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Possibilities for Energy Saving Predictions in Elevators

Research article

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Abstract: Today, with the longing for smart and sustainable transportation, the elevator industry has undergone major metamorphism in the field of control algorithm, electric drive, and the motor. Amongst these, regenerative drive (RD) plays a pivotal role in making elevator technology more energy efficient. Rather than wasting the recovery energy from the machine as heat, RD recovers it as green energy. Conventional direct current (DC) motors ruled the elevator industry for many years and were adopted as standard type of elevator motors. But with the advancement in electric drive technology, alternating current (AC) motors, especially induction motors, flourished in the later part. Recently with the introduction of Permanent Magnet Synchronous Motors (PMSM) technology, the elevator revolution began in terms of power quality, ride quality, and green energy. Likewise, contrasted with different types of vertical transportation machines, PMSMs have better powerful execution, compact size, and higher system-level efficiency. Recently, with the rapid improvement in intensity hardware, utilization of rare earth magnetic materials, and indubitably advanced research, PMSM has rapidly changed systems globally. PMSM is a multivariable, nonlinear, and high-coupling framework. The torque and stator current present a unique capacity connection. Attractive fields can be decoupled to gain decent power outcomes. With the presentation of regenerative PMSM, electrical drives coupled to system integrated frameworks for recovery energy has enhanced savings in power consumptions.

Keywords: *energy management • drives • elevators • PMSM*

1. Introduction

The most recent decade of the twentieth century witnessed remarkable advancement in the development of real time applications for many industries. Innovations paved way for new methods to existing applications and noteworthy advancements were seen in mechanical system, Permanent Magnet Synchronous Motors (PMSM), and electric utilization. Controlled drives with PMSM were described to be most popular in the elevator systems and other applications by Anand et al. (2018). The development of the electric motors used in elevators is represented in Figure 1. Embarking on the significant achievement right now, history has shown a quickening pattern away from the conventional direct current (DC) commutation process motors toward revolutionary, different kinds of rotating equipment – such as brushless motors. It is the relentless efforts of research that yielded steady endeavours and constant improvement in cost enhancement of electronic components and that made leaps forward in present day hardware topologies. The advancement in innovation was overwhelmingly determined by use of progressive age of power electronic switches by Mohan et al. (1989), starting the improvements of components with bipolar junction transistors enhanced by metal–oxide–semiconductor field-effect transistors MOSFETs and insulated-gate bipolar transistors (IGBT Rapidly, IGBTs have taken control over a greater number of utilizations in power electronics' industrial utilizations that were recently fabricated by SCRs and GTOs. They captured the market due to their ease and operational characteristics, according to Baliga (2001). With the initial approach to utilize diodes as the rectifier bridge to change over the AC to DC as this should arise an occurrence of non-regenerative drives (NRD),

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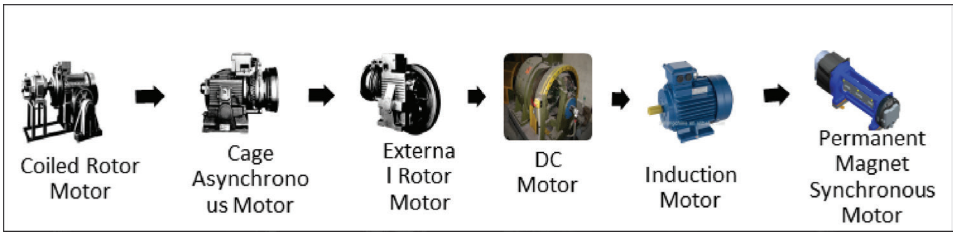

Fig. 1. Evolution of electric motors use in vertical transportation systems.

for dynamic front end that is common such as IGBTs, which are power electronic devices whose operation is controlled electronically henceforth the expression “dynamic” front end switches are most commonly found in the electric drives. The dynamic front current waveform shapes nearing to be sinusoidal, lessening absolute THD to be ≤5% according to Lee et al. (2000), Chen et al. (2011), and Anand et al. (2018). In our case study application, active front-end converters are constituted by a movement sub framework that goes about as both a converter and inverter, where AC of 50 Hz or 60 Hz is at first changed over into DC and afterward is reversibly changed over into AC with variable frequencies. Braking is an obvious part of the elevator cycle before reaching the desirable station. It is very important for the drive’s efficiency. In regenerative drive (RD), energy can return to net. In NRD it is not possible. The paper is dealing with this process.

2. Control Board

The control board is responsible for the non-power related functionality of the drive of elevator as represented in Figure 2. The control board remains mostly unmodified even when the capacity of the drive varies depending upon the elevator type as the functions discharged by the board remains unchanged, as reported by Zhong and Homik (2012) and Raghavendra Rao and Mahesh (2018). The main elements of functionality implemented by the control board are as follows:

Control: Control of the power section of the drive and overall control of the motor and brake.

Quadrature Interface: Interface to a quadrature encoder to fetch the position information of the motor.

Input/Output (I/O) port and Brake Control: Interface to ground based I/O connections including the direct interface to the Brake Power functionality.

Safety Circuit Control: Interface to the external safety chain of the elevator including car door signal, limit switches, over speed governor signal, etc., allowing additional control and sensing of the final safety signal provided to the safety circuit – power functionality.

2.1. Power section

This section of the drive depends upon the elevator capacity and speed – and also on the size of the motor.

EMI filter: In concert with the line reactor, EMI filter contains the necessary filtering for the main power flow through the drive, in order to meet the required conducted EMI ratings. It usually consists of ferrites over which the conducting wires are wound.

DC link: This component effectively decouples any higher frequency components of the power flow between the converter power and inverter power. It also contains necessary sensing information for control of the voltage on the DC link.

Pre-Charge/Charge Circuit: It allows for the ability to charge the DC Link voltage without exceeding maximum surge current requirements.

Converter Power: Bi-directional power transfer from the three-phase power lines to the DC Link is achieved through this. It also contains the appropriate sensing necessary for the control of the Converter Power and any necessary fault detection of the Converter Power.

Inverter Power: Bi-directional power transfer from the DC Link to the three-phases of the motor is performed by the inverter. It also contains the appropriate sensing necessary for the control of the inverter power and any necessary fault detection itself.

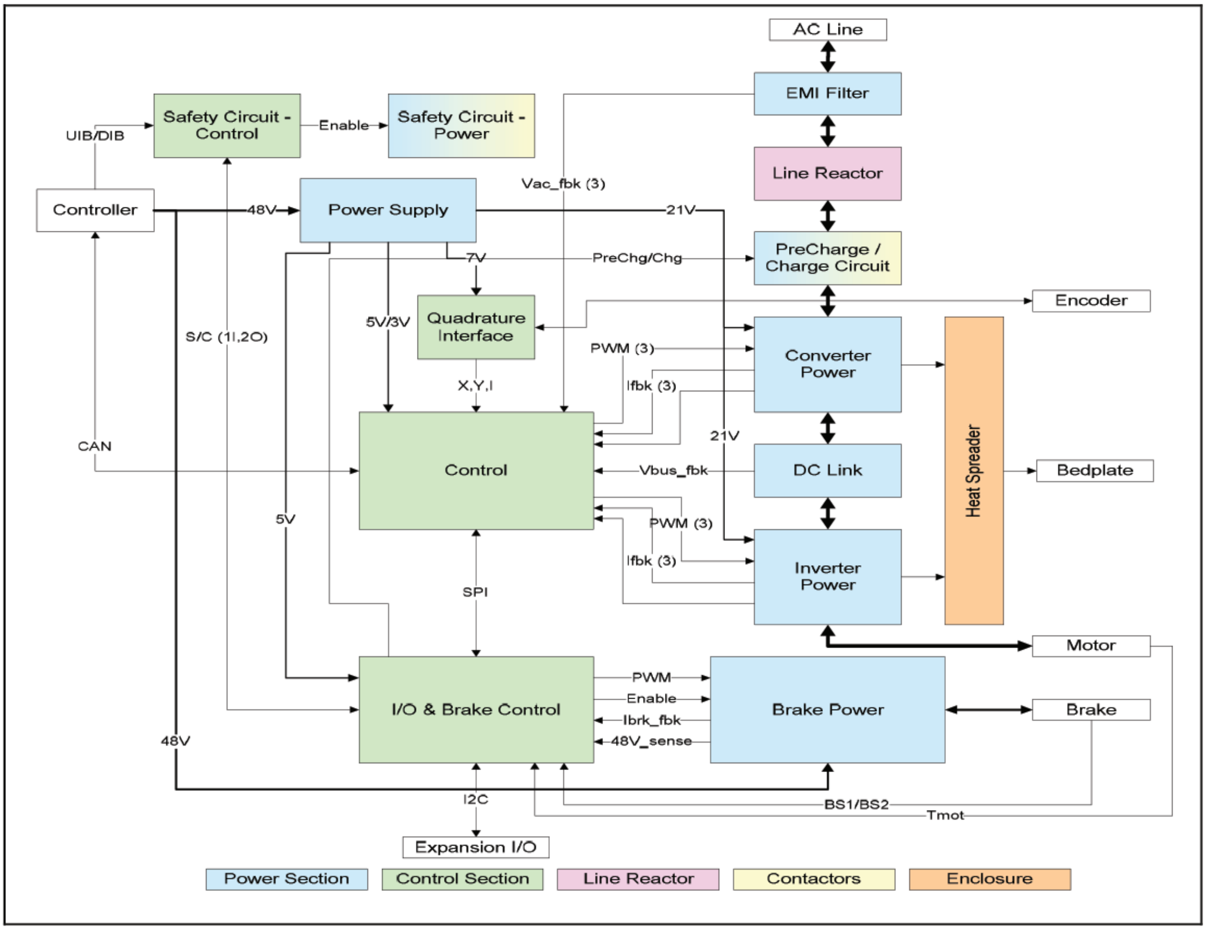

Fig. 2. Elevator configuration system.

Safety circuit power: It provides a means to disconnect the power flow to the motor and the brake in the event the safety chain is opened.

Power supply: It provides a variety of isolated output supply voltages to many different functional blocks in the drive. It usually consists of DC–DC converter with multiple output levels with galvanic isolation.

Brake Power: It provides a power amplifier allowing control of the brake. It also contains the appropriate sensing necessary for the control of the brake.

3. PMSM Regenerative Drive Analysis

The applications of electric drives can be spotted in transportation sector where electric motors are mainly used for traction and propulsion applications according to Rao (2016)" and "Rao et al. (2019). In electric trains, the power is transferred from the overhead lines to the motors using a power converter. However, in vertical transportation, the power lines are not overhead, in all cases.

The converter of the power section of drive provides the required voltages for controlling the desired torque and speed of the elevator motor according to Inoue et al. (2012) and. Consoli et al. (2012). High-power drives are very common in ships, where diesel engines are used as generators and the propulsion is generated by electric motors. Newer applications can also be found in transportation segment such as electric and hybrid vehicles and in aircraft. Generally, we see the application of RD and NRD in electric motor drives. This application is specific to vertical transportation that is required to function against gravity, with four quadrant operations showing potential regenerative energy opportunities.

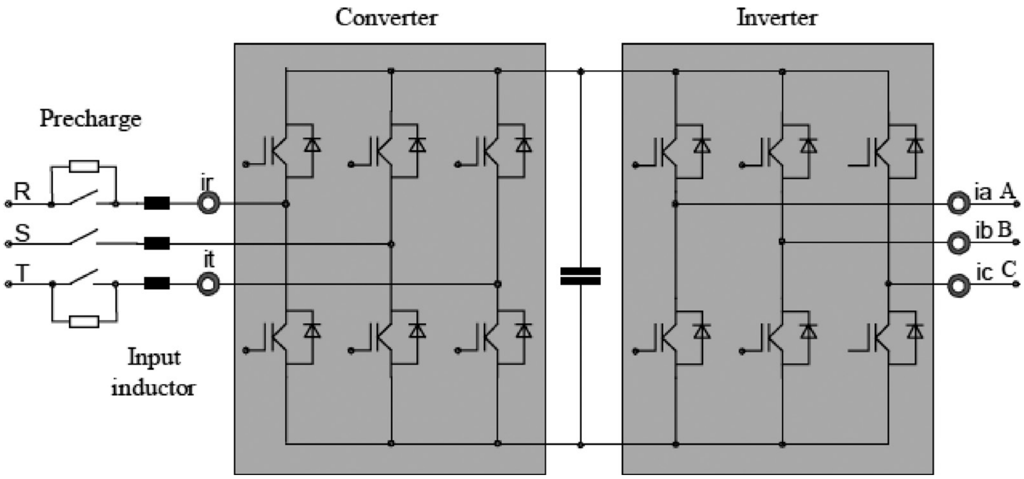

Fig. 3. Schematic Diagram of RDs. RDs, regenerative drives.

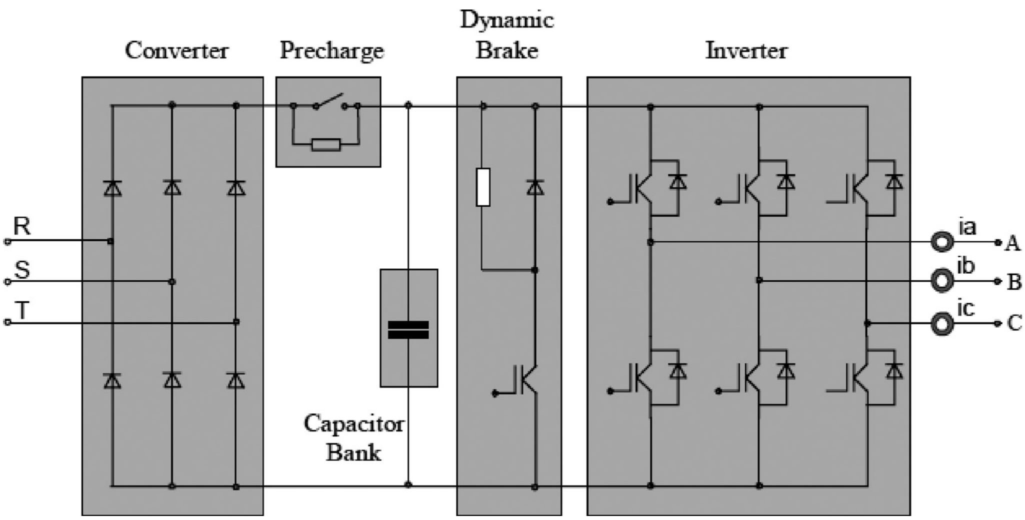

Fig. 4. Schematic Diagram of NRDs. NRDs, non-regenerative drives.

Regenerative energy is proportional to the square of the speed of elevator and is reduced by the losses in the integrated systems. Therefore, RD were adopted in gearless elevators in the recent trends in vertical transportation but were limited to higher capacity drives in studies by He et al. (2011), Anton et al. (2015), and Anand and Mahesh (2016). However, owing to recently developed low power direct drives with high efficiency PMSM, the possibilities of extracting regenerative energy are being extended to the low power range of 5 kW and below. The applications of RD into low power range have additionally facilitated by the cost optimization of semiconductor devices and using powerful digital micro-processors which are cost-effective according to Vukosavic and Levi (2003) and Clegg (1996). Traditional topology of the regenerative drive exploits DC link between inverter and converter is represented in Figure 3.

NRDs comprise mostly three-phase diode bridge at the input section followed by the DC link, which comprises of electrolytic capacitors and the inverter section consisting of the IGBT bridge powering the motor at the yield conclusion, as shown in Figure 4. In expansion, there is a dynamic brake unit as part of the drive. The brake unit consists of a transistor chopper with a resistor for dissipating the power developed during the braking cycle of the elevator. During regenerative operation of the elevator, the brake unit transistor is turned ON, thereby letting the regenerated power flow through the dynamic braking power resistors, which dissipate the energy generated as heat.

The DC link of the NRD is energized by a converter – Diode Bridge at the input side. The maximum value of DC is given by

$$U_{dc(max)} = U\sqrt{2} \tag{1}$$

The minimum value of DC voltage is given by

$$U_{dc(min)} = U\sqrt{3/2} \tag{2}$$

U is input source of the supply (utility RMS voltage in (V)).

A well-designed control strategy enables better usage of the drive converter and traction motor, as well as helps increase efficiency of the operating system. Some important control strategy parameters are elaborated in this section for a particular pattern, to achieve improved overall drive efficiency. The optimal control strategy design also aims at making the most favourable use of regenerative braking.

The standard equations of the PMSM that have been developed with rotor reference frame with constraints as eddy current and hysteresis losses are very low; thus, voltage equations are as below

$$V_d = Ri_d - \omega_r\lambda_q + \rho\lambda_d \tag{3a}$$

$$V_q = Ri_q + \omega_r\lambda_d + \rho\lambda_q \tag{3b}$$

$$\lambda_d = L_d i_d + \lambda_f \tag{4a}$$

$$\lambda_q = L_q i_q \tag{4b}$$

Matrix form is represented below

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \begin{pmatrix} -\omega_r L_q & R + \rho L_d \\ R + \rho L_q & \omega_r L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \rho\lambda_f \\ \omega_r\lambda_f \end{pmatrix}. \tag{5}$$

Torque developed is given by

$$T_e = \frac{3}{2} P \left[\lambda_d \, i_q - \lambda_q i_d \right] \tag{6a}$$

$$T_e = T_L + B\omega_m + J\frac{d\omega_r}{dt}. \tag{6b}$$

where V_d and V_q [V] denote d-axis and q-axis voltages; i_d and i_q [A] denote d-axis and q-axis currents; R [Ω] denotes per phase resistance of the stator; rad/s is the unit of electrical speed; λ_f and λ_q [Wb] are flux linkages of d-axis, field, and q-axis, respectively; ρ denotes derivative operator, L_q and L_d [H] are inductances of q-axis and d-axis, respectively; T_e [Nm] is a torque developed by the motor; P is number of the machine pole pairs; T_L [Nm] is a load torque; B [N] is a mechanical friction; ω_m [rad/s] is the unit of angular rotor speed; and J [kgm^2] is a moment of inertia.

Inertia of the PMSM is as below:

$$J = J_1 + J_2 + J_3 \tag{6}$$

$$J_1 = \frac{D}{4d^2s^2}\left(C + \frac{C_{duty}}{2} + C_{cwt} + C_{co} \right) + J_{mac} \tag{7}$$

$$J_2 = \left(\frac{D}{4d^2 s^2} \right) C_{rop} \tag{8}$$

$$J_3 = \left(\frac{D}{4r^2{}_{rop} d^2 s^2} \right) I_{mac}. \tag{10}$$

where D is drive sheave diameter in m, d is drive sheave gear ratio; S is system roping; C is car empty weight in kg; C_{cwt} is counterweight in kg; J_{mac} is sum of inertia in all sheaves in kg/m^2; C_{rop} is rope weight in kg; C_{co} is compensation rope weight in kg; and r_{rop} is the radius of compensation rope in meter.

$$Tcar\_max \quad (Tcwt)(TRst\ ) \tag{10}$$

where Tcar_max is maximum load applied to each car side rope during release of protections; T_{cwt} is maximum static tension on each counterweight rope with car at the top of the hoist way; and $TRst_a$ is the available static traction ratio (typical).

During the regenerative operation of the elevator, i.e., in the cases of empty car moving upward direction or full load moving downward direction, the motor rotates when the brakes are released due to the action of gravity. The electromotive force (EMF) (expressed in Volts) is induced in the stator coils due to the rotation of the magnetic field produced by the permanent magnets embedded in the rotor. During this operation, the inverter bridge acts as converter and charges the DC link, according to Anand and Mahesh (2016), Mirchevski (2011), and Georgiev and Mirchevski (2012); moreover, the converter bridge functions as inverter and produces AC voltage which is fed to the mains supply, thereby harvesting the energy produced by the elevator [15-16].

4. Experimental Results

Elevators in commercial office were studied to see the possibility of improving the energy efficiency of the building and one of the opportunities is through RD for these elevators. Initially, with NRD, the requirement for cooling is 7 TR for the elevator room. The original equipment does not have a RD. The experiment is conducted to check the feasibility of regeneration.

Elevators under observation are used from 08 hours till 17 hours, 6 days a week. The power peaks from the power logging data are captured to approximately identify the number of calls per day, which results in approximately 271 calls per day in 24 h, with maximum usage during daytime. The elevator speed as mentioned is 105 m/min.

The motor samples were used under the same conditions for continuous running with a duty cycle of 40% between 1st to 9th floor, with a travel distance of 45 m, as shown in Table 1, for capturing the regenerative energy and understanding the behaviour. The results are analyzed for the performances in RD drives and it can be noted in the plotted maximum and minimum power conditions for both the travel directions.

The sample motor data specifications are listed in Table 2, which have been generated after conducting real-time testing for their performance characteristics and energy that is feedback to the grid; and the associated real-time experimental set-up is captured in Figure 5.

Table 1. Round trip of both motor samples

Performance	Value
Velocity (m/min)	42
Acceleration (m/s^2)	1.3
Deceleration (m/s^2)	1.9

Table 2. Motor Parameters

Particulars	Motor 1	Motor 2
Rated voltage (V)	400	400
Starting current (A)	15.8	17.4
Running current (A)	8.1	9.6
Starts per hours	50	50
Hours per day	6	
Flight time (s)*	7	
Rated speed (m/min)	42	
Total travel distance(m)	45	
Acc/Dec (m/s^2)	0.6	
Flight time (s)*	7	
RPM	84	

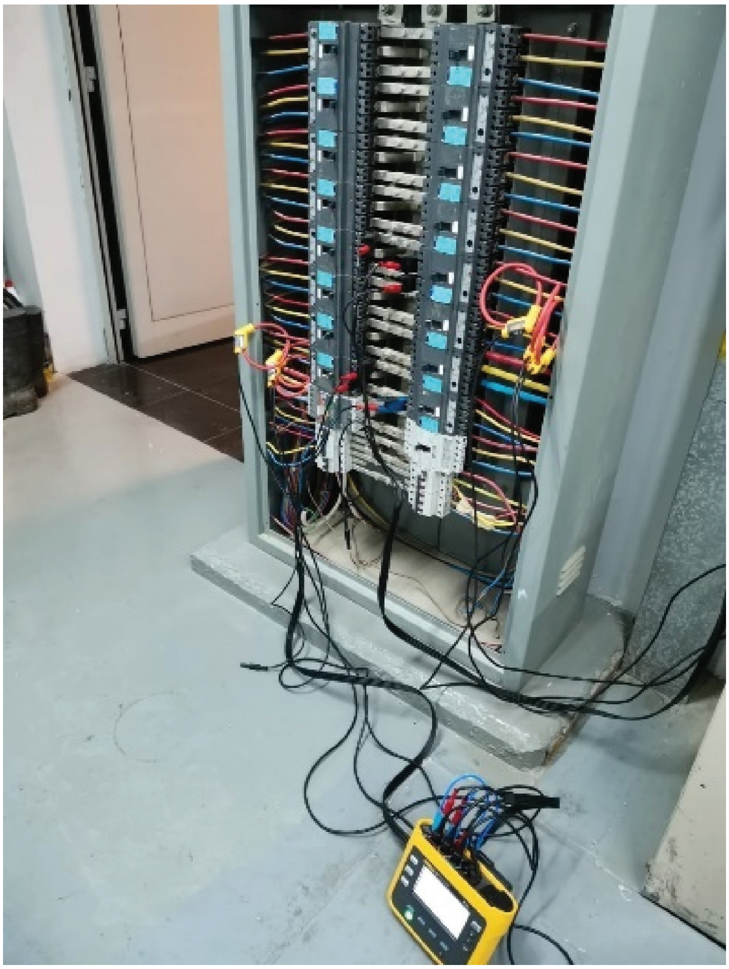

Fig. 5. Power measurements.

The data of the application motor samples were used under the same conditions for continuous running with a duty cycle of 40% between 1st to 9th floor with a travel distance of 45 m, as shown in Table 3 for the currents demanded.

The power consumption during the cyclic operation of the elevator is captured as shown in Figure 6. The data captured is for 10 min with 1 s logging interval. The tall peaks are the motoring operations (elevator car moving down

Table 3. Results of both motor samples

Outputs	Max current (A)	Average current (A)	Max KVA demand
Motor 1	13.2	7.3	7.8
Motor 2	16.9	9.8	8.3

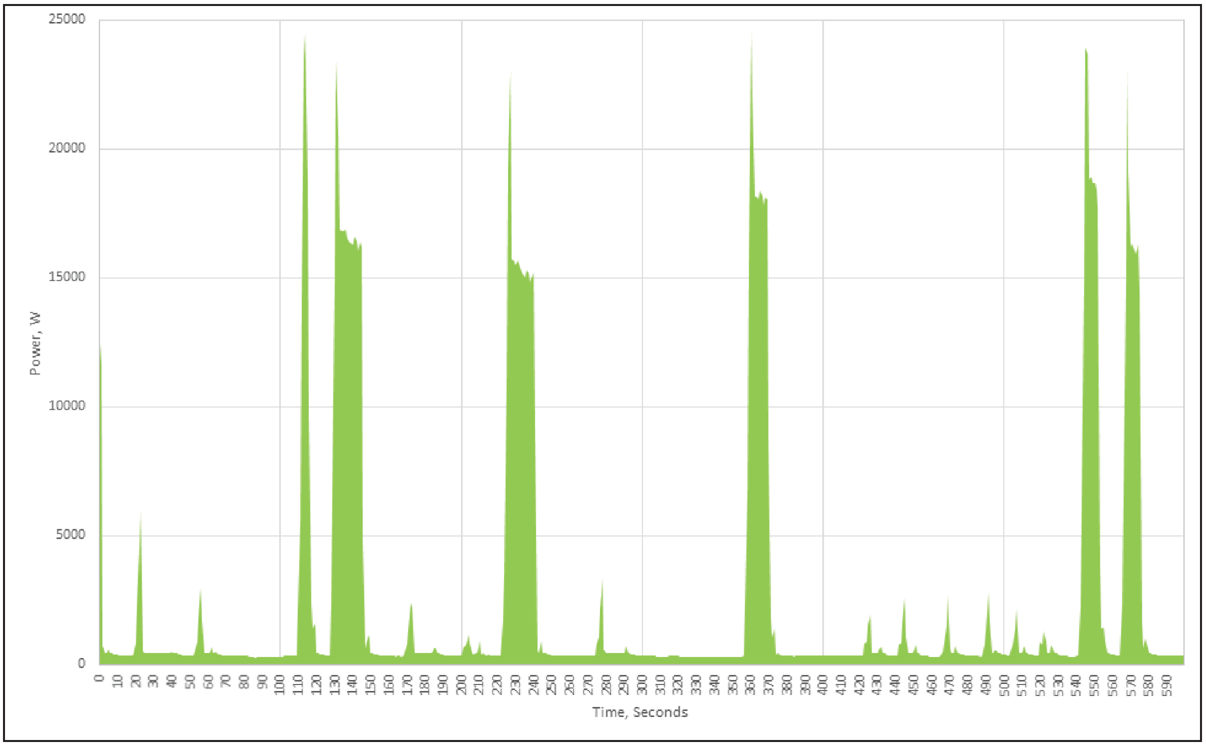

Fig. 6. Power consumption measurements in RD during elevator operation. RD, regenerative drive.

empty or with fewer passengers) while the smaller peaks seem to be the regeneration potential when the elevator car was moving up (opposite direction motor travel) in empty condition or with fewer passengers. The thickness of the peaks is determined by the floor operation. The fewer the number of floors the car is required to travel, the thinner are the size of peaks and vice versa. When the elevator is not running, there is a standby consumption of around 300 W. Current THD is around 65% with high 5th and 7th harmonics.

The power consumption of the NRD elevator during one cycle is as shown in Figure 7. The power drawn during each phase of the elevator operation can be differentiated clearly. During the acceleration, because of the inrush current, the power drawn is more, which can be seen from the peak. Once the rated speed of the elevator is reached, the acceleration becomes zero and the elevator draws rated power, which can be seen as a flat curve. And once the destination floor is approached, the motor decelerates, which is seen from the negative slope.

The power consumption at the motor terminals of the NRD is recorded as shown in Figure 8. The power consumption in positive y-axis is during the motoring mode. During the generating mode, the power is delivered by the motor, which is recorded in negative y-axis. This is the energy that is getting dissipated as heat through the dynamic braking resistors and a cause for requirement of 7 TR of cooling in the elevator room. Using the RD, this energy can be harnessed and fed back to the grid using the bidirectional switches in the converter and inverter bridges.

The break-up of energy consumption during one cycle is as shown in Table 4.

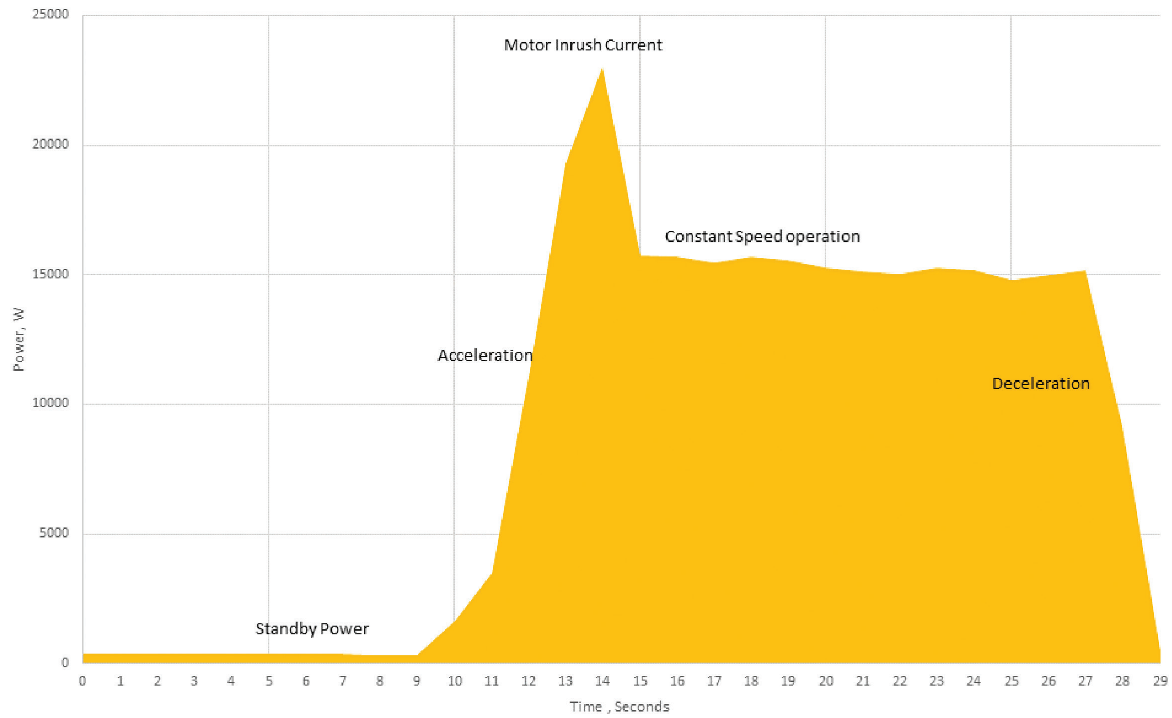

Fig. 7. Energy consumption in NRD in one cycle. NRD, non-regenerative drive.

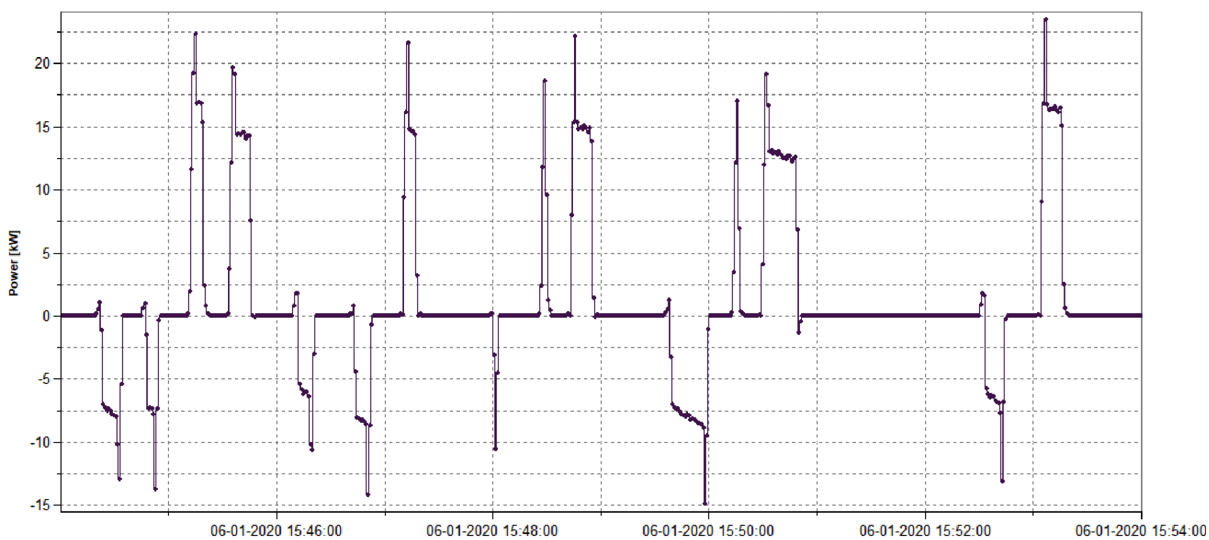

Fig. 8. Power consumption at motor terminal of NRD. NRD, non-regenerative drive.

Table 4. Energy break-up during one cycle operation

Standby energy (%)	7.19
Car up-travel energy (%)	16.01
Consumption (%)	76.80

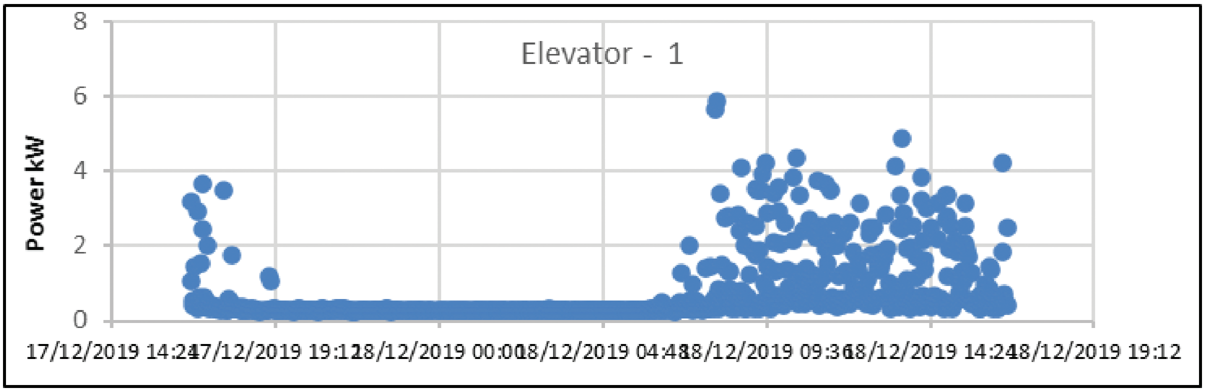

Fig. 9. Regenerative energy cluster in RD. RD, regenerative drive.

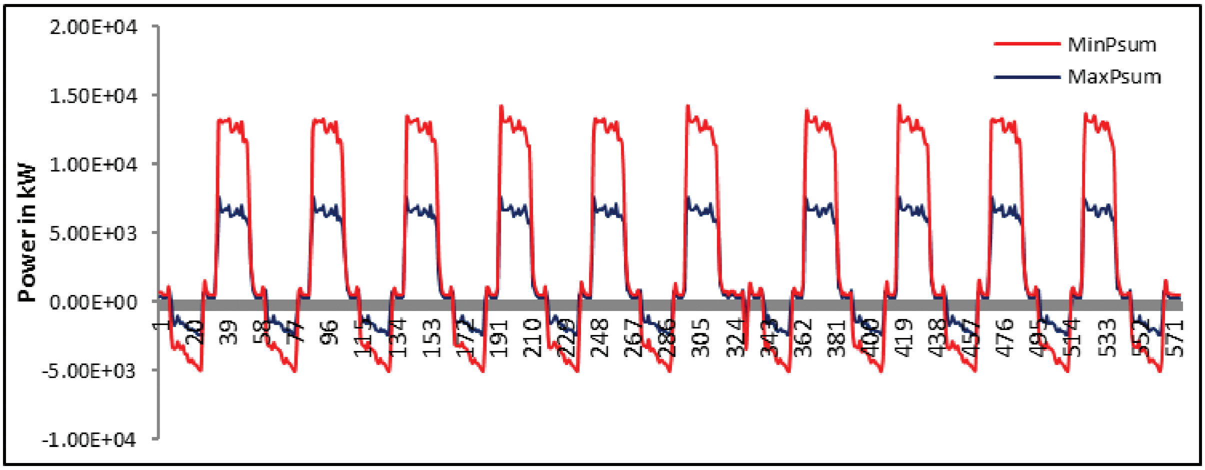

Fig. 10. Regenerative power results.

The energy cluster during regeneration mode of elevators is shown in Figure 9. If a RD is used, this energy can be harnessed. The cyclic operation power consumption of RD is as shown in Figure 10. During regeneration, the power generated is close to half of the power consumed during motoring mode. This can also be seen in Figure 8.

5. Conclusion

Drives are very common in application and are more likely subjected to frequent acceleration and deceleration, especially for passenger transportation systems. It has been analyzed and real time data was captured that indicated that in deceleration phase, kinetic energy which is proportional to the square of speed is very much available for harvesting and pumping back to the grid. From this paper it can be understood that from NRD to RD there are energy savings; however, the pattern of system utilization will determine the return on the investment. Post experimentation, it was found that generation potential is almost 50% of the motoring power; however considering the controller efficiencies and other losses, this still can safely be considered as 30%.

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