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Regenerative Energy Utilization of PMSM for Elevator Rescue System

by

Alok Yadav

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A Thesis submitted in partial fulfillment of the requirements for the degree of
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Department of Electrical Engineering

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The undersigned certify that they have read and recommended to the Institute of Engineering for acceptance, a dissertation entitled **“Regenerative Energy Utilization of PMSM for Elevator Rescue System”**, submitted by **Alok Yadav** in partial fulfillment of the requirement for the award of the degree of **Master of Science in Power Electronics and Drives Engineering**.

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ABSTRACT

This thesis explores the potential of regenerative energy recovery in elevator systems, focusing on the conversion of gravitational potential energy into electrical energy and its subsequent storage for efficient energy management. The operation of an elevator is divided into two modes: motoring mode, where electrical power is consumed to move the elevator carriage, and generating mode, where the elevator acts as a generator, converting potential energy into electrical energy. Through the implementation of regenerative control, this energy can be harvested and stored in an energy storage system. In this study, the energy is stored in the elevator's rescue system battery, which can later be utilized during power outages to maintain elevator rescue operation. This approach not only contributes to energy efficiency but also enhances the sustainability and reliability of elevator systems. The findings highlight the advantages of integrating regenerative braking technology for energy conservation and enhanced operational resilience in modern buildings.

Keywords: Regenerative Braking, Field Oriented Control, Counterweights

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LIST OF ABBREVIATIONS

BESS	Battery Energy Storage System
FOC	Field Oriented Control
IFOC	Indirect Field Oriented Control
IGBT	Insulated Gated Bipolar Transistor
PWM	Pulse Width Modulation
SOC	State of Charge
DBR	Dynamic Braking Resistor
PC	Power Contactor
MC	Motor Contactor
DOD	Depth of Discharge

CHAPTER ONE: INTRODUCTION

1.1 Background

In the vertical transportation industry, elevators play a vital role in moving people and goods safely and efficiently within multi-story buildings, reducing travel time and effort. Elevators have made it possible to construct high-rise structures, making urban living and working more convenient. As a result, building heights are increasing significantly in order to accommodate more offices and apartments within a limited area, which is vital for a growing urban city. Various elevator sizes and designs are used to meet specific building requirements. Energy consumption also varies accordingly based on an elevator's purpose, capacity, and speed, contributing to a significant amount of the building's total energy load. Despite this significant consumption, elevators have often been overlooked as a critical component in energy-efficient building systems. Given that elevators operate in all four quadrants of motion. The regeneration phase presents an opportunity for energy savings by recovering and reusing energy, improving overall efficiency.

For vertical transportation, Elevators come in various configurations to meet different building requirements. Some common types include hydraulic elevators, pneumatic vacuum elevators, and traction elevators. Hydraulic elevators operate based on Pascal's Law, using compressed fluid to lift the cabin to the desired floor. Due to the use of hydraulic cylinders and piston mechanisms for compression and lifting, these machines consume more energy and are not efficient for high-rise buildings. Hence, these are best suited for low-rise buildings and car parking systems. Pneumatic vacuum elevators uses air pressure difference principle to lift the cabin. It requires a confined sealed shaft in order to generate the pressure difference above and below the cabin to generate lift, making them suitable for buildings with limited space. Among all the above-mentioned types of elevators, traction elevators are widely used for vertical mobility due to their higher efficiency, safety, and time-saving benefits. Traction elevators operate using pulleys, an electric machine, counterweights, and steel ropes, all interconnected using a specific roping ratio. This roping ratio is used in order to reduce the torque needed to lift the cabin against the counterweights, lowering the machine's capacity requirements and overall energy consumption. The number of counterweights used in the system equals the sum of the cabin's weight and half of the elevator's rated load[1]. This ensures that, at any moment during its operation, the motor's required torque to lift the cabin remains within its rated torque. As a result, the motor generates approximately the same amount of torque under both no-load and full-load conditions. Traction elevators can be further categorized based on their machine type which include geared or gearless and whether they require a machine room or are machine-room-less.

In recent years, Permanent Magnet Synchronous Motors (PMSMs) have been widely used in traction systems due to their high torque-to-inertia ratio, compact design, broad speed range, and superior power density[2]. Furthermore, due to their compactness, they are much easier to install and assemble compared to traditional geared induction motors. The geared induction motors are usually of bulky size with an additional gearbox, requiring a larger machine room and more manpower for installation and commissioning. For their operation, a higher-rated controller and circuit breaker are required, which increases their electricity consumption as well. As an induction motor operates at its rated speed, a gearbox is used for speed reduction and power transmission. However, these gearboxes require regular maintenance, such as oiling and lubrication, making them more costly and inefficient. Due to these reasons, in modern-day elevator systems, gearless PMSMs are preferred over traditional geared induction motors. Furthermore, in PMSMs, starting and stopping jerks can be effectively reduced due to their adjustable high torque-to-inertia characteristics. Hence, these motors offer smoother operation and improved performance.

An elevator, as an integrated system with PMSM, can operates across all four quadrants[3]. At certain times, the PMSM in the elevator functions as a generator, regenerating energy based on its capacity, the building height, and the number of passengers[4]. This regeneration specifically occurs during forward and reverse braking phases, offering an opportunity to harness energy efficiently. One effective approach to utilizing this energy is through the implementation of a back-to-back converter topology, which enables the PMSM drive system to operate in both motoring and regenerative modes[5]. Traditionally, the generated energy was dissipated as heat through dynamic braking resistors, leading to a loss of usable energy and an increase in ambient temperature. Therefore, an optimized framework for utilizing regenerative energy in PMSM-based elevators is essential to enhance energy savings, operational reliability, and overall system sustainability.

1.1.1 Four Quadrant Operation

The elevator operates by moving the carriage up or down using a counterweight. A traction rope system, consisting of pulleys, interconnects the carriage, machine, and counterweight. The counterweight reduces the load on the motor by providing opposing torque to balance the carriage's weight. This allows the motor to generate torque within its rated capacity from no load to full load. As the cabin's load and direction of movement change, the amount of energy consumed or generated by the machine also varies.

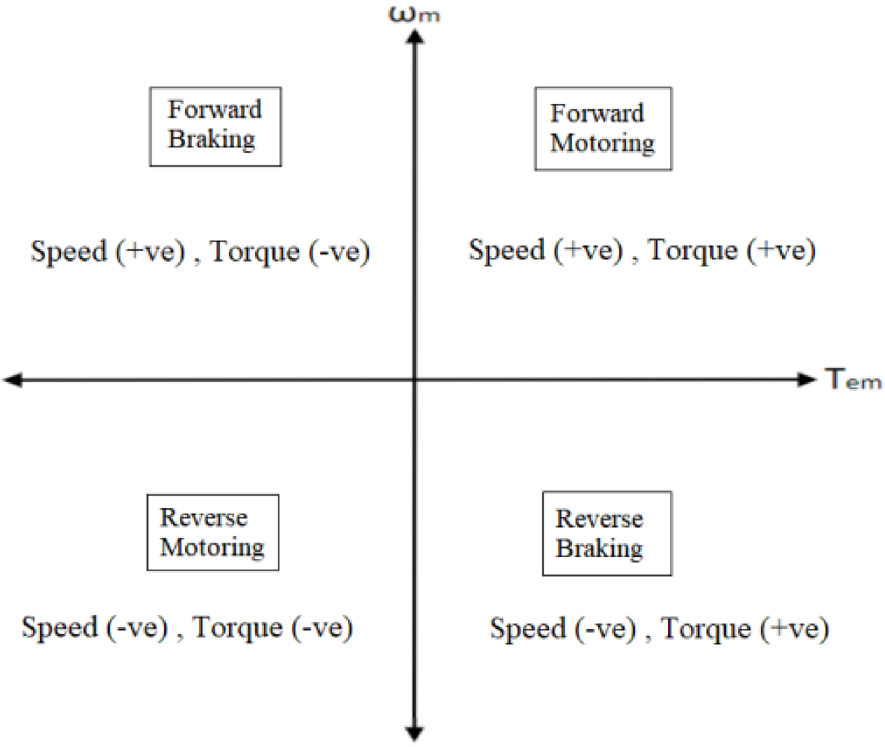

Figure 1.1: Four quadrant operation of elevator

The torque-speed plot of machine are illustrated in Figure 1.1. According to the mechanical power equation, $P = \text{Torque} \times \text{Speed}$, the operating regions are classified based on the sign convention of torque and angular speed. When both torque and speed of the machine are positive, the system operates in the forward motoring and when both of them are negative, then it operates in reverse motoring phases. In these two regions (quadrant I and quadrant III), the sign of power is positive, hence the machine consumes power from the grid for its operation. Conversely, if the speed is positive while the torque is negative, the system enters the forward braking phase, whereas if the speed is negative and the torque is positive, then it operates in the reverse braking phase. In both of these braking regions (quadrant II and quadrant IV), the torque opposes the direction of rotation; as a result, the net torque due to load torque and motor torque causes the motor to rotate, operating it as a generator. This results in a reverse power flow compared to the motoring operation. PMSM can achieve all these four combinations of speed and torque directions with use of AC drives and can efficiently control varying torque and speed as well[3]. This capability of the machine and AC drive is vital for the utilization of regenerative energy in elevators to reduce their overall energy consumption.

1.1.2 Elevator Rescue System

In complex systems such as elevators, which integrate components like electrical machines, variable voltage variable frequency drives, and converters, faults are bound to occur. For this reason, to ensure passenger safety during their usage and enable rescue operations during power failures, a reliable backup mechanism is essential. This system must safeguard the passengers during elevator operation by relying on a dedicated backup energy storage system, typically a battery energy storage system. During the rescue operation, the elevator control system measures the current and operates the elevator in the braking region so that due to regeneration, the amount of power required to facilitate the nearest floor rescue decreases. Furthermore, this decreases the capacity of the backup battery as well. Traditionally, these batteries are charged using power from the main grid, which raises the elevator's overall energy consumption, leading to higher power usage. However, by harnessing the regenerated energy from the motor-driven system, this energy can be stored and reused in the backup rescue system, significantly reducing the elevator's net power consumption. This approach not only conserves regenerated energy but also repurposes it to meet critical needs during outages, improving both energy efficiency and system reliability.

1.2 Problem Statement

In a growing urban city, power consumption has increased significantly with the increasing population and high-rise structures that require more power to meet the increased demand. Furthermore, a crowded region faces multiple challenges and difficulties for power transmission. Hence, energy saving is crucial in crowded regions for each and every building. Elevators, one of the significant power-consuming units of the building, have become an essential part of modern-day multi-story buildings. Their usage has decreased the efforts, saved travel time, and increased productivity. However, their frequent operation also results in significant energy consumption. Unlike most heavy machinery, elevators operate in all four quadrants and can also regenerate energy during braking mode. Furthermore, based on the purpose of usage and type of building the amount of energy varies. In sectors such as malls and hospitals, the generation is higher compared to residential buildings. However, the generated energy is being dissipated as heat energy through dynamic braking resistors, leading to wastage of energy, increased operational costs, and an increase in ambient temperature.

The main challenge lies in designing an efficient and reliable system to harness regenerative energy during braking. Electric drives equipped with bi-directional converters can capture this energy and store it in an energy storage system. However, storage solutions like supercapacitors are costly and have limited capacity, making them unable to store all the regenerated energy throughout the entire braking period. As a result, they are mainly used for peak shaving applications[6]. At present, the absence of a well-defined framework for utilizing regenerative energy in PMSM-based elevator systems limits the potential for reducing energy consumption and improving operational reliability.

Furthermore, currently, elevator rescue systems rely on the external power grid to charge their connected backup batteries, which increases the overall energy consumption of the elevator system. This research aimed to utilize the regenerative energy to power the rescue system, thereby reducing dependency on grid electricity. However, implementing such a system requires an optimized control strategy capable of managing bidirectional energy flow, minimizing power losses, and ensuring seamless integration with existing infrastructure. Overcoming these technical challenges is essential for developing energy-efficient elevator systems that maintain reliable and safe operation.

1.3 Objectives

The objectives of this research are described below :

Main Objective

The main objective of this thesis is to design a control system that captures regenerated energy during specific operational phases of an elevator, such as when an empty cabin ascends or a loaded cabin descends. This includes the design and implementation of an electric drive with a regenerative energy utilization framework.

Specific Objectives

- To design an FOC-based control strategy for the operation of PMSM for dynamic load.
- To calculate the rescue and additional battery capacity based on the amount of energy regenerated.
- To simulate and observe the energy storage in the rescue and additional battery backup during generating mode.

1.4 Scope

- Design of field-oriented control of PMSM-based elevators and its operation in specific braking phase for energy recovery system.
- Integration of a bidirectional converter and battery backup to store recovered energy for emergency rescue operations during power outages.
- Minimize the dependency on external source for charging by reusing the generated energy.
- Utilization of the regenerated energy for additional building loads.

1.5 Limitation

- The amount of the regenerative energy produced depends on the frequency of elevator usage and the number of operating cycles during daily operation, which ultimately determines the overall energy recovery potential.
- Performance of the overall system is constrained by the battery's storage capacity and converter efficiency, leading to energy losses.
- Initial implementation of the system increases the cost due to the need for additional components, such as bidirectional converters and advanced control systems.
- Stored energy may be insufficient for extended power outages or multiple consecutive rescue operations.

1.6 Outline of the thesis

This thesis is structured into five chapters, each covering different aspects of the research. A brief overview of each chapter is provided below:

- Chapter 1 : Introduction : This section describes the background of the elevator system and its Operation, an explanation of four-quadrant operation for PMSM-based elevators, and the elevator rescue system.

- Chapter Two : Literature Review : In this section, a comprehensive literature review is explained in brief, covering key concepts related to FOC control of PMSM operation and regeneration.

- Chapter Three : Methodology: The overall research approach and explanation of the proposed system is presented in this section, including a detailed explanation of the simulation circuit.

- Chapter Four: Results and Discussion: In this section, the result of the simulation was presented and discussed. Further interpretation was done evaluating the performance of the energy regeneration and its storage.

- Chapter Five: Conclusion: This section provides a summary of the work undertaken and the research conducted to obtain the desired objective of the thesis.

- References: This section presents all the references utilized during this research.

CHAPTER TWO: LITERATURE REVIEW

This chapter provides a comprehensive review of the relevant literature for this dissertation, focusing on the principles of PMSM, their operational characteristics , different control method of PMSM, regenerative energy utilization techniques, energy storage solutions, and their application in elevator rescue system to enhance efficiency and reliability.

2.1 Permanent Magnet Synchronous Motor

PMSMs are robust, efficient AC motors that are widely used for accurate motion control, hoisting, and industrial applications. They are characterized by their compact design, high torque to inertia ratio, high power density, and low torque ripple. Unlike other machines, PMSMs have distinctive characteristics, as their field excitation is produced by permanent magnets in the rotor, which generate the required flux instead of electromagnets. This reduces the rotor winding losses in the machine. The stator consists of a laminated iron core, around which the stator windings are wound. These laminated iron cores are used to minimize the eddy current losses. Here, the windings of the stator are wound so that they generate the sinusoidal magnetic field in order to reduce the torque ripple and harmonic distortion[7].

PMSM operates based on the principle of synchronous rotation. The stator windings, when supplied with balanced three-phase voltage, produce a rotating magnetic field at a particular frequency. This field interacts with the rotor's permanent magnet, generating electromagnetic torque and causing the rotor to rotate at the same frequency, ensuring synchronization. Hence, the rotating magnetic produced by the stator windings determines the speed of rotation of the rotor.

Furthermore, permanent magnets have a relative permeability similar to that of air. Due to this, both of them provide the same reluctance torque to the stator flux. Hence, the stator will take the path of least reluctance. As a result, the placement of permanent magnets within the rotor determines the magnetic flux distribution and the generation of reluctance torque, which ultimately influences the motor's performance characteristics and efficiency[8]. Hence, based on the placement of permanent magnet on the rotor, PMSM can also be classified as the following :

Surface Mounted PMSM

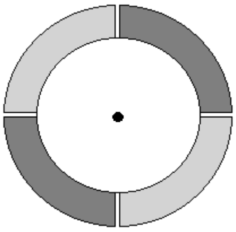

Figure 2.1: Surface Mounted rotor

For surface mount PMSM, the permanent magnets are fixed on the rotor surface using adhesives or retaining sleeves. As permanent magnets have the same reluctance as that of air gap, this design results in an isotropic magnetic structure (L_d=L_q)[9]. Hence, the rotor has negligible magnetic saliency. Due to this, there is an absence of reluctance torque, and the motor depends upon the electromagnetic interaction of the stator's magnetic field and the rotor's permanent magnets for torque generation.

Interior PMSM

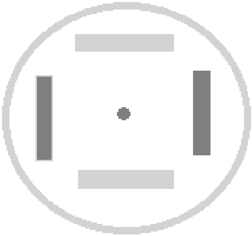

Figure 2.2: Interior rotor

For interior PMSM, the permanent magnets are fixed within the rotor core. This design makes the rotor surface smooth and round but results in magnetic saliency because the permanent magnet and the iron core have different relative permeabilities, causing a difference in inductance between the d-axis and q-axis[9]. Here, IPMSM generate electromagnetic torque and reluctance torque, improving the overall torque production without increasing the size of rotor. This robust design of rotor is useful for applications such as electric vehicles, and industrial systems.

Although, IPMSM have better torque generation and high power density, Surface mount PMSM are more commonly used in elevator industry due to their simpler rotor design, lower cost and smooth torque characteristics.

PMSM Mathematical Modelling

For PMSM, from stator's reference the motor is a three phase balance system. Here, the PMSM is assumed to be symmetrical. The core losses and eddy currents are also neglected. This helps to simplify the control implementation of PMSM.The voltage equation of PMSM in abc reference frame are as follow :

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} \tag{2.1}$$

where,

$\mathbf{v}_{abc}$: Phase voltages
R_s : Stator coil resistance
$\mathbf{i}_{abc}$: Phase currents
$\boldsymbol{\psi}_{abc}$: Stator flux linkages

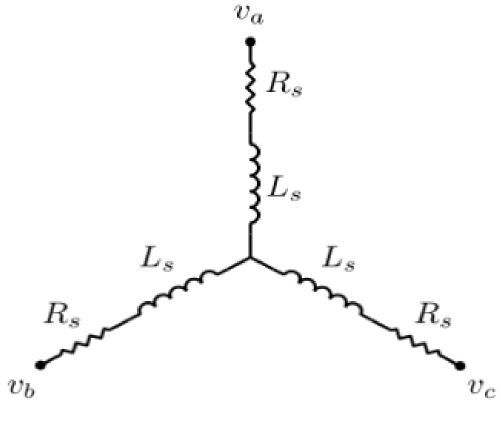

Figure 2.3: Three phase equivalent circuit of PMSM

For a surface-mounted PMSM, the rotor has uniform magnetic reluctance, resulting in equal phase inductances: $L_a = L_b = L_c = L_s$. Therefore, the stator flux linkage equations are given by[10]:

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} = L_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \psi_m \begin{bmatrix} \cos(\theta_e) \\ \cos\left(\theta_e - \frac{2\pi}{3}\right) \\ \cos\left(\theta_e + \frac{2\pi}{3}\right) \end{bmatrix} \tag{2.2}$$

Here, θ_e is the electrical rotor angle,

ψ_m is the permanent magnet flux.

Using equation (2.1) and equation (2.2), we get:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} L_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \psi_m \omega_e \frac{d}{d\theta_e} \begin{bmatrix} \cos(\theta_e) \\ \cos\left(\theta_e - \frac{2\pi}{3}\right) \\ \cos\left(\theta_e + \frac{2\pi}{3}\right) \end{bmatrix} \tag{2.3}$$

The above equation represents the voltage equation of the PMSM in the abc reference frame. Now, transforming it into the $\alpha\beta$ frame of reference, we get:

$$\frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = -\frac{R_s}{L_s} + \frac{1}{L_s} \left(\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} + \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \right) \tag{2.4}$$

where

$i_{\alpha\beta}$ is the stator current,

$V_{\alpha\beta}$ is the stator voltage,

L_s is the stator inductance,

$e_{\alpha\beta}$ is the back EMF. And the back EMF is given by the following equations:

$$e_\alpha = -\sqrt{\frac{3}{2}} \psi_m \omega_e \sin(\theta_e) \tag{2.5}$$

$$e_\beta = \sqrt{\frac{3}{2}} \psi_m \omega_e \cos(\theta_e) \tag{2.6}$$

Here, abc is transformed into two phase Clarke transformation. However, the dynamics of PMSM is typically modeled in the rotor oriented dq reference frame (Park's transformation) aligned with rotor flux. Furthermore, using the Park's transformation, the voltage Equation in rotor reference frame are [11]:

$$V_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_e \psi_q \tag{2.7}$$

$$V_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_e \psi_d \tag{2.8}$$

where,
V_d, V_q are the stator voltages in the d-axis and q-axis (V),
i_d, i_q are the stator currents in the d-axis and q-axis (A),
ψ_d, ψ_q are the flux linkages in the d-axis and q-axis.

Depending on the rotor type, the d-axis and q-axis inductances are equal to each other for a surface-mounted PMSM, i.e., $L_d = L_q$. Hence, the flux linkages are given by:

$$\psi_d = L_d i_d + \psi_m \tag{2.9}$$

$$\psi_q = L_q i_q \tag{2.10}$$

where,
L_d, L_q are the d-axis and q-axis inductances,
ψ_m is the permanent magnet flux linkage.

Substituting the above equations (2.9) and (2.10) into the voltage equation, we get:

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{2.11}$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e (L_d i_d + \psi_m) \tag{2.12}$$

Electromagnetic Torque equation for PMSM is expressed as[12] :

$$T_e = \frac{3}{2}\frac{P}{2}[\psi_m i_q + (L_d - L_q) i_q i_d] \tag{2.13}$$

where,

P is number of Poles of PMSM

Furthermore, in equation(2.13), we have two set of components which contributes to overall torque production, the initial terms corresponds to the electromagnetic torque resulting from the interaction between the stator magnetic field and the rotor permanent magnets, while the second difference terms arises from the reluctance torque due to the difference between the d-axis and q-axis inductances. For surface mounted PMSM, we have L_d=L_q due to which reluctance torque becomes zero, and the overall torque generation is due to electromagnetic interaction only.

$$T_e = \frac{3}{2}\frac{P}{2}\psi_m i_q \tag{2.14}$$

Here, the number of poles in PMSM is directly proportional to the electromagnetic torque. Furthermore, the number of poles of PMSM also influences its operating speed. According to the synchronous speed formula we have,

$$N_s = \frac{120 f}{P} \tag{2.15}$$

Where, N_s is the synchronous speed of the PMSM,

f is the electrical supply frequency in Hz.

Here, number of poles is inversely proportional to synchronous speed for the same supply frequency. For control of PMSM the term pole pairs is used widely for relating the electrical and mechanical quantities of PMSM. Here, One Pole represents north or south while single pole pairs refers to north and south as a set.

Hence, the Mechanical dynamics of PMSM are expressed as follow :

$$J\frac{dw_m}{dt} + Bw_m = T_e - T_L \tag{2.16}$$

Where,

J is the moment of inertia (kg·m^2),

B is the viscous friction coefficient,

T_L is the load torque (Nm),

ω_m is the mechanical angular velocity (rad/s).

SMPMSM are widely used for elevator applications particularly in gearless traction designs. They have simpler rotor and robust mechanical design with permanent magnet mounted on rotor surface. Hence, compared to interior PMSM they are more economical due to their simpler rotor design and manufacturing process. Despite being costly, IPMSMs are also used in some of the high-speed elevator machines.

2.2 Control Methods for PMSM

For accurate speed and torque control of PMSM, various methods are available based on the operation of PMSM. Various control method of PMSM are described in below figure 2.4[13]:

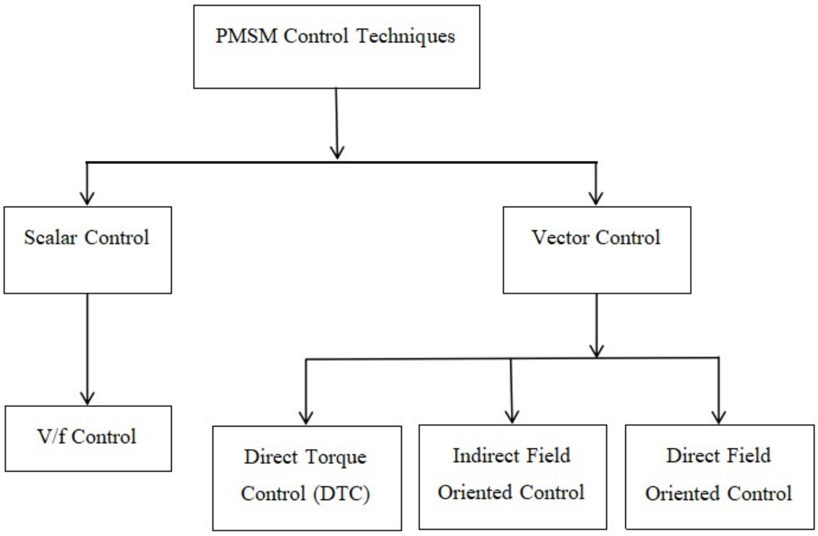

Figure 2.4: Different control techniques of PMSM

1. Scalar Control (V/f control)

Scalar control is magnitude based control method, which controls the PMSM by controlling only the magnitude of voltage, current or frequency without decoupling the torque and flux. Here, phase of the variable is not considered. In this method, a constant voltage to frequency (v/f) ratio is maintained to keep the magnetic flux constant and avoid magnetic saturation in PMSM. This is a simple and less complex technique as no rotor position feedback is required. However, for dynamic load condition, this method is not reliable. As there is no decoupling of torque and flux component which results in poor dynamic response. Therefore, this technique is generally used for applications, where cost needs to be minimized such as fans and in some industrial drives.

2. Vector Control

In Vector control method the torque and flux components of the PMSM are decoupled which enables independent control of both components, similar to separately excited DC motor. Here, the stator currents of PMSM is transformed into two orthogonal components, d-axis and q-axis. This decoupling of current allows accurate control of PMSM and also improves the dynamic response. Based on the control of current, vector control can be further classified into the following types :

a) Direct Torque Control (DTC)

In this method, the motors torque and stator flux are directly controlled without using current controller or transformation block. Here, hysteresis controllers compare the reference value with the actual torque or flux component and the switching table is used to determine the switching states of inverter[14]. DTC have fast dynamic response as no PI controllers are used and the implementation is also simple with no need for transformations[15]. However, due to direct control it results in high torque ripple and requires higher sampling rate.

b) Indirect Field Oriented Control

This is a type of vector control where the rotor angle is measured indirectly using rotor's electrical model. Hence, it is termed as Indirect FOC. The rotor angle (θe) is calculated using the measured rotor speed (wm). The electrical angle is obtained as :

$$\theta_e(t) = p \int_0^t w_m(t) dt \tag{2.17}$$

Where,

- θ_e is the electrical rotor angle,
- p is the number of pole pairs,
- ω_m is the rotor speed in rad/s.

Here, Rotor speed is measured using sensors and rotor flux angle is calculated using the rotor speed making it more robust, simpler and easier for implementation. However, the rotor flux angle is dependent upon accurate speed measurement. Furthermore, this method is more sensitive to parameter variations.

c) Field Oriented Control

In this method, the stator current is transformed into two orthogonal components: the d-axis current id and the q-axis current i_q, which are defined in the rotating reference frame of the motor[16]. The d-axis current i_d is mainly responsible for controlling the motor's flux, which directly influences the magnetic field within the machine. Meanwhile, the q-axis current i_q is responsible for generating torque, which helps to determine the motor's output power and improve dynamic response.

FOC effectively decouples the flux and torque-generating components, allowing independent control of each parameter[17]. This decoupling enables the motor to maintain stable operation, even under varying load conditions, by dynamically adjusting id and i_q. As a result, FOC improves the torque accuracy, efficiency, and dynamic performance of PMSM, making it a widely adopted control strategy for high-performance applications such as electric vehicles, robotics, and industrial automation[18].

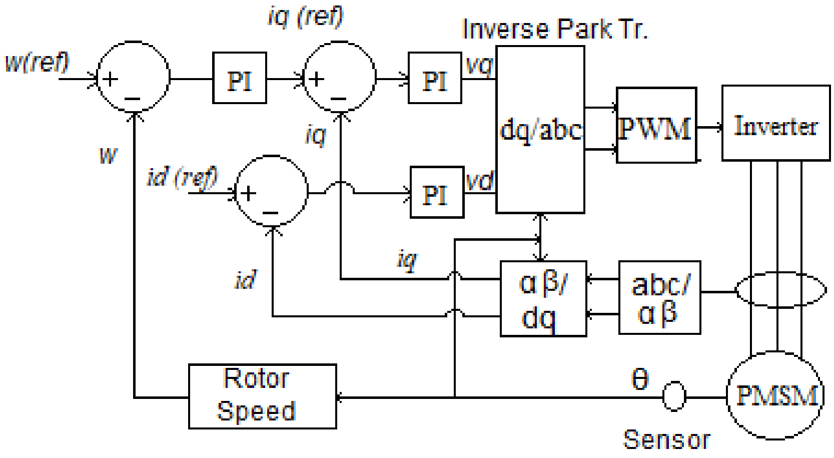

Figure 2.5: Field oriented control strategy

Above control consists of two inner Proportional Integral (PI) controllers, which process the reference current signals with the actual motor output currents for both the d-axis and q-axis components. These controllers ensure that the motor operates with precise control over flux and torque.

For decoupling of current, Clarke-Park transformation is applied, which converts the three-phase stator currents (i_a, i_b, i_c) into a rotating reference frame, effectively decoupling the motor's output current into d-axis (i_d) and q-axis (i_q) component. Additionally, an outer PI controller is responsible for regulating motor speed. It calculates the difference between the reference speed (desired speed) and the actual motor speed, which is measured using a speed sensor. The output of this PI controller generates the reference i_q signal, which directly influences the torque production of the motor. By continuously adjusting i_q based on speed error, the system maintains accurate speed regulation even under load variations. Further, to obtain the maximum torque per ampere control, the i_d component of the stator current is forced to become zero[19]. This makes the angle between the q-axis component orthogonal with the rotor flux. For this PI controller is used for the stator's d-component current, and a zero reference value is provided to this controller. This hierarchical control structure ensures smooth, efficient, and precise operation of the PMSM, making FOC a preferred technique.

Furthermore, PMSM voltage equation, torque equation and mechanical equation can be re-arrange as following to obtain the field oriented control strategy[20]:

$$\frac{di_d}{dt} = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}pw_r i_q \tag{2.18}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q - \frac{L_d}{L_q}pw_r i_d - \frac{\psi_m p w_r}{L_q} \tag{2.19}$$

$$T_e = \frac{3}{2}p[\psi_m i_q + (L_d - L_q)i_d i_q] \tag{2.20}$$

$$\frac{dw_r}{dt} = \frac{1}{J}(T_e - Bw_r - T_m) \tag{2.21}$$

where, p is the number of pole pairs, ω_r is the rotor speed in rad/s.

The mathematical equations above are used to formulate field oriented control strategy for PMSM. In this approach, the measured values of i_q, i_d, and ω_r are compared with their reference values and fed into a PI controller[21]. The controller then generates the necessary signal for the PWM block, which produces the gate signals for the PMSM.

2.3 Bi-directional Converter

The bi-directional converter is composed of fast switching semiconductors such as MOSFETs and IGBTs connected in a way to allow the flow of energy in both directions between two connected power circuits.

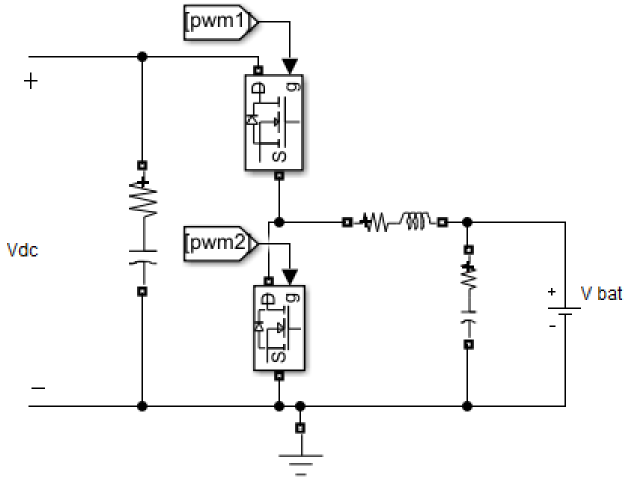

Figure 2.6: Bi-directional Converter circuit

In a bidirectional converter, the direction and amount of power flow are controlled by adjusting the switching of semiconductor devices. An inductor and capacitor are used as passive components to smooth current and voltage waveforms, respectively, thereby reducing ripple at the input and output. The required values of inductance and capacitance can be calculated using provided design specifications and following equations :

$$L = \frac{(V_{\text{in}} - V_{\text{out}}) \cdot V_{\text{out}}}{I_{\text{ripple}} \cdot f_s \cdot V_{\text{in}}} \tag{2.22}$$

$$C = \frac{I_{\text{ripple}}}{8 \cdot V_{\text{ripple}} \cdot f_s} \tag{2.23}$$

where,
V_{in} is the input voltage,
V_{out} is the output voltage,
F_s is the switching frequency,
I_{ripple} is the ripple of the inductor current.

Here, these equations provide us with the required parameter for the converter circuit design and ensure efficient converter operation.

During the course of this thesis, some research papers have been reviewed and are briefly described below:

In (Cheng et al., 2021) the author have described about the four-quadrant operation control of PMSM drive systems. Here, an exponential functional-based sliding mode reaching law (ESMRL) is designed so that it will adapt to the changes in the grid side inverter. The DC bus voltage is also regulated in order to achieve unity power factor control on the grid side. The mathematical model of PMSM is based on the Port-controlled Hamiltonian (PCH) control. Here, the PCH control is used due to its simple design and good steady state property. The proposed design facilitates four-quadrant operation, allowing the PMSM to function efficiently in both motoring and regenerative modes. Furthermore, it allowed bi-directional energy flow, reducing the energy losses. This method adapted to the variations in the grid-side inverter and sliding mode surface to ensure stable and optimized energy management. Moreover, the regenerative braking mechanism effectively converts kinetic energy into electrical energy, contributing to overall system efficiency and sustainability. The simulation results validated the effectiveness of the proposed control strategy.

In (Hui Qi et al., 2015), a regenerative braking strategy for PMSM drive systems has been proposed, which utilized a back-to-back converter topology. Here, the paper discussed the stable four-quadrant operation of PMSM without the use of a DC link braking resistor. In order to operate in all four quadrants smoothly, the system integrated a rotational inertia observer designed using model reference adaptive system theory. This design provided real-time data on motor's inertia, which is again utilized for an energy management strategy to optimize the control of the overall system. During the braking period, the role of the grid-side converter and motor-side inverter reverses. The motor-side converter controls the output DC link voltage while the grid-side converter operates as an inverter. Hence, a controlled rectification was established during the regeneration period where the PMSM operated as a generator, motor side converter as a controlled rectifier, dc link capacitor as a filter to smooth out the output. Here, field-oriented control was used in order to control the PMSM. Here, mathematical calculation had been carried out for implementation of field-oriented control strategy. Furthermore, in order to operate the PMSM in max torque per ampere at all instances, the id component of stator current was reduced to zero. This resulted in max torque as i_q component is perpendicular to the flux component producing max torque. The experimental results showed that the regenerative braking strategy effectively stabilizes the regenerative voltage at 700V, ensuring safe operation without damaging electronic components. Here, the system demonstrated an improved speed response and successfully recovered regenerated energy during braking operations.

In (Jabbour et al., 2016), the paper described about the regeneration capability of elevator system and method to recover this energy. Here, a super-capacitor based energy recovery system had been proposed in order to store and recover the braking energy with the help of a bidirectional DC-DC converter connected to the DC link of the motor drive. Traditionally, the DC link reference voltage for ERS was kept constant and the value was choosen higher than the rectified grid voltage and lower than the braking resistor circuit voltage. However, this approach did not ensure maximum benefits which ERS can provide, as elevator may consume energy from grid and not from super-capacitors. Hence in order to solve the problem, two fuzzy-logic controllers (FLCs) had been developed to dynamically adjust the DC-link voltage based on the elevator operating conditions and AC grid voltage variations. This adjustment made sure that minimal energy shall be consumed from the grid. With the use of two fuzzy-logic controllers, the current ripple in the super-capacitor was also minimized in order to protect the capacitors from overheating and to extend their operation lifetime. Furthermore, the proposed system could be integrated into any existing elevator installations without requiring any modifications to the existing motor drive. Here, the proposed scheme was validated experimentally on a real elevator system which showed improved energy efficiency and extended operation lifetime of the super-capacitors. This control scheme offered a practical solution for enhancing the sustainability and performance for both new and retrofit elevator systems.

According to (Kun-Yu lin et al., 2017), significant amount of energy gets wasted during the operation of Elevators, especially during braking. By installing regenerative power drive system, elevators could effectively utilize the regenerated energy and this energy can be fed back into the main grid supply. This process reduces overall power consumption and enhances energy efficiency of elevator system. The study analyzed the impact of regenerative drives, distinguishing between power-saving rate and regenerative energy ratio, and conducted experiment in elevator with and without regenerative drive. Here, the findings showed that heat generation in the elevator machine room decreased, eliminating the need for additional cooling systems like air conditioning, further improving energy savings. Further, the results also indicated that the amount of regeneration depends upon the time usage of elevator and load it carried, heavier elevator loads yielded greater regenerative power. By using high-efficiency motors the regeneration could be further enhanced, improving the energy efficiency. Additionally, the study emphasized on the amount of regeneration based on the building types and compared multiple buildings based on the amount of usage of elevator and load capacity to validate the findings.

In (S. Marsong et al., 2016), the author had described various components of elevator with their purpose. The operation of elevator was explained in detail and further classified into motoring mode and generating mode based on the carriage load and direction of operation of elevator. Mathematical equation of PMSM was utilized to formulate a control strategy using PI controllers. The proposed system was designed in Simulink and was validated experimentally in a building. The result demonstrated that EERU system effectively reduced the overall energy consumption compared to conventional elevator systems. The study emphasized the practical implementation and real-world performance of regenerative units, proving their potential for large-scale adoption in high-rise buildings. These findings reinforced the benefits of integrating energy recovery systems into elevator drives to enhance sustainability and operational efficiency.

In (An Thi Hoai et al., 2021), the paper emphasized the increasing need for energy efficiency in modern buildings, especially in elevator systems. For any elevator, there are motoring period where the elevator significantly consumed the energy from main grid supply and the generating period where the energy is regenerated. Traditionally, these regenerated energy was getting dissipated as heat in braking resistors. Super-capacitor energy storage system was used for mitigation of the energy loss associated with these operations. SCESS reused the regenerative braking energy by storing the surplus energy generated during braking period and releasing it during acceleration time, thereby reducing the overall energy consumption of the system. One of the advantage of utilizing SCESS was its ability to stabilize the DC bus voltage, which prevented fluctuations during regenerative braking period. The system used a DC-DC bi-directional converter to manage the energy flow effectively. The control strategy for SCESS was based on two primary loops: the inner current loop, which managed the charging and discharging process of the super-capacitors and the outer voltage loop, which ensured that the DC link voltage remained stable at a fixed value. Simulation was conducted on a elevator system and the result highlighted the potential of SCESS to significantly reduce energy consumption in elevator systems, providing a sustainable solution to the energy challenges faced by multi-story buildings.

In (Kermani et al., 2021), the paper investigated energy efficiency in elevators by implementing a Hybrid Energy Storage System (HESS) comprising Battery Energy Storage (BES) and Ultra-capacitor Energy Storage (UCES) to optimize the power use and reduced the operational costs associated with elevator system. Conventional elevators dissipated regenerative energy as heat, leading to waste of regenerated energy, whereas HESS enabled the energy reuse, improving overall efficiency. This research was conducted using Induction motor and Indirect FOC control strategy to control the machine. Here, the Motor was operated in motoring mode, stationary mode and generating mode for fixed interval time and the storage of energy was observed in the HESS. The findings indicated that ultra-capacitors, with their high power density, effectively absorbed the rapid energy fluctuations of elevator, while the batteries, with their high energy density, stored the regenerated energy effectively. BESS was again used for supplying other common building loads such as pumps, AC etc. Economic analysis of the proposed system, revealed that the HESS implementation resulted in significant cost savings. The initial investment in the system was projected to be recovered within six years. These findings demonstrated that integrating a hybrid storage system for elevator energy recovery significantly reduced residential electricity consumption. The combination of BES and UCES, coupled with advanced control strategy, helped to recover and reuse the energy properly, minimizing peak power demand and achieving an energy-efficient building.

(Lakhe et al., 2021), the paper focused on designing a universal control for Permanent Magnet Synchronous Motors with uncertain system dynamics. In this paper, two approaches were discussed and simulated: conventional field-oriented vector control and a simplified control approach. For vector control, proportional-integral (PI) controllers were used to compare the d-q axis currents with their reference values and generate signals for PWM generation. Similarly, the speed of the PMSM was also measured and compared with reference value to generate the required error signal for inner current control loop. Through empirical analysis, generalized mathematical expressions were derived to determine the control gains for multiple PMSMs with varying power ratings. These expressions enabled automatic gain calculation based on the motor power ratings in vector control and for the simplified control method two parameters, the number of pole pairs and flux linkage were used to determine the value of required control gains. The simplified approach provided much faster and more straightforward gain calculation for its two PI controller compared to the vector control where the gains are calculated for three PI controllers. For the validation of these control strategies, the research was conducted in the MATLAB/Simulink environment using PMSMs rating ranging from 0.2 HP to 10 HP. The simulation results confirmed that both methods ensured accurate tracking of reference speed and d-q axis reference currents. The simplified control method, which reduced the number of PI controllers by eliminating the cascaded control structure of speed and current loop, utilized linear mathematical equations for gain determination. However, the vector control approach demonstrated higher accuracy. Compared to the conventional gain tuning methods, the proposed strategies proved to be easier to implement and less time-consuming.

(B. Plangklang et al.,2013) studied the operation of PMSM as generator in regenerative mode. Mathematical equation of PMSM were derived and used to compute the gains of the PI controller. The simulation was conducted using the calculated gains and through simulations the motor's behavior under different loading conditions was analyzed. It was observed that when voltage was supplied to the PMSM, it operated at the provided reference speed and generating torque consuming power from grid and functioning as a motor. Conversely, when the motor was being rotated without external power input under no-load or light-load conditions, the PMSM operated as a generator and generated electrical energy. This regenerative energy had the potential to be fed back into the system supply to compensate for energy consumed, reducing the overall power waste. The motor's operating characteristics were studied under both positive and negative loads, confirming its dual operational behavior, where it operates as a motor under positive load and as a generator under negative load. The study's findings demonstrated that PMSMs could effectively recover and reuse energy through regenerative braking, a principle applicable and required for elevator energy recovery system.

These literature reviews provided deeper insights into the regeneration process and effective methods for capturing regenerative energy to minimize the overall energy consumption of elevators. Additionally, various control techniques for PMSM were examined, leading to the selection of a suitable control strategy to ensure efficient elevator operation under variable load conditions. These findings form the foundation for the subsequent research and implementation discussed in the following chapters.

CHAPTER THREE: METHODOLOGY

3.1 Approach

The methodology for this research involved a structured approach, incorporating advanced control strategies and energy recovery techniques. From the literature review various ideas and techniques of control strategy were collected for this research. By comparing various control strategy, the most suitable method obtained for the control of PMSM was Field Oriented Control Strategy, which is highly effective in independently managing the motor's torque and flux components. This ensured precise control and optimal performance, even under varying load conditions. The overall methodology that has been followed during this dissertation is shown in Figure 3.1.

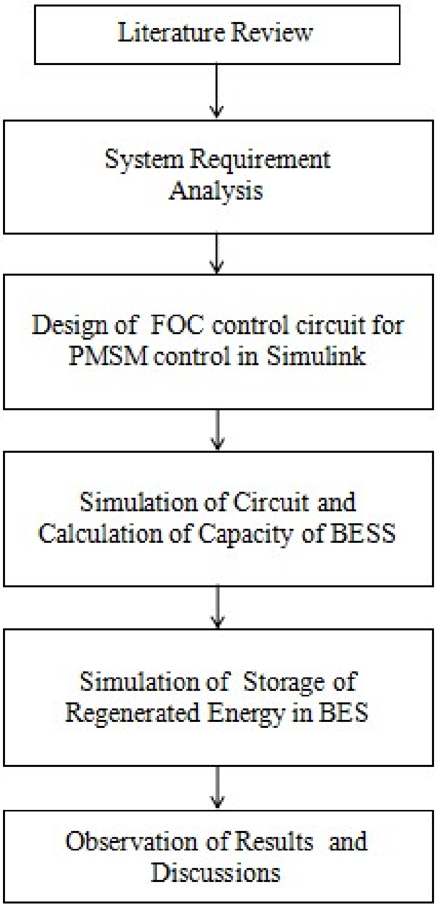

Figure 3.1: Flowchart of Methodology

3.2 Tools and Software

This section lists the tools and software used during the research.

3.2.1 MATLAB Simulink

MATLAB refers to Matrix laboratory is a programming software developed by MathWorks for coding, simulating of various real world circuits to observe the results. Within MATLAB also there are various tools such as simulink, control blocks, signal processing algorithms etc. Here, in Simulink various models of components for electrical, electronics and other fields devices are available which are built based on the real world parameters. With the help of these model various complex control system can be designed and simulated to observe the outcomes of the circuit. This gives a brief idea and knowledge of operation of the system and helps to minimize the error and prevent unnecessary extra works before designing the system in hardware. For this research MATLAB Simulink was used extensively for circuit simulation and observation of the results.

3.2.2 Microsoft Office

Microsoft Office (MS Office) is application software, widely used for documentation for academics purpose, and business applications. The software helps to organize the content properly in readable format by the user to store the electronic copy of the document which can be printed to get hardcopy as well. For this research it was used for arranging all the processes, circuits and results in a standard readable format.

3.2.3 Overleaf

Overleaf is a cloud-based La-TeX editor software, used widely for research writing purpose. Here, the software offer various tools and format which assist the user in writing a manuscripts, thesis and technical reports. It offers real time support and easily arrange the content in provided standard format. Here, wide range of format, templates are available for writing papers. Furthermore, it offers cloud based storage with the help of which the document could be access from any other devices as well.

3.3 Overall Control System Design

For this research, passenger elevator with six person capacity was taken for the simulation. Here, the elevator travelled for a height of $10\,\mathrm{m}$. Then, the entire elevator control system was developed using the MATLAB Simulink environment. The technical specifications of machine, load capacity of counterweights used for the simulation were sourced from Johnson Lifts Pvt. Ltd., India. The simulation was run for a total time duration of $30.8\,\mathrm{s}$ for $10\,\mathrm{m}$ vertical travel distance for a 3 stop building. The detailed specifications of the machines for six-person is presented in Table 3.1 :

Table 3.1: Machine Parameters

Parameters	**Units**	**Value**
Rated Power	kW	3.1
Number of Phases	–	3
Rated Voltage	V	380
Rated Current	A	8
Rated Speed	rpm	145
Rated Torque	$\mathrm{N\,m}$	204
Rated Capacity	kg	408
Radius of Wheel	m	0.17
Efficiency	–	0.85
Inertia	$\mathrm{kg\,m^2}$	1.92
Armature Inductance	mH	44.7
Stator Phase Resistance	Ω	2.9
Pole Pairs	–	10

For this research, a surface-mounted PMSM was used, as it is widely used for elevators. The radius of the machine wheel was 0.17m and its efficiency was 0.85. For elevator the counterweights were used in order to decrease load on motor with use of pulley and a roping ratio. Here, counterweight factor of 0.5 and roping ratio of 2:1 was taken which decreased the torque requirement by half for full load. For calculation of unbalanced load due to the use of counterweights and roping ratio for full load we have,

$$\textit{Unbalance Load (UB)} = \frac{\textit{Cabin load}}{\textit{Roping Ratio}} - \frac{\textit{Rated load} \times \textit{CWT factor}}{\textit{Roping Ratio}} \tag{3.1}$$

$$
\begin{aligned}
UB &= \frac{408}{2} - \frac{408 \times 0.5}{2} \\
&= 102 \text{ kg}
\end{aligned}
$$

$$
Torque\,required = \frac{UB \times 9.81 \times \; Radius\,of\,wheel}{Machine\,efficiency} \tag{3.2}
$$

using above expression,

$$
Torque\,required = \frac{102 \times 9.81 \times 0.17}{0.85}
$$

We have, Torque = $200\,\mathrm{N\,m}$, which was needed to be generated by the PMSM in order to lift the fully loaded cabin.

Using the machine parameters and the above-calculated values, a complete system circuit model was developed in MATLAB Simulink, which is presented in Figure 3.2.

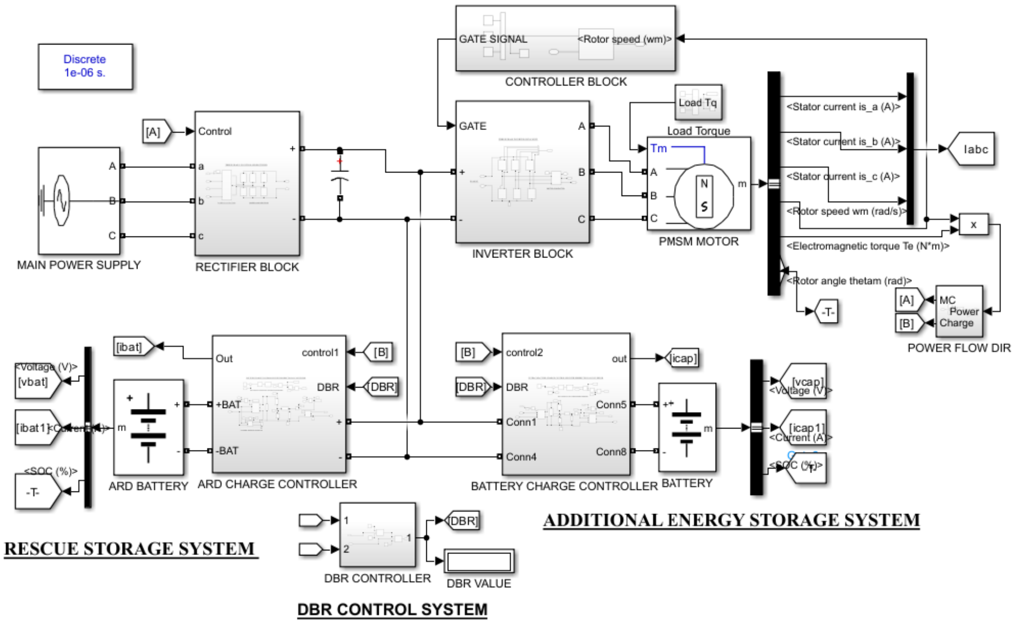

Figure 3.2: Circuit design of Overall system

In this system, the $380\,\mathrm{V}$ grid supply undergoes rectification before being delivered to the inverter. As illustrated in Figure 3.3, the rectification block was designed using six power diodes to rectify the three-phase grid supply. Here, the power contactor used in the circuit functions as a circuit breaker, disconnecting power to the entire system in the event of a safety hazard. Furthermore, it was also used to disconnect the main power supply during the regeneration period in order to isolate the system from the main power source and utilize the regenerated energy for the storage system.

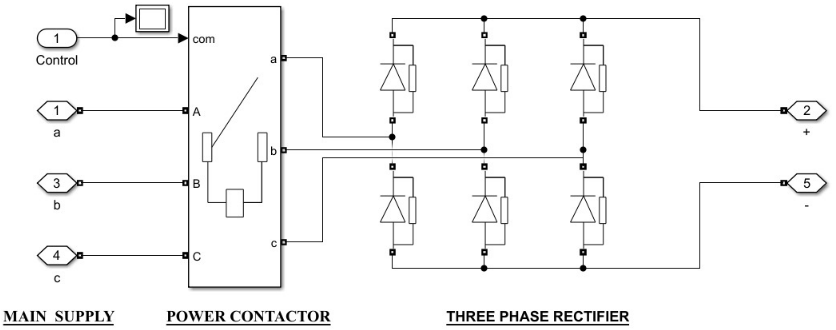

Figure 3.3: Three phase rectification block

For Inverter block six IGBT switches were used, which operated based on the gate pulses received from FOC block. The rectified DC output was supplied to this inverter block. Here, motor contactor was used for protection of motor in the event of any failure.

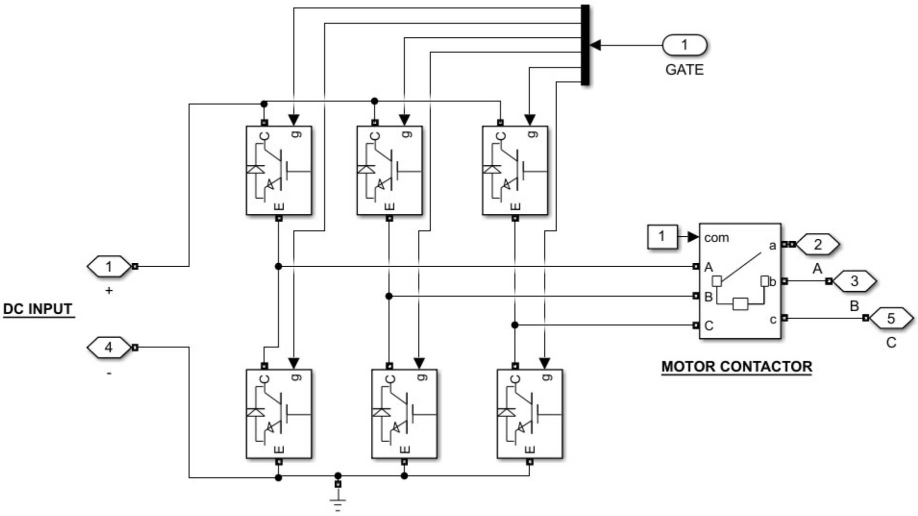

Figure 3.4: Three phase inverter block using IGBT

3.3.1 Field Oriented Control Strategy

The FOC block continuously monitored the output of the stator current and rotor angle of the PMSM. Clarke and Parks Transformation block was used to decouple the three-phase stator current into d and q components taking the rotor position as reference. Using a PI controller, the reference speed was compared with the measured speed of the motor, and an error signal was generated. This error signal was then compared with the measured i_q current to generate another error signal, which was fed into a second PI controller. This second PI controller produced the control signal required to maintain the torque component of the motor. Similarly, third PI controller was used in order to keep the d-component of the stator current zero, so that only the stator current's q-component remained which would be orthogonal with the rotor field, and the motor will generate maximum torque per ampere. Therefore, zero reference value was provided for d-component PI controller. The output of the q-component PI controller and d-component PI controller was again transformed into three phase quantity using inverse transformation block. These control signals were then subsequently supplied to the PWM generator block where the PWM signal was generated required for the inverter block. The inverter block supplied the PMSM based on the received signals thereby establishing a closed loop feedback control system.

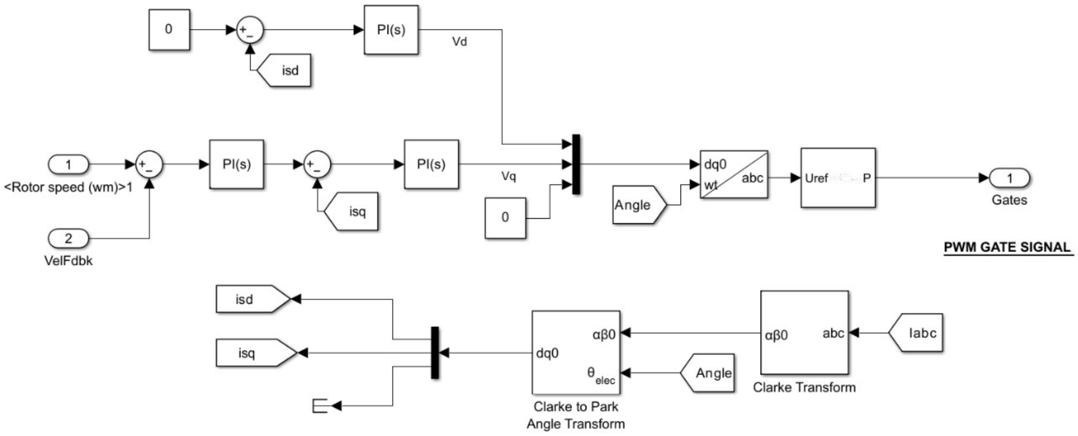

Figure 3.5: Field Oriented Control Block

Here, the output rotor angle was used for Clarke and Park transformation block for the decoupling of three phase stator current into d and q component and vice versa. This was used so that the quadrature component of stator current would remain orthogonal with the rotor field during the entire operation.

3.3.2 Energy Storage Control Strategy

The regenerated power must be processed properly in order to achieve the required charging voltage for the battery. A bi-directional converter was used for this purpose, allowing the battery to be charged during regeneration period and supplying power to the elevator during a power failure to facilitate nearest-floor rescue.

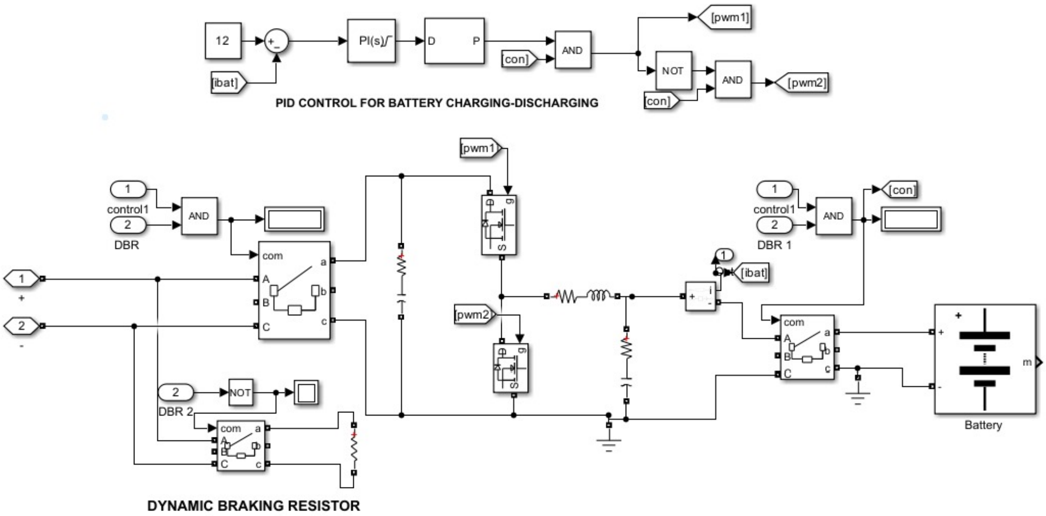

Figure 3.6: Bi-directional battery charge controller block

For design of bi-directional converter following value of inductor and capacitor were used for the circuit:
Input Voltage (V_{in}) = 500 V
Output Voltage (V_{out}) = 55 V
Current Ripple (I_{ripple}) = 3 A
Voltage Ripple (V_{ripple}) = 0.55 V
Switching Frequency (f_s) = 5000 Hz,

$$L = \frac{(V_{\text{in}} - V_{\text{out}}) \cdot V_{\text{out}}}{I_{\text{ripple}} \cdot f_s \cdot V_{\text{in}}} \tag{3.3}$$

$$L = \frac{(500 - 55) \cdot 55}{3 \cdot 5000 \cdot 500} = 3.2\,\text{mH}$$

$$C = \frac{I_{\text{ripple}}}{8 \cdot V_{\text{ripple}} \cdot f_s} \tag{3.4}$$

$$C = \frac{3}{8 \cdot 0.55 \cdot 5000} = 0.000136F$$

Furthermore, a dynamic braking resistor was also implemented to dissipate excess energy once the state of charge of the battery energy storage system exceeded 95%. Based on Figure 3.7, the DBR control logic operates such that if the SoC of the BES is greater than 95%, a logic value of 1 is generated as the output. This signal turns the switch to the on position, resulting in the connection of the braking resistor to the circuit. Therefore, the excess energy is dissipated in the form of heat across the resistor.

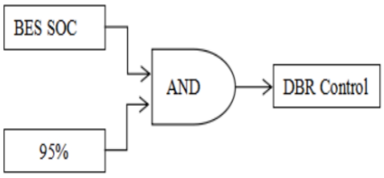

Figure 3.7: DBR control system

In the event of multiple power failures, repeated use of the rescue battery could lead to the battery being fully discharged without sufficient recharging through the regeneration method. For any elevator system a safety circuit checks and measure the battery condition and then only operates the elevator. For this control system also to ensure passenger safety during hoisting, additional control logic was designed into the system to maintain the state of charge of the rescue battery above 40%. If a condition arises when the regenerated energy is not adequate or if the elevator has been off for long time due to which the SOC of the rescue battery reduced below the 40% threshold, then this control logic sent a signal to the charge controller, signaling it to charge the battery directly using the rectified output of the main grid supply.

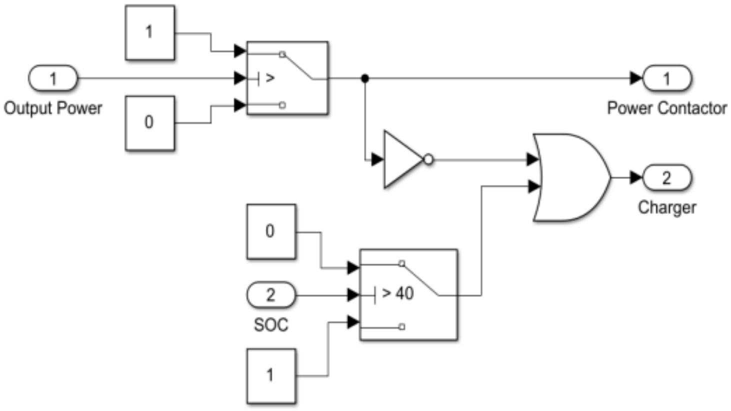

Figure 3.8: Control Logic for charging

In this way the SOC of battery was constantly monitored. Here, the simulation was operated for time duration of 30.8 s, and the PMSM was operated in quadrant I and quadrant IV i.e. motoring and regenerative mode by varying the speed and load torque of the machine. Here, the loaded cabin was hoisted up to simulate motoring mode, and again after some time it was hoisted down to simulate the regenerative mode of operation. The power waveform was observed for both quadrants and analyzed. Further, the simulation was again simulated for 30.8 s to operate the PMSM in the remaining two region, quadrants II and quadrant III. Hence, the machine was operated in all four quadrants by changing the magnitude and direction of the speed and torque of the PMSM.

For speed control, trapezoidal speed curve was provided for each cycle of PMSM to reduce the starting jerk of elevator. Below were the speed parameter used :

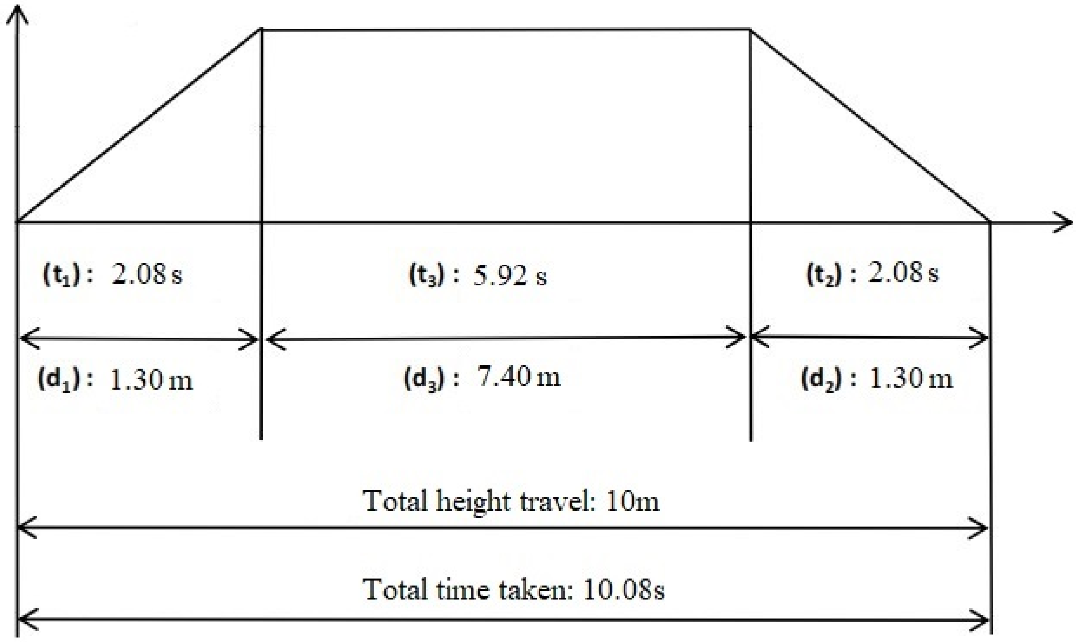

Figure 3.9: Trapezoidal speed curve

In the trapezoidal speed profile shown above, the time taken by the PMSM to accelerate to its rated speed of 15.18 rad/s was 2.08 s. After then, the PMSM operated at a constant speed for a duration of 5.92 s and then decelerated for another 2.08 s until it came to a complete stop condition. The total vertical distance traveled by the cabin was 10 m.

For the simulation, using the trapezoidal curve value, the following input speed profile was provided as input to the machine.

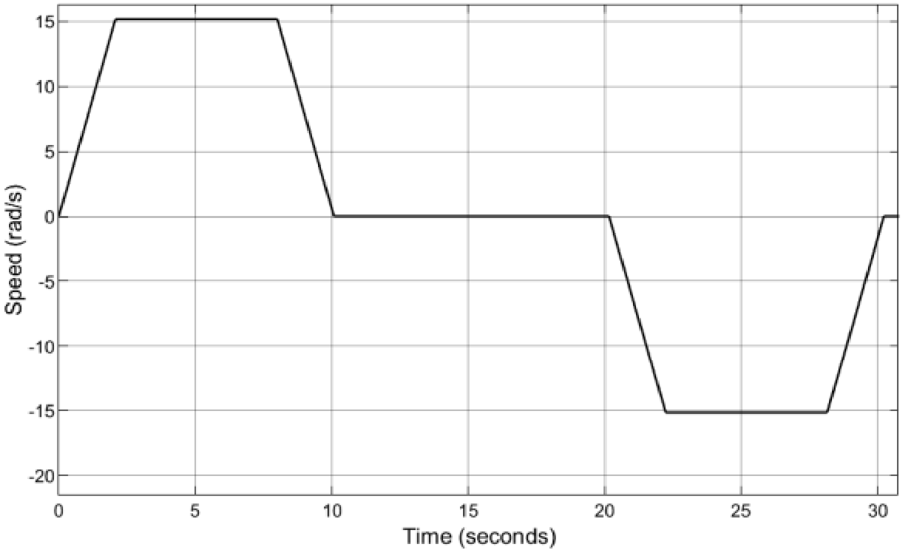

Figure 3.10: Input speed profile for the system

As per Equation (3.1), the unbalanced load of the counterweight against the fully loaded cabin was 102 kg in the negative direction. Using the Torque Equation (3.2), the load torque was found to be 200 Nm in negative direction which is presented in Figure 3.11.

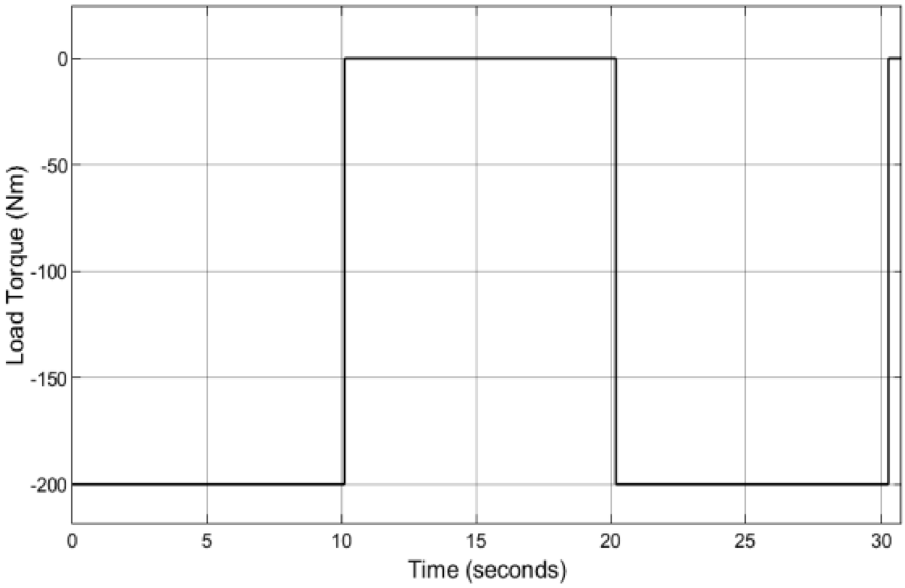

Figure 3.11: Input negative load torque profile for full load condition

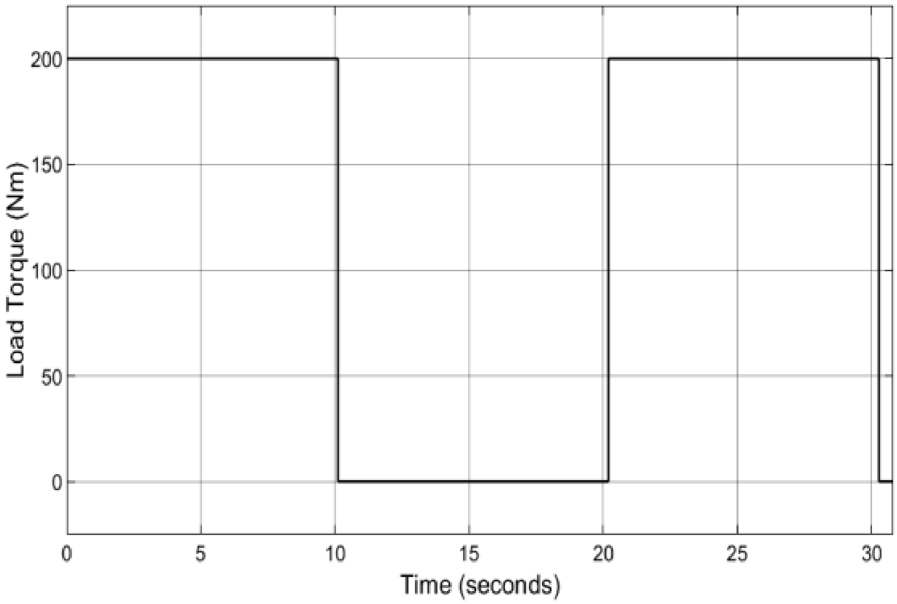

Figure 3.12: Input positive load torque profile for no load condition

Again, using Equation (3.1), the unbalanced load of the counterweight against the empty cabin was 102 kg. Using the torque Equation (3.2), the load torque was found to be 200 Nm in the positive direction, as illustrated in Figure 3.12.

Initially, the system was simulated in quadrant I and quadrant IV with stationary mode in between. At the beginning of the simulation, in quadrant I the elevator system was provided with a forward speed input, lifted the fully loaded cabin upward at the rated speed of $15.18\,\mathrm{rad\,s^{-1}}$. Since the cabin was fully loaded, its weight exceeded that of the counterweight, resulting in a net load torque acting downward. Hence, negative load torque was developed based on the sign convention. To counteract this effect and enable upward movement, the PMSM generated positive electromagnetic torque and operated in motoring mode to lift the cabin.

After motoring mode, the elevator was stopped by reducing both the speed and load torque to zero for stationary operation. During the stationary mode, no active energy exchange occurred, allowing the motor to enter a stopped condition.

Again, the loaded cabin was moved in the downward direction, during which the speed of PMSM became negative and hence, PMSM operated in quadrant IV as the motor developed positive electromagnetic torque. Here, the PMSM operated in regenerative mode, and the generated power was fed back to the storage system via the converter. The overall system's output data was monitored and analyzed.

Similarly, the PMSM was operated in quadrant II and III in no load condition and the output were observed and analyzed. Initially, the system was operated without an energy storage system in order to observe the maximum power generated during the regeneration mode for the machines. Using this power, further calculation was done to calculate the required capacity of the battery storage system.

CHAPTER FOUR: RESULTS AND DISCUSSION

In this research the proposed system was simulated in MATLAB Simulink environment for total time duration of $30.8\,\mathrm{s}$ and the PMSM was operated in all four quadrants. Initially, it was simulated for quadrants I and IV, with a fully loaded cabin. We observed the following mode :

- Motoring Mode
- Stationary Mode
- Regenerative Mode

Similarly, the simulation was again conducted for quadrant II and quadrant III operated at their rated speed and full load torque. Both the full load case and no load cases were simulated, and their outputs were analyzed and compared. Finally, the entire simulation was operated using the rescue battery as source for the observation of rescue operation by cutting of the main power supply using power contactor.

4.1 Full Load Simulation output

Initially, the PMSM was simulated for quadrant I and quadrant IV and the output waveform of speed and electromagnetic torque of PMSM was obtained and are shown below :

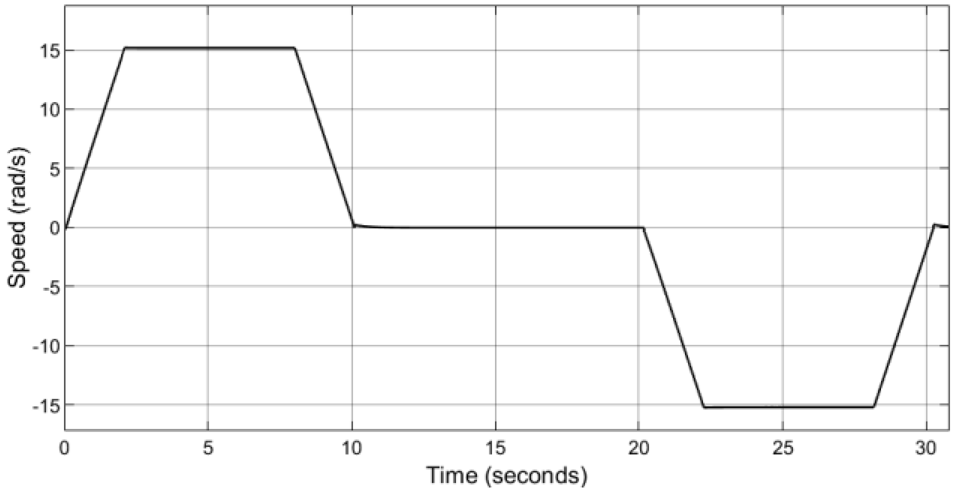

Figure 4.1: Output speed waveform for full load condition

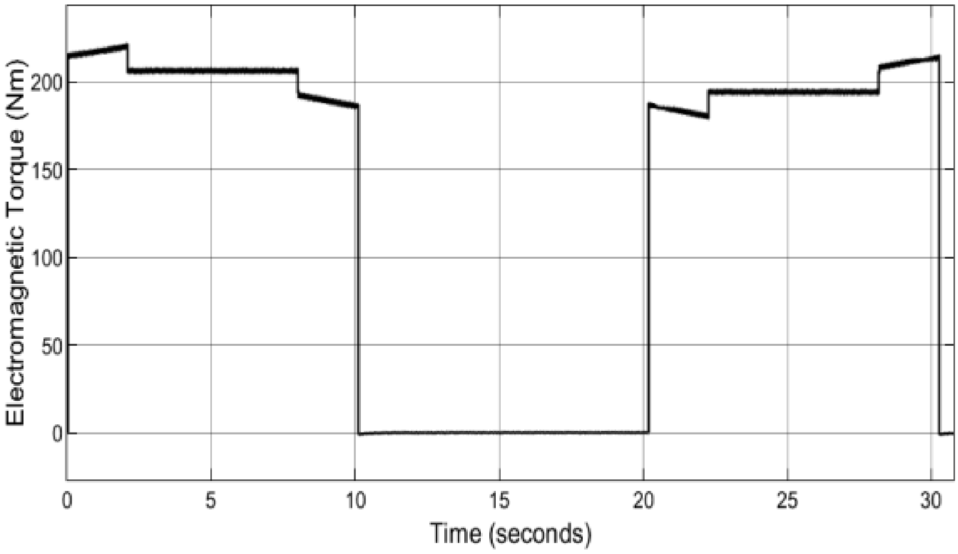

Figure 4.2: Output electromagnetic torque waveform for full load condition

As illustrated in Figures 4.1 and 4.2, the FOC controller tracked the provided speed and load torque profile. Here, the PMSM operated as per the provided trapezoidal speed curve generated positive electromagnetic torque against the provided negative input load torque waveform.

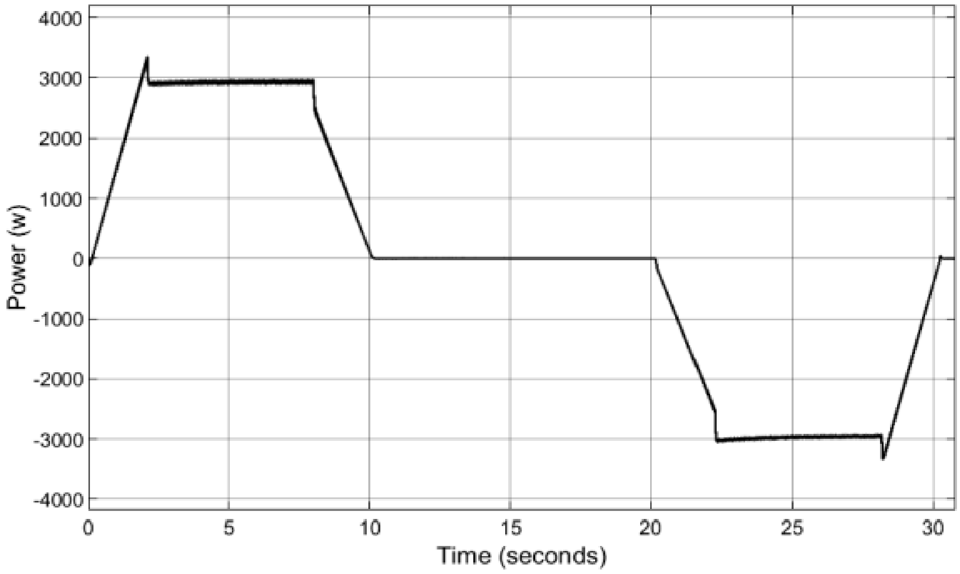

Figure 4.3: Output Power waveform for full load condition

As observed in Figure 4.3, the power remained positive and was increasing during the motoring mode until the system reached its rated speed of $15.18\,\mathrm{rad\,s^{-1}}$, after which it remained constant at this value. During the speed change, we observed that the sign of power became negative due to which regeneration occurred for a fraction amount of time period. This was due to braking of the PMSM until the motor came to a complete stopped condition.

In stationary mode, no power was consumed by the motor. After then, the fully loaded cabin was operated downward direction due to which the sign of speed became negative and the motor generated positive electromagnetic torque of $200\,\mathrm{N\,m}$ to balance the negative load torque, and the PMSM acted as a generator. Here we observed that the waveform of the power was negative signifying a reversal in power flow and feedback into the system. From the simulation, the time duration of regeneration and regenerated power were used for the calculation of the battery capacity required to store the regenerated energy. Based on the obtained power waveform area of generating mode, the amount of generated energy was approximately $5.723\,\mathrm{W\,h}$ per regeneration cycle. From the literature review, the number of times the elevator operated per day was taken approximately 250 times[22]. Using these outputs the capacity of battery energy storage system was estimated as follow:

$$\text{Daily Energy} = 5.723 \times 250 = 1430\,\mathrm{W\,h\,d^{-1}}$$

As per Johnson Lifts Pvt. Ltd., India, a lead-acid battery with a capacity of $48\,\mathrm{V}$ and $336\,\mathrm{W\,h}$ is used for emergency rescue operations for six person elevator system. In this study, the same lead-acid battery specification was employed to simulate the rescue system under power failure conditions. However, to store the exceeded regenerated energy, an additional battery storage system was utilized. Based on calculations, the required additional battery capacity was used, whose capacity was determined to be 48 V and $1095\,\mathrm{W\,h}$. Since lead-acid batteries were commonly used for such applications due to their reliability and cost-effectiveness, the nearest commercially available lead-acid battery with a capacity of $48\,\mathrm{V}$, $30\,\mathrm{A\,h}$ was selected for the simulation. The overall system, including the rescue battery and the additional energy storage battery, was simulated again to analyze its performance. During the simulation, the State of Charge of both batteries was monitored and analyzed.

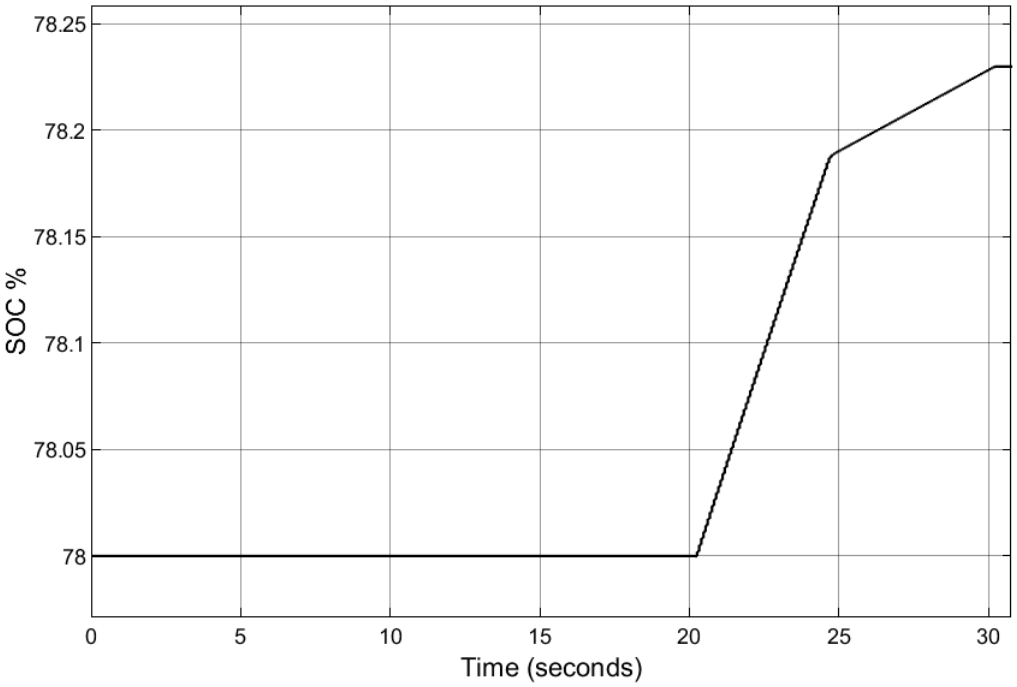

Figure 4.4: SOC waveform of rescue battery for full load condition

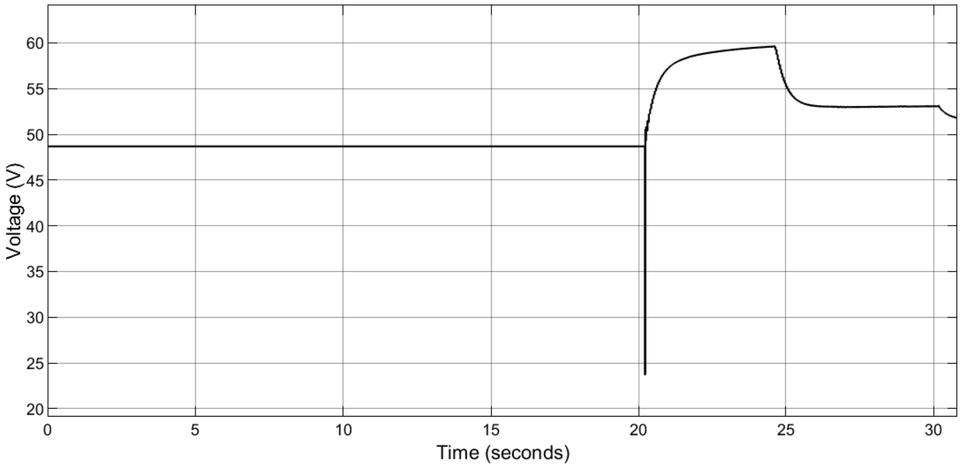

Figure 4.5: Voltage waveform of rescue battery for full load condition

Here, as observed in the above waveform, the battery SOC remained constant until the regeneration period. During the regeneration period the battery received energy from the PMSM and then got charged throughout this braking period.

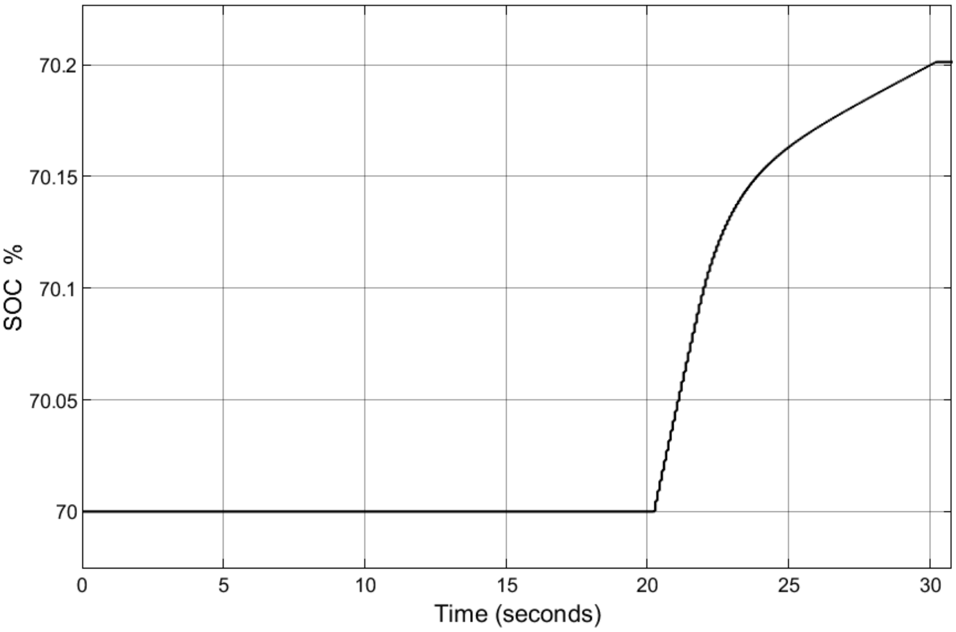

Figure 4.6: SOC waveform of additional battery for full load condition

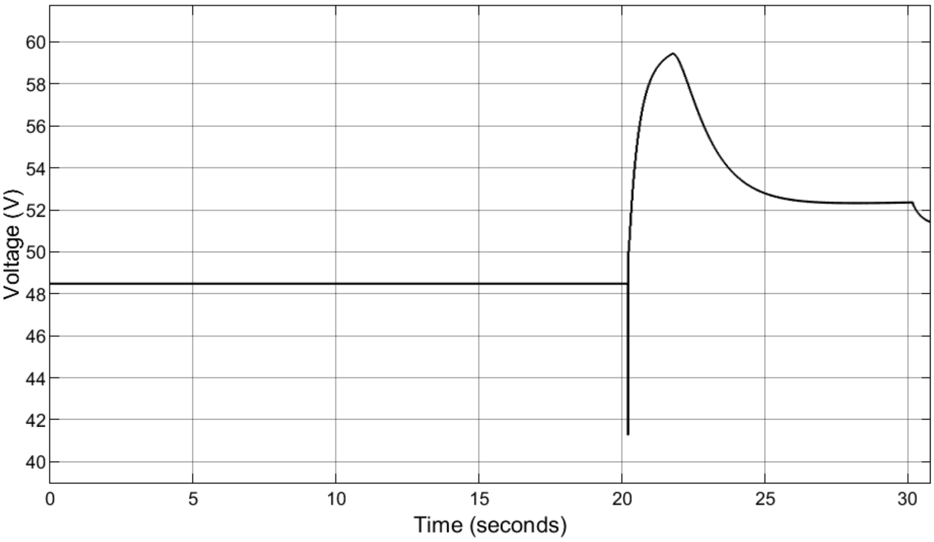

Figure 4.7: Voltage waveform of additional battery for full load condition

From Figure 4.4 and Figure 4.6, it was observed that the charging behavior of both batteries was notably different. This was due to their difference in wh capacity. The rescue battery, having a lower storage wh capacity compared to the additional battery, charged relatively faster. Furthermore, the regenerated energy was stored effectively within the storage system, which would have been otherwise dissipated.

4.2 No Load Simulation output

The simulation was again run for no load condition. For this no load condition the motor had positive load torque input due to which the motor had to generate negative electromagnetic torque in order to operate the motor at desired speed and the waveform obtained were as below :

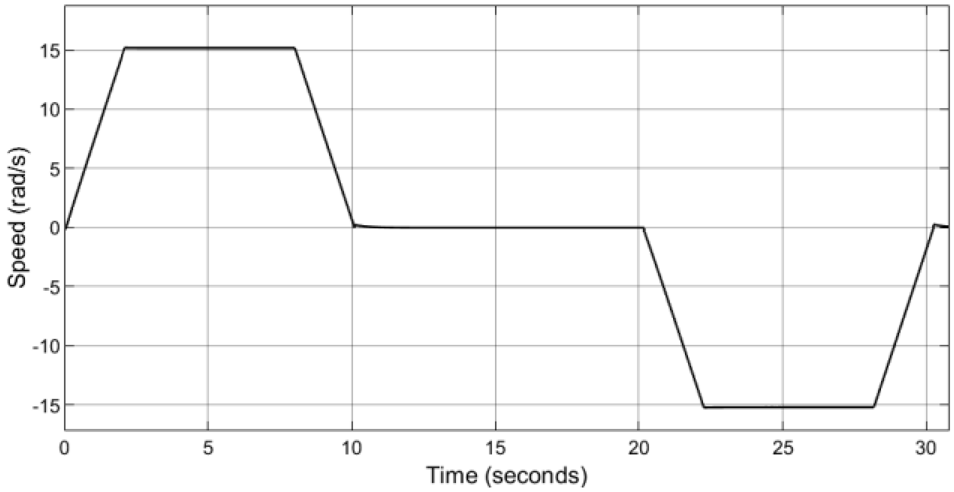

Figure 4.8: Output speed waveform for No Load condition

In this scenario, the FOC block tracked the specified input profile speed and obtained the desired speed accurately. The obtained output electromagnetic torque was as follow :

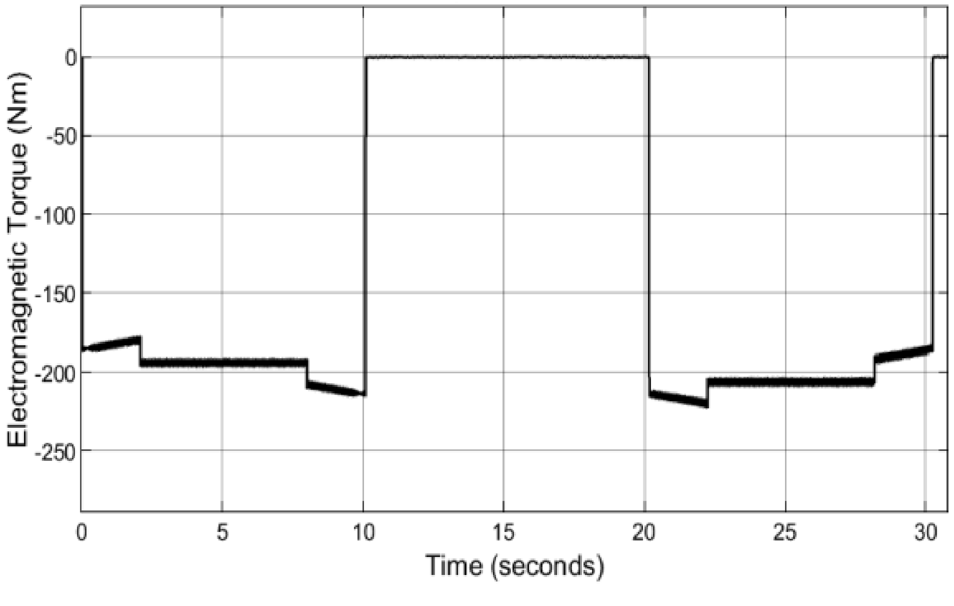

Figure 4.9: Output electromagnetic torque waveform for no load condition

Here, as illustrated in Figure 4.9, for the no-load condition, PMSM motor generated negative electromagnetic torque in order to balance the net positive load torque provided to the motor. The machine operated at a speed of $15.18\,\mathrm{rad\,s^{-1}}$ and generated negative $200\,\mathrm{N\,m}$ electromagnetic torque to counteract the unbalanced load of counterweights against the empty cabin in the first cycle.

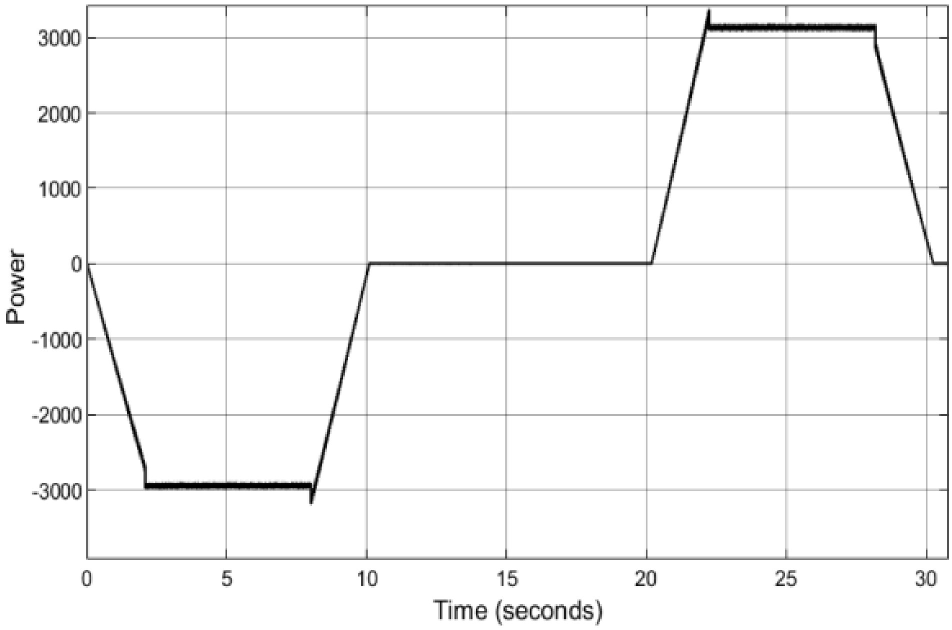

Figure 4.10: Output power waveform for no load condition

Here, the machine operated in quadrant II in forward braking mode, which can be observed in the power waveform curve, where power was negative. During this braking period, the machine regenerated energy, which was fed back into the system via converters. After then, the machine was stopped in the stationary mode. During which no power exchange occurred and both the speed and torque of machine was zero. In last cycle, the machine was operated in negative speed of $15.18\,\mathrm{rad\,s^{-1}}$ (downward direction) with no load inside the cabin and we observed that the motor generated negative electromagnetic torque to balance the unbalanced load of counterweights. Since both the speed and torque had the negative sign, the power consumed by the machine was also positive, the machine operated in quadrant III, reverse motoring mode. This can be observed in the power waveform curve as well. Based on the obtained power waveform area of forward braking mode, the amount of generated energy was the same as obtained in quadrant IV. Below are the waveform of the battery which got charged during the forward braking period. We can observe the SOC of battery kept on increasing during the braking period and after then it remained constant.

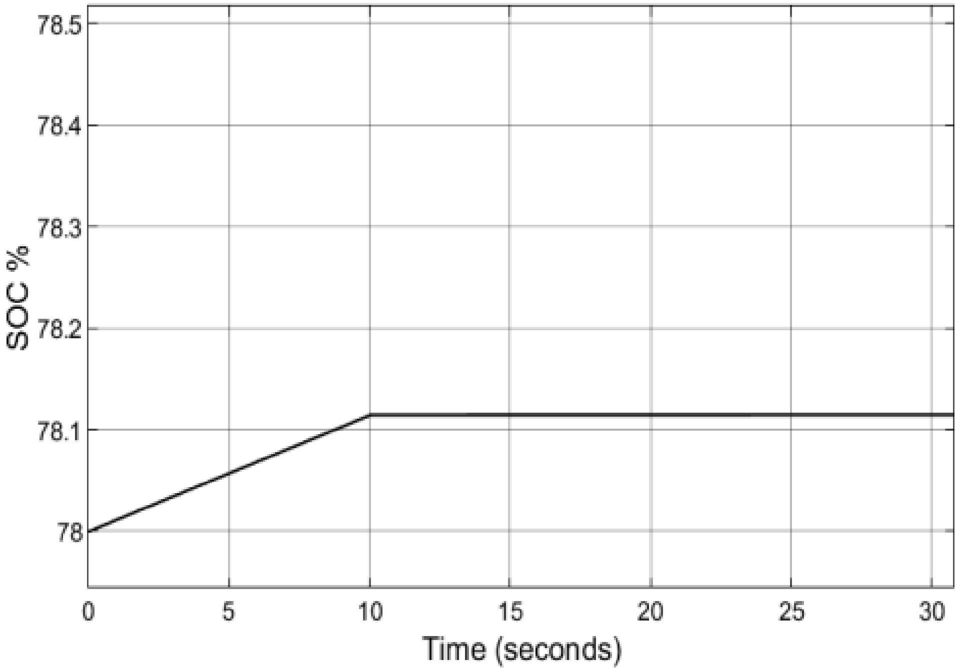

Figure 4.11: SOC waveform of rescue battery for no load condition

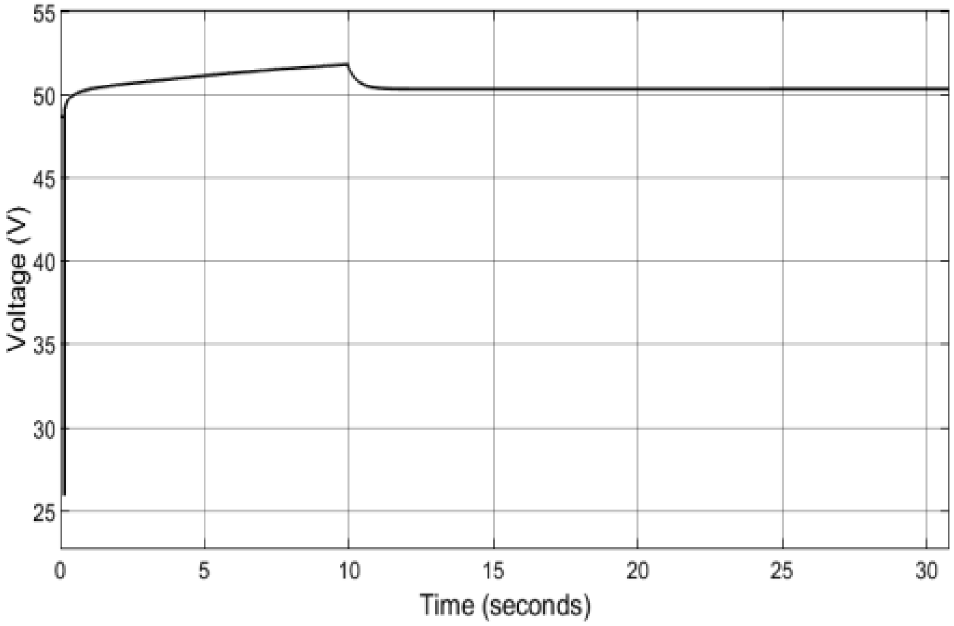

Figure 4.12: Voltage waveform of rescue battery for no load condition

Here, it can be observed that the battery storage system gets charged smoothly during the machine operation in forward braking mode. After then, the SOC remained constant as the PMSM operated in reverse motoring mode.

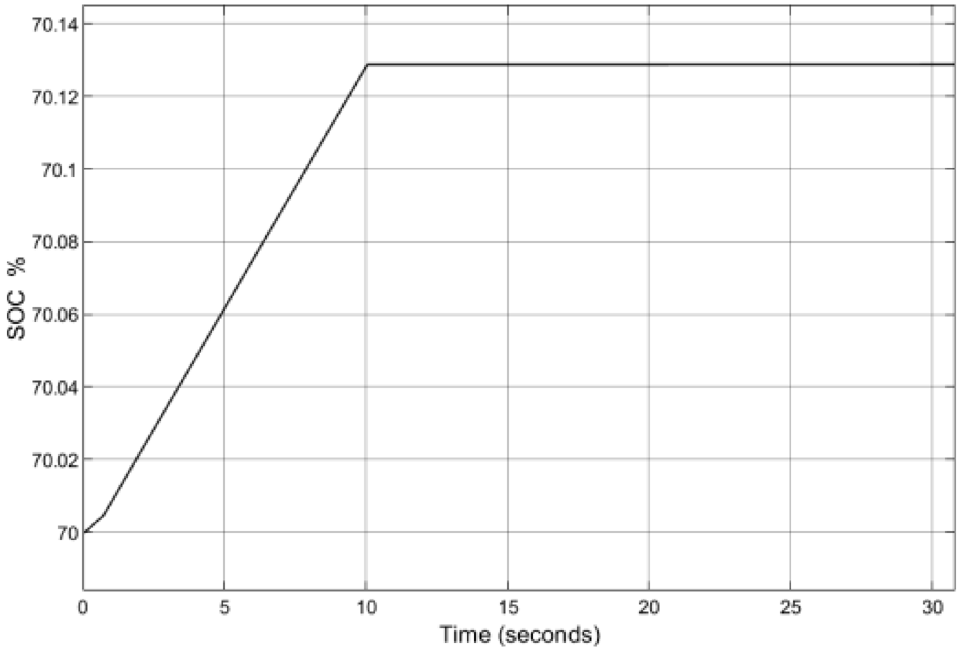

Figure 4.13: SOC waveform of additional battery for no load condition

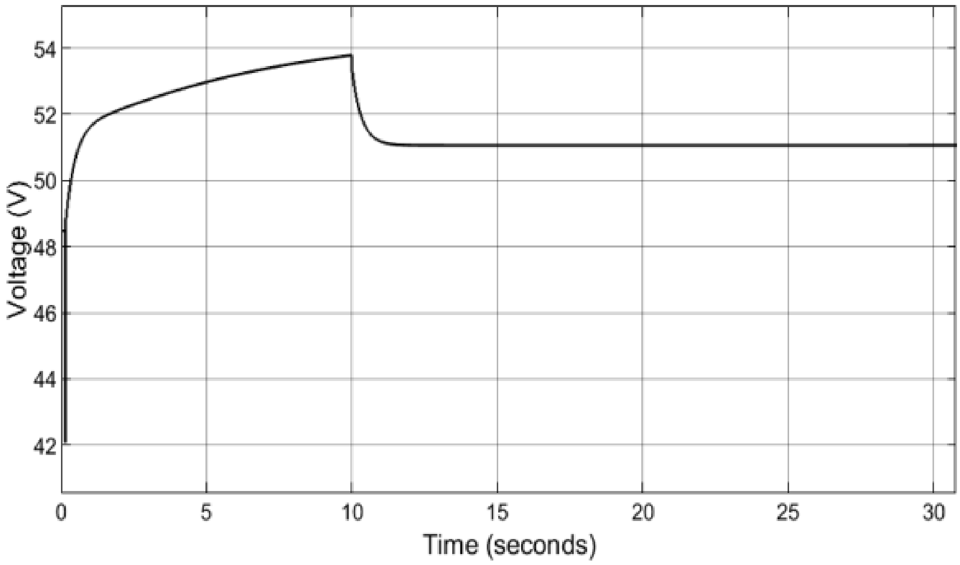

Figure 4.14: Voltage waveform of additional battery for no load condition

4.3 Simulation Results of Rescue operation

The PMSM motor was operated again using the rescue battery by disconnecting the external power source. The state of charge (SOC) of the battery and machine parameters were again observed under this condition for time duration of $10.4\,\mathrm{s}$. To reduce the power requirement during the rescue operation, the speed of the machine also got reduced to 3.8 rad/s while maintaining the 200 Nm load torque. and the waveform observed are as follow :

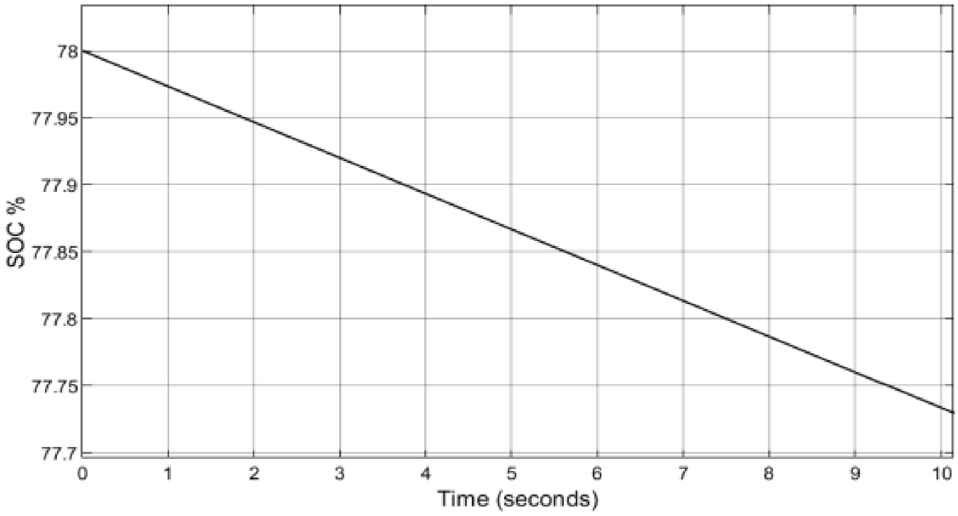

Figure 4.15: Discharge of rescue battery

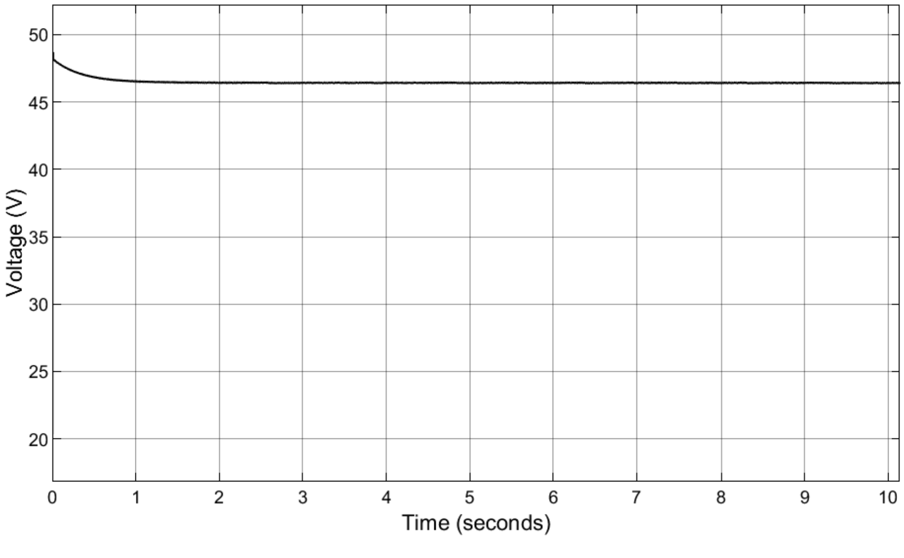

Figure 4.16: Voltage Waveform of rescue battery during rescue operation

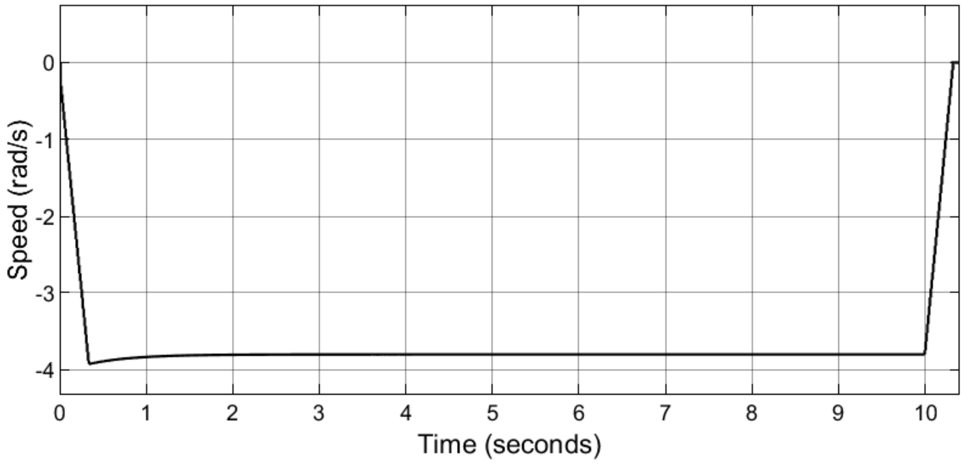

Figure 4.17: Output speed waveform during rescue operation

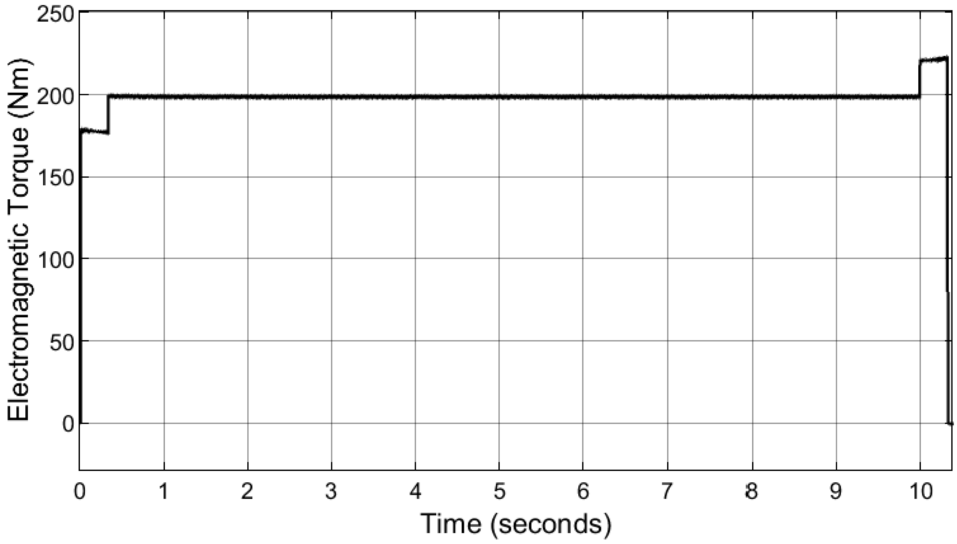

Figure 4.18: Output electromagnetic torque waveform during rescue operation

When the grid supply was disconnected, the rescue battery effectively supplied power to the PMSM via a bi-directional converter, enabling the machine to operate for a specific duration. Furthermore, during the power failure mode, the PMSM operated in reverse braking mode, where speed was negative, and electromagnetic torque was positive. This operational technique allowed the PMSM to function in regenerative mode, ultimately reducing power consumption from the rescue battery during the rescue operation. Thus, during a power failure, the battery backup efficiently provided the necessary power to sustain PMSM operation for a certain period to facilitate nearest floor rescue operation.

CHAPTER FIVE: CONCLUSION

In this research, a PMSM based elevator control system was designed and tested through simulation. The PMSM was controlled using the FOC method, and the machine was operated in all four quadrants. The machine's output was observed in both motoring and generating mode. Regeneration of energy was observed during the generating mode of the machine, and the data was used to estimate the required capacity of the elevator's rescue battery storage system as well as the capacity of additional battery storage system. The entire system, including the battery storage, was simulated to observe the storage of the regenerated energy during the regeneration process. The results confirmed that the regenerated energy was successfully captured and stored. This energy, which was conventionally being dissipated as heat in dynamic braking resistor was effectively recovered and stored in the storage system.

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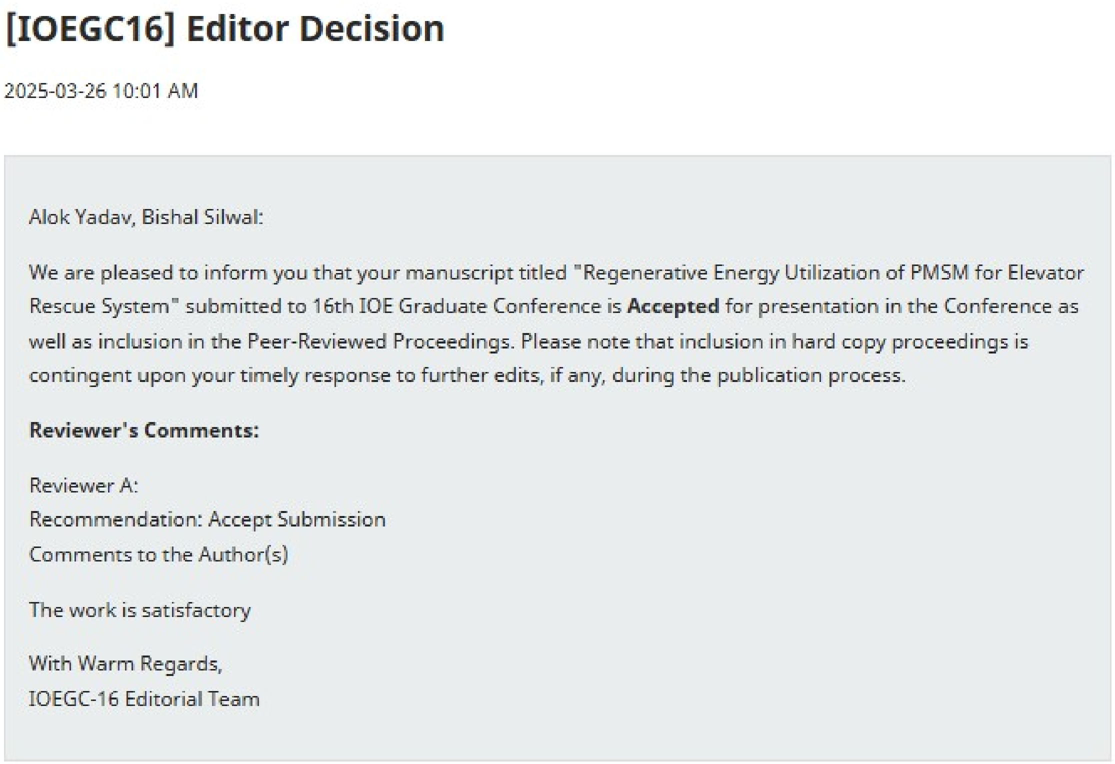
APPENDIX A: PUBLICATION

Conference paper



[IOEGC16] Editor Decision

2025-03-26 10:01 AM

Alok Yadav, Bishal Silwal:

We are pleased to inform you that your manuscript titled "Regenerative Energy Utilization of PMSM for Elevator Rescue System" submitted to 16th IOE Graduate Conference is **Accepted** for presentation in the Conference as well as inclusion in the Peer-Reviewed Proceedings. Please note that inclusion in hard copy proceedings is contingent upon your timely response to further edits, if any, during the publication process.

Reviewer's Comments:

Reviewer A:
Recommendation: Accept Submission
Comments to the Author(s)

The work is satisfactory

With Warm Regards,
IOEGC-16 Editorial Team

Regenerative Energy Utilization of PMSM for Elevator Rescue System

Alok Yadav [a], *Bishal Silwal* [b]

Abstract:

With the rise of multi-story buildings, the demand for elevators is also increasing, leading to a higher energy requirement. An elevator operates by hoisting its carriage up or down by supplying the necessary torque to balance the weight difference between the carriage and counterweights. Due to varying carriage loads, the elevator sometimes operates in regenerative mode, converting gravitational potential energy into electrical energy. The amount of regenerated energy depends upon the height of building and the capacity of elevator. Traditionally, this regenerated energy was dissipated in braking resistors. However, with the implementation of regenerative control, this energy can be harnessed for various purposes. This paper explores the potential of regenerative energy recovery in elevator systems and its storage for backup and additional power needs, ultimately improving overall system efficiency, reliability, and sustainability.

Keywords:

Field Oriented Control, Regenerative Braking, Counterweights, Pulse Width Modulation

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IOE Graduate Conference
[Placeholder for Publication Information]

Regenerative Energy Utilization of PMSM for Elevator Rescue System

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Abstract

With the rise of multi-story buildings, the demand for elevators is also increasing, leading to a higher energy requirement. An elevator operates by hoisting its carriage up or down by supplying the necessary torque to balance the weight difference between the carriage and counterweights. Due to varying carriage loads, the elevator sometimes operates in regenerative mode, converting gravitational potential energy into electrical energy. The amount of regenerated energy depends upon the height of the building and the capacity of the elevator. Traditionally, this regenerated energy was dissipated in braking resistors. However, with the implementation of regenerative control, this energy can be harnessed for various purposes. This paper explores the potential of regenerative energy recovery in elevator systems and its storage for backup and additional power needs, ultimately improving overall system efficiency, reliability, and sustainability.

Keywords

Field Oriented Control, Regenerative Braking, Counterweights, Pulse Width Modulation

1. Introduction

1.1 Background

Elevators are commonly used in buildings, especially high-rise structures, and are widely used for vertical transportation. The amount of energy usage differs depending on the type of structure, such as residential apartments, healthcare facilities, or commercial buildings. As a result, elevators, as a component, account for a significant portion of a building's total energy consumption. Elevators employ machines such as Permanent Magnet Synchronous Motors (PMSMs), which can operate in all four quadrants [1]. These motors consume power to operate during motoring mode and can also generate power during regenerative mode. Here, the amount of regenerated energy depends on the direction of the loaded or empty cabin against the counterweights. The counterweights used for the elevator are the sum of the cabin weight and half of the elevator's rated load[2]. With the variation of the cabin load and the direction of movement, the amount of energy regenerated varies. In many conventional elevator systems, this regenerative power is converted to heat energy by the externally connected dynamic braking resistor which results in wastage of regenerated energy [3]. With proper control strategy implementation, this energy could be stored and utilized for various purposes in order to reduce the overall energy consumption of the building.

In recent years, Permanent Magnet Synchronous Motors (PMSM) have been widely utilized due to their superior torque-to-inertia ratio, high power density, broad speed range, and high torque capacity [4]. In the elevator sector, gearless PMSM motors are favored over traditional geared induction motors because of their compactness, enhanced efficiency, and extended maintenance cycles. These motors consume less energy, operate more smoothly, and deliver faster and more efficient performance. However, the absence of an optimized regenerative energy system utilization framework for PMSM-based elevators limits the efforts to reduce the energy consumption, enhance operational reliability, and improve the system's overall sustainability.

1.2 Energy Recovery with PMSM Drive

The challenge lies in developing an efficient and reliable solution to utilize regenerative energy during braking periods to enhance the sustainability and energy efficiency of the elevator system. With the use of back-to-back converter topology, the PMSM drive system can operate in both motoring mode and regenerative mode. The regenerative converter system consists of a grid-side converter connected to a DC bus with capacitors in parallel and a fully controllable bidirectional converter connected on the motor side [5]. During the time of regeneration, the cabin load drives the PMSM, which then operates as a generator to produce electrical energy. Battery energy storage system stores this regenerated energy. Further, a Dynamic Braking Resistor is also used to dissipate excess energy that cannot be further stored in the storage system.

1.3 Elevator Rescue System

In complex systems such as elevators, which integrate various components like electrical machines and variable voltage variable frequency drives, faults are bound to occur. For this reason, it is vital to establish a backup mechanism to guarantee passenger safety and facilitate rescue operations during power failures. This system safeguards passengers during elevator operation and relies on a dedicated energy storage solution, typically a battery energy storage system. Traditionally, these batteries are charged using power from the main grid, which raises the elevator's overall energy consumption and leads to higher power usage. By harnessing the regenerated energy from the motor-driven system, the energy can be stored in the elevator's rescue backup system, effectively reducing the total energy consumption by the overall system.

2. Methodology

The methodology for this research involves a structured approach, incorporating advanced control strategies and energy recovery techniques. The overall elevator control system was designed and developed in MATLAB/Simulink environment. The strategy employed for the control of PMSM is the Field-Oriented Control (FOC) method, which is highly effective in managing the motor's torque and flux components independently. This ensures precise control and optimal performance, even under varying load conditions. The system also consists of a bi-directional converter designed to capture, store, and reuse the energy generated during the regeneration period, thereby improving overall energy efficiency.

2.1 Field Oriented Control

The motor's stator current comprises of two orthogonal components: the d-axis component and the q-axis component. The d-axis component is responsible for regulating the motor's flux, while the q-axis component governs the torque. Field-Oriented Control (FOC) is employed to decouple these components, enabling accurate and independent torque regulation even under dynamic load conditions.

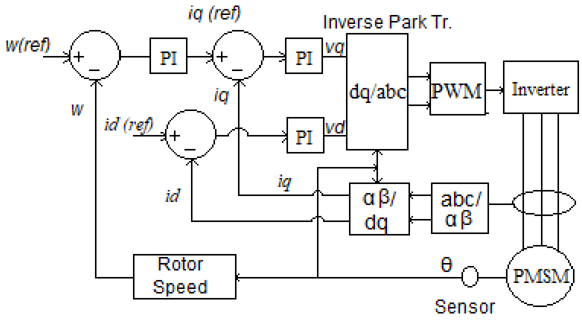

Figure 1: Field Oriented Control Strategy [6]

The PMSM can be represented by using the following set of nonlinear mathematical equations, expressed in the d-q reference frame [7, 8]:

$$\frac{di_d}{dt} = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}pw_ri_q \tag{1}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q - \frac{L_d}{L_q}pw_ri_d - \frac{\lambda pw_r}{L_q} \tag{2}$$

$$T_e = 1.5p[\lambda i_q + (L_d - L_q)i_di_q] \tag{3}$$

$$\frac{dw_r}{dt} = \frac{1}{J}(T_e - Fw_r - T_m) \tag{4}$$

where,
L_d, L_q are the inductances of the d-axis and q-axis.
V_d, V_q are the voltages along the d-axis and q-axis.
i_d, i_q are the currents along the d-axis and q-axis.
λ is the magnetic flux of the motor.
p is the number of pole pairs.

The mathematical equations above are used to formulate a control strategy for PMSM. In this approach, the measured values of i_q, i_d, and ω are compared with their reference values and fed to a PI controller. The controller block then generates the necessary gate signals required for the inverter to operate the PMSM.

2.2 Energy Storage Control Strategy

The regenerated power must be processed to achieve the required charging voltage for the battery. A

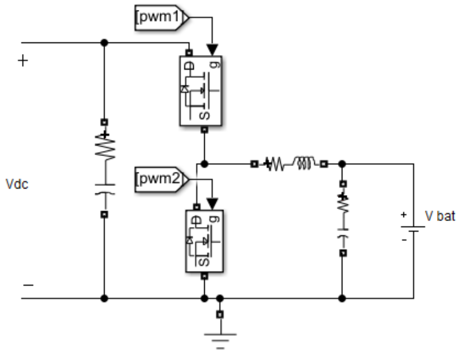

Figure 2: Bi-directional DC-DC Converter

bi-directional converter is used for this purpose to charge the battery during regeneration mode and also to supply the stored energy back to the elevator during the power failure mode.

2.3 Overall Control System Design

The control system was developed using the MATLAB Simulink environment. The technical specifications of the PMSM Motor used in this system were sourced from Johnson Lifts Pvt. Ltd., India. The detailed specifications of the machine are presented in Table 1.

Parameters	Units	Value
Rated Power	kW	3.1
Rated Voltage	V	380
Rated Current	A	8
Inertia	kg.m^2	1.92
Rated Speed	rpm	145
Rated Torque	N.m	204
Rated Capacity	kg	408
Duty	%	S5-40

Table 1: Machine Parameters

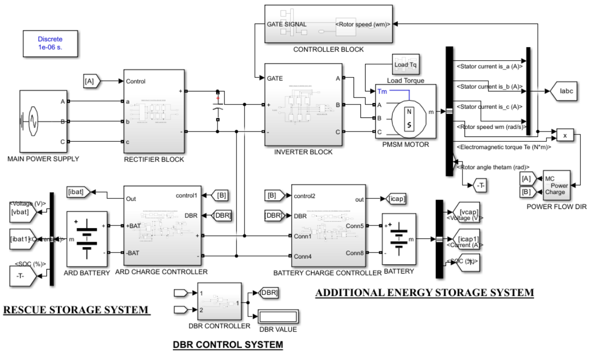

Figure 3: Circuit Design of FOC based PMSM Regeneration System

In this system, the 380 V grid supply undergoes rectification before being delivered to the inverter. The inverter then powers the PMSM based on the gate pulses generated by the FOC controller block. The FOC controller continuously monitors the PMSM output, compares it with the provided reference value, and generates the appropriate gate signals. These signals were subsequently supplied to the inverter, thereby establishing a closed-loop feedback control system. Here, the Charge Controller blocks were used to control the charging and discharging of the batteries. The Dynamic Braking Resistor (DBR) was implemented in order to dissipate excess energy once the storage system reached full charge [9].

Here, the Simulation was conducted for both motoring and regenerative mode, with the energy regenerated during the regenerative mode being quantified. The PMSM was run at rated speed of 15.18 rad s^{-1}(145 rpm) and rated torque of 204 N m. Here, the Net load torque, Speed, and direction of rotation were varied at certain time intervals, as shown in Figure 4 and Figure 5:

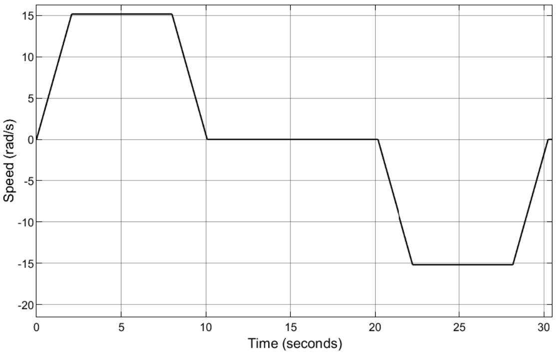

Figure 4: Input Speed Profile for the System

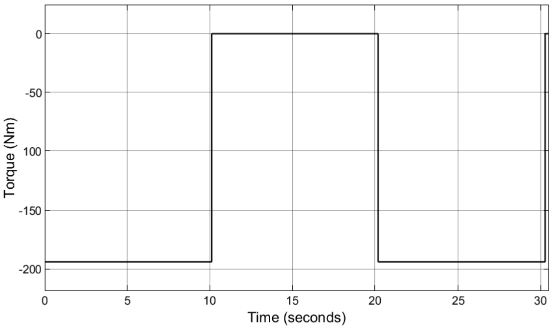

Figure 5: Input Net Load Torque profile for the system

At the beginning of the operation, the elevator system lifted the fully loaded cabin in the upward direction at the rated speed. Since the cabin's weight exceeded the counterweight, the resulting net load torque acted in the downward direction. To counteract this effect and enable upward movement, the PMSM generated positive torque (Motoring Mode). During the Stationary mode no active energy exchange occurred, which allowed the motor to be in a stopped condition. Again, the loaded cabin was moved in downward direction, during which PMSM operated in Reverse braking mode. In this mode, the PMSM operated as a generator feeding power back to the converter. The system's output data were monitored and collected for the calculation of the battery energy storage system capacity required for the storage of regenerated energy.

3. Results and Discussion

The proposed circuit was simulated in MATLAB/Simulink for the time duration of 30.5 s, and the output obtained was observed and analyzed.

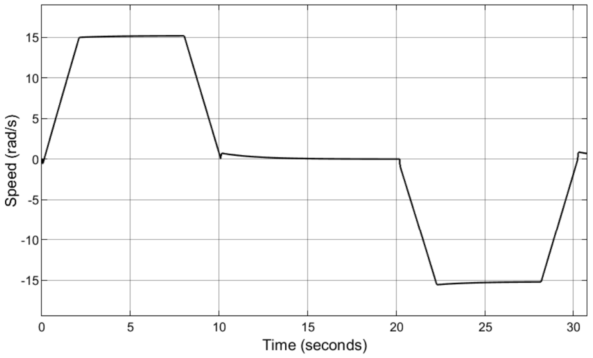

Figure 6: Output waveform of Speed

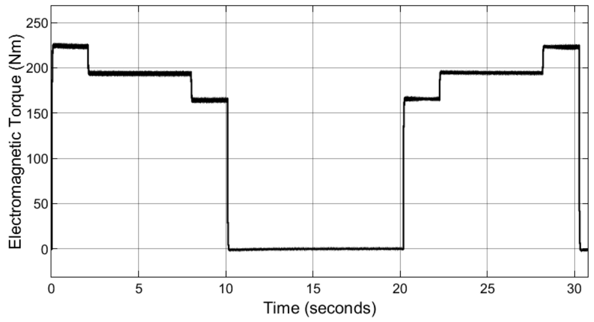

Figure 7: Output waveform of Electromagnetic Torque

As illustrated in Figures 6 and 7, the FOC controller tracked the provided speed and load torque profile. Consequently, the PMSM operated under the given input conditions and direction.

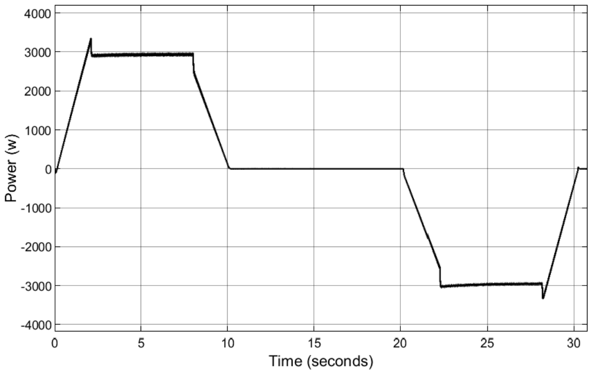

Figure 8: Output waveform of Power of the System

As observed in Figure 8, the power remained positive and was increasing during the motoring mode until the system reached its rated speed, after which it remained constant. During the braking period, we observed that the sign of power became negative due to which regeneration occurred for a small amount of time period. In stationary mode, no power was consumed by the motor. When the fully loaded cabin was operated downward, the sign of speed became negative, and the PMSM acted as a generator. Here, we observed that the waveform of the power was negative, signifying a reversal in power flow and feedback into the system.

From the simulation, the time duration of regeneration and the amount of regenerated energy were used for the calculation of the battery capacity required to store the regenerated energy. Based on the analysis of the power waveform area, the amount of energy generated was approximately 5.533 Wh per cycle. From the literature review, the elevator was assumed to operate approximately 250 times per day in regeneration mode [9]. Hence, the required battery energy storage capacity was estimated to be around 1.38 kWh.

$$\text{Daily Energy} = 5.533 \times 250 = 1388.33 \text{ Wh/day} \tag{5}$$

Generally, for a 6-person elevator system, a battery with a capacity of 48 V and 336 Wh is utilized for rescue operations. For this paper also the same battery capacity was employed for the rescue system. Consequently, the additional battery capacity required was determined to be 48 V and 1052 Wh. The overall system was simulated along with the battery energy storage systems, and the State of Charge (SOC) of the batteries was observed.

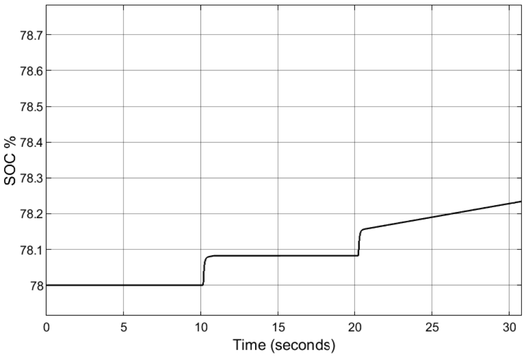

Figure 9: SOC of Rescue Battery Storage System

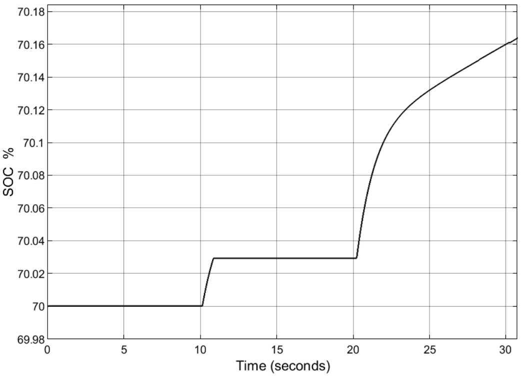

Figure 10: SOC of Additional Battery Storage System

From Figures 9 and 10, we observed that the charging behavior of both batteries was notably different. This was due to their difference in Wh capacity. The rescue battery, having a lower storage capacity compared to the additional battery, got charged relatively faster. Furthermore, the regenerated energy was stored effectively within the storage system, which would have been otherwise dissipated.

4. Conclusion

In this paper, a regenerative PMSM control system was designed and tested through simulation. The regenerated energy was analyzed for each cycle, and the data was used to estimate the required capacity of the battery storage system. The entire system, including the battery storage, was again simulated to observe how energy was stored during the regeneration period. The results confirmed that the regenerated energy was successfully captured and stored, demonstrating the system's effectiveness in energy recovery.

Acknowledgements

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APPENDIX B: PLAGIARISM TEST REPORT

Alok Yadav

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Tribhuvan University

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