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A regenerative braking energy recuperation from elevator operation in building by active rectifier

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ABSTRACT

Elevators- means of vertical transportation to carry people and goods are an indispensable part in offices, high-rise buildings, hospitals, commercial areas, hotels, car-parks when blooming urbanization develops worldwide. However, the level of energy consumption in elevator operation is significant, so energy saving solutions have been outlined and applied in practice. With frequent braking phases, regenerative braking energy is wasted on braking resistors. Therefore, this paper proposes regenerative braking energy recuperation method for elevator operation in building by active rectifiers enabling the braking energy to be fed back into utility grid. Simulation results conducted by MATLAB with data collected from OCT5B building-RESCO new urban area, Hanoi, Vietnam have verified saving energy of using active rectifiers replacing diode rectifiers up to 33%.

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1. INTRODUCTION

Elevators are very important with high-rising buildings [1]-[3], however, these electrical transport systems can account for a considerable proportion of energy consumption in buildings while the regenerative braking energy obtained by operation modes of elevators at the time of lifting-up with light load and lifting-down with heavy load is burned on the braking resistors, causing wastage and air pollution [1]-[2]. Therefore, improving the energy efficiency of elevator operation has attracted more attention from manufacturers and researchers, most of whom have proposed various energy saving solutions applied in practice [4]-[9]. Priyanka Priyanka Kubade, and S. K. Umathe [10]; A. Rufer, and Philippe Barrade [11] recovered regenerative braking energy by supercapacitors energy storage device and reutilized it when the more energy is required by another elevator motor; M. Shreelakshmi, and Vivek Agarwal [12] combined fuel cell for the ride-through operation with supercapacitor bank for storing the regenerative braking energy; Shili Lin, Wenji Song, Yongzhen Chen, *et. al.* [13] used the battery energy storage system to suppress the voltage fluctuation of the DC grid of elevator, making it capable of replacing the resistor in the braking system of the elevator; Supapradit Marsong and Boonyang Plangklang, *et. al.* [14], Boonyang Plangklang, Sittichai Kantawong, Sirichai Dangeam, *et. al.* [15] designed an energy-regenerative unit integrated with permanent magnet motor elevator systems which can be save up to 43%; Konstantinos Kafalis and Athanasios D. Karlis [16] showed supercapacitor or flywheel energy storage systems (SCESS, FESS) driven by a permanent magnet motor in which FESS are mainly used for power applications from l kW up to 1 MW, while supercapacitors for l-100kW and 200Wh-500Wh respectively and FESS save regenerative braking energy more effectively than SCESS about 6%. Furthermore, optimization techniques such as: linear programming, mixed-integer linear programming, quadratic programming, model predictive control, dynamic programming are applied to minimize energy consumption in elevator operation. A. Mesemanolis, C. Mademlis, and I. Kioskeridis [17], Nikolaos Jabbour and Christos Mademlis [18], [19] used an energy management system based on an adaptive neuro-fuzzy control technique applied to an elevator motor drive to adjust the elevator acceleration/deceleration rate and speed so as to maximize the regenerative capability of the motor drive and therefore to increase the efficiency of the whole elevator system: Endika Bilbao, Philippe Barrade, Ion Etxeberria-Otadui, *et. al.* [20] applied optimal energy management strategy of an elevator with energy storage capacity based on dynamic programming (DP) to reduce grid power peaks by 65%, and braking resistor energy losses have been reduced by 84%. This paper proposes another regenerative braking energy recuperation solution-the active rectifier with bidirectional energy flow replacing diode rectifier so that the regenerative braking energy will be backed to the grid. The simulation results on MATLAB of buildings in Hanoi, Vietnam indicate that energy savings is up to 33%.

2. ENERGY SAVING FOR AN ELEVATOR

The elevator system as Figure 1 comprises of mainly parts: active rectifier is able to turn energy back grid in order to recover regenerative braking energy and the voltage oriented control (VOC) is used to control the rectifier method similar to the field-oriented control method (FOC) of elevator driven motor [21]-[25]. In this section focusing on modelling and controlling the active rectifier-a crucial device in the elevator operation energy saving.

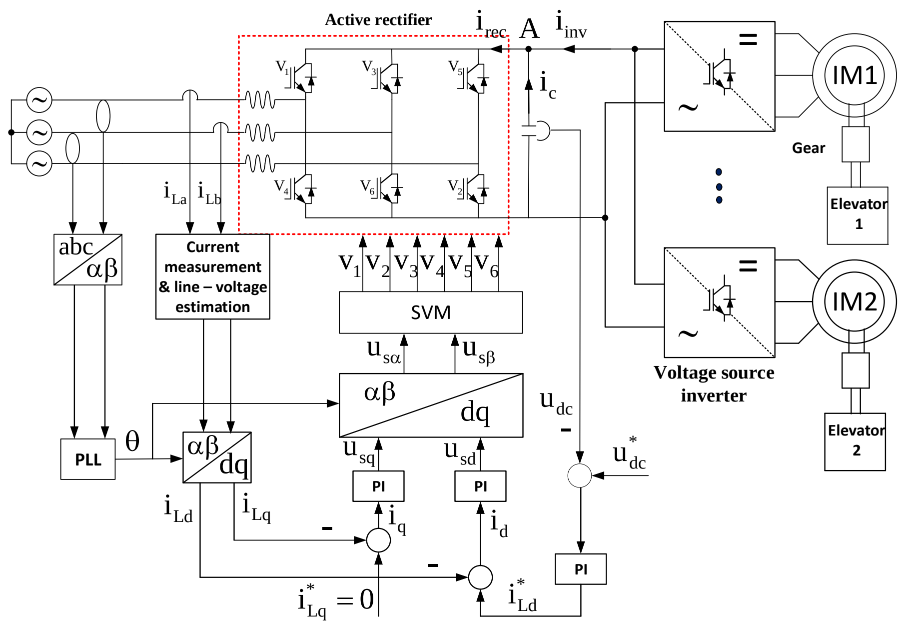


Figure 1. Control scheme of elevator system

From Figure 1 and Figure 2 (a), the three voltage equations for balanced three-phase system without the neutral connection (Figure 2 (a)) can be written as.

$$\begin{bmatrix} U_{La} \\ U_{Lb} \\ U_{Lc} \end{bmatrix} = R \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} + \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} \tag{1}$$

and one for currents.

$$C\frac{du_{dc}}{dt} = S_a i_{La} + S_b i_{Lb} + S_c i_{Lc} - i_{inv} \quad (1)$$

Where Sa, Sb, Sc-the switching function of the active rectifier

Using the Clarke and Park transformations to convert the system of (1) from the coordinates *(abc)* to the coordinates *(dq)* [22].

$$\begin{cases} u_{Ld} = Ri_{Ld} + L\frac{di_{Ld}}{dt} - \omega_L L i_{Lq} + u_{sd} \\ u_{Lq} = Ri_{Lq} + L\frac{di_{Lq}}{dt} + \omega_L L i_{Ld} + u_{sq} \end{cases} \quad (2)$$

$$c\frac{du_c}{dt} = (i_{Ld}S_d + i_{Lq}S_q) - i_{inv} \quad (3)$$

Given

$$\begin{cases} S_d = S_\alpha \cos\omega_L t + S_\beta \sin\omega_L t \\ S_q = -S_\alpha \sin\omega_L t + S_\beta \cos\omega_L t \end{cases} \quad (4)$$

$$\begin{cases} S_\alpha = \frac{1}{\sqrt{6}}(2S_a - S_b - S_c) \\ S_\beta = \frac{1}{\sqrt{2}}(S_b - S_c) \end{cases} \quad (5)$$

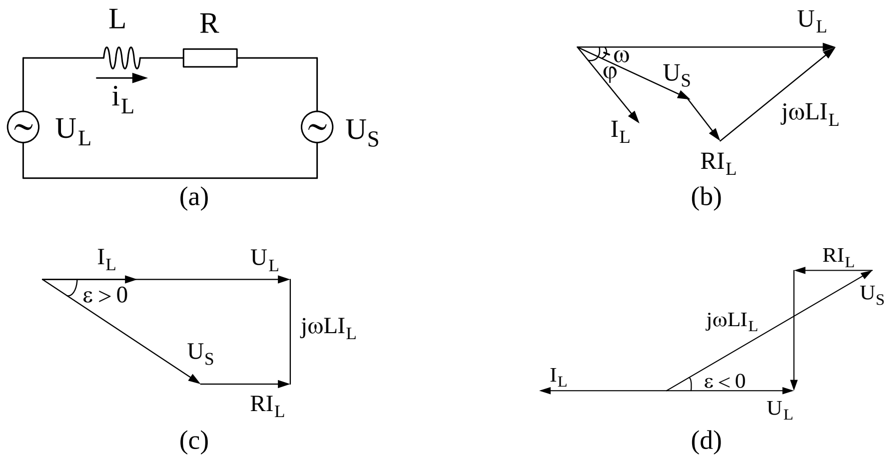


Figure 2. Phasor diagrams, (a) single-phase diagram of rectifier circuit, (b) general phasor diagram, (c) Rectification at unity power factor, (d) Regeneration at unity power factor

Therefore, the mathematical model structure of the active rectifier in the *dq* coordinates is shown in Figure 3

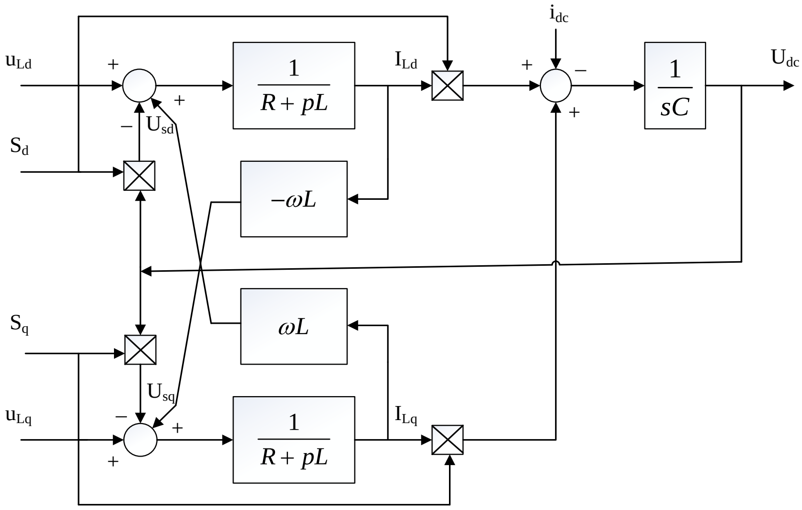


Figure 3. Active rectifier model in *dq* coordinates

2.2. Design of control loops

In order to achieve great advantages of the active rectifier. In this section, designing three control loops phase locked loop, current loop and voltage loop is performed.

2.2.1. Phase locked loop (PLL)

The PLL performs the determination of the phase angle between the grid voltage vector and the α-axis of the coordinate system *αβ*, which is also the angle between the d-axis of the rotation coordinates *dq* with α-axis of fixed coordinates *αβ*, for converting current and voltage vector coordinates as shown in Figure 4. Figure 5 shows voltage vectors on the axes *αβ* and *dq* and Figure 6 shows control structure of PLL phase-lock loop.

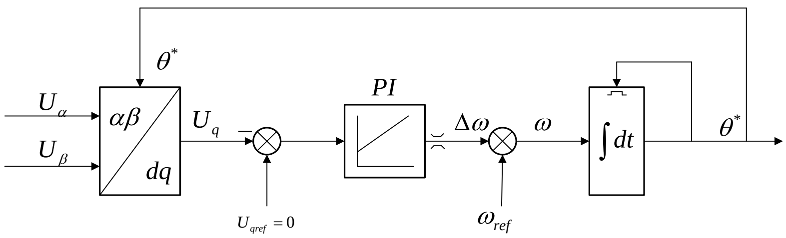


Figure 4. PLL scheme

with *Uq* is calculated according to the transformation formula.

$$Uq = -U.\sin(\theta * - \theta) = U.\sin(\Delta\theta) \tag{6}$$

$\Delta\theta$ is small, $Uq = U.\Delta\theta$

where:

U_q : source voltage on q-exis of *dq* coordinates

θ^* is the PLL block output leaning angle

θ is the source voltage phase angle

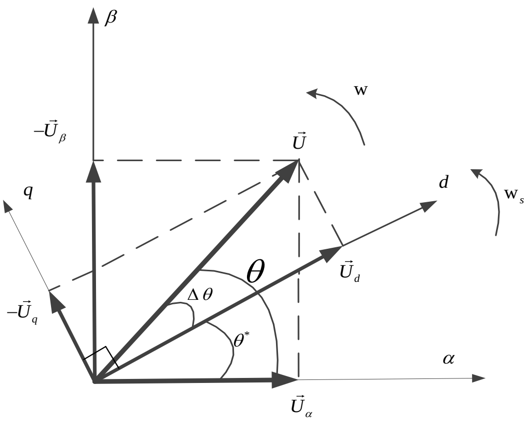


Figure 5. Voltage vectors on the axes *αβ* and *dq*

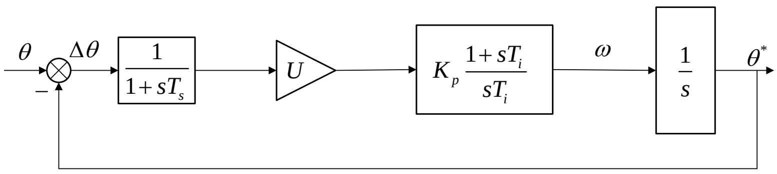


Figure 6. Control structure of PLL phase-lock loop

The closed-loop phase transfer function.

$$F_{k\theta}(s) = \frac{F_{h\theta}(s)}{1+F_{h\theta}(s)} = \frac{k_1 \frac{1+T_{i\theta}.s}{s^2}}{1+k_1 \frac{1+T_{i\theta}.s}{s^2}} = \frac{k_1.T_{i\theta}.s+k_1}{s^2+k_1.T_{i\theta}.s+k_1} \equiv \frac{2.\xi.\omega_n.s+\omega_n^2}{s^2+2.\xi.\omega_n.s+\omega_n^2} = G_k \;\; s \tag{7}$$

Using the symmetric optimization method with the standard function *G_k(s)*[25], then seeking $k_{p\theta}, T_{i\theta}$.

$$\Rightarrow \begin{cases} k_1 = \omega_n^2 \\ k_1.T_{i\theta} = 2.\xi.\omega_n \end{cases} \Leftrightarrow \begin{cases} k_1 = \frac{k_{p\theta}.U}{T_{i\theta}} = \omega_n^2 \\ T_{i\theta} = \frac{2.\xi.\omega_n}{\omega_n^2} = \frac{2.\xi}{\omega_n} \end{cases} \Leftrightarrow \begin{cases} k_{p\theta} = \frac{\omega_n^2.T_{i\theta}}{U} \\ T_{i\theta} = \frac{2.\xi}{\omega_n} \end{cases}$$

Where ω_n- Oscillation cycle, ξ-Damping ratio (select $\xi = 0.7$).

2.2.2. Design current control loop

Inner loop circuit-current loop: The task is to bring reactive power Q ≈ 0 and coefficient cosφ ≈ 1. Deriving from (3): Ignoring the coupling component *ωL,* transfer function relating $i_{Ld}$with Δu_{Ld} is computed straight forwardly (Figure 7).

$$\frac{I_{Ld}}{U_{Ld}-U_{sd}} = \frac{1}{R+L.s} \tag{9}$$

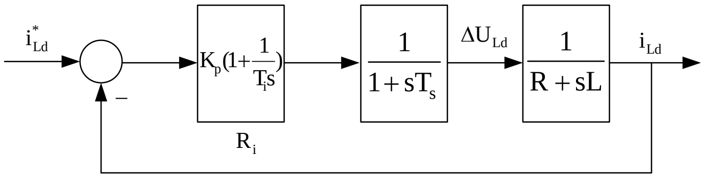


Figure 7. Control structure of i_{Ld} current controller

The closed-loop transfer function of the inner loop i_{Ld} turns out to be.

$$G_k(\mathrm{s}) = \frac{k(1+T_i s)}{1+T_2 s\ \ T_a.s + k(1+T_i s)} \quad (8)$$

To calculate controller parameters, the module optimal method is used [26].

$$\Rightarrow \begin{cases} T_i = T_1 = \dfrac{L}{R} \\ T_a = 2kT_2 \end{cases} \Leftrightarrow \begin{cases} T_i = \dfrac{L}{R} \\ \dfrac{T_i}{k_p} = 2\dfrac{1}{R}T_s \end{cases} \Leftrightarrow \begin{cases} T_i = \dfrac{L}{R} \\ k_p = \dfrac{L}{2T_s} \end{cases}$$

Similarly, synthesising i_{Lq} control loop as i_{Ld} control loop. Then, considering the components ωL to compensate the coupling of inner control loops as Figure 8.

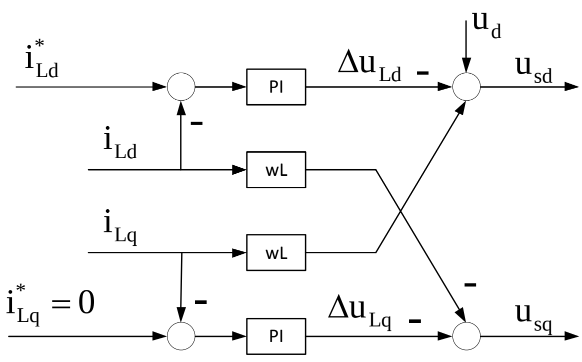


Figure 8. Decoupled current controller block diagram

2.2.3. Design voltage control loop

Designing voltage control loop is to balance energy from grid unity to load by keeping the voltage on the U_{dclink} unchanged at the fixed value. From the (3).

$$Cs.U_{dc} = I_{Ld}.S_d + I_{Lq}.S_q - I_{inv}$$

Given

$$I_{Lq}=0 \Rightarrow U_{dc} = \frac{I_{Ld}.S_d - I_{inv}}{Cs} \quad (9)$$

Regarding I_{inv} as a noise component, so it is omitted.

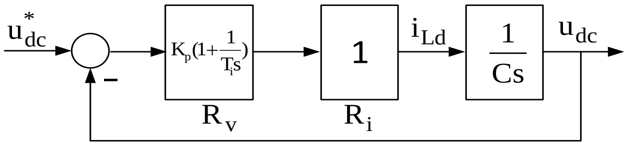


Figure 9. Voltage controller block diagram

The closed-loop transfer function of voltage control loop.

$$F_{kV}(s) = \frac{F_{hV}(s)}{1+F_{hV}(s)} = \frac{k_1 \dfrac{1+T_{iV}.s}{s^2}}{1+k_1 \dfrac{1+T_{iV}.s}{s^2}} = \frac{k_1.T_{iV}.s+k_1}{s^2+k_1.T_{iV}.s+k_1} \equiv \frac{2.\xi.\omega_n.s+\omega_n^2}{s^2+2.\xi.\omega_n.s+\omega_n^2} = G_k(s) \quad (10)$$

Use the symmetric optimal method with the standard function $G_k(s)$.

$$\Rightarrow \begin{cases} k_1 = \omega_n^2 \\ k_1.T_{iV} = 2.\xi.\omega_n \end{cases} \Leftrightarrow \begin{cases} k_1 = \dfrac{k_{pV}}{T_{iV}.C} = \omega_n^2 \\ T_{iV} = \dfrac{2.\xi.\omega_n}{\omega_n^2} = \dfrac{2.\xi}{\omega_n} \end{cases} \Leftrightarrow \begin{cases} k_{pV} = \omega_n^2.T_{iV}.C \\ T_{iV} = \dfrac{2.\xi}{\omega_n} \end{cases}$$

3. SIMULATION RESULTS

The simulation is conducted by data collected from OCT5B building-RESCO new urban area, Hanoi, Vietnam. Simulation results verifying energy saving capability of the active rectifier are Considered by scenarios: full load up-the most energy consumption; full load down-the most energy saving when the elevator operates in ten floors of buildings with total time about 50,76s (in which running time of each floor: accelerating phase-0.66s, holding speed phase-2.14s, braking phase-0.66s, dwell time-2s).

Table 1. Parameters of elevator system for OCT5B building

Parameters	Values
Number of floors	10
Distance between floors (m)	2,8
Cabin's weight (kg)	1200
Counterweight (kg)	1600
Passangers weight (kg)	1000
Maximum speed, v_{max} (m/s)	1
Acceleration and deceleration, a_{max} (m/s^2)	1.5
Pulley diameter, *D* (m)	0.4
Transmission ratio, *i*	1/20
Transmission performance, η	80%
Nominal power P (kW) of each motor	15
Number of elevators	2

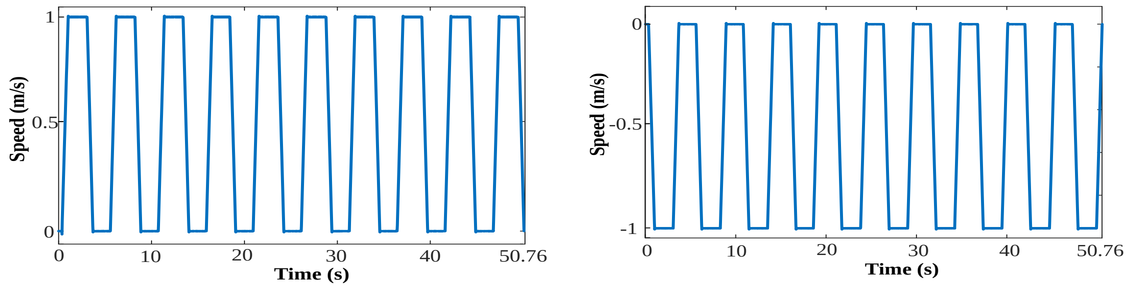
Table 2. Parameters of active rectifiers

Parameters	Values
Phase inductance, L(mH)	2
Phase resistance, R (Ω)	0.05
Capacitance of DC link capacitor C (μF)	1000

Table 3. Parameters of controllers

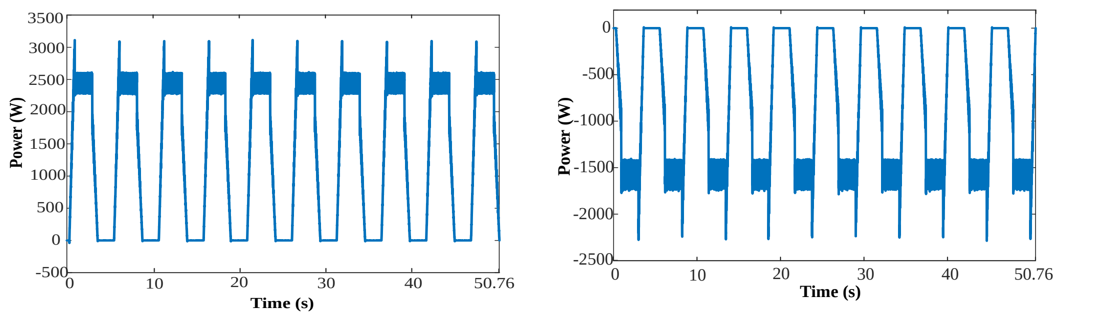
	K_p	T_i
Current loop	2	0.04
Voltage loop	0.56	0.0035
Phase Locked Loop (PLL)	0.74	0.007

Figure 10 and Figure 11 show that the speed value with full load up process is 1m/s, and full load down one is -1m/s suitable for the change situation of the regenerative power; namely, the power as the full load elevator moving up consumed up to 2600W meanwhile the power as the full load elevator moving down backs grid utility about -1700W. With often operation processes of elevator: accelerating, holding speed, braking causing voltage fluctuation on bus DC demonstrated in Figure 12 with the diode rectifier. In the case of full load up, traction motor operating in accelerating phase needs to mobilize power, so voltage decrease, voltage fluctuation is from 620 to 650V DC (Figure 12 (a)); with full load down, the traction motor works as the electric generator turning power to line, which causes voltage on DC bus to increase from 650 to 800VDC (Figure 12 (b)).



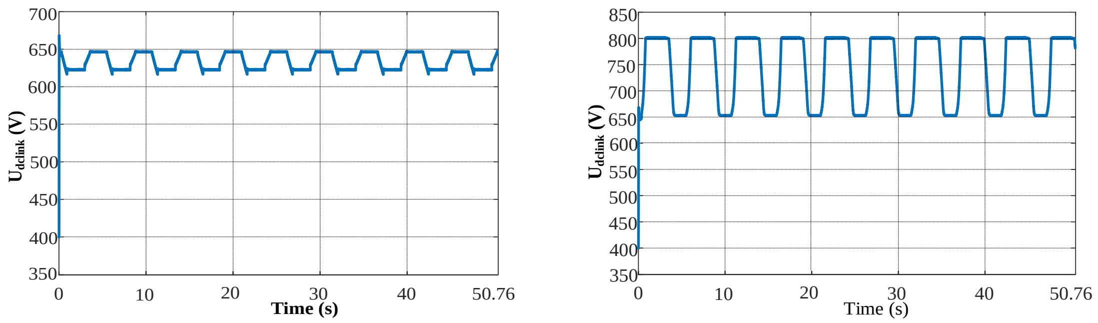
(a) (b)

Figure 10. Speed responses, (a) full load up, (b) full load down



(a) (b)

Figure 11. The change situation of the regenerative power, (a) full load up, (b) full load down



(a) (b)

Figure12. Responses of voltage on U_{dclink} with diode rectifier, (a) full load up, (b) full load down

On contrary, the active rectifier still ensures the grid voltage within the range allowed 650 VDC in Figure 13 and guarantees the safety of the power supply system of the elevator when the elevator runs up, and runs down with full load.

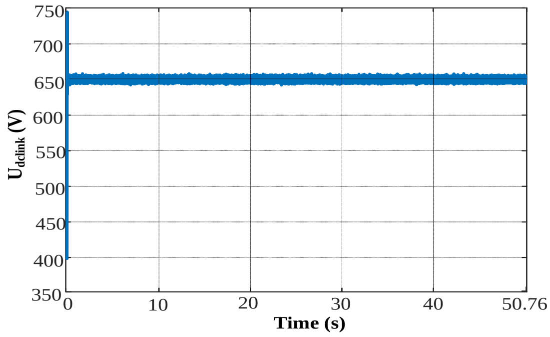


Figure 13. Response of voltage on U_{dclink} with active rectifier when full load up and full load down.

Comparing level of energy saving when using active rectifier in Figure 14, Figure 15 shows consumption energy response of grid source when elevator moves up with full load is 46Wh, and regenerative braking energy turns source when the elevator moves down with full load and uses active rectifier is 15,8Wh. Therefore, percent of saving energy is 33%.

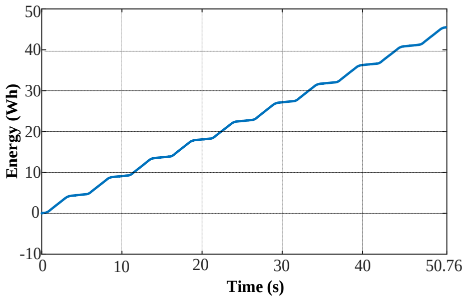


Figure 14. Consumption energy response of grid source when elevator moves up with full load

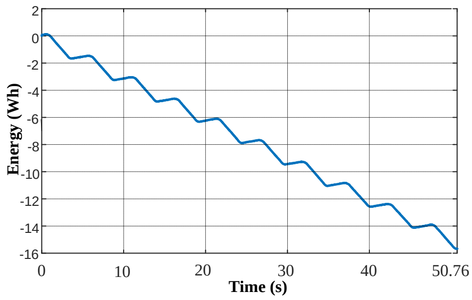


Figure 15. Regenerative braking energy flows back source with active rectifier when the elevator moves down with full load

4. CONCLUSION

In this paper, the main focus is on enhancing elevator efficiency by reducing its consumption energy. The simulation results of elevator drive system with the active rectifier replacing diode one in OCT5B building-RESCO new urban area, Ha noi, Vietnam showed by using active rectifier, energy can save up to 33%.

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BIOGRAPHIES OF AUTHORS

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