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Research Paper

COMPARATIVE STUDY OF RECENT ADVANCEMENTS IN REGENERATIVE DRIVES IN ELEVATOR SYSTEMS

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Regenerative motor-drive systems are nowadays widely applied in numerous industrial applications. This paper is centered on comparing the application of the two well-known and recently used types of drives for AC gearless elevators. This paper presents a comparative evaluation of the regenerative Permanent Magnet Synchronous Motor (PMSM) and AC Variable Voltage Variable Frequency (VVVF) drives. The study includes a detailed analysis of energy consumption, line running, accelerating and peak current and peak demand for each elevator control system. This paper shows the simulated results of output power, hoisting power, regenerative power, power savings which are compared for these drives along with the implementation of Automatic Rescue Device (ARD) for emergency operation using a battery with ultra capacitor combination which is charged by the regenerated power using converters.

Keywords: Elevator, Electric drive, Regenerative drives PMSM, AC VVVF, ARD, Lithium ion battery ultra Capacitor, Inverter, Peak demand

INTRODUCTION

Power Quality is an increasing concern for utilities and their commercial and industrial electrical customers. In recent years, the proliferation of higher electronic loads and controls have taken a sensitive place to electrical grid disturbances, such as voltage sags, dips, outages, over voltage, harmonics distortion and so on. The growing demand of low CO2 emissions, leads to heavy market penetration of generating energy capable to assure low exhaust emission.

The DC motor is widely used for elevator motion control with Ward Leonard system using a motor generator (MG) set and subsequently, using thyristor drives in the 1980s and 1990s. Gate Turn Off devices (GTOs) controlled the DC motors for elevator application to obtain better voltage and power factor control. The DC motor with its brushes

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requires frequent maintenance therefore, the next logical choice for elevators was to employ AC motor and reduce maintenance cost. A GTO current source inverter and AC induction motor were used for elevator applications. Here the GTO switching frequency was nearly 4 kHz and special GTO gating scheme was used to suppress the voltage spikes. A transistor based current source PWM inverter system with sinusoidal input and output was applied to high-speed elevators in the late 1980s. The switching frequency employed was 2.7 kHz and the individual input current harmonics were reported to be less than 5%. Over the last decade, Variable Voltage Variable Frequency (VVVF) vector controlled AC drive using Insulated Gate Bipolar Transistor (IGBT) switching devices and AC induction motor has been the most popular motion control system for elevators.

The VVVF AC system has replaced the Ward Leonard MG, silicon controlled rectifier or SCR, GTO and transistor inverter (AC) based systems for majority of elevators. The vector-controlled drives provide a DC servo like performance and the AC induction motor does not need frequent maintenance.

A current controlled AC inverter with a high switching frequency (6-12 kHz) provides a good control of torque down to zero speed with low torque ripple. There is a substantial amount of overhauling energy when an elevator travels in a high-rise building with excess energy in the system. A line regenerative drive, therefore, offers substantial energy savings for high-speed elevators. The energy saving is not so clear however, for gearless elevators travelling at the lower end of the gearless speed range, for example at 2.5 m/s. However another motor drive is rapidly gaining popularity in elevator market, i.e., the PMSM drives. Permanent-Magnet Synchronous Motors have performance advantages over DC excited-synchronous motors and are becoming more common in fractional horsepower applications because they are smaller, lighter, more efficient and reliable. So in this discussion, we compare both PMSM drive and AC VVVF drive for a lift car with a capacity of 8 passengers travelling at 1m/s speed for 3 floors.

REGENERATIVE DRIVES IN ELEVATOR APPLICATIONS

When an electric motor is driven by a Variable Frequency Drive (VFD), electric power delivered to the motor is regenerated while the motor decelerates by applying negative torque to the motor shaft. Usually energy storage capacity inside the VFD is very limited so regenerative energy should be returned to the grid or quickly dissipated by a braking resistor. Otherwise, the dc bus will be overcharged and an over-voltage fault can occur. Dynamic braking resistors have been widely used to convert regenerated energy into heat loss because of simplicity and low installation cost. But a regenerative power unit provides a significant energy cost saving opportunity, especially in applications that require frequent run and stop, deceleration with high inertia load, and overhauling torque. Such applications include spindle drives, decanter centrifuges, hoists, cranes, elevators, and torque dynamometer test rigs.

Motor Selection

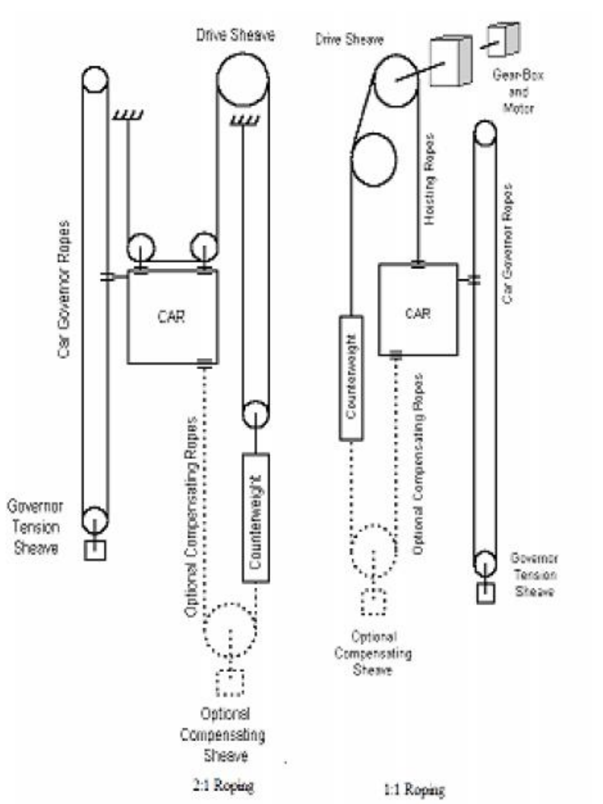
Motor selection is important in an elevator drive system, as mentioned earlier the DC motor-generator sets are being replaced by various motors, of these most popular are the Permanent Magnet Synchronous Motors and AC VVVF drives.

- Variable Voltage Variable Frequency (VVVF) drives eliminate the need for a DC hoist motor and replace it with an AC motor. VVVF provides many of the same advantageous characteristics of the DC motor, such as smooth acceleration and deceleration and excellent speed control without the issues related to usability of power.
- Permanent-Magnet Motors have performance advantages over DC excited-synchronous motors and are becoming more common in fractional horsepower applications because they are smaller, lighter, more efficient and reliable. Large industrial motors originally used wound field or rotor magnets. Permanent-magnets have traditionally been used only on smaller motors because of the difficulty in finding a material capable of retaining a high-strength field. Recent improvements in material technologies have made it possible to create high-intensity permanent-magnets, allowing the development of compact, high-power motors without the extra real estate of field coils and excitation means.

Gearless Elevator Arrangement

Figure 1 shows the arrangement for a typical gearless elevator. Figure 1a shows the 2:1 roping arrangement and Figure 1b shows the 1:1 roping arrangement, The 2:1 roping arrangement cuts the torque requirement roughly by a factor of two. For a given elevator speed, the motor speed for 2:1 roping arrangement is double that for a 1:1 roping.The 2:1 arrangement, however, increases the rope speed by a factor of two and is used for speeds up to (rope speed 8m/sec). For speeds over 4 m/s, 1:1 roping arrangement is used.

Figure 1: Typical Gearless Elevator Roping Arrangement



Vector Control

The line regenerative VVVF drives described in this paper use an indirect field orientation with current controlled PWh4 inverter.The field producing component establishes a field in the stator and, more importantly, in the rotor. The field orientation algorithm is based on the d-q model for the induction motor. The algorithm permits the field producing current (Id) and torque producing current (Iq) to be considered as DC variables similar to the field and armature currents of a DC motor.

Regenerative Energy Retrieval

The Regenerated energy from the motors is retrieved by the help of the regenerative converter, a cost-effective solution that can replace the dynamic braking transistor and resistor network. It absorbs excess regenerative energy from the VFD and returns it to the ac power source. During motoring, the VFD delivers power without the regenerative converter in the main power flow. So there is no conduction loss in the regenerative converter during motoring. The regenerative converter is activated when regenerative energy charges dc link capacitors of the VFD. The regenerative converter returns stored energy in the dc capacitors to the grid. But instead of using a separate converter for regenerated energy, a single converter can be used for both motoring as well as regenerative energy. Such types of converters are:

- Sinusoidal PWM converter
- Matrix Converter
- Current Source Inverters

Elevator Position Control

The elevator control is performed by an Intel 80186 microprocessor. A second encoder mounted on the over speed governor detects the position of the elevator in the hoist way. Optical switches at each floor define the floor position. The elevator controller generates the precise S-curve for single or multi floor runs based on hall and car calls and passes the speed command information to the DSP to control the elevator speed. A load weighing system on the elevator senses the precise load on the elevator in pounds and passes that information to the elevator controller. The 80186 controller has job specific data such as speed, capacity, number of floors and the percent counterweight. The 80186 processor evaluates the unbalance on the car after it receives the load information before the start of each run and calculates the precise amount of pre torque needed for smooth operation of elevator.

ENERGY CONSUMPTION

Gearless Elevator Energy Consumption

The elevator energy consumption depends on a number of factors such as the type of drive used, capacity of the elevator, speed of the elevator, traffic pattern in the building, full load mass of the system, type of gearless machine used, type of roping, etc. A good analytical tool to evaluate the energy consumption is therefore of great interest. An analytical approach to evaluating the average energy consumption is presented in this section.

Unit of Energy

The unit of energy universally used is kilowatt-hour, kWh. It is defined as the energy consumed by an appliance or system with a power of one kilowatt or 1000 watt for a period of 1 hour.

Elevator Flight Times

The elevator flight time for a given number of floors depends on the rated speed of the elevator, acceleration and deceleration rates, jerk rates and the door open and close times. The methodology presented, however, is applicable to a different acceleration rate with a small variation in flight times. The average energy consumption number using different accelerate or deceleration rate is not affected much since an elevator travelling at lower accelerate or deceleration rate generally spends more time to get to a given floor and thus makes fewer total number of trips overall per day.

Energy Consumption for Single and Multi-Floor Runs

The bar charts in Figure 2 show the energy consumption for a one hour single-floor runs of a gearless elevator rated 1000 kg at 1 m/s. The duty cycle for this test is 35%. A Voltech power analyzer is used to measure the energy consumption. The bar charts show the energy consumption for no load, balanced load and full load conditions. The elevator for this test is run single floor up and down with 35% duty adjusted with the off time. In practice, the door time typically provides the required off time between runs. It is clear that the VVVF non-regenerative drive is more efficient for this type of duty since there is very little overhauling energy that is fed back to the system. The elevator in fact does not even attain its rated speed of 1 m/s in this case. Figure 3 shows the energy consumption for a 10-floor run for one hour with a 35% duty cycle. Here, the regenerative drive is more efficient except for the balanced load case when there is very little overhauling energy.

Figure 2: Energy for One-Hour 10-Floor Run 35% Duty

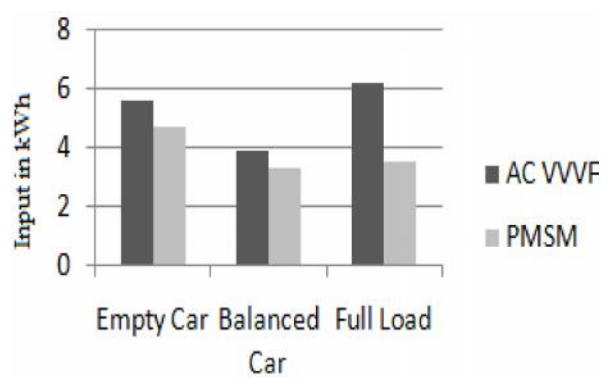


Figure 3: Single Floor One-Hour Energy with 35% Duty

Peak vs. Off-Peak

Power consumption is typically represented by kilowatts or kW. Utility and power distribution companies typically charge by kW, however, different rates apply to the time of use – peak demand usage versus off-peak usage.

Power Factor

Another element in understanding energy use and distribution is the power factor or, in simple terms, how much effort it takes to push electricity through a building or power grid. The power factor indicates how efficiently a building accepts and uses electricity.

Power Factor = Active Power/Apparent Power = kW/kVA

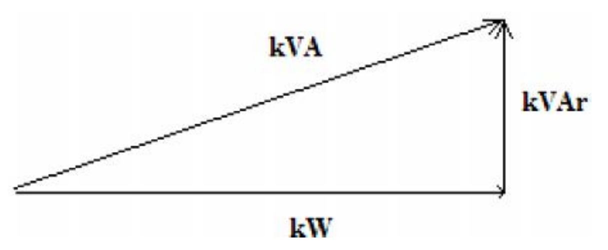
= Active Power/(Active Power + Reactive Power)

= kW/(kW + kVAr)

Higher kVAr indicates low power factor and vice versa. In electrical terms kW, kVA, and kVAr are vectors and must be summed.

Power factor is the ratio of true power or watts to apparent power or volt amps, so the theoretical best value for a power factor is one (on a scale of zero to one). In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system and require larger wires and other equipment. Because of the costs of larger equipment and wasted energy, electrical utilities will usually charge a higher cost to industrial or commercial customers where there is a low power factor.

Figure 4: Vector Diagram Showing Relationship Between KW and kVA



COMPARATIVEEVALUATION OFVVVF ANDPMSMDRIVES

For Comparative Evaluation, the following parameters are considered for an elevator system.

Table 1: Elevator Parameters

Type of Use	Residential
Total Travel distance in (m)	12 m
No. of Floors	3
Total Full Load (Lift car + 8 persons)	1000 Kg
Counter Weight (40% Loading)	622 Kg
Rated Speed	1 m/sec
Line Voltage	400 V
Suspension	2:1
Type of Gear	Gearless
Regenerative Drive	Yes
Motor Output in kW	5.58

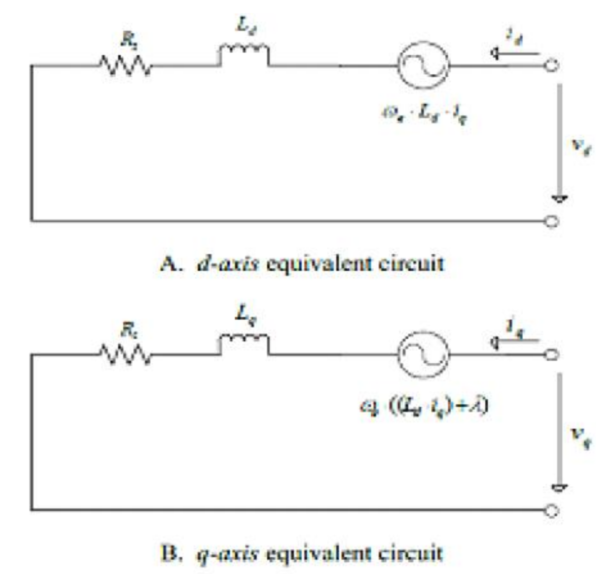
Based upon the above parameters, the following calculated parameters are developed and compared.

SYSTEM MODELLING

Motor Modelling

Consider the equivalent circuit of PMSG based on WECS.The model of PMSG is established in the d-q synchronous reference frame as shown in Figures 4a and 4b, respectively.

Figure 5: Equivalent Circuit of PMSM in d-q Reference Frame



$$\frac{d}{dt}i_d = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}pw_r i_q \qquad ...(1)$$

$$\frac{d}{dt}i_q = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q + \frac{L_d}{L_q}pw_r i_d - \frac{{}^{a}pw_r}{L_q} \qquad ...(2)$$

The electromagnetic torque equation is given by

$$T_e = 1.5^{\circ} \left[{}^{a}i_q + (L_d - L_q) i_d i_q\right] \qquad ...(3)$$

where

L_q = q axis inductance

L_d = d axis inductance

R = Resistance of the stator windings

i_q = *q* axis current

i_d = *d* axis current

v_q = *q* axis voltage

v_d = *d* axis voltage

w_r = Angular velocity of the rotor

ª = Amplitude of flux induced

p = The number of pole pairs

The voltage equations of PMSM as shown in Figure 5 are given by

$$\frac{d}{dt}w_r = \frac{1}{J}(T_e - Fw_r - T_m)$$

$$\frac{d}{dt}- = w_r \quad \text{...(4)}$$

where

J = Inertia of rotor

F = Friction of rotor

¯ = Rotor angular

Power Converter

Power converter consists of rectifier, DC-link and inverter. Rectifier will convert AC voltage output from PMSG based on WECS to DC voltage. Inverter will convert DC voltage from DC-link capacitor to AC voltage at fundamental frequency. The relation of AC voltage at fundamental frequency and DC voltage is given by

$$V_B = \frac{1}{2\sqrt{2}} m_B v_{dc} \angle ¢_B \quad \text{...(5)}$$

Simulation Diagrams Based on Equations

Figure 6: Simulation Diagram for D-Axis Current with ARD

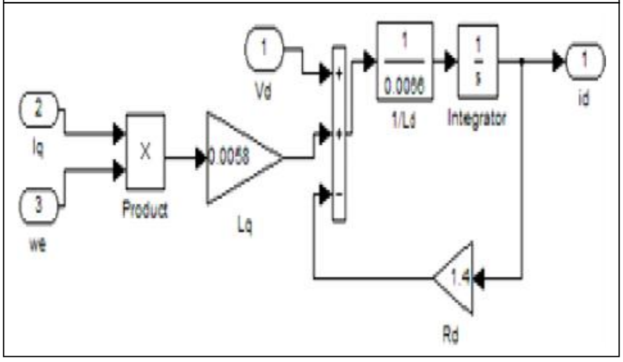


Figure 7: Simulation Diagram for Q-Axis Current with ARD

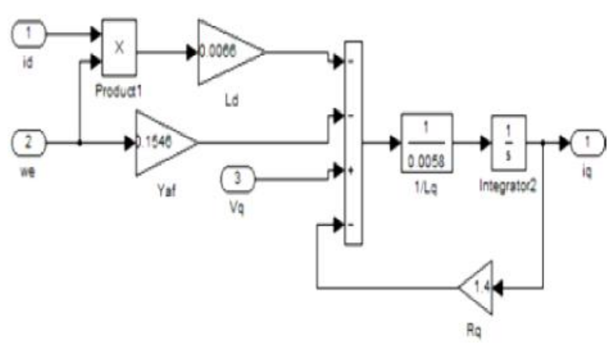


Figure 8: Simulation Diagram for D-Q Axis Current (I_{dq})

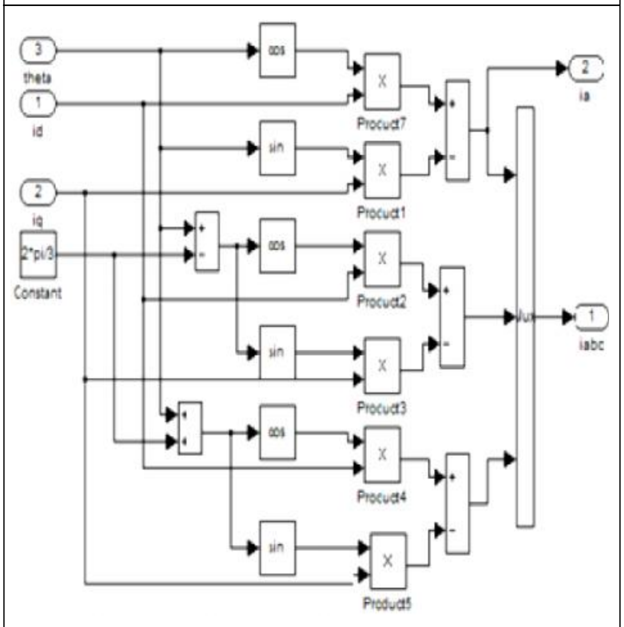


Figure 9: Simulation Diagram for Torque, Speed and Current

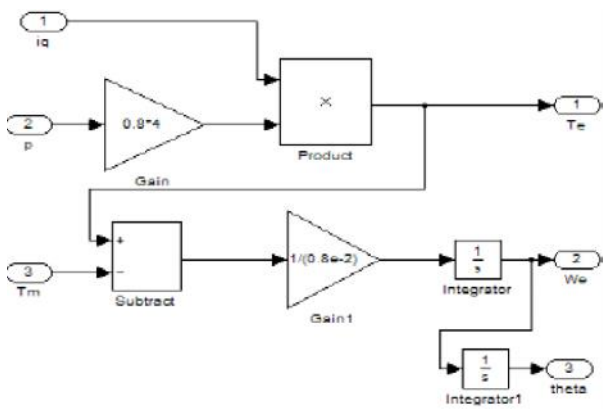


Figure 10: PMSM Drive

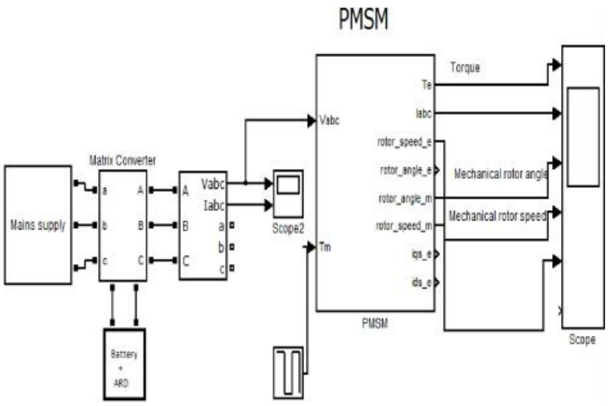
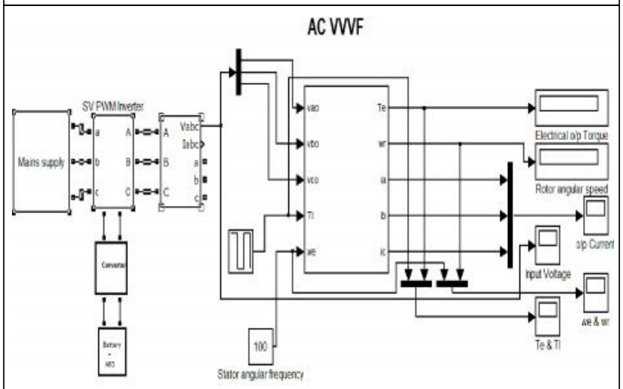


Figure 11: AC VVVF Drive



Mechanical System's Motion Equations

In order to derive the motion equation that describes the elevator's mechanical system it is assumed that the mass of the drive belt is ignored due to its material composition and length. In practice, the drive belt or drive cable is constructed from steel and its significant mass contributes to the load torque in a non-linear fashion depending upon the position of the car. The motion equation of the entire system from the motor's perspective is:

$$T_{em} = J_M \frac{d\mu_m}{dt} + B \cdot \mu_m + T_L \quad \text{...(5)}$$

where

J_M is the motor's moment of inertia

μ_m is the angular speed of the rotor

B is the friction coefficient of the motor

T_L is the load torque placed on the motor's shaft

The load torque that is placed on the drive pulley which is mounted on the motor's shaft is expressed in Equation (6).

$$T_L = R_P \cdot F_L + J_P \frac{d\mu_m}{dt} \quad \text{...(6)}$$

If the elevator car is moving upwards the load force is defined by Equation (7)

$$F_L = \frac{1}{2}\left[g \cdot (M_c - M_{cw}) + M_c \frac{du_c}{dt} \right] \quad \text{...(7)}$$

The load torque for car moving in upward direction is expressed as

$$T_L = \frac{1}{2} R_P \cdot g \cdot (M_c - M_{cw}) + \frac{1}{4} R_P^2 \cdot M_c \frac{d\mu_m}{dt} + J_P \frac{d\mu_m}{dt} \quad \text{...(8)}$$

The equation for load torque when the elevator car is moving downwards has the form

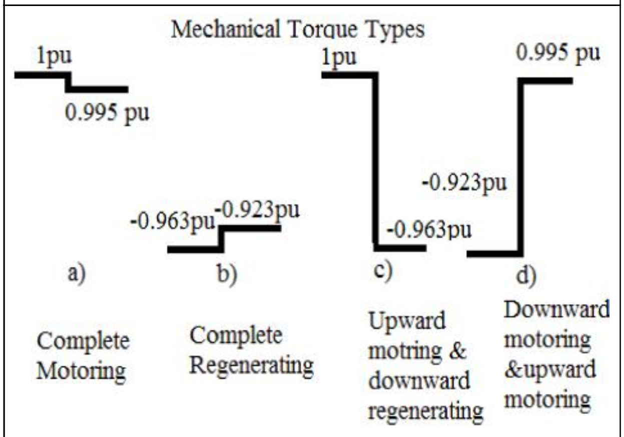
$$T_L = \frac{1}{2}R_P \cdot g \cdot (M_{cw} - M_c) + \frac{1}{4}R_P^2 \cdot M_{cw}\frac{d\mu_m}{dt} + J_P\frac{d\mu_m}{dt} \quad ...(9)$$

Substituting the load torque equation for when the elevator car is moving upwards (Equation 8) into the motor's motion equation (Equation 9), the motion equation of the entire system is obtained as:

$$T_{em} = \left(J_m + \frac{1}{4}R_P^2 \cdot M_c + J_P\right)\frac{d\mu_m}{dt}$$

$$+ B \cdot \mu_m + \frac{1}{2}R \cdot g \cdot (M_c - M_{cw}) \quad ...(10)$$

Figure 12: Different Types of Motoring Torques



RESULTS AND DISCUSSION

Using these parameters, Simulation diagram of the elevator using the SIMULINK in MATLAB/Simulink SimPowerSystems toolbox is developed.

The Automatic Rescue device used is placed in such a way that apart of regenerated energy is fed to battery ultra capacitor arrangement such that whenever the mains supply goes off the elevator slowly reaches the next floor so that passengers are not trapped in between the floors.

Figure 13: Simulink Diagram of Model Elevator

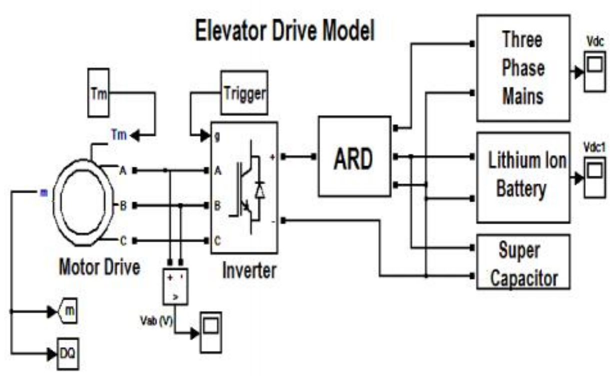
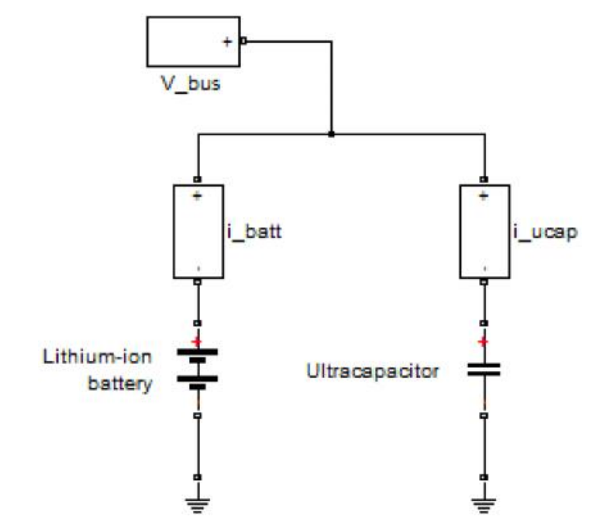


Figure 14: Arrangement of Battery and Ultracapacitor



The Simulation results are as shown

Figure 15: Inverter Input in kW

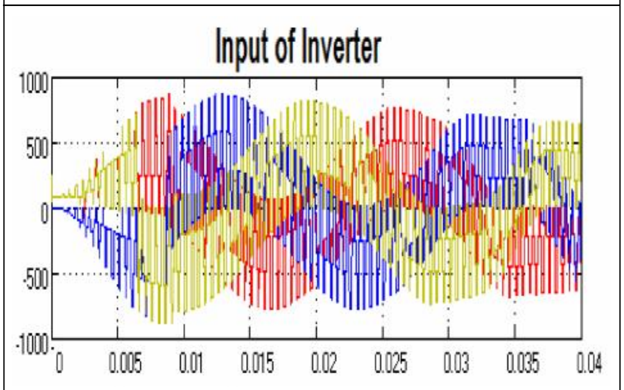


Figure 16: Inerter Output in kW

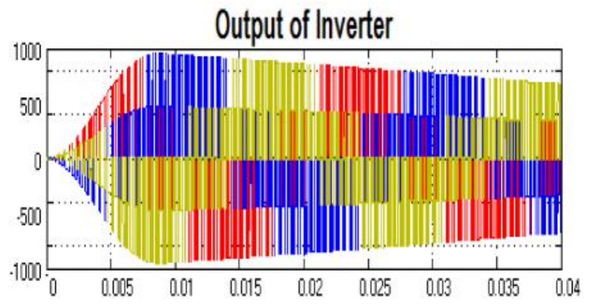


Figure 17: Inverter Efficiency

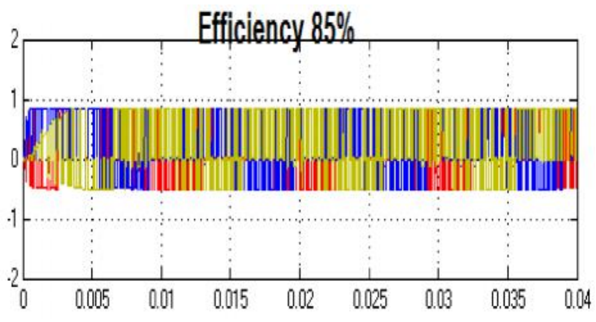


Figure 18: Torque Produced During ARD Operation

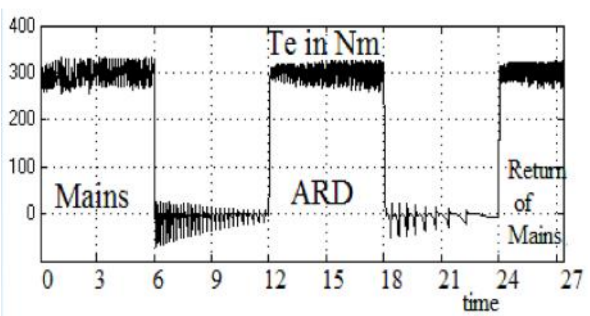
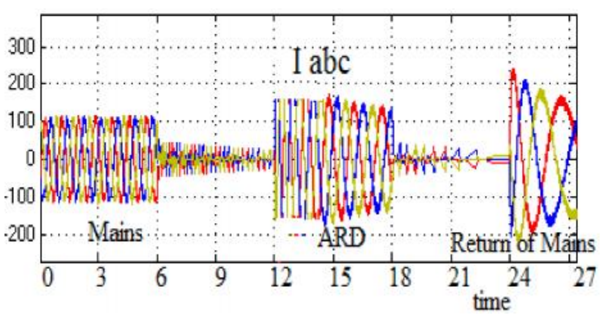


Figure 19: Stator Current During ARD Operation



As seen from the above results for an Elevator system with an ARD with inverter efficiency of 85%, the electrical torque produced in an ARD operation is as shown in Figure 17 and the current drawn is shown in Figure 18. As seen the current taken during ARD operation is more than the normal operation since the motor is restarted.

The maximum current which is shown in the Figures 19 and 20 show the peak acceleration current for both the drives and Figures 20 and 21 shows the power consumed and regenerated during complete run in an elevator.

As shown the PMSM drives consume lesser current and power than AC VVVF drive

Figure 20: Elevator Car Speed in m/s

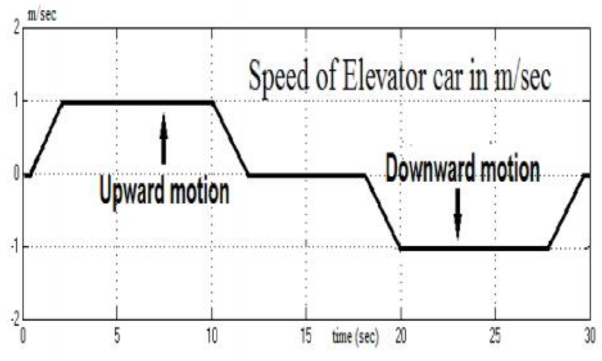


Figure 21: Max. Acceleration of PMSM Drive

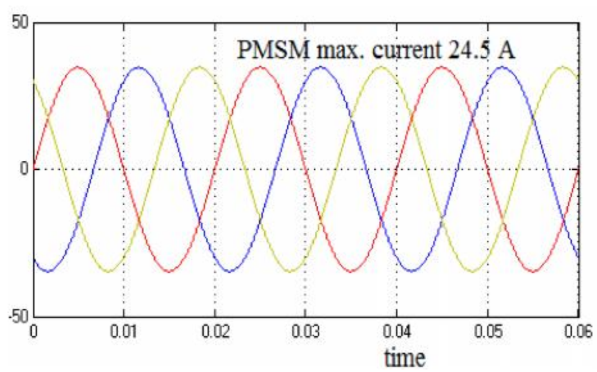


Figure 22: Max. Acceleration of PMSM Drive

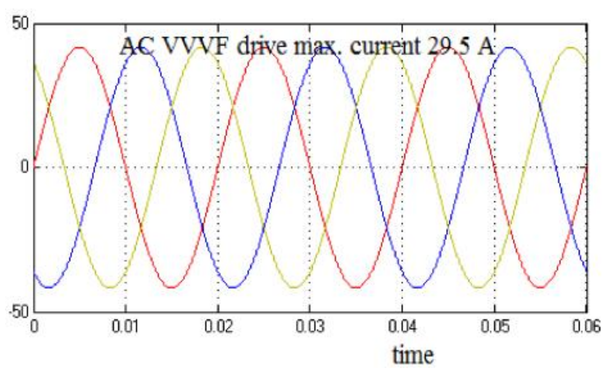


Figure 23: Power Consumed per Run in PMSM Drive

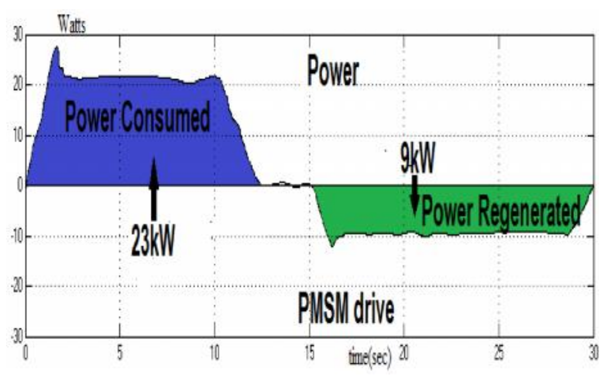
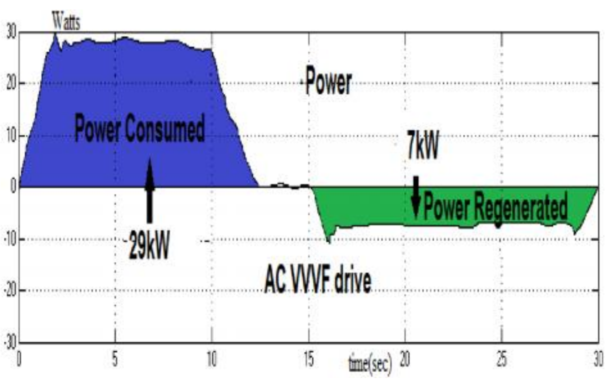


Figure 24: Power Consumed per Run in AC VVVF Drive



and the power regenerated is more in case PMSM drives. The detailed comparison of both the drives is shown in Table 2. From the

Figure 25: Electrical Torque Produced in p.u. for Normal Operation

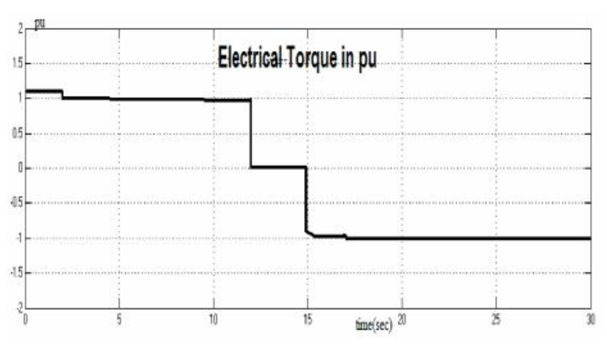


Table 2: Final Results

S. No.	Parameter	PMSM	AC VVVF
1.	FL/FS line output power in kW	7.6	8.3
2.	Line FL/FS running current in A	10.7	12.9
3.	Line FL/FSRMS acceleration current in A	19.6	23.6
4.	Line FL/FS peak acceleration current in A	24.5	29.5
5.	FL/FT energy consumption/ run in kW	23	29
6.	FL/FT energy regeneration/ run in kW	9	7
7.	Estimated Energy/run in kW	12	21
8.	Total run time in sec	12	12
9.	Motor efficiency In %	93	87%
10.	Installation cost	more	less
11.	Savings	more	less
12.	Inverter efficiency	86%	86%
13.	% of Hoisting power Regenerated	45.45%	29.62%
14.	If ARD can be used	YES	YES

Table we can see that the overall efficiency of the PMSM drive is more than the AC VVVF drive.

CONCLUSION

Regenerative Motors produce energy when the motor is in an overhaul condition. In an elevator, this occurs when the motor is used to brake a descending unit. Until recently, the electricity generated was sent through a series of resisters that dissipated the energy as heat into the machine room. With the introduction of regenerative drives, the energy produced can be fed back into the building or power grid. Because the harmonics are purified, there is no line loss and 100% of the power that isharnessed is usable.

However from the results it is clear that that the introduction of PMSM in the modern elevators shows that it not only consumes lesser energy per run but also regenerates more energy compared to the AC VVVF drives which are now mostly available in the market.

So PMSM regenerative drives even though are costlier than the rest save more energy than VVVF drives and with recent advancements, they can also be used for heavy applications.

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