Energy Storage and Recovery System for Lift

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ABSTRACT

The elevator, from the grid side, is an impulsive load. Most of the energy used is lost during braking and/or deceleration phases. There are different ways to recover the loosen energy, but only one way is really convenient in terms of cost and efficiency: store and recovery the energy. An energy storage system requires having an accumulator that performs in an optimal way: high efficiency, bidirectional, long life, quick response time. The advantages of using an energy storage system for such application are: lower engaged power, higher efficiency due to recovery of breaking energy and energy continuity during blackout to finish the race.

1. INTRODUCTION

The lift, from the energy point of view, is an electrical to mechanical energy transformer and vice versa. The transformation takes place through the intermediate stages of acceleration, travel, deceleration and braking. All of these steps involve:

- Energy losses in the form of heat due to self-consumption by the various parties involved in the movement. Improving the performance of each component can decrease the energy absorbed from the grid. This energy contribution is only dissipative and does not allow any energy recovery but only a reduction due to a functional optimization.

- The electric to kinetic energy transfer necessary for the movement. This energy is a conservative type then regenerative. The value increases during the acceleration phase, is constant during the travel and decreases during the deceleration down to zero when it stops.

- The electrical to potential energy transfer. Also this energy is of the conservative type and therefore regenerative. The potential energy is transferred to the lift when the weight goes up, at the highest floor reaches the maximum value, while it is being transferred out from the elevator as it descends to reach the minimum value when the weight is at the lowest level.

- Electric power from the grid strongly intermittent with high amplitudes and short duration. The average power required for the lift operation is much lower.

In the following paragraphs an energy recovery and storage system combined with the lift system is described. It allows recovering of the breaking energy that is normally lost into heat, it can reduce the electric power from the grid to the average value and help to improve the overall system efficiency.

2. ENERGETIC ANALYSYS

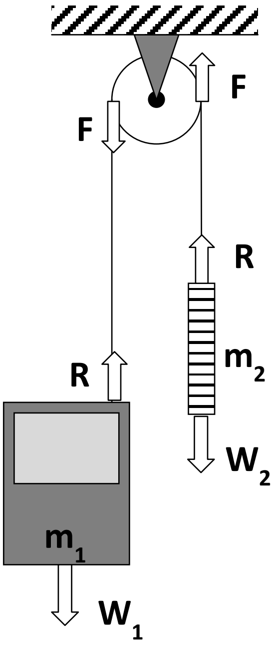

Figure 1.

With reference to Figure 1, $\boldsymbol{m_1}$ is the mass of the car, $\boldsymbol{m_2}$ is the mass of the counterweight, $\boldsymbol{W_1}$ and $\boldsymbol{W_2}$ the corresponding weight forces, $\boldsymbol{R}$ the pull of the rope and $\boldsymbol{F}$ the force applied for the movement, the balance of forces at the car level is the following:

Forces on $\boldsymbol{m_1}$
$$\boldsymbol{W_1 - R + F = m_1 a} \tag{1}$$

Forces on $\boldsymbol{m_2}$
$$\boldsymbol{-W_2 + R + F = m_2 a} \tag{2}$$

This yields the equation of the motion:

$$\boldsymbol{a = \frac{dv}{dt} = \frac{2F + W_1 - W_2}{m_1 + m_2}} \tag{3}$$

where $\boldsymbol{a}$ is the acceleration of the car and $\boldsymbol{v}$ is speed. The above equation shows that the accelerations, or speed change, depends on the weight difference between the car and the counterweight. It shows also that $\boldsymbol{a}$ depends on the sum of the mass involved in the movement.

From the energy point of view we can write:

Power
$$\boldsymbol{P = \overbrace{v(W_1 - W_2)}^{\text{Steady State Power}} + \overbrace{(m_1 + m_2)v\frac{dv}{dt}}^{\text{Dynamics Power}}} \tag{4}$$

Kinetic energy
$$\boldsymbol{E_c = \frac{1}{2}\,(m_1 + m_2)\,v^2} \quad \text{(conservative)} \tag{5}$$

Potential energy
$$\boldsymbol{E_p = (W_1 - W_2)\,(h_1 - h_2)} \quad \text{(conservative)} \tag{6}$$

Where $\boldsymbol{h_1}$ and $\boldsymbol{h_2}$ are the start and the stop level of the car.

To the above equations, in the energy balance, all the powers necessary to make the movement possible, i.e. friction and internal losses of each component involved in the movement itself should be added. Each of these quantities can be reduced by optimizing design of each component, improving the individual and the overall performance.

Nevertheless, the improvement that would result could not involve forms of recoverable energy. In fact, the recoverable energy is only of conservative nature.

Follows an analysis of each energy equation:

a) Power

The power is given by two addenda:

- The steady state power, which depends on the weight difference between the car and the counterweight and the speed, is the power required to charge the potential energy. It's the only reason that justifies the counterweight presence and explains why the elevator without counterweigh needs more power for its own movement.
- The dynamic power, which depends on the sum of the masses of the cab and the counterweight and the speed, is the power required to charge the kinetic energy. Therefore the lift with counterweight requires more energy for the acceleration and deceleration.

b) Kinetic energy

The kinetic energy is a conservative energy and therefore recoverable. The elevator with counterweight requires more energy for the acceleration, and, if not recovered, part of it is converted into potential energy and part is usually dissipated into heat during the deceleration phases. Kinetic Energy assumes values that are relevant for high-speed lifts, and even more for plants where each race is interrupted by multiple intermediate stops. For elevators without counterweight this energy contribution is much smaller (less than half).

c) Potential energy

The potential energy is a conservative energy and therefore recoverable. Without counterweight the energy required to lift the load is higher. If the energy is not recovered the potential energy is usually dissipated into heat during the breaking phases.

The importance of energy recovering can be shown comparing different plant configurations and the amounts of energy involved in the system operation. Table 1 shows the comparison between different plants, electric and hydraulic elevators, i.e. with and without counterweight, showing the amount of recoverable energy. It is clear from Table 1 how recoverable energy is more relevant with high speed elevators and with multiple stops per travel, and also it seems that there is no convenience to recover energy for plants without counterweight. Further in the article it is described that there are other advantages for the elevator without counterweight which makes the recovery system even more attractive than for the one with counterweight.

Table 1 gives a clear view of how the amount of energy that can be recovered can be very significant. If not recovered all that energy is lost into heat, which will require also other energy consumptions to cool the room.

Stated that a recovery system is desirable for such application, the question now is: what can be done with recovered energy? There are two possibilities: recover back to the grid or store it.

To recover the energy back to the grid a reversible inverter is necessary. There are different products on the market that can perform this. The cost of such inverter is almost double compared to a standard one. The energy given back is impulsive and of no convenience to the grid supplier, in most countries they would not even accept to receive back such impulsive energy and if they do it would not be paid. Also, the power required for the operation cannot be reduced to the average value, and in some countries the cost of the electric bill depends strongly on the power rate.

The best way to recover energy is to store it into an accumulator which makes energy available for the future operations. The important question is: which type of accumulator is suitable for the correct operation?

Table 1. Energy Comparison Between Different Types of Plants

Item	***Unit***	**Low speed**	**Medium speed**	**High speed**	**Standard Hydraulic**	**High eff. Hydraulic**
Motor power	*kW*	3	7	17	12	13
Plant efficiency	*%*	85%			50%	75%
Load	*kg*	480				
Car weight	*kg*	500				
Counterweight	*kg*	740			0	
Speed	*m/s*	1	2,5	6	0,6	1
Travel	*m*	24	48	75	24	24
Number of stops		8	16	25	8	8
Maximum travel time	*s*	25	20	14	41	25
Acceleration energy	*kJ*	10	62	357	3	6
Upward required energy	*kJ*	69	140	224	473	320
Deceleration recoverable energy	*kJ*	7	45	258	1	4
Downward recoverable energy	*kJ*	50	101	162	118	180
Multiple stops in one travel	*kJ*	3	5	8	0	0
Upward energy without recovery	*kJ*	84	357	2654	473	320
Upward energy with recovery	*kJ*	78	226	1018	473	320
Upward Energy Recovered in %	*%*	8%	37%	62%	0%	0%
Total Energy with Recovery	*kJ*	27	125	855	355	140
Recovered Energy	*%*	67%	65%	68%	25%	56%
Saved Energy on 50000 cycles	*kWh*	787	3224	24981	1642	2504

3. THE ACCUMULATOR

The accumulator suitable for lift applications does not need to be energy intensive but it should be power intensive. This means that it does not require to store very high energy quantity but to have enough energy to supply few travel and to be able to transfer high power in short time in both directions. The storage system must have the following main characteristics:

- High efficiency: recover as much energy as possible from the storage. The energy lost must be minimized otherwise the recovery convenience is vanished.
- The storage and the regeneration must be fast and quick. The timing shall be compatible with the elevator travels speed profile.
- Long service life. The expected time should be higher than 10 years.

- Low purchase price. The accumulator system, including the control unit, should be paid back in few years from the energy saving.
- Low maintenance cost.
- Reversible. The energy, or the power, should be able to go in both directions.

In Table 2 a comparison between different types of accumulators is shown. The battery taken into account is standard lead acid type. There are much better batteries on the market which have higher efficiency but also higher cost and anyway are not suitable for the impulsive power of an elevator and the reversibility is not so good. Other accumulators considered are: fuel cells, electrolytic capacitors, supercapacitors, superconductors and flywheel. About flywheel, the low speed types with mechanical bearings are here considered.

Table 2. Accumulators Comparison

Item		**Battery**	**Fuel cells**	**Capacitors**	**Supercap.**	**Smes**	**Flywheel**
Cost	€/kW	75	1500		600-1000	700-1000	50-100
Efficiency	%	50-60	40-55	95	90	95	95
Reversibility		no	no	Good	Optimum	Good	Optimum
Maintenance costs		High		Low	Low	Medium	Very low
N° cycle		2000		>10^5	>10^6	>10^6	>10^6
Life	years	3-5			7-8		>10
Time to hold a charge		years		days	days	days	> 2 h

The table shows that the flywheel is the best solution except for the time to hold the charge, which is few hours. This means that the flywheel needs to be supplied from the grid. The average power consumption of the flywheel tested is about 50 W.

The life of the flywheel is only limited by the bearings which should likely be changed after 7 to 10 years of operation at very low maintenance cost.

The best choice is the flywheel. The developed solution (Figure 2) has the following characteristics:

Nominal energy	600	kJ
Nominal power	15	kW
Nominal speed	12000	rpm
Efficiency	> 93	%

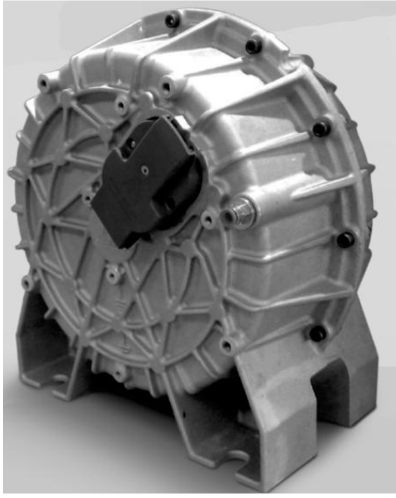

Figure 2. The Accumulator

4. THE SEM (Storage Energy Management) SYSTEM

The energy exchange between the elevator and the accumulator must be through a suitable electronic control unit. It is necessary for the system connection to be asynchronous and that ensures the functionality of the two devices allowing the proper energy exchange. This connection can be made through a *DC Bus*.

In this way the electrical machines of the elevator, fed through an inverter (INVM), can exchange the energy with the *DC Bus*. Similarly, the flywheel accumulator (ACC), which is also fed through an inverter (REGA), exchanges energy with the *DC Bus*. The energy exchange, within the limits of energy stored in the flywheel, can take place without energy request from the grid. However, the average energy required to operate the whole system needs to be taken from the grid, which will power the *DC Bus*. If a universal power interface to the power grid is required, then the voltage of the *DC Bus* must be set at a value greater than the maximum voltage of the grid. It will then be necessary to provide the interface to the grid with a step-up that stabilizes the *DC Bus* voltage to the desired value. It may be required also that the interface controls the unitary power factor (PFC). The configuration of the final accumulation and regeneration system is shown in Figure 3.

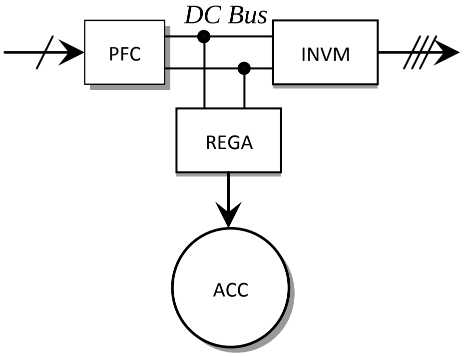

Figure 3. The SEM block diagram

To control multiple elevators at the same time, each lift, using its own inverter, must be connected to the *DC Bus* link. Figure 4 shows the complete control unit according to the diagram of Figure 3 for a single 15 kW plant.

Figure 4. Control Unit

Defining UP the phase in which the load is carried from the lower floor to the upper floor, P_s the required power and E_s the required energy after t_c time, while DOWN when the load is carried from the upper floor to downstairs, P_d the generated power and E_c the final energy, while P_c is the power absorbed from the grid, the exchange energy can then be represented as in Figure 5.

During the UP phase, the elevator absorbs energy both from the grid and the accumulator, while during the DOWN phase the elevator provides energy to the flywheel that can also absorb energy from the grid to recharge. Figure 6 shows the energy flow during the various operational phases. As it is shown in Figure 7, the power absorbed by the grid is much less than the power required to move the lift and is no longer strongly impulsive. In addition, the figure shows the energy savings that can be obtained after several operation cycles.

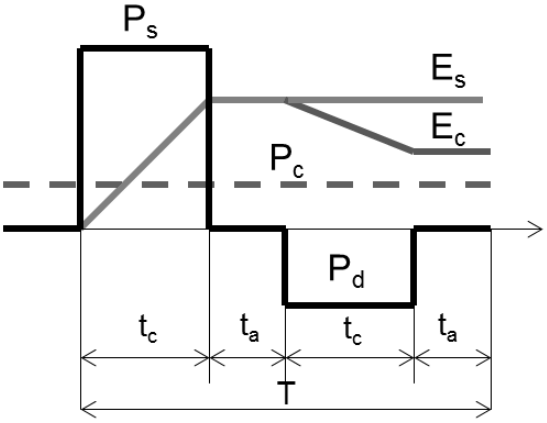

Figure 5. Energy and Power exchange

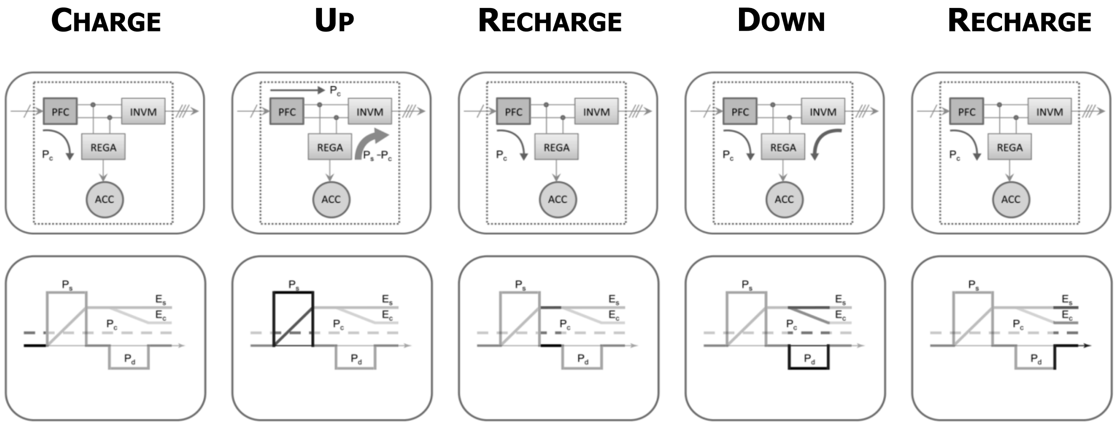

Figure 6. SEM Energy Flow during the various operational phases

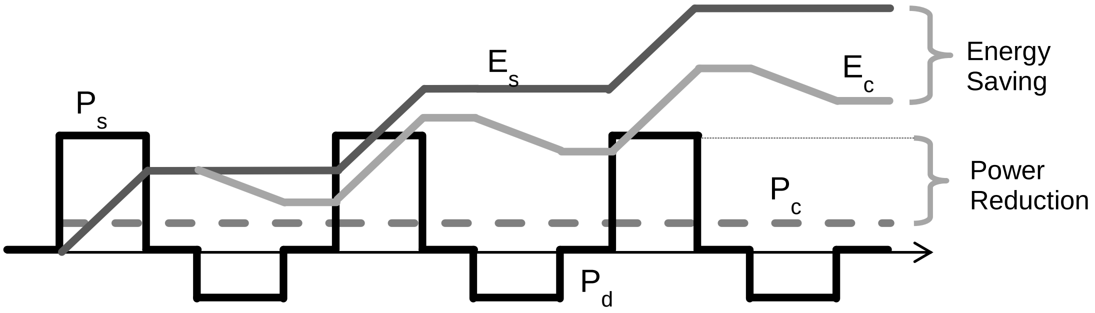

Figure 7. Power Reduction and Energy Save

5. SYSTEM EFFICIENCY

From the efficiency point of view the system can be schematized as in Figure 8. It is divided into three functional blocks.

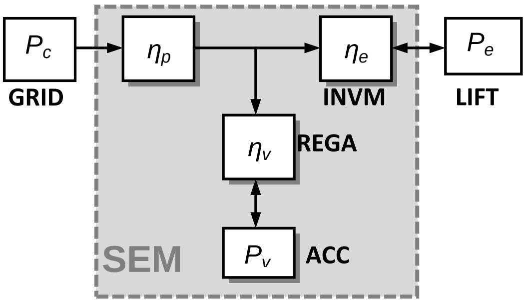

Figure 8. SEM Efficiency block diagram

The PFC block overall performances are denoted by η_p. The power absorbed by the grid is denoted by P_c.

The block REGA represents the energy storage system and is indicated by η_v and the exchanged power is denoted by P_v.

The block INVM represents lift with the inverter and the overall performances are indicated by η_e. The lift mechanical power is indicated with P_e.

There are three phases for the energy flow, UP, RECHARGE and DOWN. During the UP phase the grid supplies the power P_c, the accumulator provides the power P_{vs} and the elevator receives the power P_e. Follows the CHARGE or RECHARGE phase when the elevator is stopped and the accumulator is charged with the power P_{vc} which comes only from the grid through the PFC power (P_c). During the charging phase regeneration of power due to the lift decelerating can occur. If this happens, during this phase the accumulator is recharged with the power P_{vr} , sum of the regenerated power from the elevator P_e and the power absorbed by the grid P_c.

For the various phases described above the following equations can be written:

UP: $$P_e = P_c\eta_p\eta_e + P_{vs}\eta_v\eta_e \quad (7)$$
CHARGE: $$P_{vc} = P_c\eta_p\eta_v \quad (8)$$
DOWN: $$P_{vr} = P_c\eta_p\eta_v + P_e\eta_e\eta_v\chi_i \quad (9)$$

where χ_i is the regeneration coefficient, which is zero for a non-regenerative plants while is up to 1 for regenerative plants. It is assumed that the power absorption from the grid P_c is the same in all the three phases.

For the energy, assuming that the timing for the UP and the DOWN phases in one cycle are equal to t_c, the stop time between each travel is t_a, the equations are:

$$E_c = 2P_c(t_c + t_a) = 2P_c t_c\left(1 + \frac{t_a}{t_c}\right) \quad (10)$$

$$E_e = P_e t_c \quad (11)$$

$$E_v = P_{vs}t_c - 2P_{vc}t_a - P_{vr}t_c = 0 \quad (12)$$

from which

$$\frac{t_a}{t_c} = \frac{P_{vs} - P_{vr}}{2P_{vc}} \tag{13}$$

The total efficiency is then given by:

$$\eta_t = \frac{E_e}{E_c} = \frac{1}{2}\frac{P_e}{P_c}\frac{1}{1+\frac{t_a}{t_c}} \tag{14}$$

Hence, replacing the previous equations, after several steps we get:

$$\eta_t = \frac{\eta_p \eta_e \eta_v^2}{1 - \chi_i \eta_e^2 \eta_v^2 - \frac{P_c}{P_e}\eta_p \eta_e (1 - \eta_v^2)} \tag{15}$$

were:

η_p: is the efficiency of the PFC module, whose value is of the order of 0.93 to 0.95.

η_v: is the performance of the storage system. It is due to the efficiency of the inverter η_{vi}, in the order of 0.93 to 0.97, and the efficiency of the accumulator η_{vt}, in the order of 0.87 to 0.95. Then $\eta_v = \eta_{vi}\ \eta_{vt}$.

η_e: this parameter is more difficult to define because it includes various parts of the plant. It is composed of the lift inverter η_{ei} (internally to the SEM, in the range 0.93 to 0.97) and the lift itself η_{ec}. Supplying the lift electric motor by an inverter its efficiency can be improved if it is opportunely controlled. Said k_m (value>1) the contribution of the best performance due to the inverter, it is possible to write: $\eta_e = \eta_{ei} k_m \eta_{ec}$. Also $P_c = P_e/\eta_{ec}$.

χ_i: is the coefficient of the regeneration. The value is of the order of 0.5-1, depends on the plant reversibility. It is 0 for non-regenerative plant. Also $P_d = P_e \eta_{ec} \chi_i$.

P_c: is the power absorbed from the grid, which can be limited to a desired value to which the SEM will not overcome (programmable setting value).

P_e: is the mechanical power of the lift considering all the moving weights (cabin, counterweight, ropes, pulleys, etc..).

Without the SEM the total efficiency is given by $\eta_t = \eta_{ec}$.
The total efficiency η_t can be expressed as:

$$\eta_t = \eta_{ec}\sigma_{sem} \tag{16}$$

Where $\boldsymbol{\sigma}_{sem}$ is the efficiency contribution due to the presence of the SEM:

$$\sigma_{sem} = \frac{\eta_p \eta_{ei} \eta_v^2 k_m}{1 - \chi_i \eta_{ei}^2 \eta_v^2 k_m^2 \eta_{ec}^2 - \frac{P_c}{P_e}\eta_p \eta_{ei} k_m \eta_{ec} (1 - \eta_v^2)} \tag{17}$$

The SEM improves the whole efficiency only if $\boldsymbol{\sigma}_{sem}> 1$. The meaning $\boldsymbol{\sigma}_{sem}> 1$ is not so obvious. This does not means that the SEM has efficiency higher than 1 but that in the plant, attributing the recovered energy to the SEM, its presence makes the efficiency contribution higher than 1. This can be reached easily for regenerative ($\chi_i \neq 0$) and high efficiency plants. For non-regenerative plants, like old hydraulic plants, the advantage of using the SEM is mainly due to the drastically reduction of the engaged power, which in some countries gives a high reduction of the electric cost. Also, considering that the elevator normally makes about of 50% of empty travels, in which the efficiency of the motor can be improved through the inverter, a big advantage can be taken through the parameter k_m (k_m can be improved also using an high efficient motor and reducing the pressure drop on the valve block).

6. CONCLUSIONS

In the present article a recovery and energy storage system has been presented. It has been shown that the recovered energy can be significant, and that, for high speed installations, a drastic reduction of the energy consumption is possible. It is also shown that the instantaneous power absorbed by the grid can be reduced drastically to the cycle average value. With a consequent reduction of the strongly intermittent absorption from the grid and the considerable reduction of electrical costs related to the high installed power, especially in those countries where the cost of electricity also depends on the power rate. In particular, with reference to Figure 9, considering plants having an overall efficiency of 50% of the lift (typically hydraulic), the power that can be installed with respect to the elevator nominal power is in the ratio indicated in the graph as a function of the number of travels per hour and the race time, both for systems with and without regeneration.

The accumulation system realized, called SEM (Storage Energy Management), is constituted by a high efficiency flywheel accumulator. This solution offers an excellent price performance ratio.

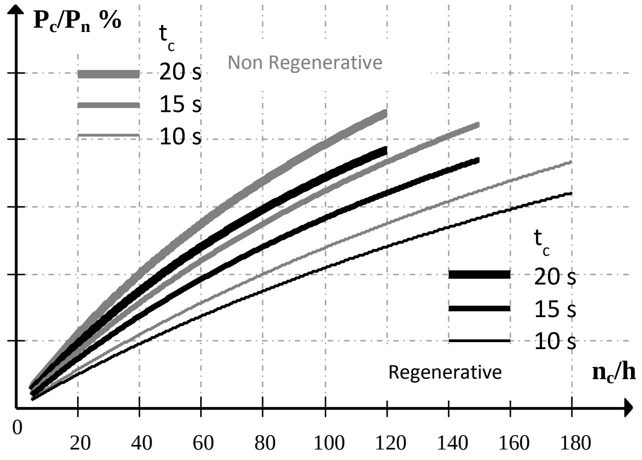

Figure 9. Power Ratio (P_c/P_n) vs Number of Travel per Hours (n_c/h)

The SEM accepts any voltage and frequency from the grid, either with single or three phase supply, supplying anyways the elevator with three phase power.

The presence of the PFC allows to keep power factor always unitary. It is then suitable to be installed easily on any plant, both new and existing, electric and hydraulic type, without any change in the panel control or in the plant or to the electric motor. No special knowledge is required for the installer and any technician can install it quickly and easily. Thanks to the accumulated energy, in the event of an energy blackout, the SEM gives the continuity of operation to complete the race without any speed variation. The internal inverter allows to have a comfortable travel and a precise stop to the floor for any load.

The advantage of using SEM with electric elevators is that it can reduce the energy consumption, specially for medium to high speed elevator, can reduce the required power and can give continuity of operation in case of energy blackout.

For hydraulic elevator the biggest advantage is to reduce the power to the average value making the power rate comparable to the electric elevator. It makes the hydraulic elevator work as if it has the counterweight (Electric counterweight). Also, if the power unit of the elevator is provided by a regenerative valve block, the descending energy can be stored and reused during the UP race. The valve block can be made easily regenerative allowing the oil to flow back through the pump instead of going directly in the tank. In this way the rotation would be reversed and the electric motor of the pump would work as generator and recharge the storage. If an external high efficient motor, PM Brushless, is used instead of the low efficiency submersible induction motor, than the recovered energy can be very significant. In any case, the use of the SEM, for the hydraulic elevator allows to reduce drastically the gap with the electric elevator in terms of power and consumption, making the trade off comparable between the two technologies. This allows for instance to bring the rated power of an hydraulic elevator from 15 kW or even 25 kW down to 3 kW single phase, which is comparable to an electric elevator without SEM, or even better.

The advantage of using SEM with both elevators topologies is not only in terms of energy and/or power, but mainly economics. The energy saving and the power reduction can halve the electric bill, which will allow to pay back the SEM investment in very short time.