation that forms triangular waveform between $1.32A$ and $1.43A$.

For the three phase transformer waveforms shown in Figure 4.24, no major observations can be noticed except the presence of a transient fluctuation at the start of v_p that is higher in frequency than it in v_p with peaks of $382.9V$ and $259.7V$ and steady state amplitudes of $363.6V$ and $268.3V$ respectively.

By comparing v_t and v_o of the three phase sinusoidal PWM inverters in figures

4.25 and 4.26 feeding three phase PMSM and transformer separately, a high frequency harmonic is embedded in the waveform of v_o for the inverter feeding transformer. However, no significant disruptions were caused to the waveform. Also, a resembling harmonic is shown for v_o of the inverter feeding PMSM as well. A low frequency harmonic is present in v_o of the inverter feeding PMSM causing one phase to have relatively higher amplitude of $223.4V$ compared to other two phases with amplitudes of $253V$ and $217.2V$.

For the three phase PMSM plots in Figure 4.27 and during system transient phase between 0s and 0.05s, τ_{em} is fluctuating periodically between $63.3 Nm$ and $-2.1 Nm$ with an average above zero ($23.7 Nm$) indicating acceleration that is seen in ω_m plot. Also, at the steady state period between 0.05s onward τ_{em} is fluctuating between $-18 Nm$ and $18.4 Nm$ with an approximately average of zero, reasoning the error due to the FOC. Also, during this period steady state ω_m is converging to $377 rad/s$.

Li-Ion battery experienced some benefits of regenerative braking caused by the system transient phase between 0s and 0.06s where SOC remained constant at some periods before it gets less noticeable after 0.08s. Also, large semi-sinusoidal pulses can be seen for i between 0s and 0.06s with maximum value of $78.9A$ and this corresponds to reversed pulse for v_o of $429.3V$. The spike distortion of i and v_o from 0.06s onwards is thought to be caused by the three phase sinusoidal PWM inverters switching mechanism.

Since ω^* is set as constant, EMS will enable the Li-Ion battery to supply power by default as seen in Figure 4.30 and thus no reduction in super-capacitor v_o and i as

shown in Figure 4.29.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Operating Actions

5.1.1 Speed Variation

For ω^* of $3600\text{ rpm} \equiv 377\text{ rad/s}$ and an acceleration of $12,000\text{ rpm/s}$ starting at 0.1 s and other parameters from the individual systems:

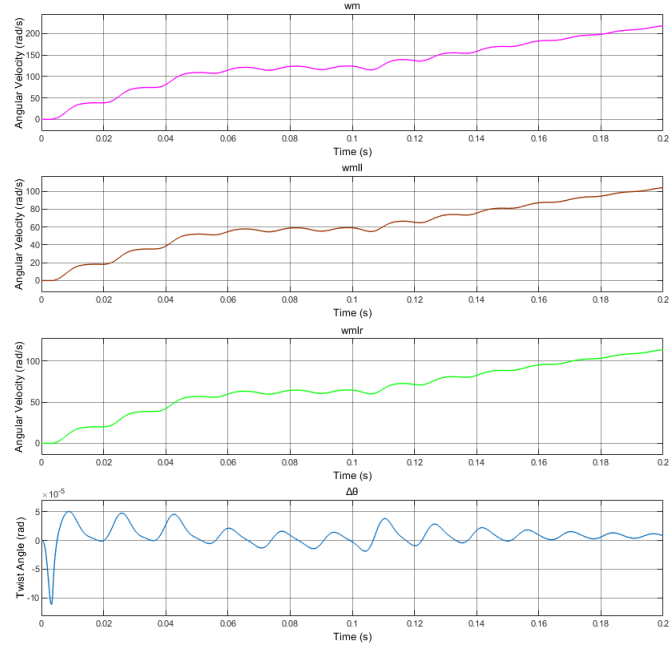


Figure 5.1: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle During Reference Speed Variation

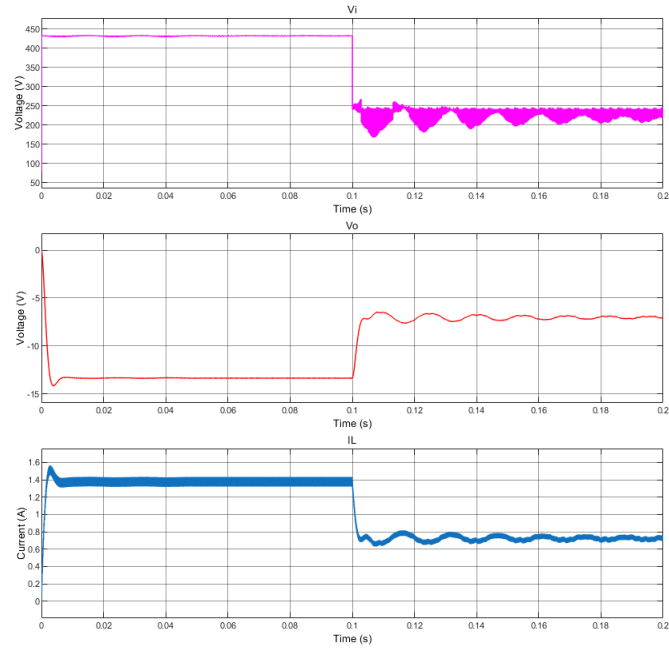


Figure 5.2: Input, Output Voltages and Inductor Current for DC/DC Converter During Reference Speed Variation

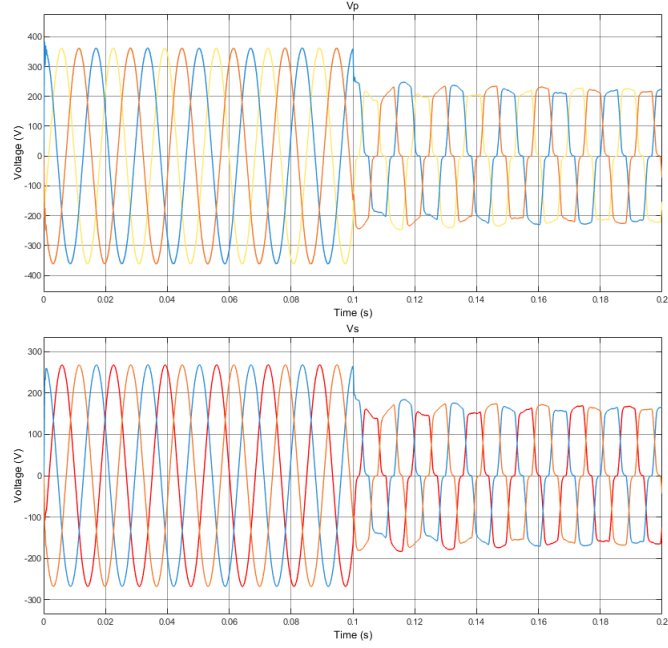


Figure 5.3: Primary and Secondary Voltages for Three Phase Transformer During Reference Speed Variation

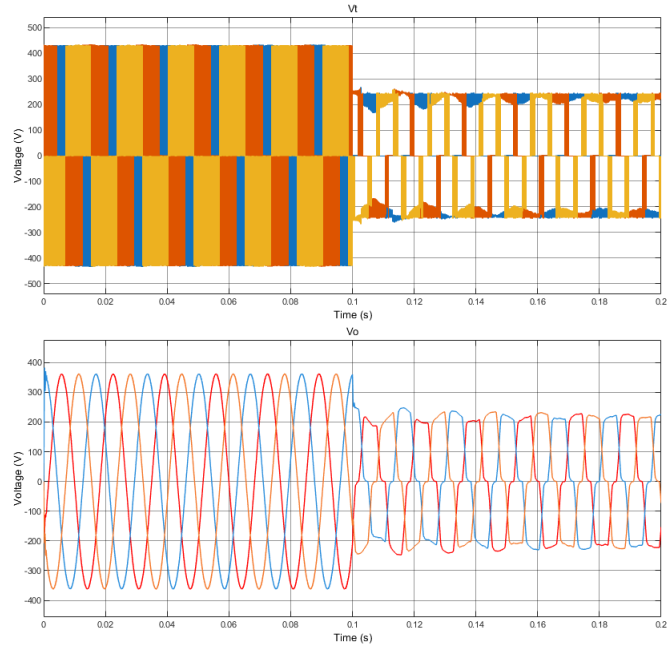


Figure 5.4: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase Transformer During Reference Speed Variation

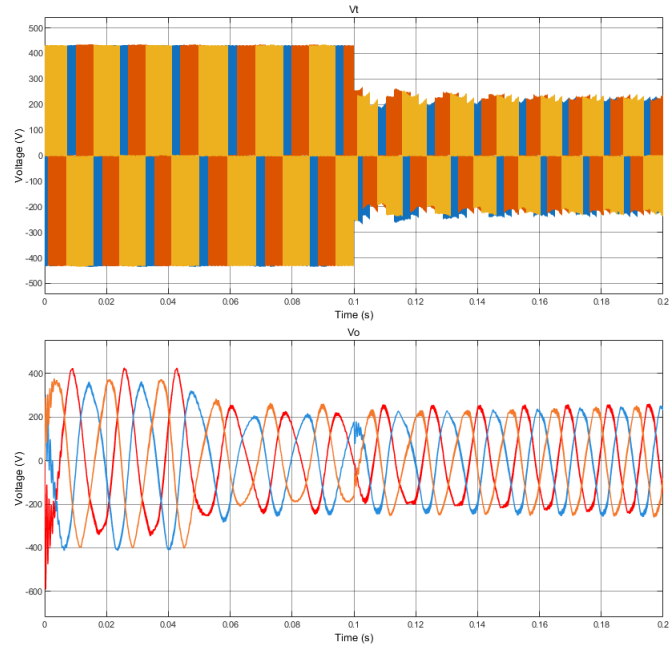


Figure 5.5: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase PMSM During Reference Speed Variation

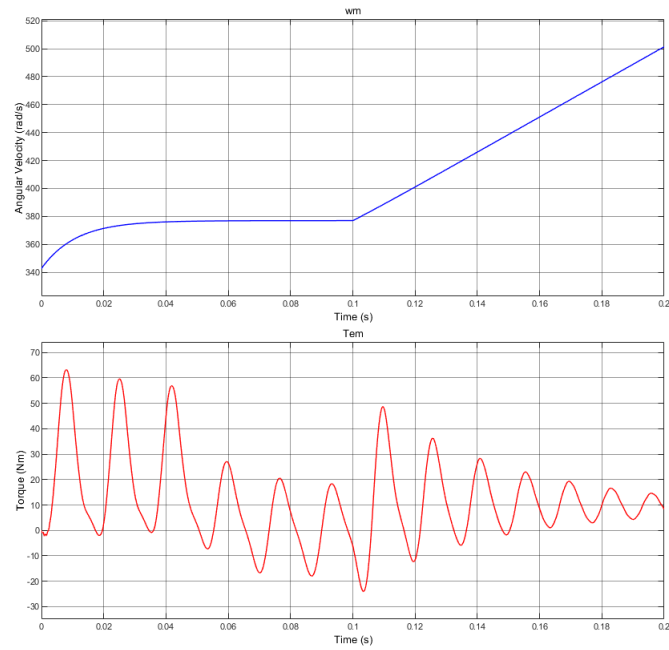


Figure 5.6: Angular Velocity and Electromagnetic Torque of Three Phase PMSM During Reference Speed Variation

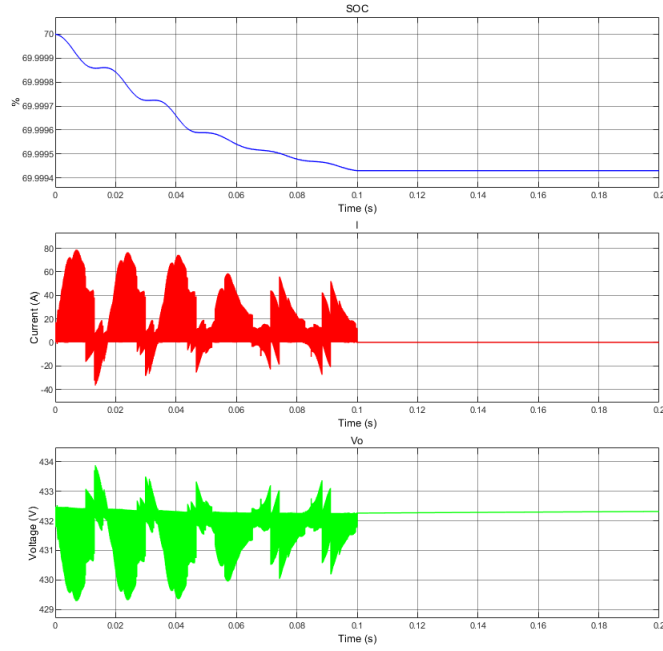


Figure 5.7: State of Charge, Current and Voltage of Li-Ion Battery During Reference Speed Variation

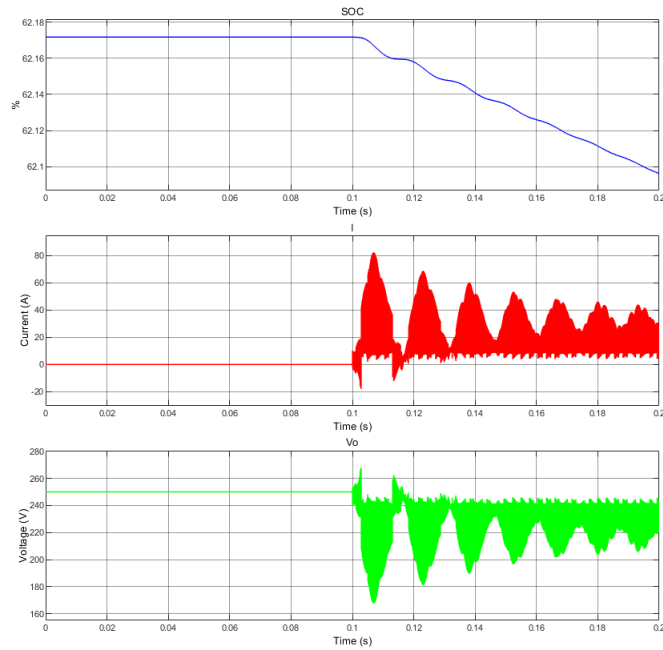


Figure 5.8: State of Charge, Current and Voltage of Super-capacitor During Reference Speed Variation

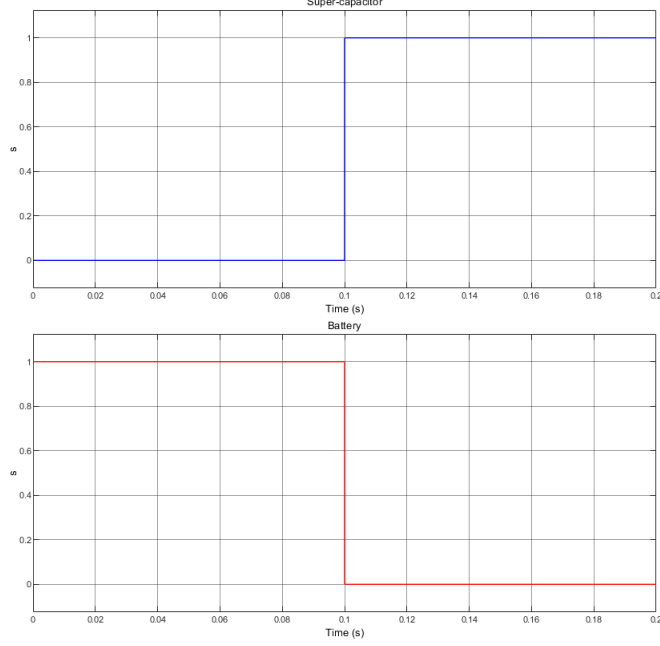


Figure 5.9: Signals of EMS During Reference Speed Variation

As ω^* starts increasing at 0.1s, no special pulsating pattern is observed for ω^m , ω^{mll} and ω^{mlr} compared to Figure 4.22. However, a pulse can be seen for $\Delta\theta$ at 0.11s with decaying amplitude of $3.8 \cdot 10^{-5} \text{ rad}$. The continuous increase in ω^* caused $\Delta\theta$ to oscillate around $8.8 \cdot 10^{-6}$ instead of zero for constant ω^* case shown in Figure 4.22.

Reference to Figure 5.2, the increase in ω^* caused severe distortion to v_i of the DC/DC converter forming a downward triangular shapes with decaying trough of $167.6V$ and reducing the mean from $431.4V$ to $220.4V$. In addition, v_o increases from steady state value of $-13.4V$ to $-7V$ and this is accompanied by a fluctuation around $-7V$ that converges within 0.1s. v_o pattern is similarly present in i_L but with opposite opposite peaks/troughs, with i_L steady state dropping from $1.38A$ to $0.72A$.

v_p and v_s of the three phase transformer experienced distortion in their waveforms in Figure 5.3. This is reasoned to the passive design of LCL filter where f_o was set

to be constant as discussed in Sub-section 3.4.4. Design of active LCL filter shall maintain their waveforms.

In figures 5.4 and 5.4, v_t of the three phase sinusoidal PWM inverter feeding three phase transformer experienced higher severe distortion during increase of ω^* than the other inverter feeding the three phase PMSM, while both suffered a drop in voltage. Also, v_o for both inverters has more harmonic distortion due to the normal design of LCL filters, adaptive filters may reduce and control these additional harmonics. This was also observed for the three phase transformer v_s plot in Figure 5.3.

During acceleration at 0.1s, τ_{em} is shown to have an initial peak of 48.8 Nm that decay in oscillation reaching a steady state value of 10.7 Nm.

Both Li-Ion battery and super-capacitor experienced a regenerative charging due to system dynamics shown as flat lines in *SOC* plots of both in Figures 5.7 and 5.8 but was lesser for the super-capacitor. Super-capacitor had no negative current at steady state indicating no regenerative charging except at the beginning of its operation.

Since acceleration is 12,000 rpm > 2000 rpm, super-capacitor was activated at 0.1s by the EMS to supply power during the acceleration as seen in Figure 5.9.

5.1.2 Regenerative Braking

ω^* will be decreased at a rate of -1800 rpm/s at 0.1s then changes to $-12,000 \text{ rpm/s}$ at 0.15s to show effects of regenerative braking on both battery and super-capacitor.

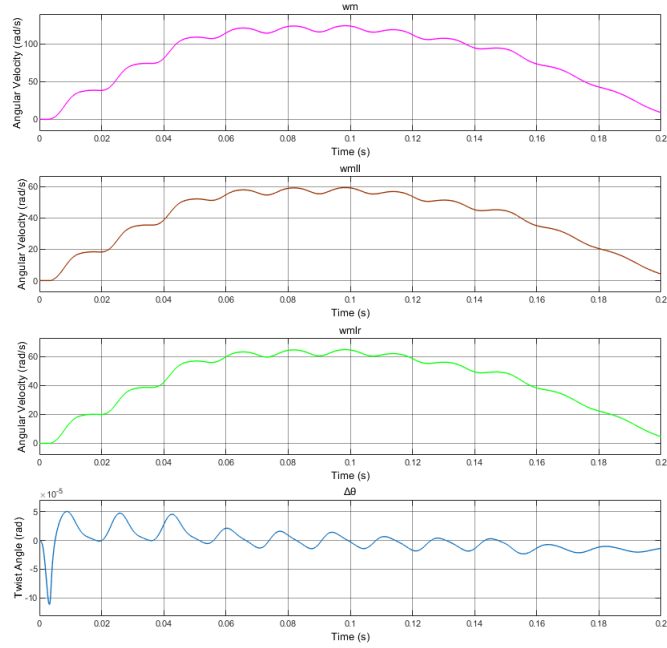


Figure 5.10: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle During Regenerative Braking

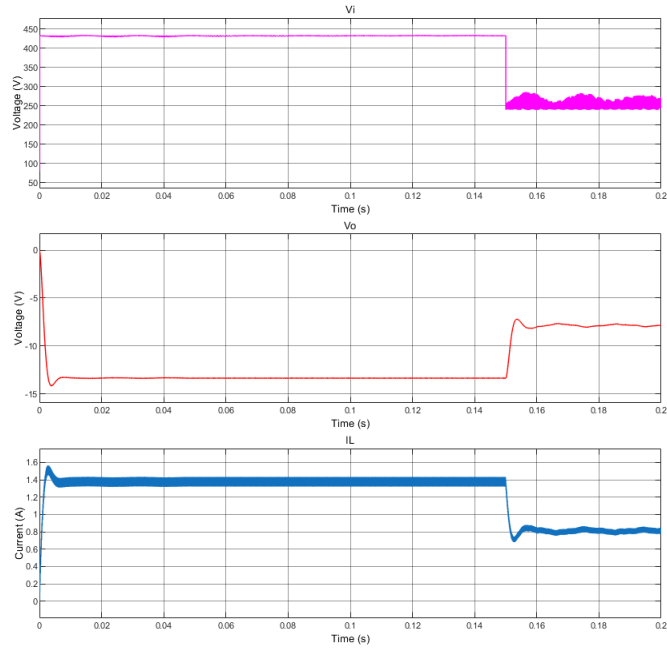


Figure 5.11: Input, Output Voltages and Inductor Current for DC/DC Converter During Regenerative Braking

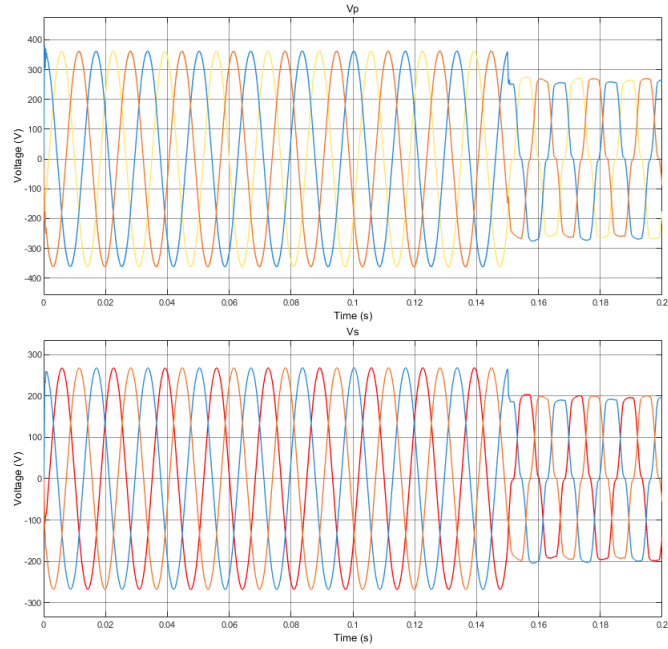


Figure 5.12: Primary and Secondary Voltages for Three Phase Transformer During Regenerative Braking

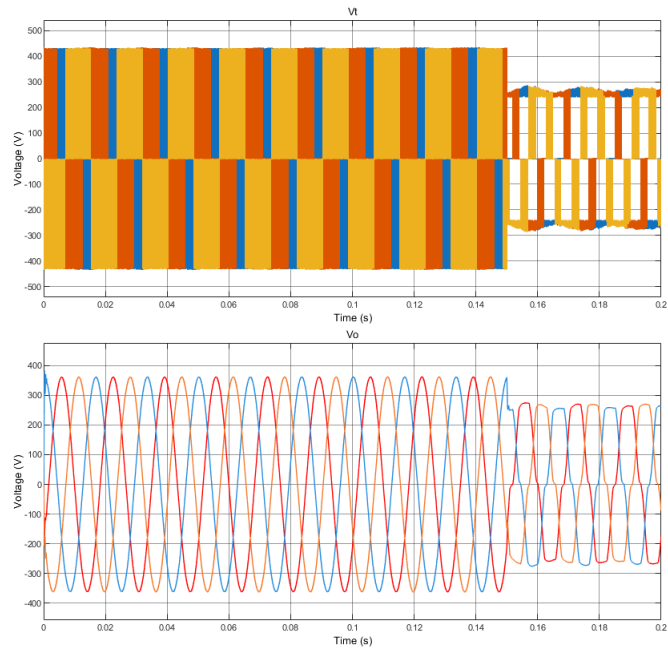


Figure 5.13: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase Transformer During Regenerative Braking

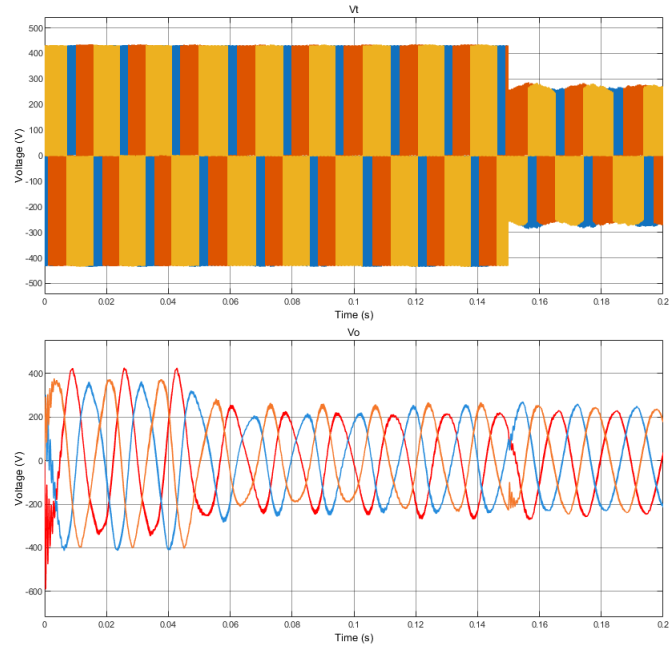


Figure 5.14: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase PMSM During Regenerative Braking

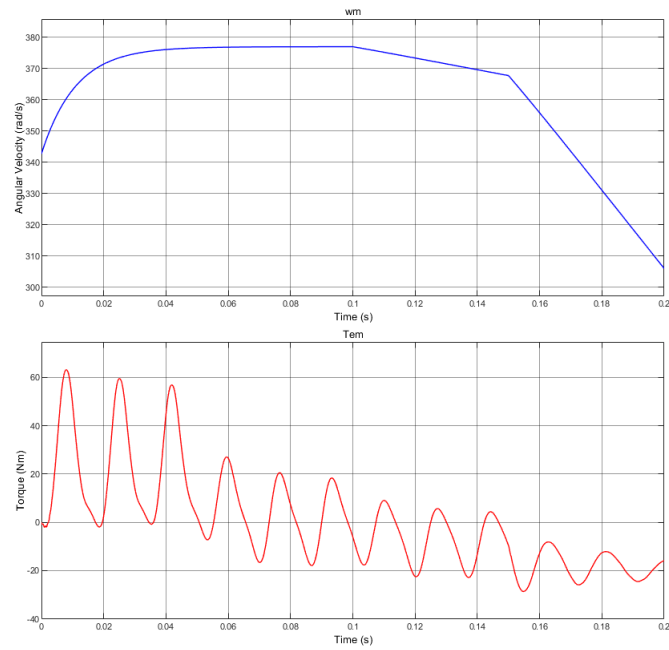


Figure 5.15: Angular Velocity and Electromagnetic Torque of Three Phase PMSM During Regenerative Braking

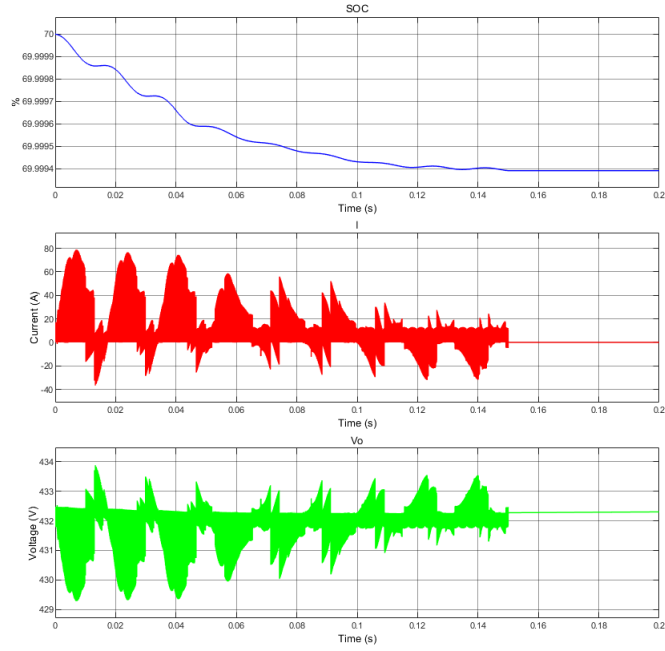


Figure 5.16: State of Charge, Current and Voltage of Li-Ion Battery During Regenerative Braking

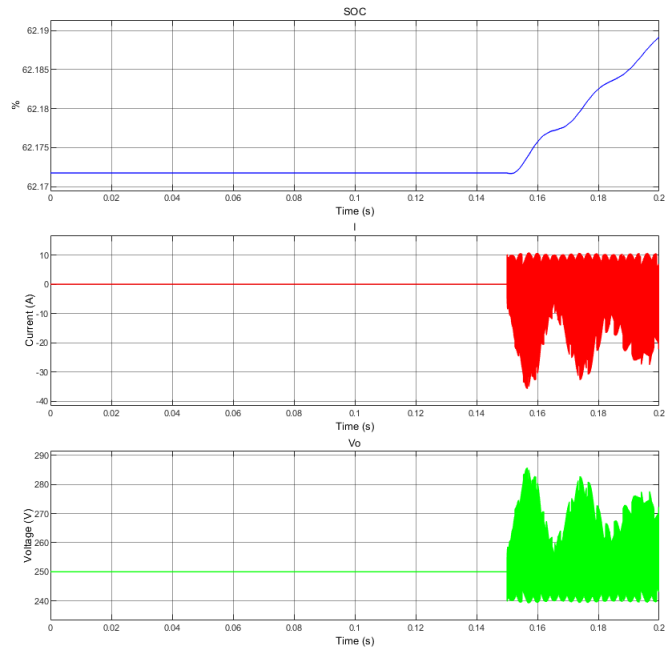


Figure 5.17: State of Charge, Current and Voltage of Super-capacitor During Regenerative Braking

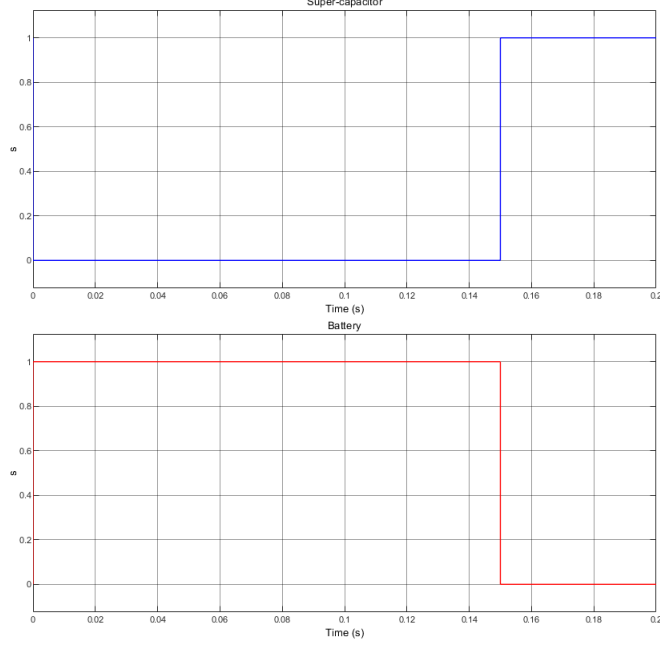


Figure 5.18: Signals of EMS During Regenerative Braking

As ω^* starts decreasing at 0.1s, no special pulsating pattern is observed for ω^m , ω^{mll} and ω^{mlr} compared to Figure 4.22. The opposite pattern to Figure 5.1 can be noticed in Figure 5.10 for $\Delta\theta$ where its average value at steady state is declining further below zero as acceleration rate decreases.

This opposite pattern is also seen in v_i of the DC/DC converter in Figure 5.11 where the triangular pattern with maximum peak of 285.9V is facing upward instead of downward in contrary to what was shown in Figure 5.2. It is worth noting that this triangular pattern did not appear when ω^* was accelerating at a rate of -1800 rpm/s but at $-12,000\text{ rpm/s}$. By comparing v_o average during the two different acceleration rates. It can be concluded that as acceleration decreases beyond deceleration threshold of 2000 rpm/s , average v_o moves positively further away from its nominal value of $-12V$.

In addition, τ_{em} average decreases as acceleration rate decreases reaching average of $-6.59 Nm$ at $-1800 rpm/s$ and $-18.51 Nm$ at $-12,000 rpm/s$.

Effects of regenerative charging is more pronounced in super-capacitor than Li-Ion battery and this can be reasoned due to low acceleration rate ($-12,000 rpm/s$) at which is operated. Figure 5.18 indicates 0.15s as the time instance where EMS switched between the Li-Ion battery and super-capacitor.

5.1.3 Conventional Braking

ω^* will be decreased at a rate of $-1800 rpm/s$ at 0.1s then changes to $-12,000 rpm/s$ at 0.15s to show effects of conventional braking on both battery and super-capacitor.

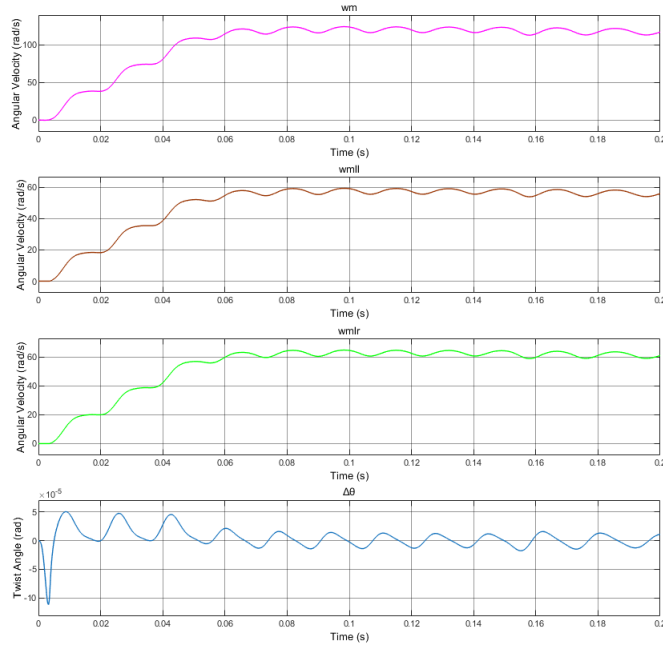


Figure 5.19: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle During Conventional Braking

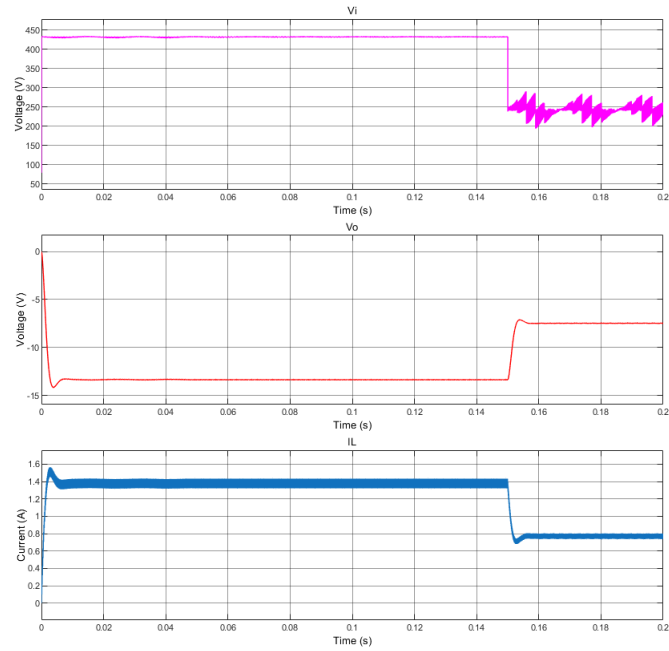


Figure 5.20: Input, Output Voltages and Inductor Current for DC/DC Converter During Conventional Braking

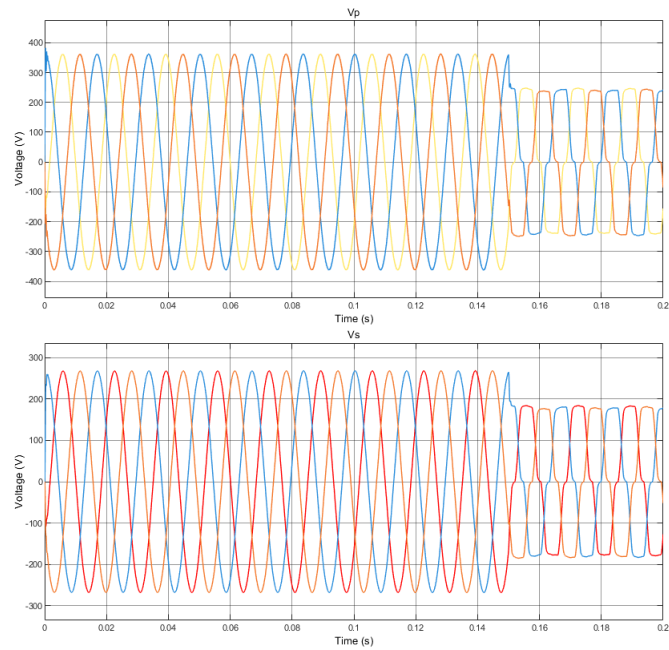


Figure 5.21: Primary and Secondary Voltages for Three Phase Transformer During Conventional Braking

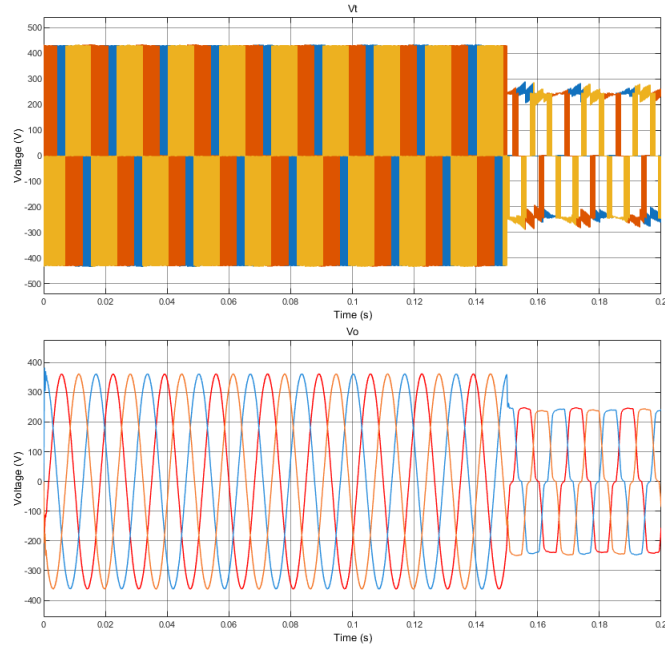


Figure 5.22: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase Transformer During Conventional Braking

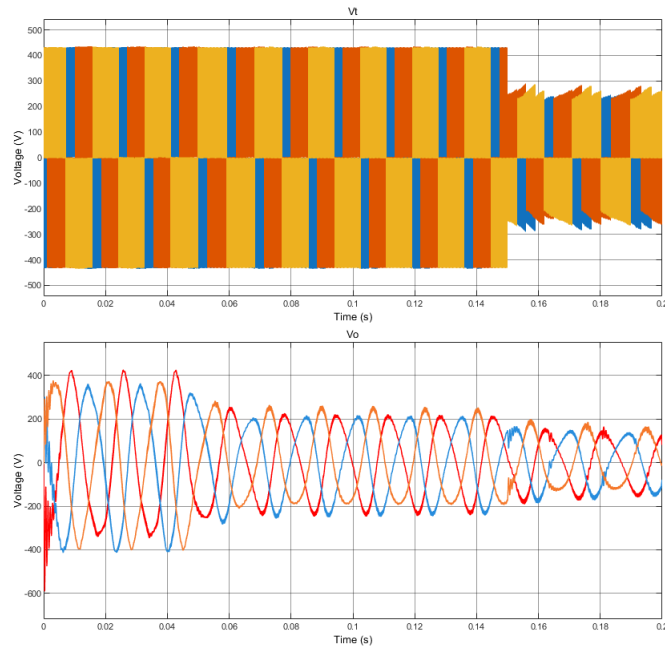


Figure 5.23: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase PMSM During Conventional Braking

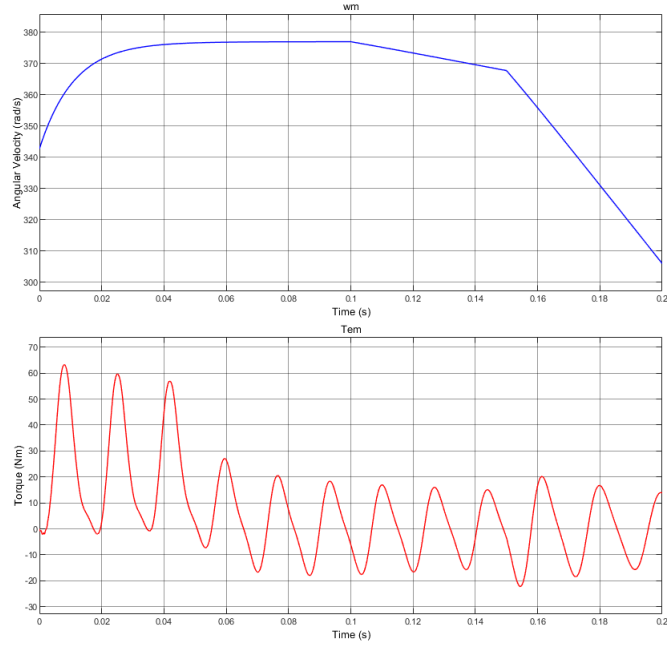


Figure 5.24: Angular Velocity and Electromagnetic Torque of Three Phase PMSM During Conventional Braking

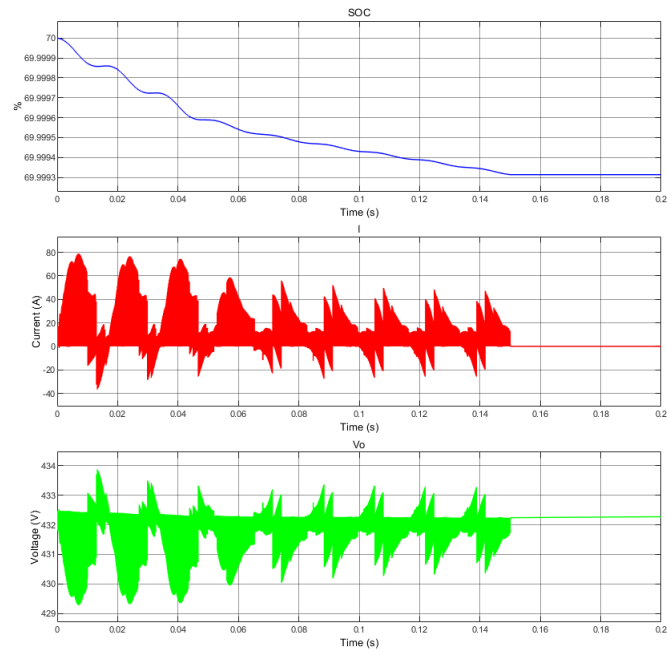


Figure 5.25: State of Charge, Current and Voltage of Li-Ion Battery During Conventional Braking

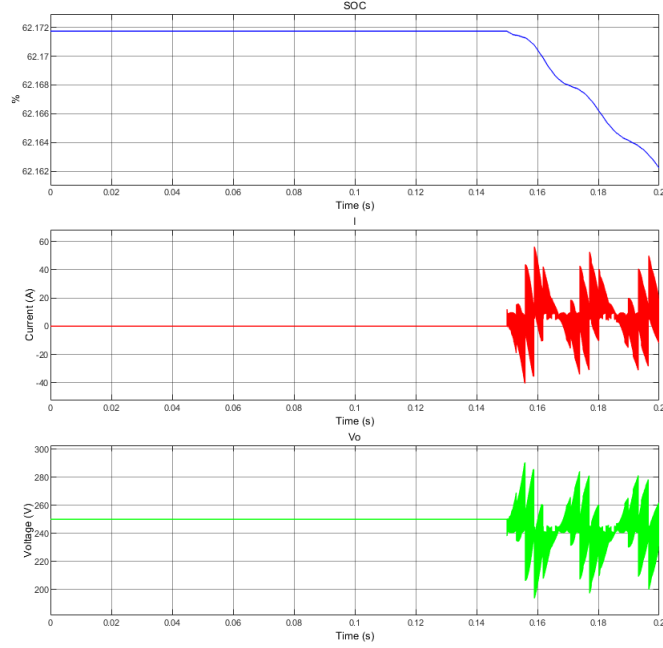


Figure 5.26: State of Charge, Current and Voltage of Super-capacitor During Conventional Braking

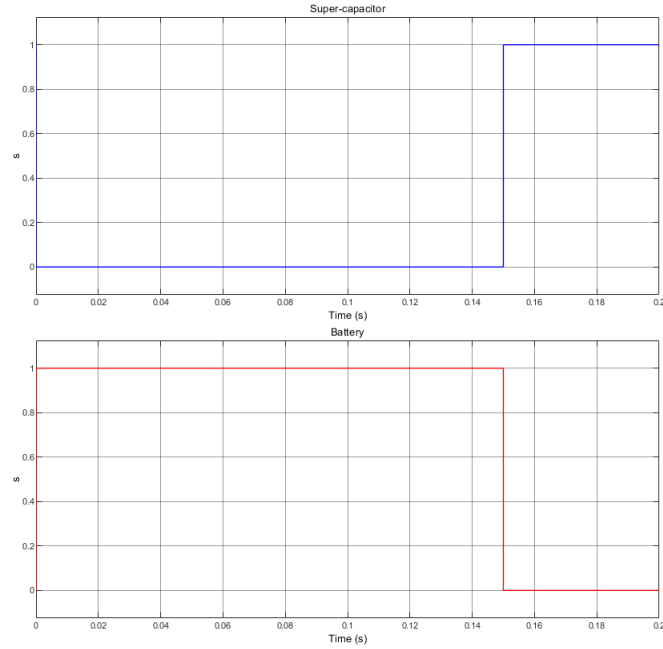


Figure 5.27: Signals of EMS During Conventional Braking

One important aspect in this case is the sharp spikes shown in figures 5.20 for v_i and in Figure 5.26 for v_o with peaks of $286.7V$ and $291.7V$ respectively.

During acceleration, average τ_{em} is maintained around zero but with higher oscillation amplitude as acceleration rate decreases.

5.1.4 AC Load Removal/Addition

The $R_{ac} = 10\Omega$ fed by the three phase transformer is removed and then re-connected at 0.13s and 0.16s respectively with ω^* of $3600\text{ rpm} \equiv 377\text{ rad/s}$ and other parameters from the individual systems:

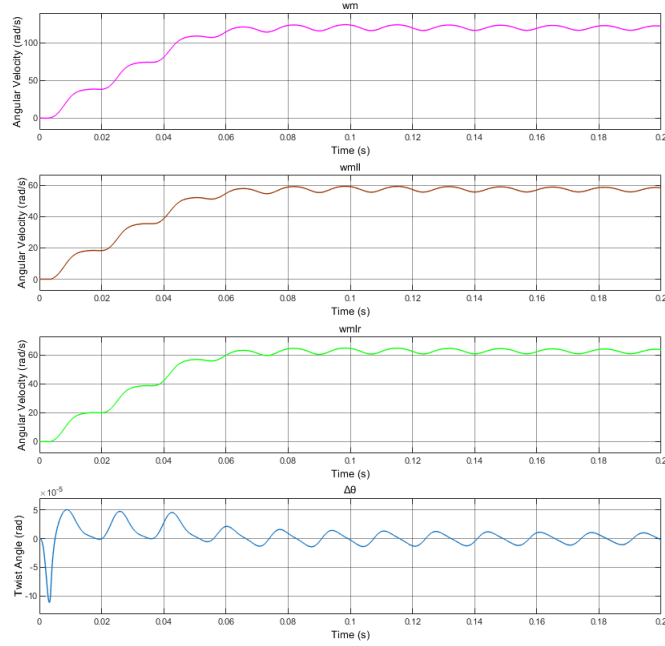


Figure 5.28: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle During AC Load Removal/Addition

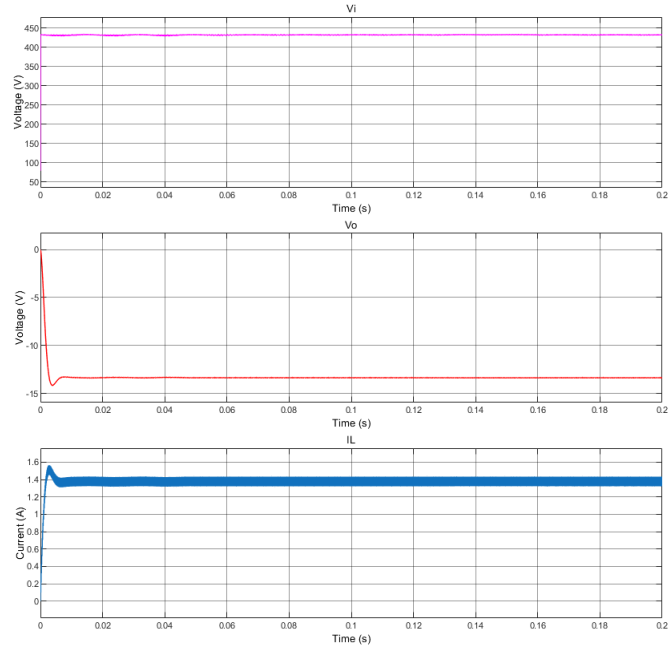


Figure 5.29: Input, Output Voltages and Inductor Current for DC/DC Converter During AC Load Removal/Addition

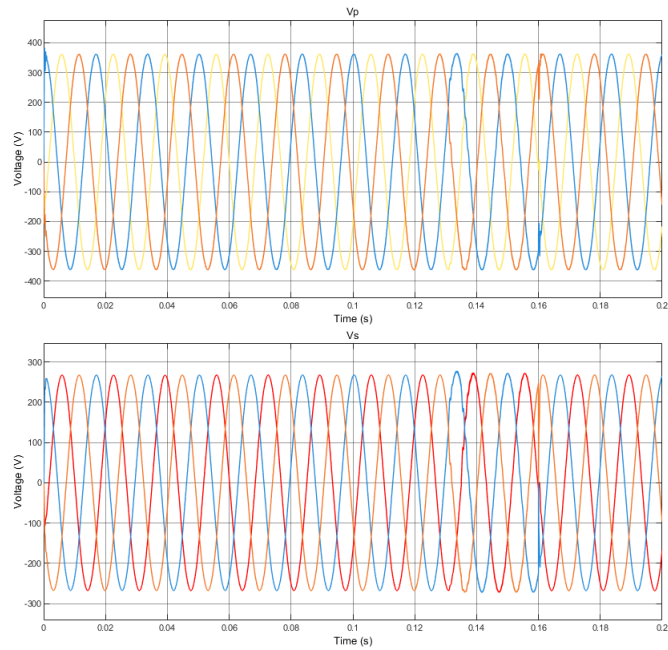


Figure 5.30: Primary and Secondary Voltages for Three Phase Transformer During AC Load Removal/Addition

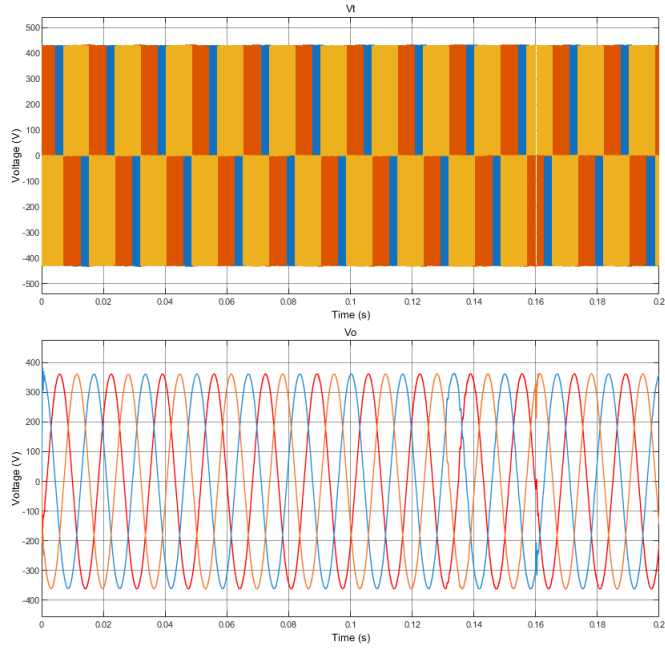


Figure 5.31: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase Transformer During AC Load Removal/Addition

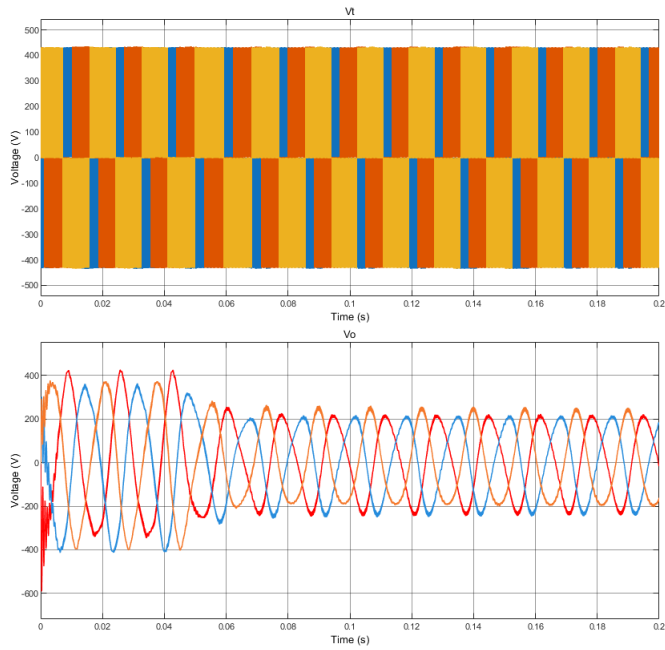


Figure 5.32: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase PMSM During AC Load Removal/Addition

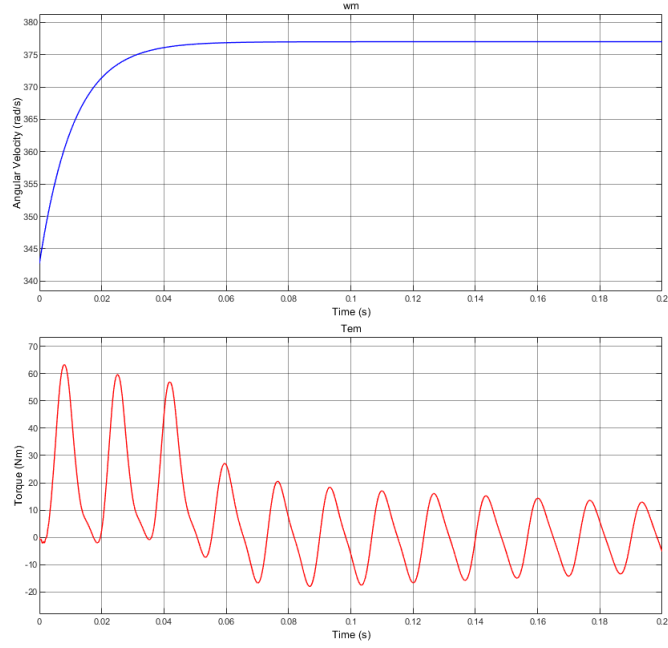


Figure 5.33: Angular Velocity and Electromagnetic Torque of Three Phase PMSM During AC Load Removal/Addition

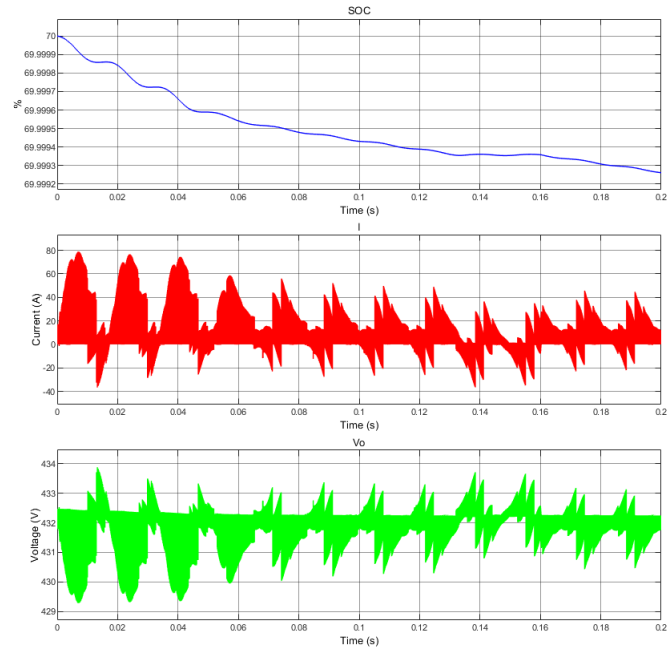


Figure 5.34: State of Charge, Current and Voltage of Li-Ion Battery During AC Load Removal/Addition

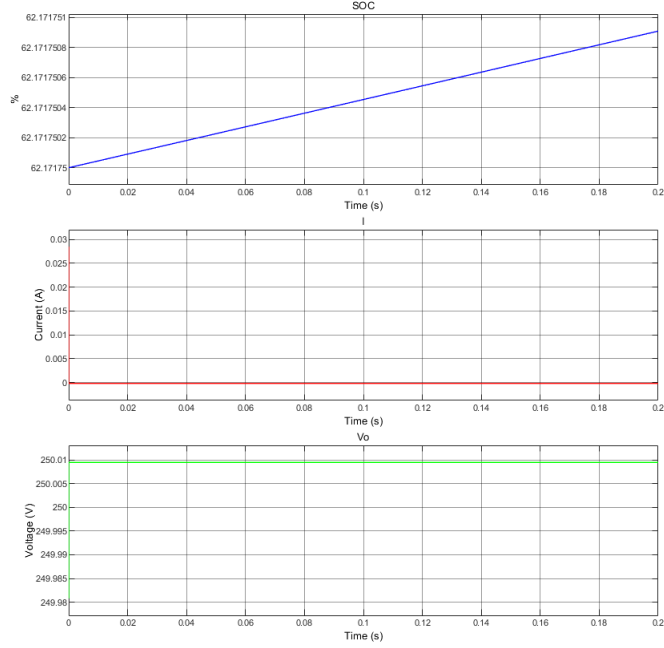


Figure 5.35: State of Charge, Current and Voltage of Super-capacitor During AC Load Removal/Addition

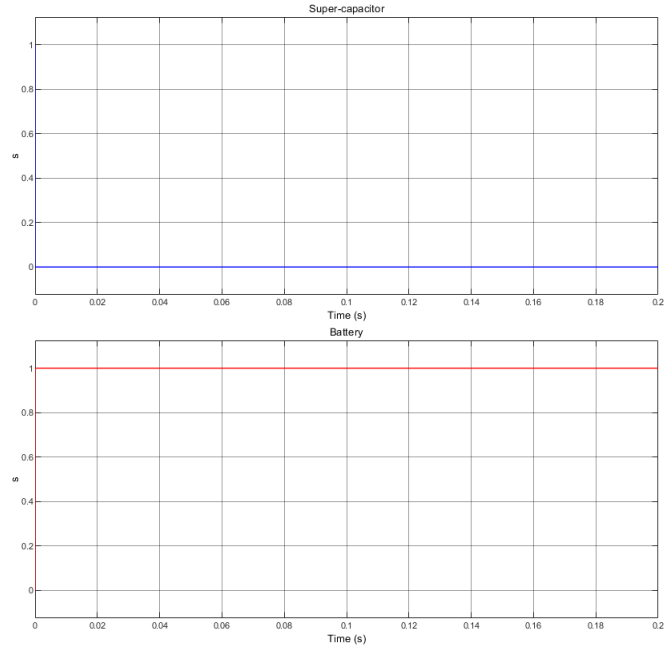


Figure 5.36: Signals of EMS During AC Load Removal/Addition

No significant differences were observed between this case and Sub-section 4.3 except for small distortion observed for v_p and v_s in Figure 5.30 during removal and

addition of R_{ac} .

5.1.5 DC Load Removal/Addition

The $R_{dc} = 10\Omega$ fed by the DC/DC converter is removed and then re-connected at 0.13s and 0.16s respectively with ω^* of $3600\text{ rpm} \equiv 377\text{ rad/s}$ and other parameters from the individual systems:

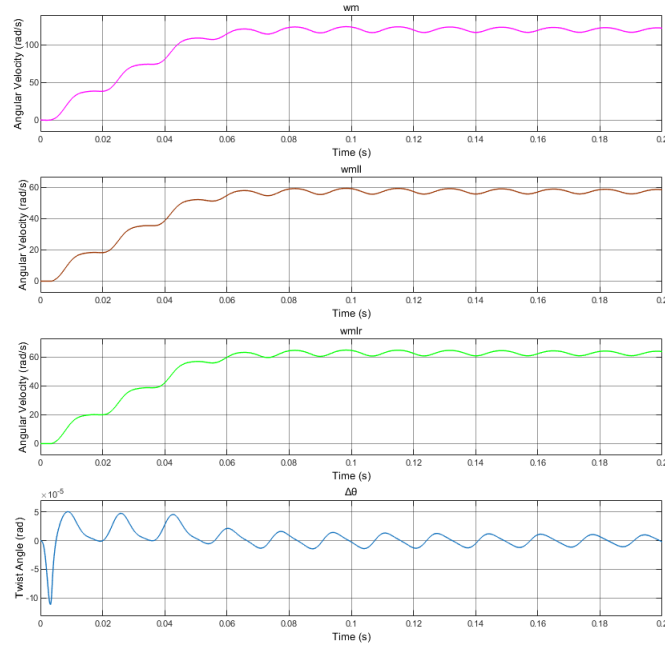


Figure 5.37: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle During DC Load Removal/Addition

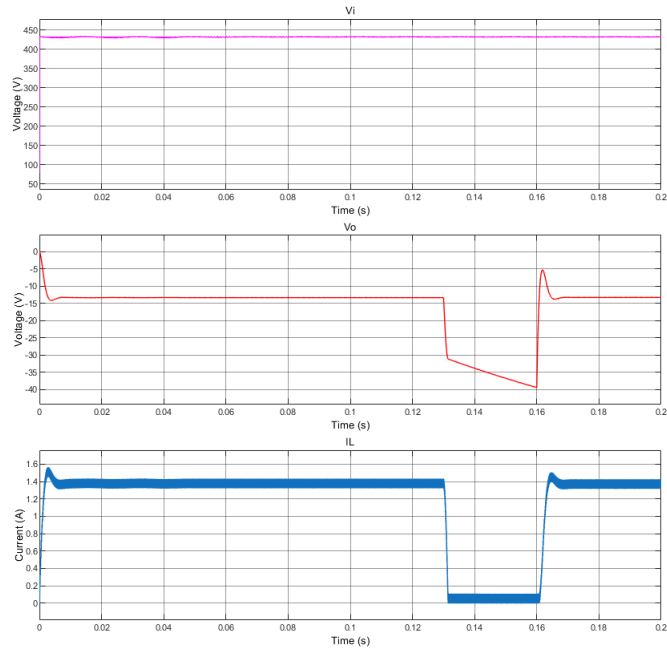


Figure 5.38: Input, Output Voltages and Inductor Current for DC/DC Converter During DC Load Removal/Addition

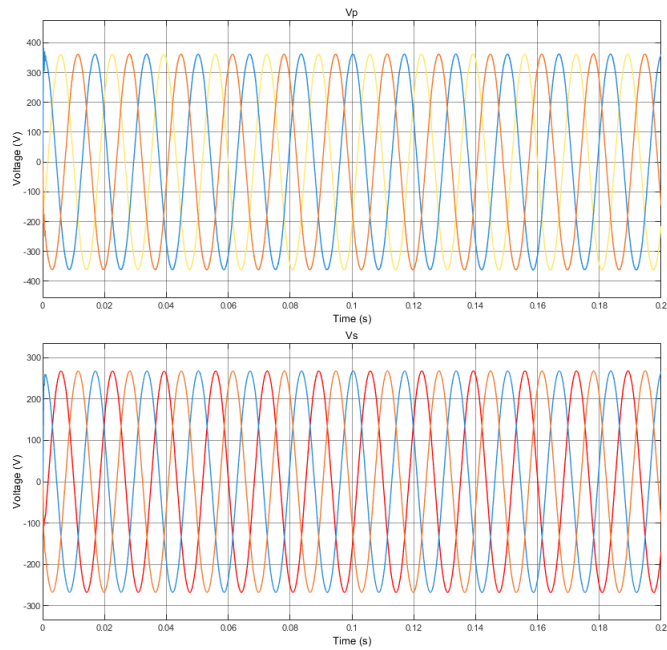


Figure 5.39: Primary and Secondary Voltages for Three Phase Transformer During DC Load Removal/Addition

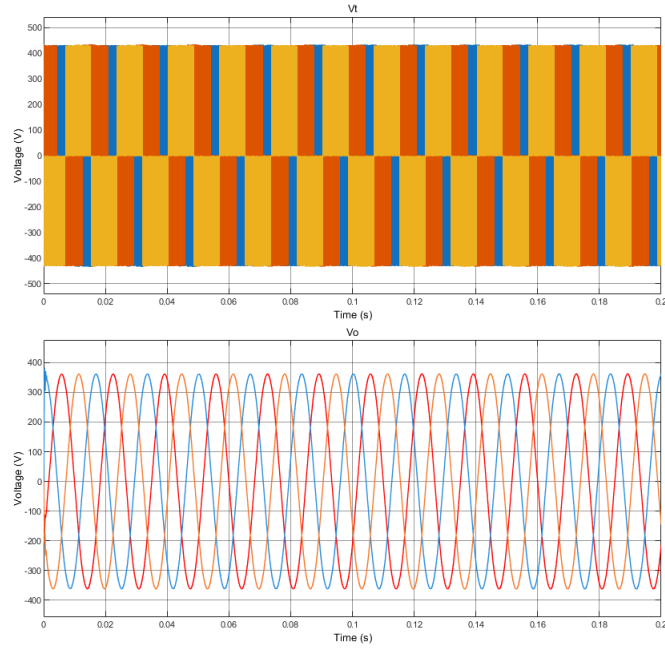


Figure 5.40: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase Transformer During DC Load Removal/Addition

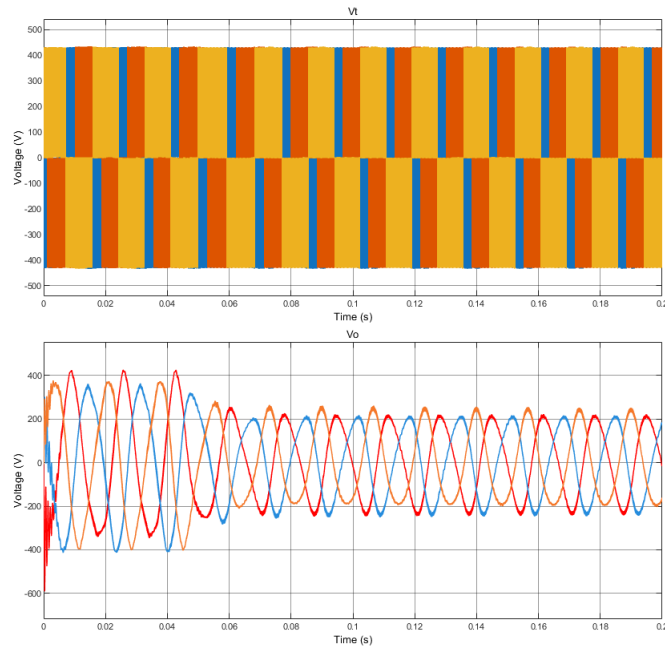


Figure 5.41: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase PMSM During DC Load Removal/Addition

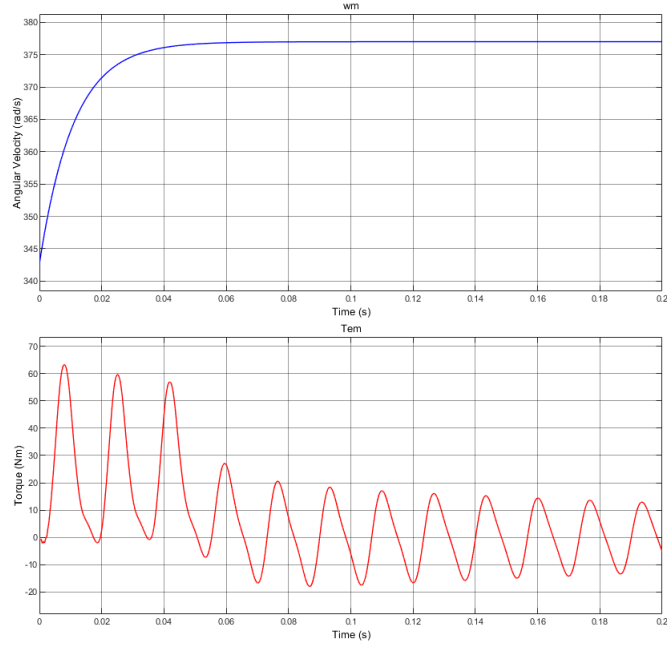


Figure 5.42: Angular Velocity and Electromagnetic Torque of Three Phase PMSM During DC Load Removal/Addition

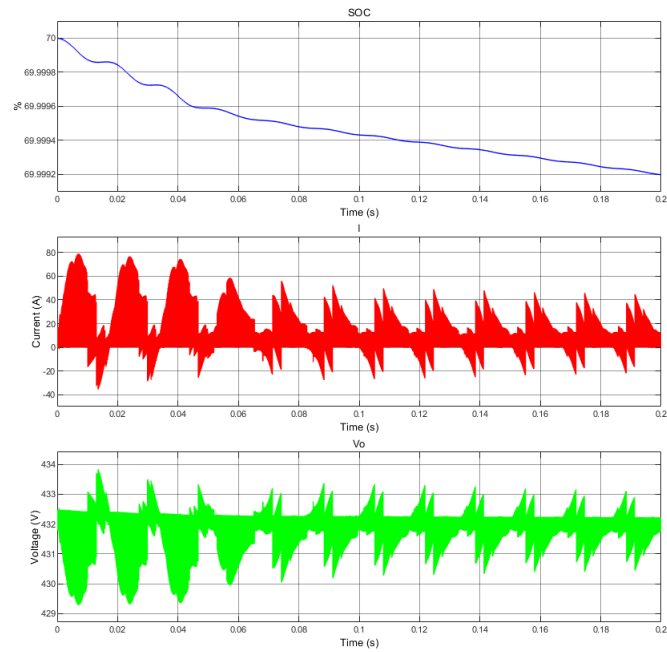


Figure 5.43: State of Charge, Current and Voltage of Li-Ion Battery During DC Load Removal/Addition

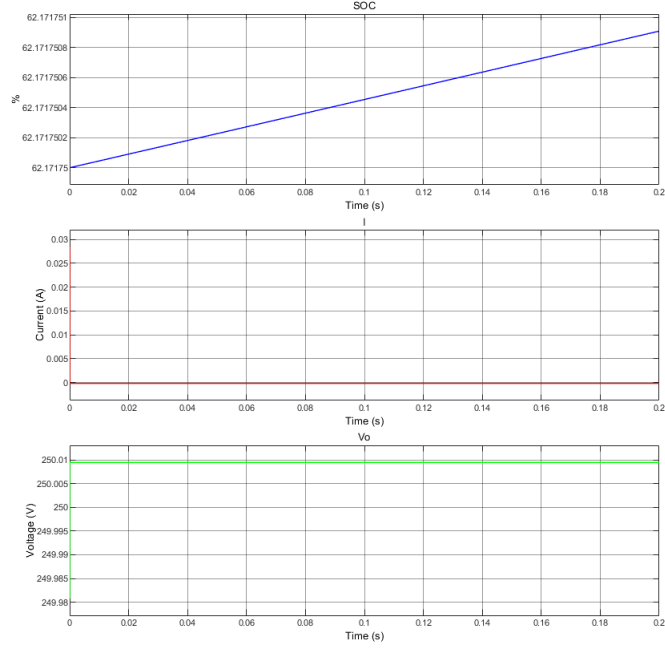


Figure 5.44: State of Charge, Current and Voltage of Super-capacitor During DC Load Removal/Addition

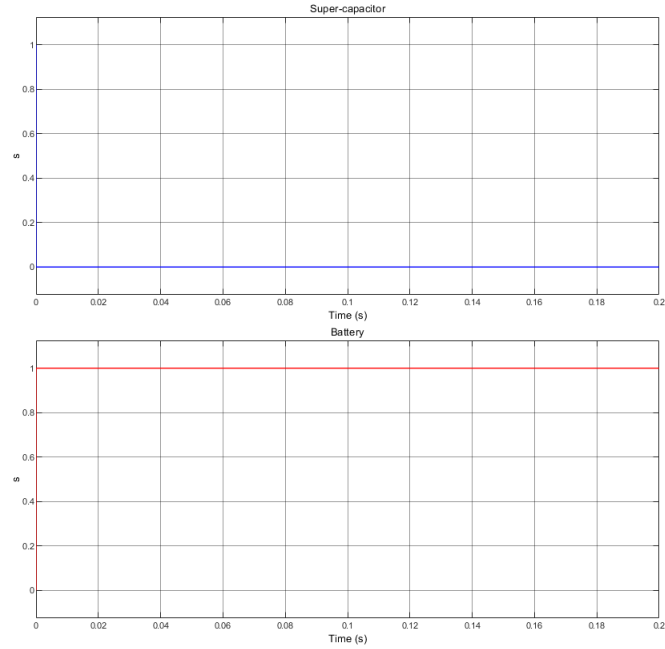


Figure 5.45: Signals of EMS During DC Load Removal/Addition

Similar to the previous case, no significant differences were observed compared to Sub-section 4.3 except of the sharp drop of $-31V$ continuously decreasing linearly to

$-39V$ for v_o of the DC/DC converter in Figure 5.29 during removal of R_{dc} and the accompanied drop in average i_L from $1.38A$ to $0.25A$.

5.1.6 AC Fault in Three Phase Transformer

The three phase to ground fault is activated at the transformer input between $0.12s$ until $0.17s$ (3 cycles of $60Hz$) with ω^* of $3600\text{ rpm} \equiv 377\text{ rad/s}$ and other parameters from the individual systems:

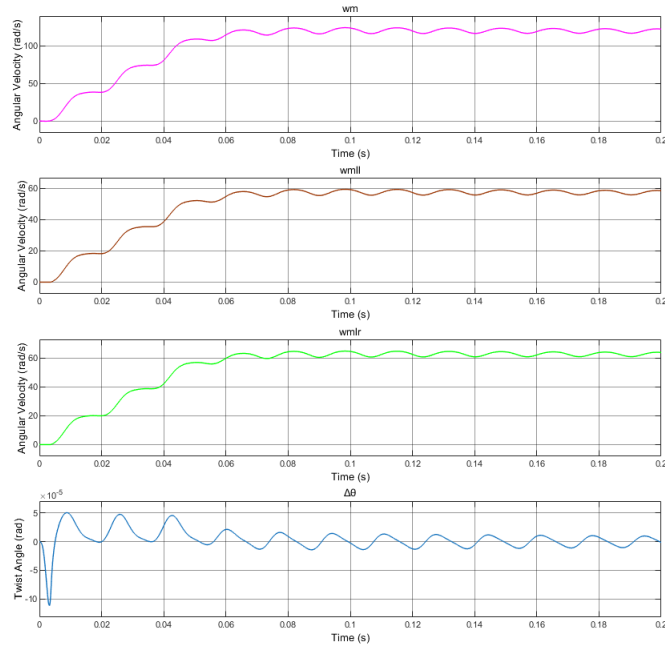


Figure 5.46: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle During AC Fault in Three Phase Transformer

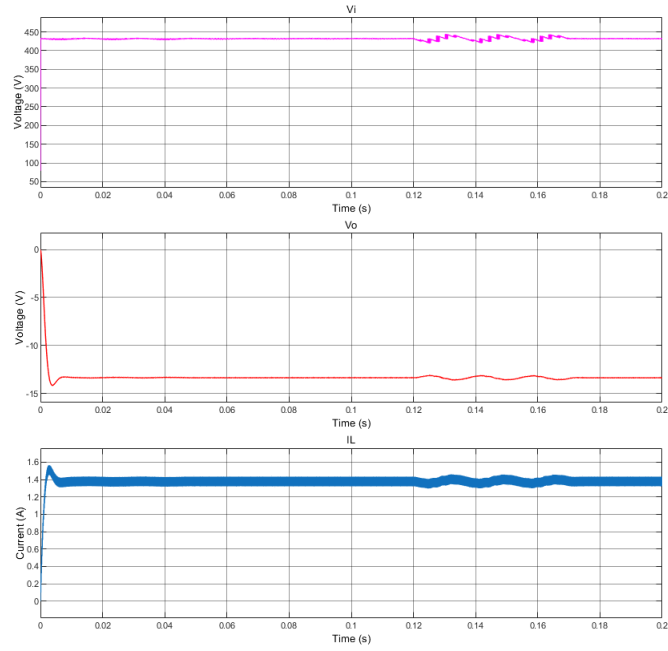


Figure 5.47: Input, Output Voltages and Inductor Current for DC/DC Converter During AC Fault in Three Phase Transformer

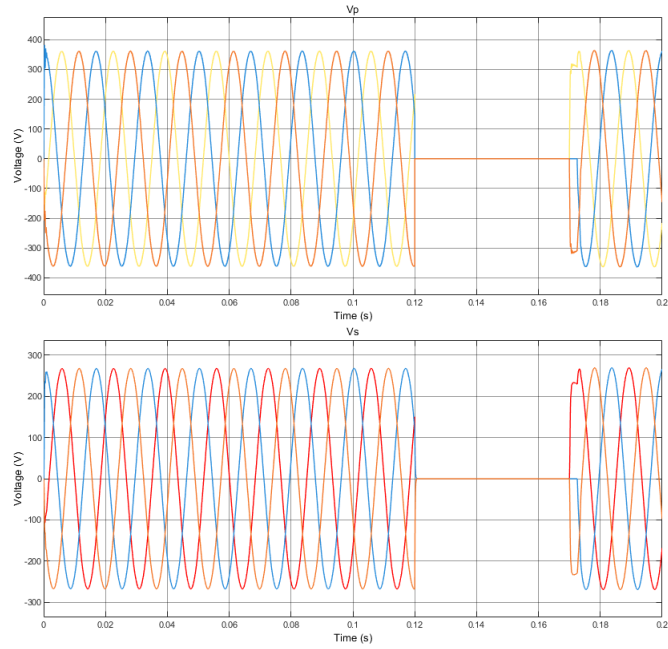


Figure 5.48: Primary and Secondary Voltages for Three Phase Transformer During AC Fault in Three Phase Transformer

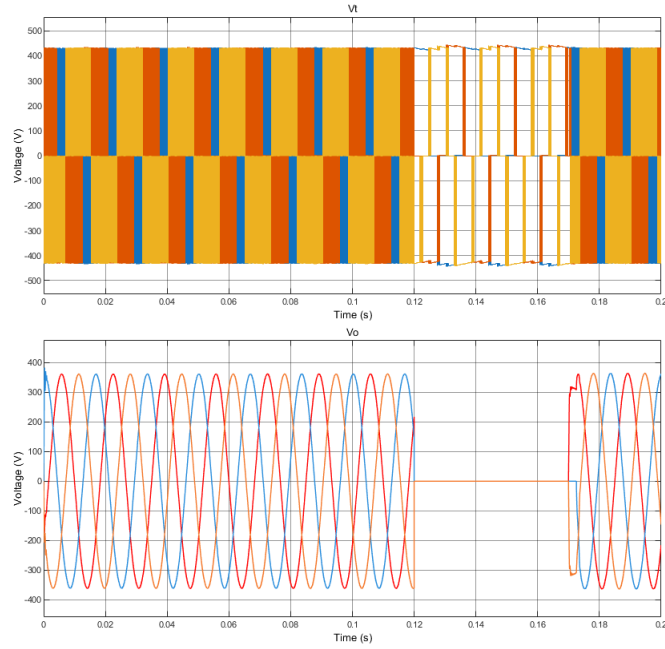


Figure 5.49: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase Transformer During AC Fault in Three Phase Transformer

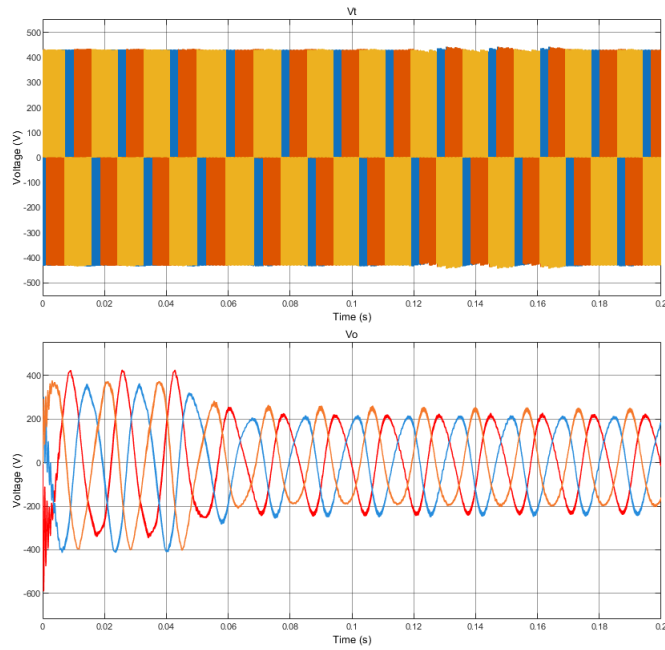


Figure 5.50: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase PMSM During AC Fault in Three Phase Transformer

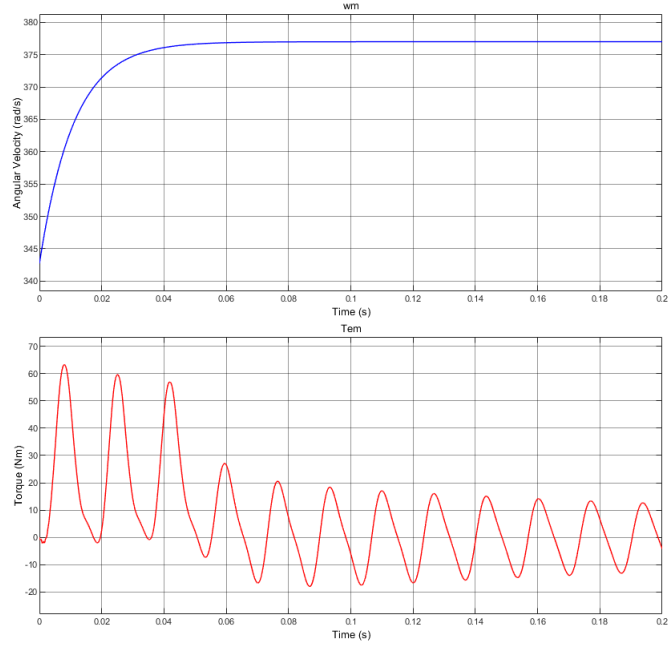


Figure 5.51: Angular Velocity and Electromagnetic Torque of Three Phase PMSM During AC Fault in Three Phase Transformer

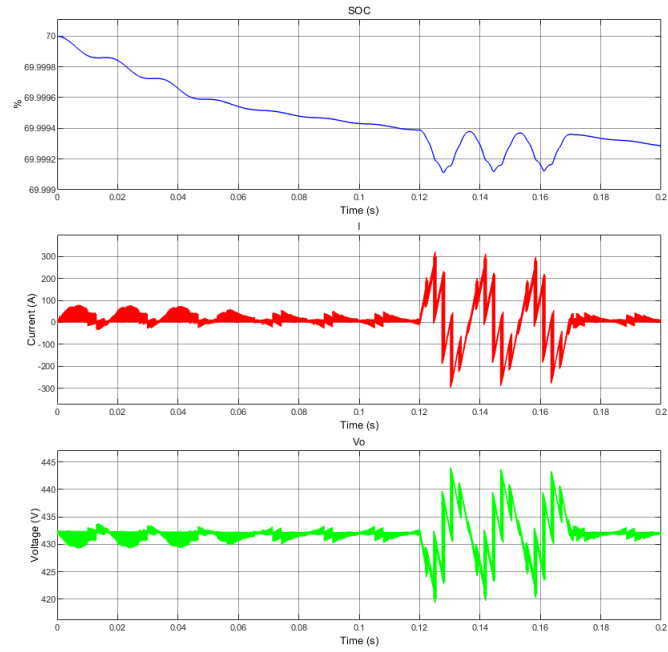


Figure 5.52: State of Charge, Current and Voltage of Li-Ion Battery During AC Fault in Three Phase Transformer

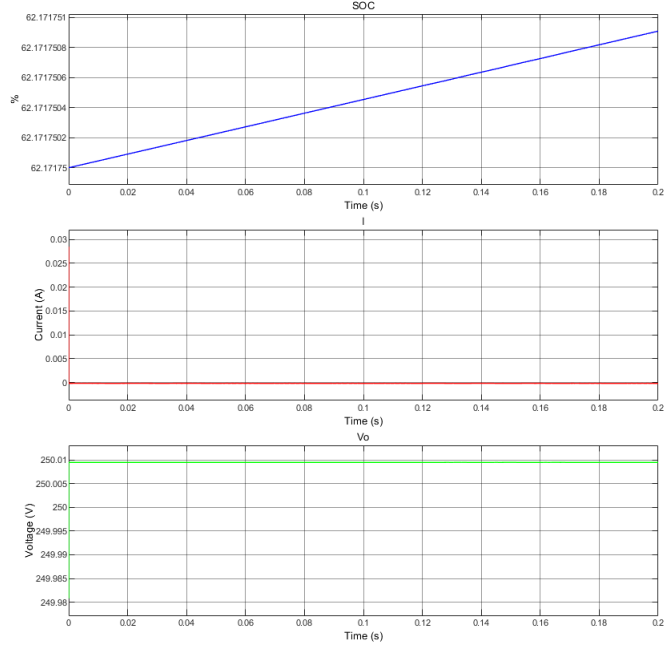


Figure 5.53: State of Charge, Current and Voltage of Super-capacitor During AC Fault in Three Phase Transformer

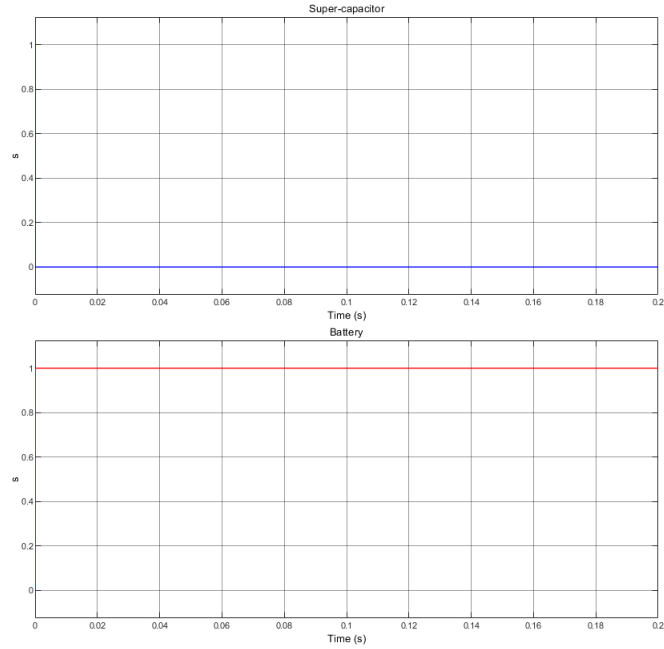


Figure 5.54: Signals of EMS During AC Fault in Three Phase Transformer

In Figure 5.47, v_i experienced a zig-zag fluctuations an average of 432.4V. This is followed by a low amplitude and low frequency disturbance for both v_o and i_L during

the duration of the AC fault.

τ_{em} in Figure 5.51 experienced an increased amplitude fluctuations from $16.17 Nm$ to $18.49 Nm$ when the fault was introduced, and it continues to decay afterwards maintaining an average of zero.

In Figure 5.52, the fault caused a sharp spikes of $292.8A$ and $44.37V$ for both i and v_o . SOC experienced a drop during upward spikes, however it is small due to Li-Ion battery large Q of $100 Ah$ and was recovered via regenerative braking.

5.1.7 AC Fault in Three Phase PMSM

The three phase to ground fault is activated at the PMSM input between $0.12s$ until $0.17s$ (3 cycles of $60Hz$) with ω^* of $3600 rpm \equiv 377 rad/s$ and other parameters from the individual systems with regenerative braking:

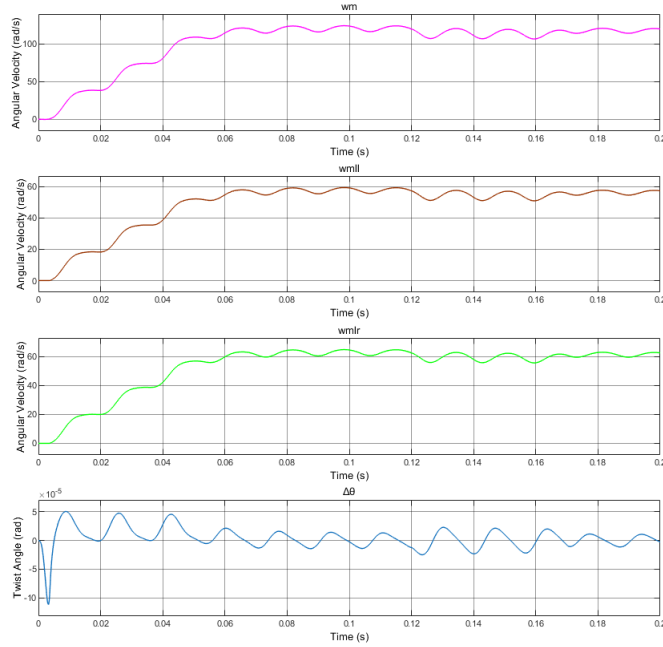


Figure 5.55: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle During AC Fault in Three Phase PMSM

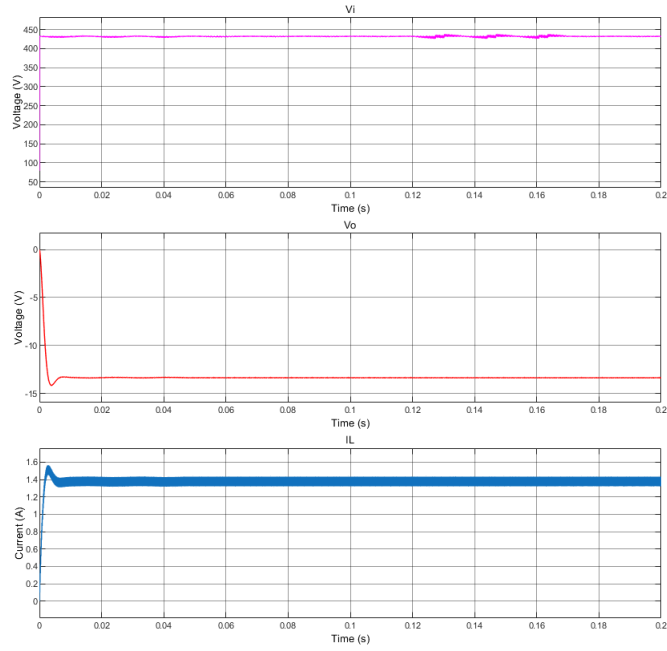


Figure 5.56: Input, Output Voltages and Inductor Current for DC/DC Converter During AC Fault in Three Phase PMSM

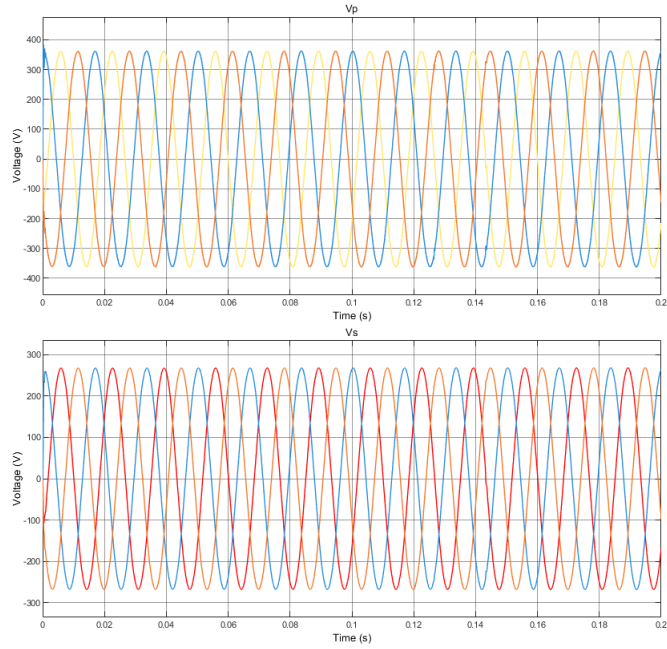


Figure 5.57: Primary and Secondary Voltages for Three Phase Transformer During AC Fault in Three Phase PMSM

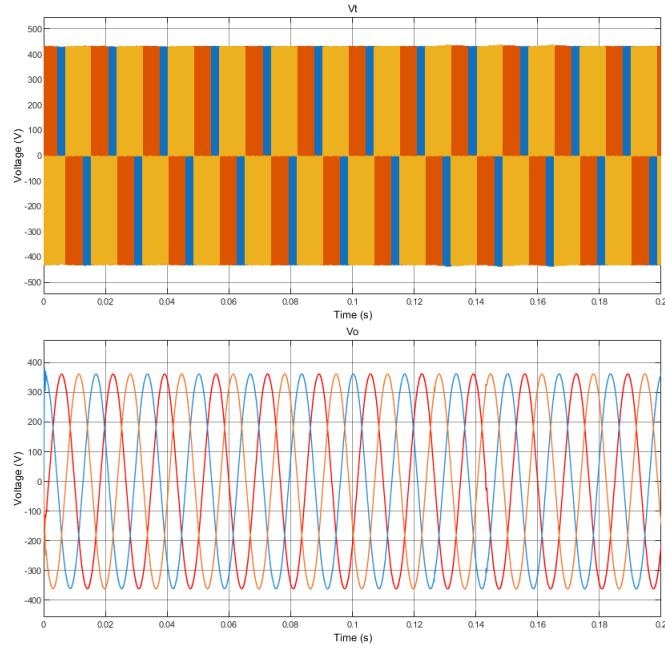


Figure 5.58: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase Transformer During AC Fault in Three Phase PMSM

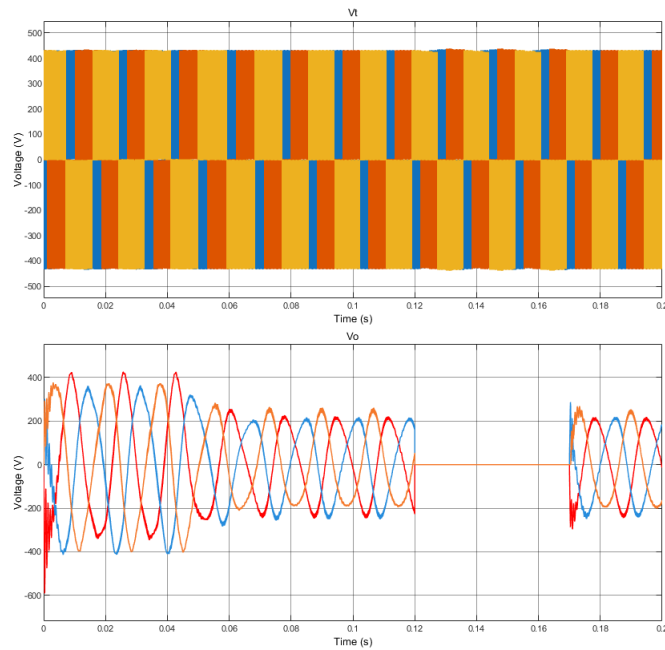


Figure 5.59: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase PMSM During AC Fault in Three Phase PMSM

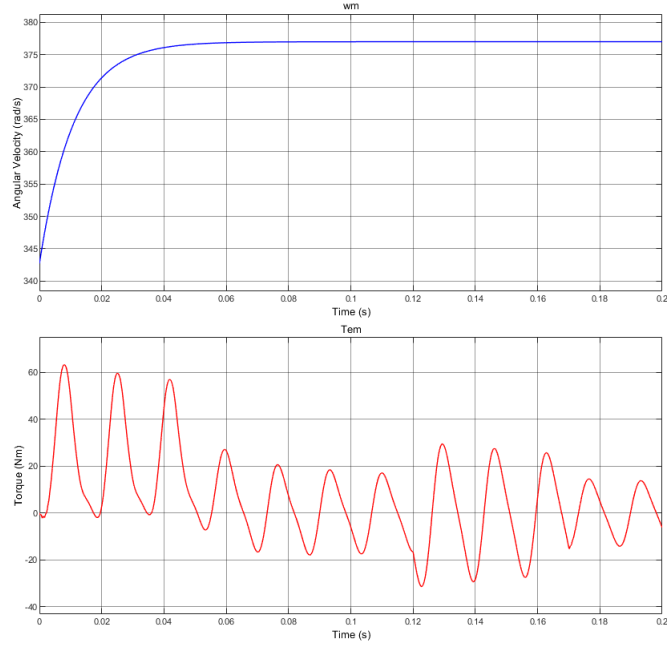


Figure 5.60: Angular Velocity and Electromagnetic Torque of Three Phase PMSM During AC Fault in Three Phase PMSM

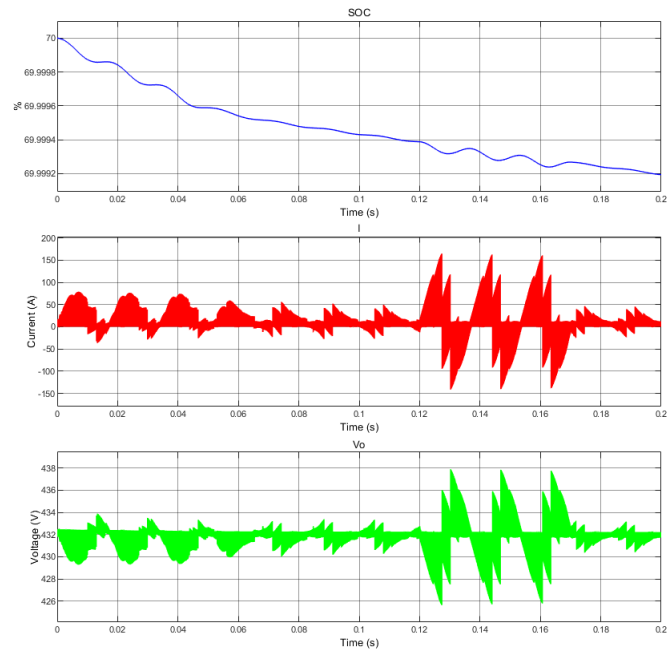


Figure 5.61: State of Charge, Current and Voltage of Li-Ion Battery During AC Fault in Three Phase PMSM

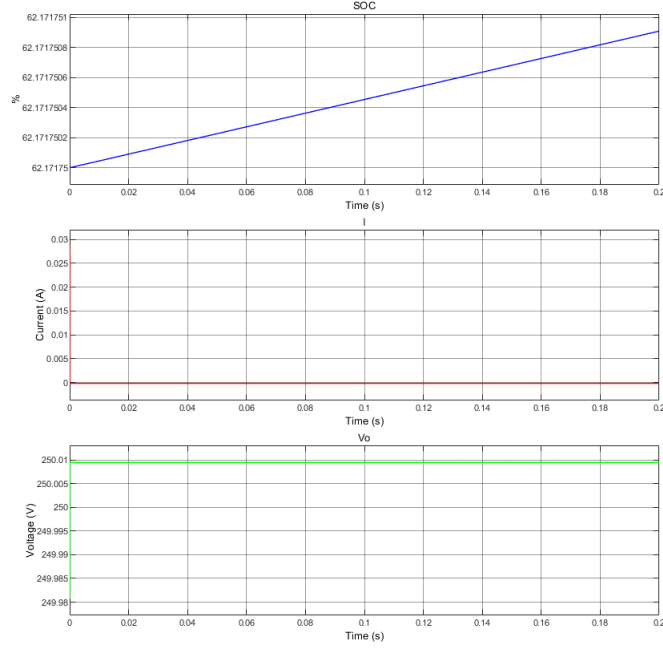


Figure 5.62: State of Charge, Current and Voltage of Super-capacitor During AC Fault in Three Phase PMSM

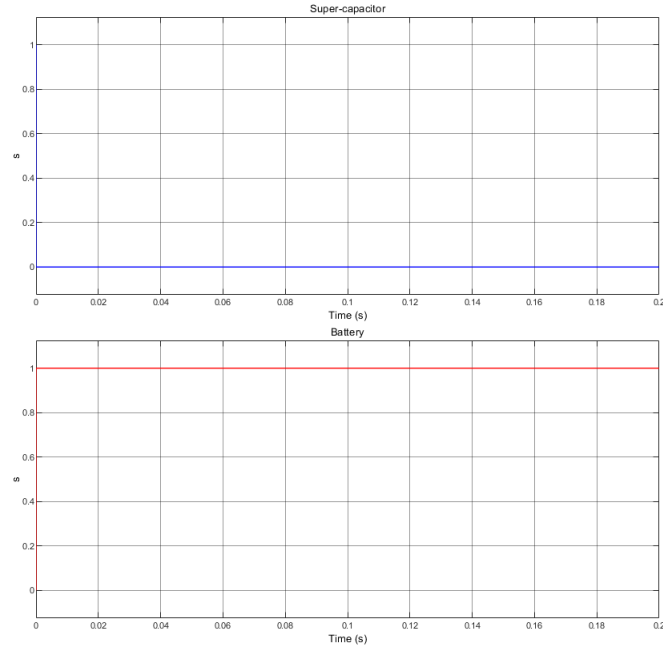


Figure 5.63: Signals of EMS During AC Fault in Three Phase PMSM

This is the only case where disturbance on DS ω_m , ω_{mll} and ω_{mlr} are noticeable during the ac fault as shown in Figure 5.55. During this period, $\Delta\theta$ amplitude in-

creased from $9.61 \cdot 10^{-6} \text{ rad}$ to $3.52 \cdot 10^{-5} \text{ rad}$ and decays after removal of the fault.

In Figure 5.56, no noticeable effects of this fault is observed for the DC/DC converter. τ_{em} oscillates in Figure 5.60 at amplitude of 45.39 Nm and decays afterwards maintaining an average of zero.

Li-Ion battery experienced no significant disruptions to its declining *SOC* during the fault. But both i and v_o show periodic spikes of amplitudes 130.1 A and 436.3 V respectively as shown in Figure 5.61.

5.1.8 DC Fault

The ground fault is activated at the DC/DC converter output between 0.12s until 0.17s with ω^* of $3600 \text{ rpm} \equiv 377 \text{ rad/s}$ and other parameters from the individual systems:

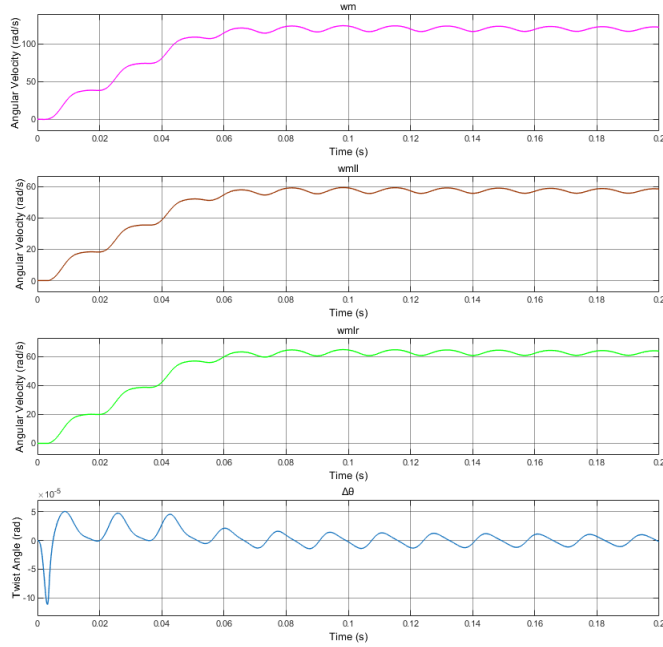


Figure 5.64: DS Angular Velocities for Input, Left and Right Front Wheels and Twist Angle During DC Fault

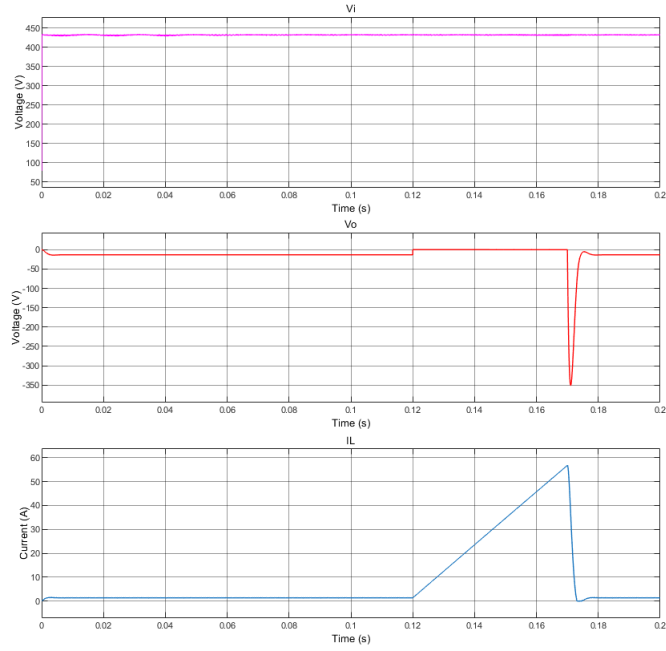


Figure 5.65: Input, Output Voltages and Inductor Current for DC/DC Converter During DC Fault

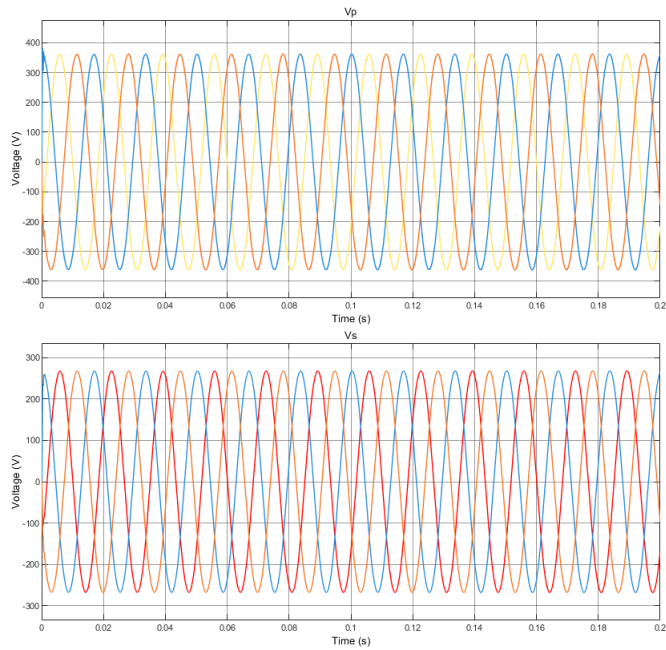


Figure 5.66: Primary and Secondary Voltages for Three Phase Transformer During DC Fault

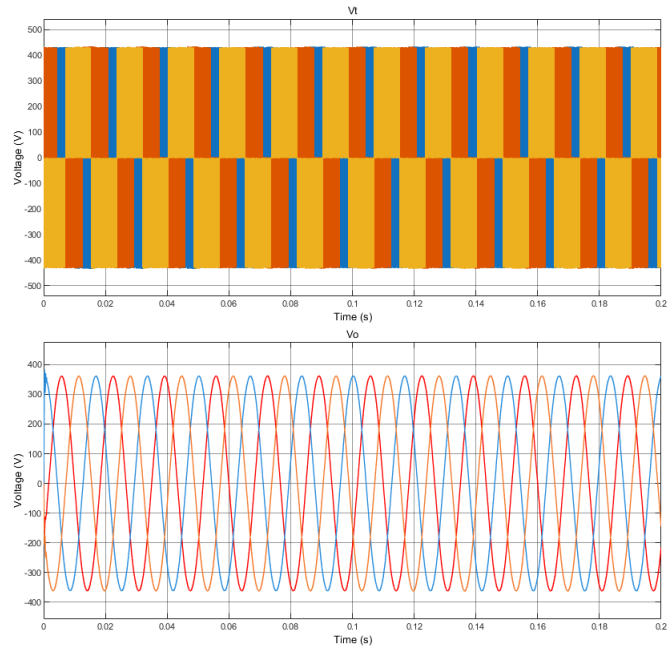


Figure 5.67: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase Transformer During DC Fault

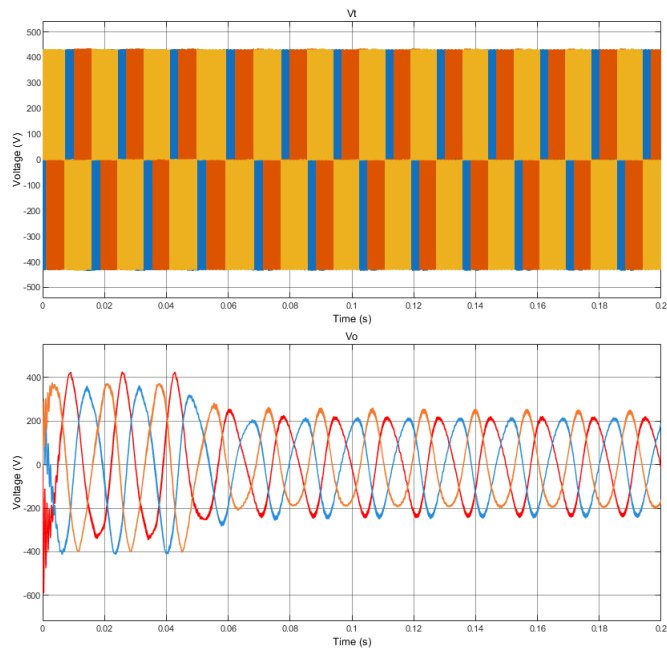


Figure 5.68: Terminal and Output Voltages for Three Phase Sinusoidal PWM Inverter of Three Phase PMSM During DC Fault

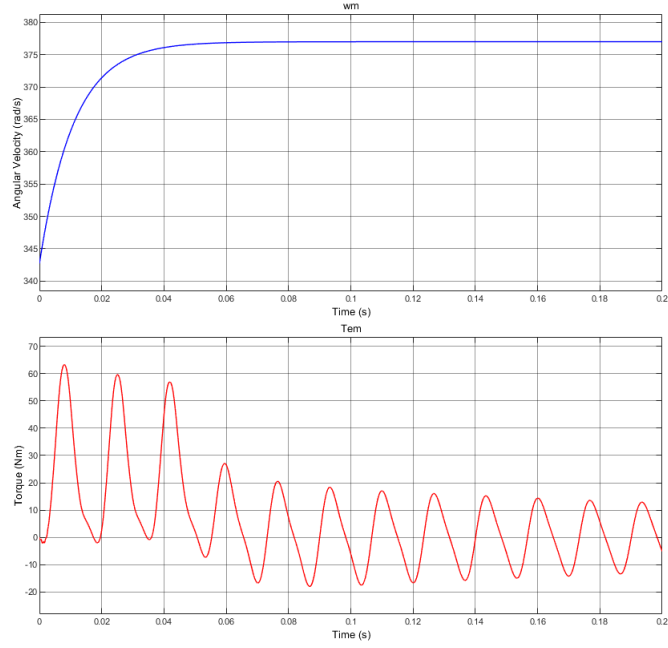


Figure 5.69: Angular Velocity and Electromagnetic Torque of Three Phase PMSM During DC Fault

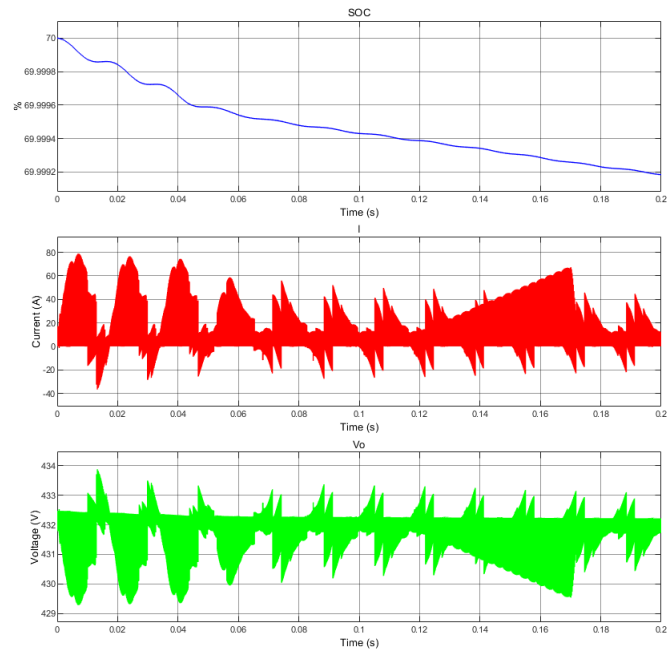


Figure 5.70: State of Charge, Current and Voltage of Li-Ion Battery During DC Fault

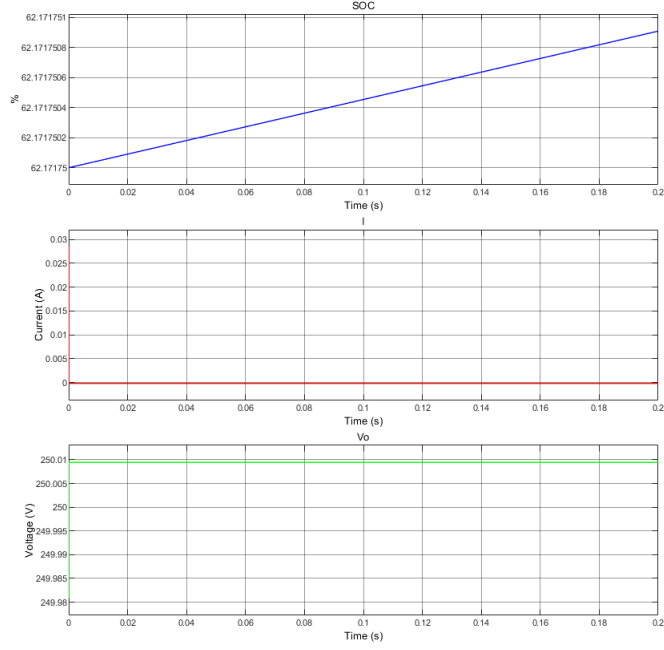


Figure 5.71: State of Charge, Current and Voltage of Super-capacitor During DC Fault

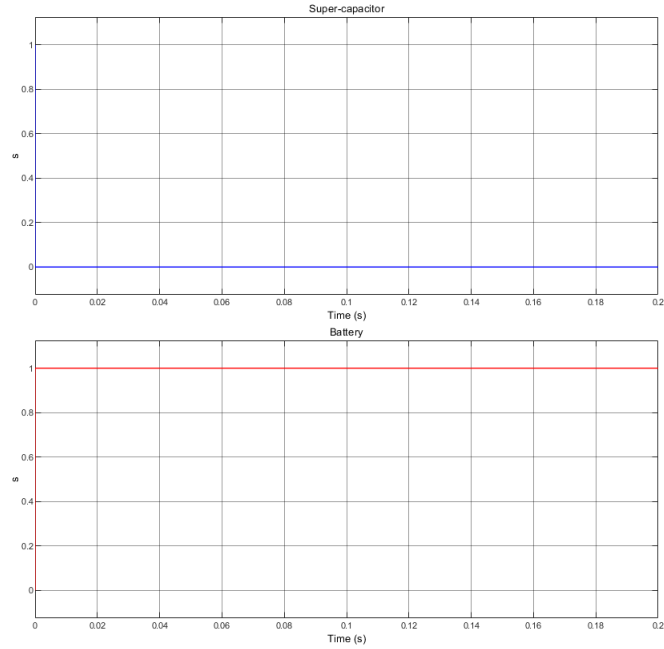


Figure 5.72: Signals of EMS During DC Fault

In Figure 5.65, v_i and v_o experienced a downward spike during the fault recovering of $4.49V$ and $-575.1V$ respectively. i_L on the other hand has an upward spike of

65.75A.

i and v_o of the Li-Ion battery shown in Figure 5.70 have a linear increase and decrease during the dc fault period respectively with no noticeable impact on SOC declining pattern.

5.2 Mitigation Strategies

The literature has various strategies for mitigating interactions, and these will require extensive additional work to investigate their impacts on EVs system dynamics.

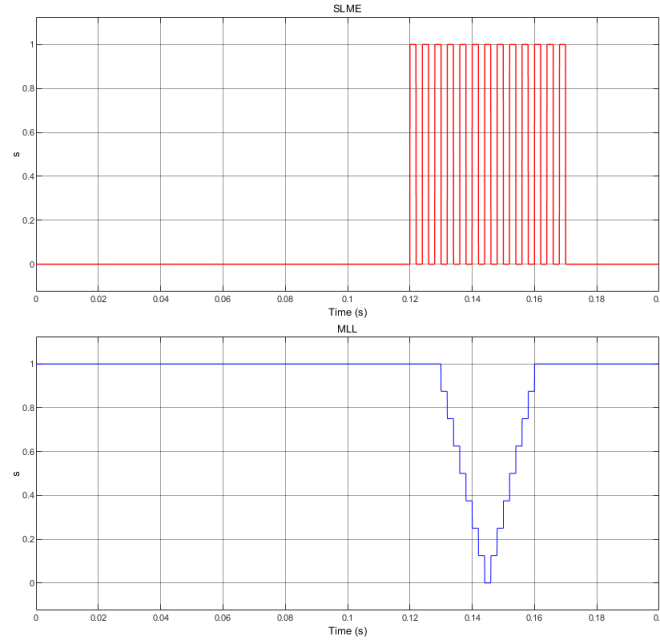


Figure 5.73: Signals of SLME and MLL Strategies

5.2.1 Single-level Multi-edge Switching Loading

Taking DC fault case, in this case the fault is introduced and cleared multiple times between 0.12s and 0.17s. It is important to note that switching frequency of SLME

must be sufficiently fast to avoid parameters recovering to their normal values.

By comparing figures 5.65 and 5.74 for the DC/DC converter, magnitude of spike in v_o and i_L have decreased but increased in numbers; corresponding to the number of switching occurred by the SLME. Also, by comparing figures 5.70 and 5.75, it can be observed that Li-Ion battery current maintained the stable pattern and managed to mitigate the increasingly fault current shown in Figure 5.70.

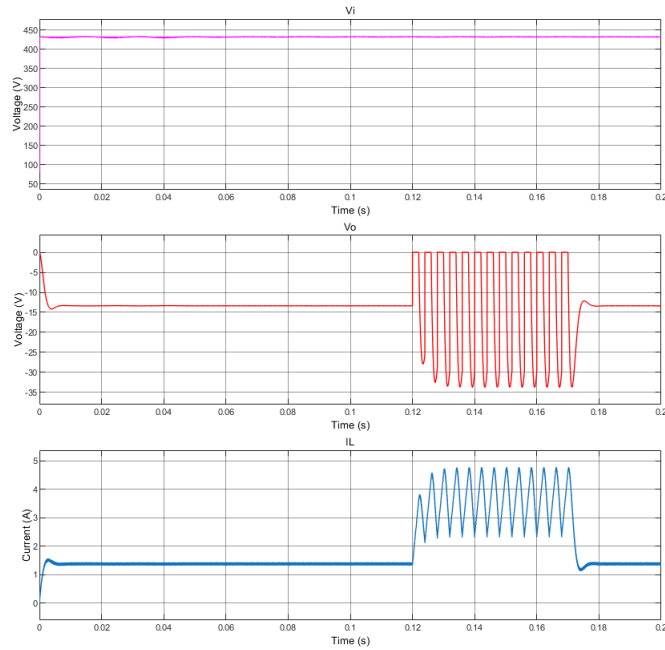


Figure 5.74: Input, Output Voltages and Inductor Current for DC/DC Converter During DC Fault with SLME

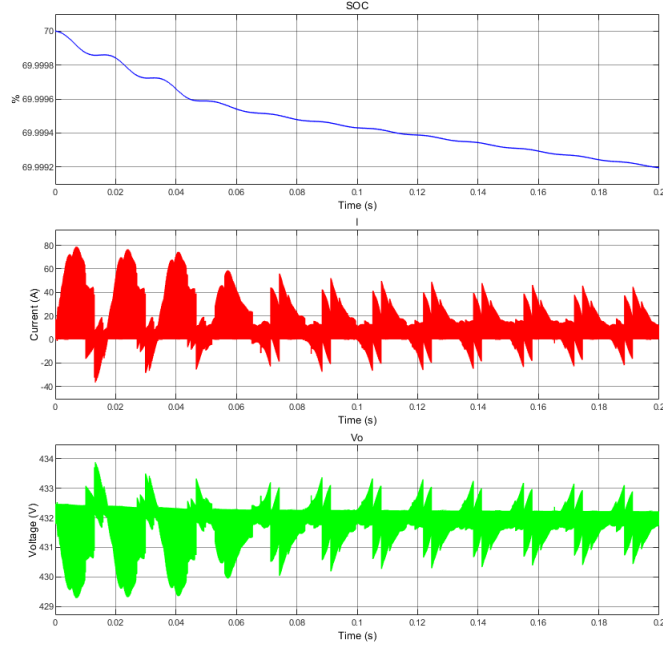


Figure 5.75: State of Charge, Current and Voltage of Li-Ion Battery During DC Fault with SLME

5.2.2 Multi-level Loading

For DC load removal/addition case, no significant improvement on the systems except the DC/DC converter. In this case the R_{dc} was increased in steps reaching infinite (open circuit) then recovering back incrementally to R_{dc} . By comparing figures 5.38 and 5.76, it is observed that v_o downward spike is lower in Figure 5.76 than in Figure 5.38.

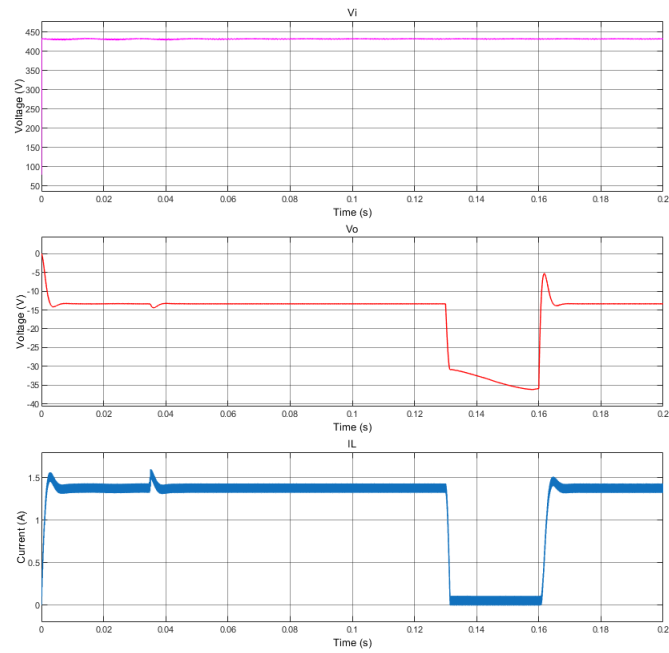


Figure 5.76: Input, Output Voltages and Inductor Current for DC/DC Converter During DC Load Removal/Addition with MLL

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

By summarizing observations of the previous operating actions, below can be deduced:

1. Three phase PMSM inertia acted as a low pass filter, and this explains why only ac fault in the three phase PMSM barely managed to disturb wheels speeds and twist angle.
2. DC/DC converter experienced high sensitivity across all the operating actions. Practically, this requires high tolerance components and robust thermal dissipation techniques.
3. Super-capacitor had a more violent dynamic behavior compared to Li-Ion battery during both regenerative and conventional braking with high magnitude and number of spikes.
4. Generally speaking, electrical faults were the most disturbing operating actions

on the EV systems followed by mechanical variation of reference speed.

5. The two briefly studied mitigation strategies; SLME and MLL managed to reduce the increasing magnitude of fault current for the Li-Ion battery and spikes magnitudes of voltage and current of the DC/DC converter using SLME during DC fault. While MLL reduced spike magnitude of the DC/DC converter voltage but resulted in higher inductor current spike. This indicates that no mitigation strategy can bring all system parameters to acceptable levels with minimal dynamic oscillations and spiking.

6.2 Future Work

This work can be extended by conducting:

1. Frequency analysis on outputs of all operating actions studied.
2. Sensitivity analysis to identify and rank the systems contributing to most harmonics and disturbances.
3. Integration of additional auxiliary electrical systems and other main systems e.g., chargers.
4. Investigation of various architectures of DC/DC converter, three phase transformer and sinusoidal PWM inverters on the EV system dynamics.
5. Further investigation of the mitigation strategies highlighted in the literature.

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