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Sustainable Elevator Design Using Regenerative Energy Storage in Geared and Gearless Machines

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Abstract: The rapid growth of urban infrastructure has led to an increased reliance on elevators in high-rise buildings, making them a significant source of electrical energy consumption. Elevators operate through motoring and braking cycles, during which substantial energy is dissipated as heat via dynamic resistors. This study proposes an energy storage mechanism to harness regenerative energy produced during elevator operation for auxiliary power. A comparative analysis between geared and gearless elevators was conducted using simulation and experimental validation. MATLAB/Simulink models were developed, incorporating components such as a three-phase power supply, rectifier, inverter, DC–DC converter, and storage battery. A three-phase induction motor simulated the geared system, while a permanent magnet synchronous motor (PMSM) represented the gearless configuration. Simulation results showed that the PMSM drive produced higher DC voltages (170–220 V) than the geared drive. Experimental verification showed that the geared system with an 18.5 kW induction motor produced 0.68 kW of regenerative power per cycle, whereas the gearless PMSM achieved 6.65 kW. These results confirm the superior energy-recovery efficiency of gearless drives, due to their minimal mechanical losses. The proposed regenerative braking and battery storage approach offers a sustainable, energy-efficient alternative to reduce grid dependency in modern building elevator systems.

Keywords: Battery Energy Storage (BES); Regenerative Energy; Geared and Gearless Drives; Permanent Magnet Synchronous Motor; Variable Voltage Variable Frequency.

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1. Introduction

Energy saved equals energy produced. To achieve sustainability, energy performance and efficiency have become significant issues worldwide. Elevators are becoming a typical feature in multi-story structures. Compared with older systems, modern drives and efficient inverters dramatically reduce operating costs. Excess energy is converted to heat by brake resistors in older systems, rather than being recycled through energy recovery utilising battery energy storage elevator systems. A green building is designed, built, and operated to solve sustainability issues such as energy, the environment, and water. According to the Green Building Council, a green building "consumes less water, optimises energy efficiency, conserves natural resources, generates less waste, and provides healthier environments for inhabitants than a conventional building"(IGBC) [1]. In terms of energy, the Elevator serves as an electrical-to-mechanical energy transformer and vice versa. Acceleration, travel, deceleration, and braking are all intermediary stages in the transformation. The ability of the drive to transfer the mechanical energy of the motor and linked load into electrical energy that is returned (or regenerated) to the AC power supply is referred to as regenerative. The power generated by the traction machine in traditional elevators is wasted as heat in the building [2]. When a traction elevator lifts a fully loaded car, electrical power is transferred from the building's utility to the elevator system. That same fully loaded car, on the other end, will regenerate energy as it rises. The mechanism generates more power than it consumes when a cab climbs up with a small load and down with a heavy load. These little quantities of energy generated during each Elevator's irregular decelerations add up to significant savings over time. In other words, the mechanical system's stored energy is turned back into electrical energy [3].

The motor-generator mechanism and relationship. The motor is usually powered by electricity. The generator, on the other hand, generates electricity by turning its shaft in response to an external force. Although the two systems have distinctive characteristics, their mechanisms are identical. The hoisting motor in elevators is typically driven by a Variable Voltage Variable Frequency (VVVF) converter with an intermediate DC connection and a speed and position feedback encoder or resolver. When it comes to increasing energy efficiency and driving comfort, energy converters are the go-to solution. When a motor decelerates or a load descends, regenerative energy is returned to the VVVF. Regenerative energy, often called regenerative power, is a potential energy technology that can drive down costs. Various strategies for using regenerated energy (rather than wasting it) in elevator applications are proposed as the most effective approaches. The employment of an ultracapacitor energy storage system in conjunction with a control means to reduce current ripple and so achieve a higher level of energy savings [4]. Building sustainability certifications and green building ratings have received significant attention in various worldwide and national action plans for energy conservation. In the context of sustainable development, lift usage is critical because it significantly impacts building energy use. Roped Elevators have been widely used in numerous buildings for many years and are still in use today, despite their significant energy costs [5]. Hydraulic elevators are a more recent type of Elevator; however, because they lack a counterweight, they are no longer popular. A new elevator configuration is being proposed by the specialised industry in the sector, based primarily on regenerative PMSM electrical drives, coupled with energy storage for regeneration and power peak shaving. Such solutions provide good service and energy savings, but system modernisation can be costly.

2. Literature Review

Plangklang et al. [1] presented the implementation of Grid-connected Power Generation from a Permanent Magnet Motor Elevator using an Energy Regenerative Unit (ERU). The proposed ERU converts DC voltage to AC voltage for grid synchronisation. The ERU is operating as a three-phase module [6]. Kubade et al. [3] had presented the drive mechanism of an elevator, which is thoroughly evaluated to optimise its operation and reduce energy usage. The DBR system is replaced by a regenerative braking system that stores energy generated during braking in a supercapacitor. Super Capacitors are used as an energy storage device [7]. Kermani et al. [9] presented a method to improve and implement an existing inverter drive unit to achieve remarkable energy savings in elevator systems. An elevator's operation can be classified into two modes: motoring and generating. The goal is to create an energy-regenerative elevator system that can feed electricity back into the grid [8]. Erica et al. [4] presented the regenerative elevator operation and energy savings of the faculty elevator. They studied measurements of low and high travel demand. The results are compared with the same Elevator [9]. The effects of travel demand on regenerative potential and energy efficiency are analysed. Energy savings are calculated using two different approaches, and the impact of standby energy is highlighted [10]. Makar et al. [5] reported that regenerative energy must be stored or returned to the Grid to improve the energy efficiency of traction elevators. Using the necessary DC/DC converters, regenerative energy can be stored in batteries [11]. After reviewing the relevant literature and the authors' viewpoints, researchers concluded that energy is lost in both geared and gearless elevators. The scope of energy saving is observed. Wasted energy methods were observed. Consider the various ways in which regenerative energy could be applied.

3. Methodology

In the context of elevators incorporating a saving system, Various methods have been proposed as the optimal means to utilise the regained energy rather than waste it. Figure 1 shows the overall structure of the Elevator, which consists of three primary parts. A three-phase rectifier is employed to interface between the overall Grid and the DC link. From the DC link, the inverter supplied the overall Grid with the AC supply to the motor. The recovered supply to the motor, driven by the rectifier, is connected to the DC link via two individual bidirectional DC-DC converters for charging and discharging. The battery source powers the DC link. In charging mode, Batteries receive regenerative energy via the DC link. For the discharging mode. Distributes the regained energy to the common load. This method to provide extra power to the overall Grid requires designing and implementing the overall backup conversion system with enormous expenditure on the overall grid authorities. This finally makes no sense as a deduction. This proposed idea introduces the utilisation of energy storage to encourage the usage of a high percentage of renewable energy in elevators. Hence. The proposed idea is to denote the total energy usage of elevators. To signify the abovestated aims. The overall drive system has an overall energy revival capability for the electric machine. Its simulation is primarily performed using MATLAB and Simulink. Its simulation shows that a high percentage of energy is appropriately revived using the overall energy storage item. This is a unique concern. This proposed idea considers using a battery as an overall energy storage device. This well-stored overall battery energy is appropriately used to denote its primary purpose: providing extra overall power for common overall load applications such as light fittings. Fans. Intercoms. Rescue tools. Buzzers. The methodology for conducting the study, as mentioned above, involved statistical analysis, simulation, and validation of the feasibility of regenerative energy use in geared and gearless elevators. The proposed simulation and experimental activities were conducted to validate the feasibility of geared and gearless elevators in utilising regenerative energy.

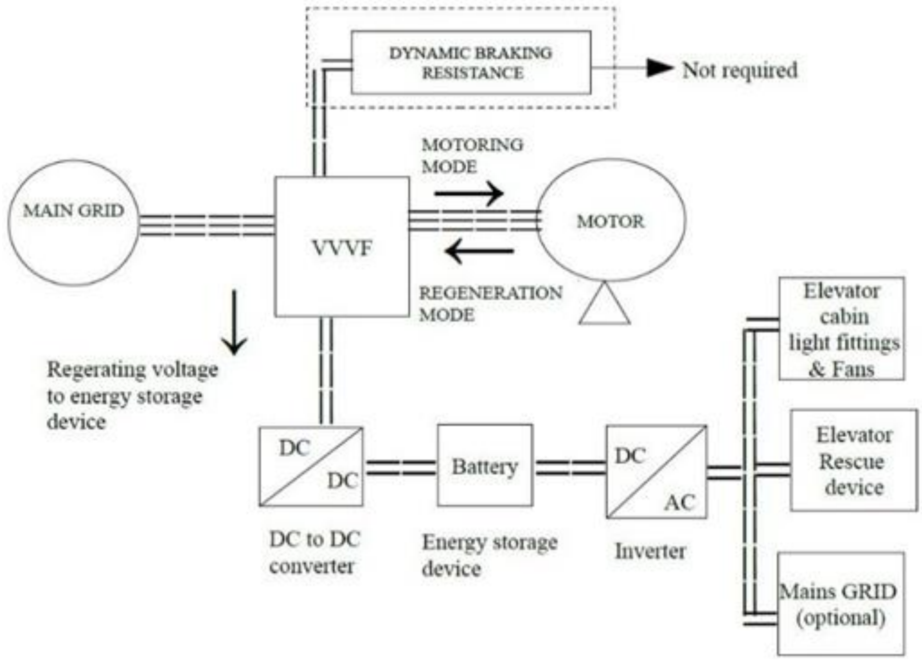

Figure 1: Block diagram of the proposed elevator system

The first stage of experimental work focused on simulating the regenerative behaviour of geared and gearless elevators. For this purpose, the simulation model of the geared and gearless elevator systems developed focused on their behaviour related to load and motion. To perform experiments on geared and gearless elevators, the simulation model described above was developed to include a variable-voltage variable-frequency (VVVF) controller. A wide range of electrical components, including a three-phase power supply, rectifier circuit, LC filter, motor drive system, braking chopper circuit, DC-DC converter circuit, energy storage battery, and, finally, the inverter circuit, were incorporated into the simulated model. To simulate geared elevators, the model included a variable-voltage variable-frequency (VVVF) drive mechanism with an induction motor. For simulating the gearless model during experiments conducted for the proposed work, the simulation model included a permanent magnet synchronous motor (PMSM) to model the behaviour of geared elevators. According to the model developed above, during the first stage of experimental work for this proposal, simulations of geared and gearless elevators utilising the variable-voltage variable-frequency (VVVF) drive mechanism were extensive. To model geared elevators during simulation work conducted during the proposed work, which focused on elevators with variable voltage variable frequency (VVVF) control. For simulating geared elevators during experiments conducted for the proposed work above, focused on elevators with variable-voltage variable-frequency (VVVF) control. As described above in the methodology for the experimental simulation work related to elevators with variable-voltage variable-frequency (VVVF) control conducted during this proposed work, the focus is on geared elevators with VVVF control.

4. Simulation Results and Discussion

MATLAB/Simulink software simulation results showed that the geared induction motor drive and the gearless PMSM drive have similar results for calculating the energy generated during regenerative mode. This is because the geared drive and the gearless PMSM drive have similar dynamic behaviour. Moreover, simulation results demonstrated that the energy generated during regenerative mode is little affected, regardless of whether it is a geared drive or a PMSM drive. This is because the method accurately calculates the energy generated in both situations. For the gearless PMSM motor drive, simulation results were obtained to determine the motor's regenerative abilities during upward motion. The simulation results showed that the PMSM motor speed remained constant at 2500 RPM, as shown in Figure 2, ensuring smooth torque production without oscillations. The developed voltage is then fed to a DC-DC converter that steps down to 54V DC to charge four 12V 18Ah series-connected VRLA batteries.

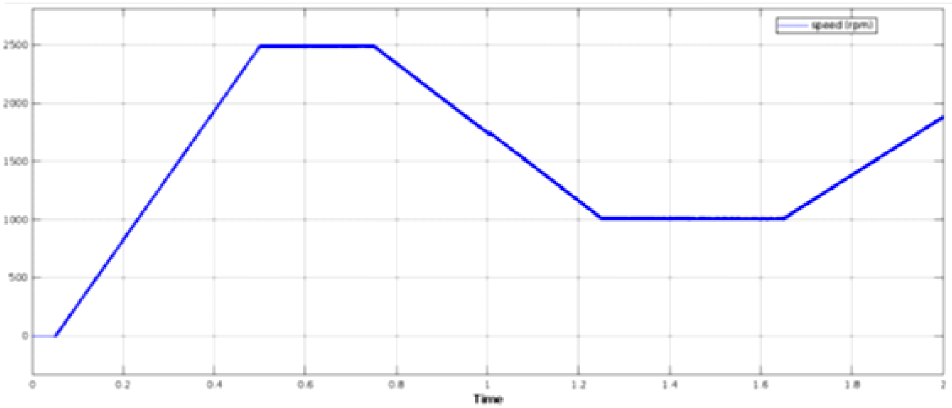

Figure 2: Simulation results of the speed curve of the PMSM gearless machine

The stator current is 165A and has a balanced three-phase sinusoidal waveform, as indicated in Figure 3, to ensure proper operation with no harmonic distortion.

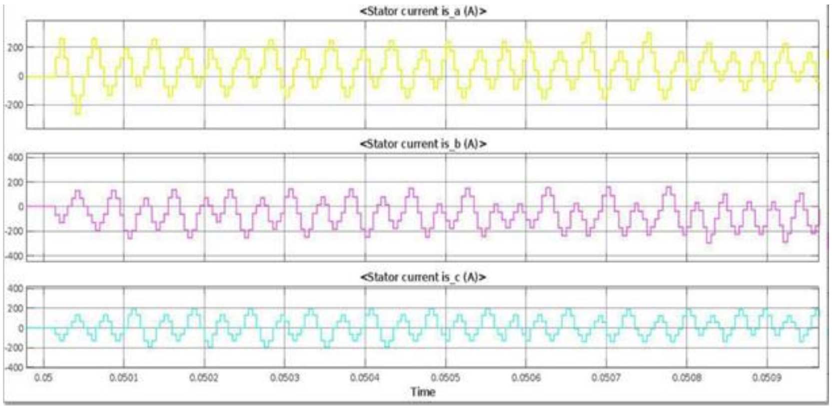

Figure 3: Simulation results of the phase stator current of the PMSM gearless machine

During the regenerative process, the driver's DC bus voltage ranged from 170 to 220V, depending on the load driving the motor, as indicated in Figure 4. The developed voltage is then fed to a DC-DC converter that steps down to 54V DC to charge four 12V 18Ah series-connected VRLA batteries.

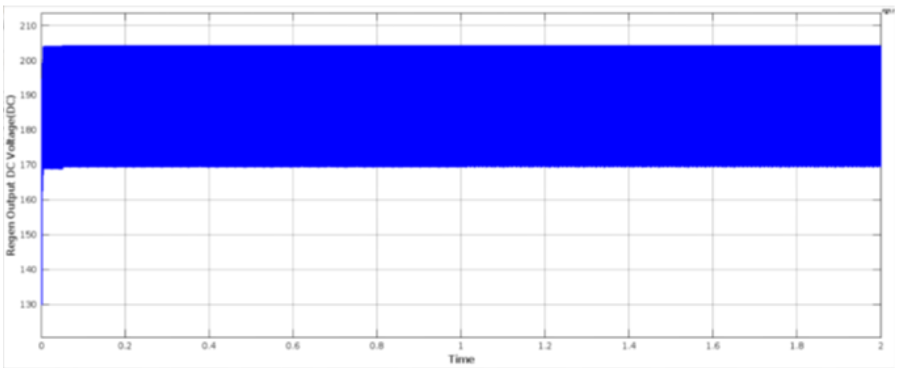

Figure 4: Simulation results of regenerated DC voltage of the PMSM gearless machine

The signal builder block in the Simulink model was used to generate the load profiles and speed variations of the lift car to simulate both upward and downward motion cycles, as illustrated in Figure 5. The voltage gain output showed steady behaviour during regeneration, validating the converter's ability to control and maintain the output voltage within the expected range during load transitions.

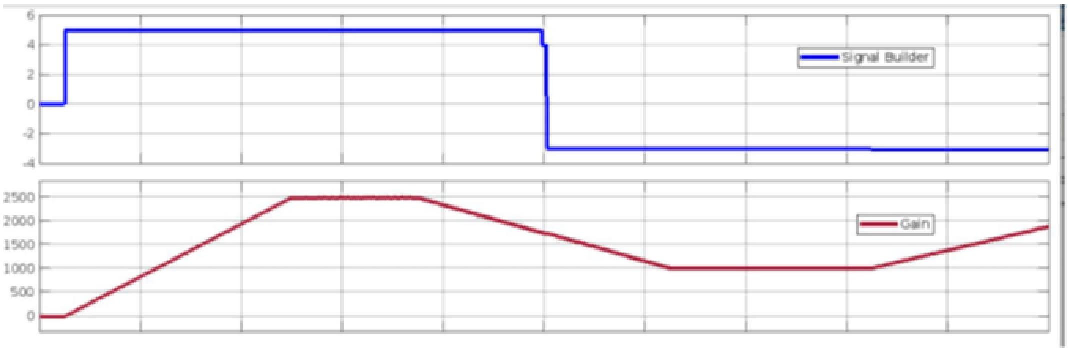

Figure 5: Simulation results of the signal builder and voltage gain of the PMSM gearless machine

The battery voltage waveform showed efficient charging behaviour, with progressive voltage increases towards 54V, and the SOC waveform increased consistently to 60%, validating the efficient storage of energy supplied by the regeneration process, as illustrated in Figure 6.

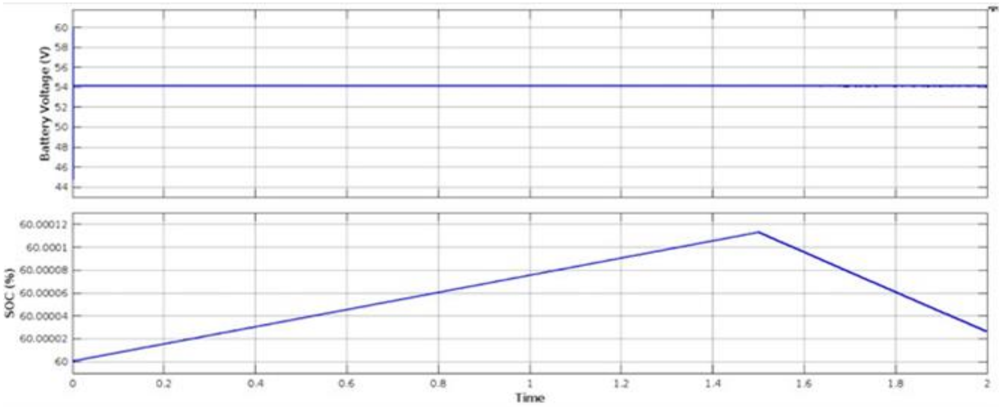

Figure 6: Simulation results of battery voltage and % SOC of PMSM gearless machine

The inverter voltage waveform indicated the overall conversion process of the stored DC power to 230V AC to synchronise with the mains grid voltage, as illustrated in Figure 7. It validated the grid interface mechanism of the proposed system, which reuses energy from the regeneration process within the buildings' electrical networks.

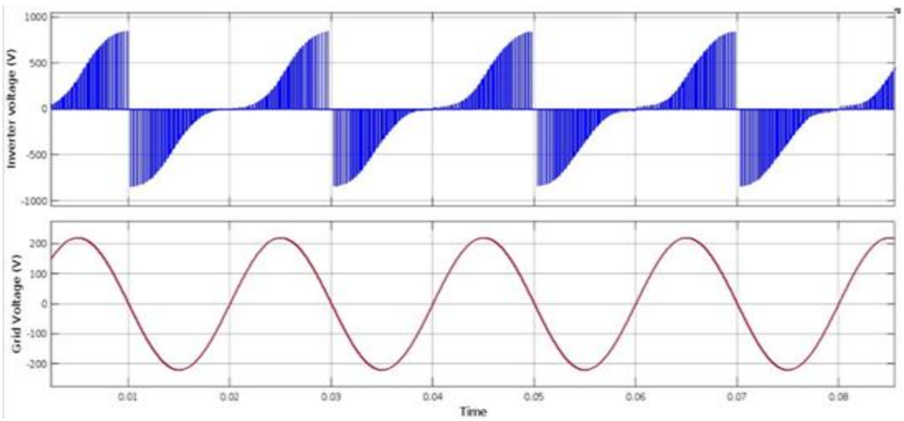

Figure 7: Simulation results of the voltage across the inverter and the grid voltage of the PMSM gearless machine

Compared to this, the geared induction motor system showed poorer regenerative energy performance. The battery voltage reached a constant 48 V DC with a SOC of 55%, as shown in Figure 8, due to inefficient energy transfer. The stator current waveform of the induction motor showed increased variations with large amplitudes because of increased mechanical inertia and frictional losses in the gearbox.

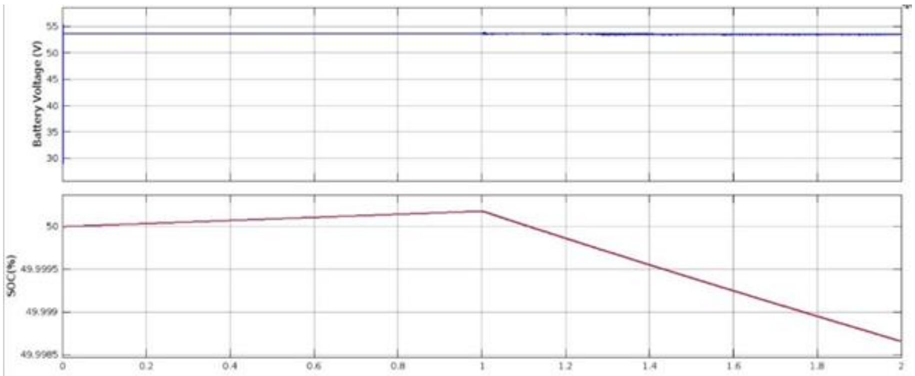

Figure 8: Simulation results of battery voltage and % SOC of geared induction motor

The inverter and grid voltage waveforms describe the energy conversion process of storing DC power, converting it to a constant 230 V AC, and synchronising with the main grid voltage, as shown in Figure 9.

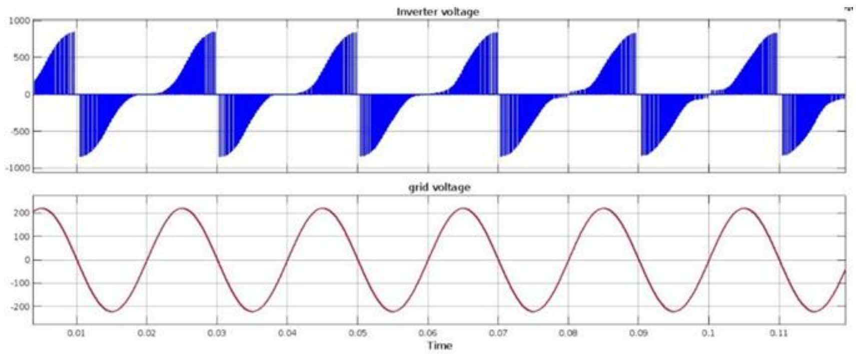

Figure 9: Simulation results of the voltage across the inverter and the grid voltage of the geared induction motor

The resultant DC voltage obtained in the simulation is 90-110 V. This is a greatly decreased value compared to the geared PMSM system, as identified in Figure 10. Hence, there is less feedback power during breaking. The voltage gain and signal builder outputs showed less stability in the simulation results for the induction motor. This explains the increased delay in the simulation results and decreased control accuracy. The SOC for the geared simulation increased slowly. This identifies inefficient charging and energy recovery. In addition, the identified inverter and grid voltage waveforms showed lower amplitude variation and fewer synchronisation periods. This explains that the simulation results have less influence on the Grid.

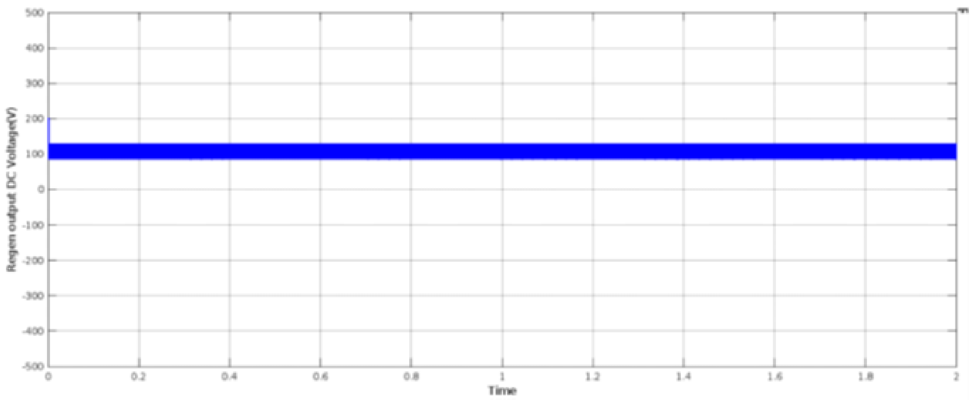

Figure 10: Simulation results of regenerated DC voltage of geared induction motor

A comparison summary of the simulation results clearly brought out the effectiveness of the gearless PMSM system in terms of regeneration and control. The PMSM had advantages in terms of DC link voltage (170-220 V) over 90-110 V for the induction motor, inverter output (230 V AC) against 215 V AC in the geared system, and rate of battery charging indicated by a quicker SOC percentage for the same duration of simulation. The PMSM model exhibited smoother stator current patterns and higher voltage gains, validating improved electrical efficiency. The simulation results in MATLAB/Simulink have confirmed that the gearless PMSM drive is significantly superior to the geared induction motor drive in terms of voltage regeneration, converter control, and energy storage efficiency. The results are consistent with those from hardware experiments, validating the gearless design. The arrangement is more promising and reliable for efficient energy-saving elevators.

5. Hardware Implementation

Hardware experimentation is another important aspect of this work. It allowed validating the theoretical and simulation results. The primary purpose of the hardware experimentation is to evaluate the real-time regenerative performance of geared and gearless elevators and to estimate the amount of electrical energy that can be recovered during braking. Two typical elevators, one with a geared induction motor and the other with a gearless permanent magnet synchronous motor (PMSM), were used for the experiments. Both elevators were equipped with Variable Voltage Variable Frequency (VVVF) drives and Dynamic Braking Resistors (DBR) to measure the exact values of regenerative voltages and currents during lift operation. In the geared lift system described in Figure 11, with the 18.5 kW motor and gearbox supporting a 16-passenger lift serving 11 floors in the commercial buildings, the test results were taken with the lift travelling upward and at a minimum cabin weight. This is because it is at this stage that the highest amount of regenerative power is regained because of the effect of counterweights. The voltage and current through which the DBR is regenerated at each floor level are measured using accurate measuring tools. Results obtained indicated that the voltage at the DBR varied between 74V and 95V, with the current measured between 2.7 A and 3.5 A.

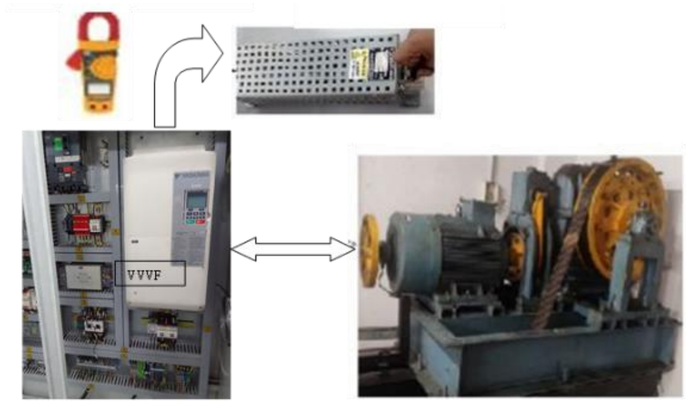

Figure 11: Hardware diagram of VVVF, DBR and geared induction motor

The power dissipated in the resistor ranged from 190 W to 330 W, depending on the floor position and weight. But when the results were averaged over several cycles, it could be deduced that the energy consumed during the 34-second cycle of travelling amounted to approximately 0.68 kW. This amount of energy, if wasted as heat in the DBR during each lift trip, could be captured using the proposed energy storage mechanism. Table 1 provides specifications for the components used to operate the gear-connected induction motor.

Table 1: Specification of various components used to drive the geared elevator using an induction motor

Component	Specification
Load	16P/1088Kgs
Speed	1.25m/s
No of floors	11
VVVF power rating	15KW
DBR power rating	25R/6KW
Elevator type	Passenger
Location	Commercial building
Total running time	34Sec
Motor type	Geared induction motor, 415V, 50Hz, 18.5KW, 34A, 1460RPM, IP 55

The gearless elevator system, on the other hand, as shown in Figure 12, is tested on a residential building with a PMSM drive rated at 6.7kW. The lift moves at 1.25 m/s and can reach up to 13 floors. Just like the geared one, the voltage and current measured across the DBR during upward motion with the empty cab were recorded. The measured results showed that the regenerative voltage varied between 268 V and 332 V, with corresponding current levels ranging from 4.2 A to 5.2 A. The instantaneous power dissipation ranged between 1.1kW and 1.7kW, depending on the path.

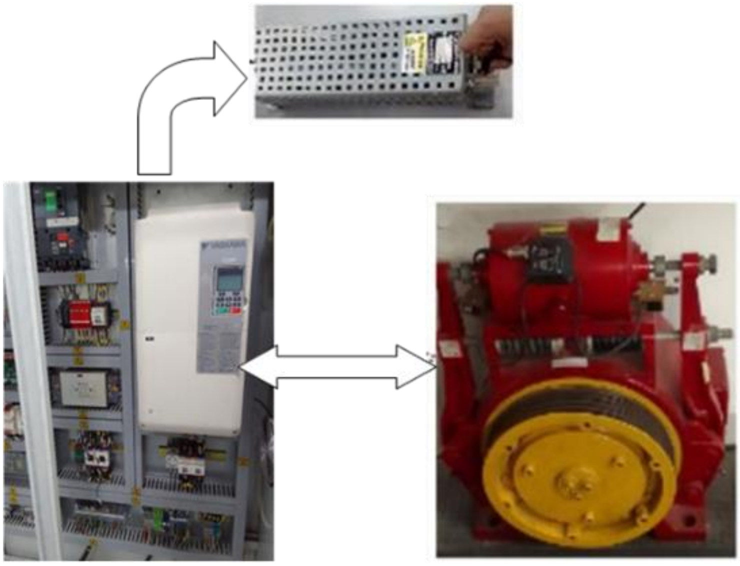

Figure 12: Hardware diagram of VVVF, DBR and PMSM gearless machine

The total amount of energy measured during the total 47-second travelling time is approximately 6.65kW. This is almost three times the size of the geared system. This is due to the gearless system's direct-drive mechanism, which eliminates gearbox losses and efficiently converts the mechanical energy of braking moments into electrical energy. Table 2 presents the specifications of the components used in the operation of the gearless, direct-driven PMSM.

Table 2: Specification of various components used to drive the gearless elevator using PMSM

Component	Specification
Load	13P/884Kgs
Speed	1.25m/s
No of floors	13
VVVF power rating	7.5KW
DBR power rating	64R/4KW
Elevator type	Passenger
Location	Apartment
Total running time	47Sec
Motor type	PMSM, 380V, 19.9Hz, 6.7KW, 15.5A, 119RPM, 20 poles, IP 40

Analysis of both systems showed that the gearless system is more efficient at power regeneration. Graphical representation of the data obtained showed a notable difference in power dissipation between the systems. In the geared system, power dissipation was higher and more uneven than in the gearless system, whose power regeneration was smoother. This is consistent with simulation results showing greater power regeneration performance in PMSM gearless systems. In further discussion of the results, it was reiterated that although the geared system is more economical and in use, its energy recovery is lower due to inherent losses in the transmission component. On the other hand, although it is initially costly, it is more economical overall in terms of energy use because of its greater regenerative capacity. This recovered power, when harnessed with proper storage in a battery system as proposed in this study, will be valuable for energising emergency rescue equipment, cabin lighting, ventilation fans, and communications during a power outage. The findings above show that the experimental results validated the simulation data, providing concrete proof that energy conservation is possible with regenerative technology in an elevator system. It was also seen that gearless lifts have a tremendous ability to generate additional power through regeneration, thereby making a greater impact by greatly diminishing grid reliance and greening building designs.

6. Hardware Results and Discussion

A comparison of the hardware analysis of the geared and gearless systems provides a clear understanding of their performance in regenerative energy use. Both systems have been tested in real-elevator installations moving at a constant speed with a negligible cabin load, as in a real situation where the counterweight's motion produces regenerative energy. In the geared system, a 3-phase induction motor and a gearbox were used, while in the gearless system, a Direct-drive Permanent Magnet Synchronous Motor was applied. Table 3 above presents the hardware analysis of the DBR's voltage and current power consumption of the Induction motor that powers an Elevator using gears. From the hardware analysis of the geared system, it was determined that the dynamic braking resistor (DBR) voltages ranged from 71V to 95V, while its currents ranged from 2.7 A to 3.5 A.

Table 3: Hardware results of voltage and current DBR and power consumed by the induction motor connected to drive the elevator using gears

Direction of Elevator	Position of Elevator	DBR Voltage (V)	DBR Current (A)	Power Dissipated (W)
UP	1	95	3.48	330.6
UP	2	91	3.58	325.78
UP	3	89	3.23	287.47
UP	4	84	3.12	262.08
UP	5	78	2.92	227.76
UP	6	74	2.77	204.98
UP	7	71	2.71	192.41
UP	8	84	3.23	271.32
UP	9	85	3.25	276.25
UP	10	79	2.95	233.05

Moreover, the calculated power dissipation per floor ranged from 190 W to 330 W, with an average of 0.68 kW over a 34-second travel cycle, as illustrated in Figure 13 above. This clearly shows that a substantial amount of transmittable regenerative power was dissipated as heat through the DBR; thus, an energy storage unit would have been valuable in such a system.

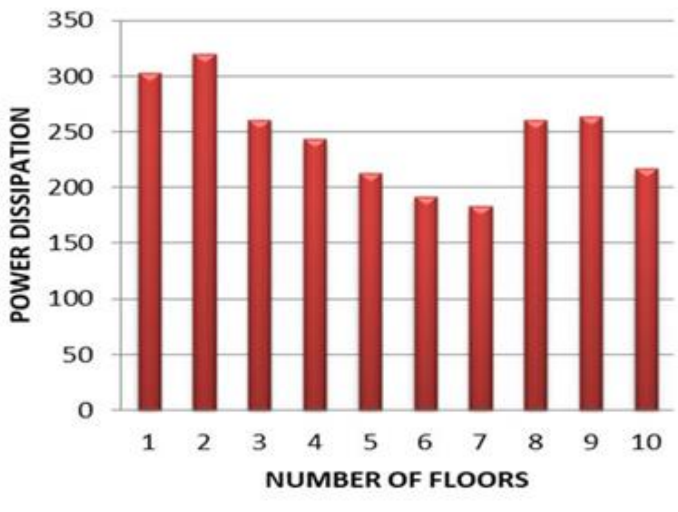

Figure 13: Power dissipation in gears

On the other hand, in gearless technology, a significantly higher regenerative power was obtained. DBR's voltage varied between 268V and 332V, while current varied between 4.2A and 5.2A. Similarly, power dissipation ranged from 1.1 kW to 1.7 kW per floor, while total regenerating power was about 6.65 kW over a 47-second operational cycle, as depicted in Figure 14. This shows that gearless technology produces nearly three times the power of a geared system. Higher values of voltage and current indicate that PMSM technology's higher power regeneration capabilities stem from its direct coupling of the motor and sheave, without an intermediary gearbox that introduces mechanical losses. Below is a depiction of precise values of DBR's current and voltage, and power dissipation in terms of gearless PMSM that is directly interfaced with an Elevator as indicated in Table 4.

Table 4: Hardware results of voltage and current of DBR and power consumed by the gearless PMSM connected directly to the elevator

Direction of Elevator	Speed on Elevator (m/s)	Position of Elevator	DBR Voltage (V)	DBR Current (A)	Power (W)
UP	1.25	1	271	4.23	1146.33
UP	1.25	2	268	4.26	1141.68
UP	1.25	3	275	4.3	1182.5
UP	1.25	4	277	4.41	1221.57
UP	1.25	5	281	4.41	1239.21
UP	1.25	6	278	4.35	1209.3
UP	1.25	7	280	4.33	1212.4
UP	1.25	8	309	4.87	1504.83
UP	1.25	9	293	4.64	1359.52
UP	1.25	10	332	5.21	1729.72

Compared with the geared system, the geared system experienced increased frictional and transmission losses, resulting in a decrease in the overall electrical energy harnessed for braking. Overall, the gearless system has a smoother torque curve and higher electrical conversion efficiency.

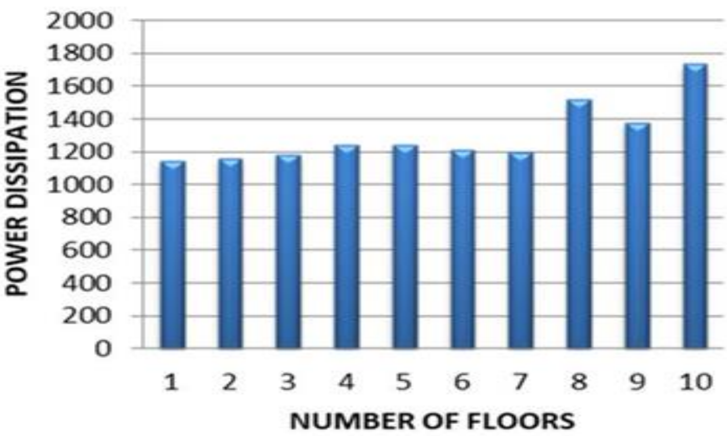

Figure 14: Power dissipation in gearless drive

The experimental results prove that, using gearless systems that incorporate regenerative storage of electrical energy, not only is this aspect of electrical energy waste eliminated, but also such systems greatly aid new-age initiatives in 'Green Buildings,' as shown in Figure 15.

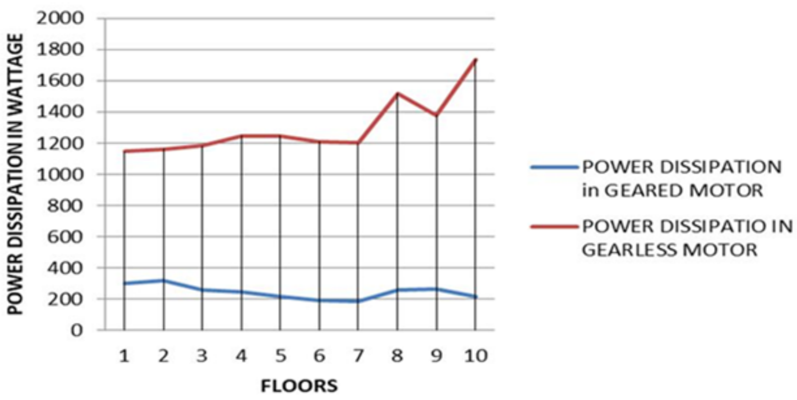

Figure 15: Comparison of hardware results for power dissipated in geared induction motor vs power dissipated in gearless PMSM

7. Conclusion

The simulation conducted in MATLAB/Simulink offered a detailed insight into the electrical and mechanical behaviour of both types of elevators. The geared type of Elevator utilising an induction motor and the gearless type utilising a permanent magnet synchronous motor (PMSM) were simulated. The simulation results showed that a regenerative voltage in the range of 170-220 V DC is generated in a gearless elevator. The obtained voltage is efficiently translated to the 54 V battery pack storage using a DC-DC converter. The inverter and grid voltages showed that DC electricity can be efficiently converted to 230 V for reuse. Thus, the effectiveness of the storage mechanism proposed had been validated. This is confirmed by the results obtained during hardware validation. The real-time results analysed on actual systems showed that the theoretical results were obtained. The geared system with the 18.5 kW induction motor produced 0.68 kW of power during regeneration. In comparison, the 6.7 kW PMSM-based gearless system developed approximately 6.65 kW of energy under similar operating conditions. The threefold increase in the value of power developed during regeneration in the latter is due to its direct-drive technology, which reduces mechanical losses and promotes electrical-drive innovations. A close alignment between the simulation results and the actual results is evident. From the above discussion, it can be concluded that gearless elevators have a high potential for energy regeneration and greater efficiency than geared elevators. The combined effect of the energy storage mechanism makes it useful not only for energy savings in elevators but also for advancing the principles of sustainable architecture. By utilising the energy wasted in elevators, the proposed method is a very economical means to save energy and provide reliable service during emergencies.

7.1. Future Scope

The scope of this research can be explored with respect to the optimal use of regenerative energy in elevators. This future work can include the design of improved converter and inverter circuits to reduce power-conversion losses. Also, newer storage solutions such as lithium or supercapacitors can be explored to improve energy storage density. More intelligent control solutions incorporating DSP and IoT technology can also be incorporated to enable auto-energy control in such elevators. This technology can be extended to a multi-elevator network or to high-speed applications to form a microgrid at the building level, enabling energy sharing between elevators and auxiliary systems. At the same time, the inclusion of smart grid communication could enable two-way energy sharing between elevators and the primary power source. In future studies, economic and environmental effects can also be evaluated to confirm the economic viability and sustainability advantages. Through continued innovation and advancement, regenerative elevator technology can emerge as a sustainable, eco-friendly solution that contributes to green buildings and reduces power consumption in large cities.

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