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Regenerative Braking and Energy Recovery in High Vertical Lift

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ABSTRACT: *At the moment there is a transmission where the world is moving towards a more sustainable future of energy for home and smart industrial applications through the optimization of power and energy by means of reducing energy losses. Regenerative braking has found a breakthrough in the locomotive and automotive industry. Regenerative braking technology provides a means of energy recovery of about 40% of the energy being converted to other forms of energy. However, there is still large under-utilization of this technology, and especially in this case where the focus is on vertical lifts. This script tries to address such issues by implementing regenerative braking technology on vertical lifts as a means of an energy recovery tool and to alleviate grid stress in times of peak power demand. After thorough research, literature review and experimental observations an effective system was designed, and the aim and objectives of the study were experimented. Implementing such technology in the context of mining sector can significantly reduce yearly operational costs by a huge percentage of monetary value as there is heavy reliance on electrical power in the industrial sector*

Key words*: Regenerative braking, Vertical lifts, Energy recovery*

I. Introduction

Industrial set-ups are at the top of Zimbabwe's energy consumption with the electrical motor being the heart of nearly all the processes that involve motion. The use of mechanical and resistive braking mechanisms to slow down and halt vertical lifts is a waste of energy as this energy is dissipated as heat to the atmosphere [1]. This also results in high operational costs as the breaks go through wear and tear with time requiring maintenance and ultimately replacement. These braking mechanisms therefore brings forth high electricity and utility bills and are proving to be inefficient [2].

Use of regenerative braking by a building elevators and industrial set-ups will help reduce the overall energy consumption and lower operating costs amidst the current global energy crisis. This in turn reduces the reliance on power from the grid and therefore alleviating stress on the grid during peak hours [4]. Such a system proves to be beneficial to both the local electricity supply authorities and to the consumer as well.

II. Principles of Regenerative Braking technology

Regenerative Braking works through converting the kinetic energy of a moving object into electrical energy. By the law of conservation of energy, when this kinetic energy is being converted into electrical energy, the object's kinetic energy gradually reduces and this causes the object in motion to slow down [6]. The electrical energy is then stored in a battery or another storage device for later or immediate use. This mechanism makes

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use of the generator effect with the object's inertia providing the movement of the rotor, a process called electromagnetic induction.

The amount of kinetic energy extracted during this process mainly depends on two main physical quantities i.e. the speed and the mass of the moving object. The faster the system is moving, and the heavier the load it is carrying, the more the kinetic energy that can be extracted through regenerative braking. This is described through the basic kinetic energy equation [9].

$$kinetic\ energy = \frac{1}{2} \times mass \times velocity^2 \quad (1)$$

However, the actual amount of electrical energy that can be recovered depends on a quantity known as back electromotive-force which is precisely generated when the motor is rotated. Back Electromotive force is the voltage generated in a motor coil when it is subjected to a changing current or magnetic field [7]. This Back EMF acts in opposition the applied voltage and reduces the current flow in the circuit. The back EMF, ε is a voltage potential generated due to the motor coils rotating in the magnetic field. The back EMF is given by

$$\varepsilon = \omega \times K_\tau \quad (2)$$

Where ε is the back EMF

ω is the angular velocity

K_τ is the motor's torque constant [10]

The amount of power being converted to electrical energy is given by:

$$P = \tau \times \omega \quad (3)$$

Where P is the power being converted to electrical energy

τ is the torque

ω is the angular velocity

The torque τ is however made up of two components i.e. the frictional torque τ_F which goes to producing heat and the torque due to current flowing in the motor τ_M [11]. Of these two components of torque, only τ_M goes into producing electrical power.

The power can thus be written as:

$$P = (\tau_F + \tau_M) \times \omega \quad (4)$$

Therefore, the total amount of power converted from mechanical energy to electrical energy is thus given by:

$$P_{mechanical-electrical} = \tau_M \times \omega \quad (5)$$

The electrical power is alternatively given by:

$$\boldsymbol{P_{electrical} = I \times \omega \times K_\tau} \quad (6)$$

Where I is the current flowing through the motor.

From Ohms law, the current is also given by:

$$I = \frac{\varepsilon}{Z} \quad (7)$$

Where Z is the impedance of the motor winding.

Therefore, from *Equation 6*, during regeneration, the amount of extractable electrical power depends on:

- Rotation rate of the rotor, $\boldsymbol{\omega}$
- Torque constant of the motor, $\boldsymbol{K_\tau}$
- Impedance of the motor winding, $\boldsymbol{Z}$

Background

Current Braking Mechanisms

To date, many braking mechanisms are being employed in various applications. Some applications may employ two or more braking mechanisms to achieve a desired transient behaviour. These braking systems include some following mentioned examples [8].

Mechanical Disc Brakes

From first principles, a disc brake is a system that reduces the speed of a rotating wheel by creating necessary friction. This is achieved when brake pads, pressed by callipers, clamp onto a brake disc. [21]. Typically constructed from cast iron, the brake disc can also be made from composite materials like ceramic or reinforced carbon. To stop the wheel, the brake pads which are made of high-friction material that is pressed against both sides of the disc using mechanical, hydraulic, or pneumatic force. Disc Brakes are commonly used in robotic applications and industrial motors [10]. The disc brake has its own limitations such as the large wear and tear of brake pads due to friction. And in some cases, losing large amounts of energy as heat during the braking process.

Dynamic/ Resistive Braking

Resistive Braking as illustrated in *Figure 1* makes use of resistors to dissipate the kinetic energy of a moving object. A resistive braking mechanism comprises of a combination of high-power resistors and a switching mechanism like a circuit breaker [12]. The braking resistor is connected in shunt across the machine terminals. The high-power resistors in the braking resistor can be switched in or out at appropriate instants of time through the switching mechanism based on some control strategy. The braking resistor improves the transient stability significantly by aiding the retardation of the machine [13, 14]. It has found popular use in wind turbines and in the hoists. This resistive braking has its own grey areas like, relent damage to motor windings if resistance is too small and losing of large amounts of energy as heat is dissipated across the braking resistor.

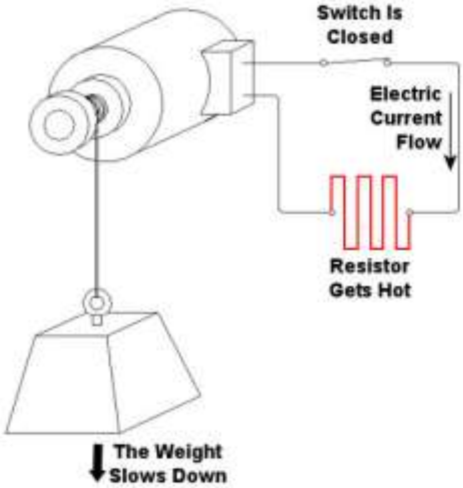


Figure 1: An Illustration of Resistive Braking

Regenerative Braking

As described earlier, regenerative braking harnesses the kinetic energy of a moving object and converts it to other forms of energy for re-use [15]. This concept is analogous to the principle of recycling. The recycled energy is then stored in a battery or otherwise used immediately. In hybrid cars, it has been seen to reduce fuel consumption and increase the range of travel. Moreso, the regenerative braking has the also notable limitations such as less effective at low speeds and it has relatively expensive to implement compared to other forms of braking [17]. But in comparison to the prior braking systems, it has its positive benefits such as the increases in the lifespan of brake pads and rotors by lessening their work, extending the range for electric vehicles, reduces stress on the grid especially during peak hours as there is a reduced need for grid power and as well as conservation of energy, hence battling climate change for fossil fuel dependent communities [22].

Methodology

The project will be carried out in four phases which are Research, Modelling and Simulation, Development and finally testing.

Research

In this phase, the existing literature on Regenerative braking systems and its application in the electric vehicle be reviewed. This will help to identify the key design considerations and potential challenges that need to be addressed. In addition, other braking methods will also be investigated and how they are being applied in other real-world instances.

Modelling and Simulation

In the Modelling and Simulation phase, three conceptual models will be developed. The best model to be used will be selected using a decision table which will take into consideration the cost, ease of implementation and expected lifespan.

Simulations will be carried out using Proteus software to come up with a virtual design. This will assist in making sure that the correct components are acquired and reduces component failure before carrying out a physical design prototype.

Development

In this phase, the chosen design will be implemented using a combination of hardware and software. This will involve combining all the required hardware components as well as designing and writing the control algorithm.

Testing

Finally, in the testing phase the system will be tested to ensure that it meets the defined requirements and objectives of the project. Additional tests will also be carried out to determine the systems transient response.

Expected Results

The proposed regenerative braking system has the following expected results:

- To recover at least 20% of the kinetic energy, resulting in a 10-20% reduction in energy consumption compared to the conventional braking systems.
- The cost of implementing the regenerative braking system will be 20% higher than current systems but the energy savings will offset this cost in 2-5 years depending on the specific application

These expected results are hypothetical but give an indication of the expected benefits of implementing such a system.

Technologies for Regenerative Braking

Control Systems for regenerative braking

Due to the sensitive applications for regenerative breaking, there is a need for control mechanisms to ensure that the braking system operates safely and efficiently. Variations in operating conditions and external disturbances can affect the performance of a regenerative braking system thus warranting the need for a control system [18].

PID controllers

A PID controller is a type of controller that uses three strategies to regulate a system: proportional, integral and derivative. The proportional strategy regulates the system based on any current error. The integral strategy regulates the system based on past errors in the system. Finally, the derivative strategy is used to predict future errors in the system. Together, these three strategies control the system in a way that keeps it operating within a desired range.

In regenerative braking, the PID controller is used to regulate the power flow between the motor and the battery. This also regulates when the power flow is in motor mode (electrical energy to kinetic energy) and regenerative mode (kinetic energy to electrical energy). In the case of electric auto motives, the PID controller adjusts the power flow in a way that keeps the vehicle operating smoothly and efficiently [20]. The Tesla electric vehicles use a variant of a PID controller to ensure that the battery is charged efficiently and the vehicle stops smoothly during regeneration.

Fuzzy Logic Controllers

Fuzzy Logic controllers are another type of controller popularly used in regenerative braking. Rather than using mathematical equations, fuzzy logic controllers use ‘fuzzy sets’ to determine the output of the controller. Fuzzy sets are a way to describe data using natural language, rather than strict numerical values. This makes the Fuzzy logic controllers more intuitive and flexible than traditional controllers. To ensure a high level of subjectivity in the fuzzy controller’s configuration, the membership function and fuzzy control rules are typically designed in accordance with expert experience and experimental data [16].

Power Regulation Methods

As in electrical vehicles, there is a great need to regulate and condition the regenerated power. Power regulation is important because it allows the system to optimize the amount of energy that is recovered for the end load [19]. Without power regulation, the system could recover too much or too little energy causing the system to overheat or underperform all depending on the point of use. Power regulation in regenerative braking is usually done with devices such as DC-DC converters, Inverters and AC-DC converters. These electronic devices allow the system to convert the regenerated power to a form that is either storable or conditioned for the point of use [20].

DC-DC Converters

DC-DC converters are a type of converter that takes DC power as input and converts it to a different DC voltage level as output. This is done through a switching element such as a transistor, to turn the input power on and off very quickly. This creates a high-frequency AC waveform which when smoothed out, produces the desired output voltage [17].

Design and interpretations

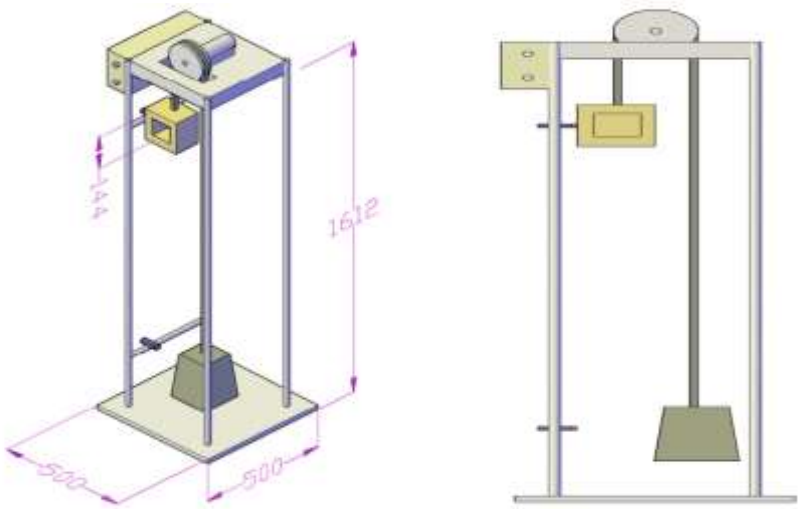


Figure 2: Elevation frame (Isometric View) - Drawn using AutoCAD. All dimensions in mm

The Elevation frame shown in *Figure 29* and *Figure 30* was designed taking into consideration the height required to generate a substantial amount of electrical energy for the concept to come to light.
Wood was used to make the cab lift and PVC was used to make the electrical controls housing. The rest of the structure was made of steel.

Software implementation

To allow system functionality, a program was written in C++ using Arduino IDE and uploaded onto the ATMega 328P chip.
The ATMega 328P microcontroller which holds the program and acts as the heart of the system. The uploaded program operates by checking a series of if-statements where only one will be true at any given time. The controller the produces output signals to the motor driver based on the currently true if-statement in the program. Experiments were carried out to determine the power, energy-recovery and reliability characteristics of the design. *Figure 3* shows the system prototype with a 12V, 30W rated DC motor and a cab weighing of 0.5kg.

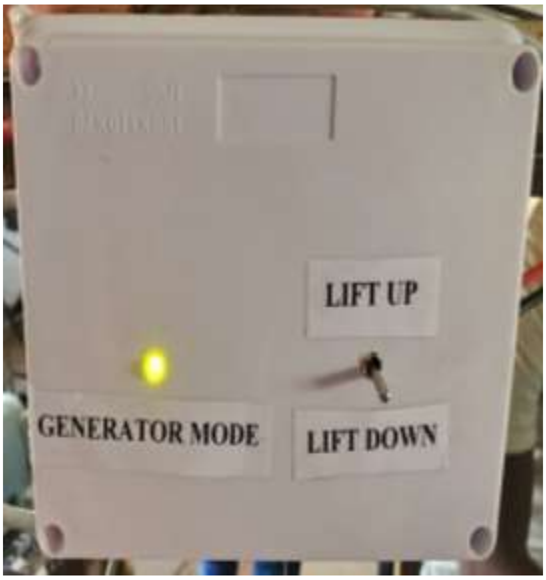



Figure 3: The designed prototype modelling a vertical lift system Control box indicating that the system is in generator mode

System Operation

When instructed to ascend through the switch, the system was able to:

- Switch on the motor to provide torque to lift the cab
- Detect when the cab had reached the maximum height by use of the upper infra-red sensor
- Turn off the motor in order to stop providing torque

When instructed through the switch to descend, the system was able:

- Switch on the motor to provide torque to lower the cab
- Switch to generator mode when the system had enough momentum *(Figure 3)*
- Turn off the motor in order to stop providing torque
- Extract the kinetic energy from the movement of the counterweight and cab
- Boost the produced DC voltage to a higher DC voltage to power an LED load and charge a battery

Detect when the cab had reached the minimum height through use of the lower infra-red sensor.

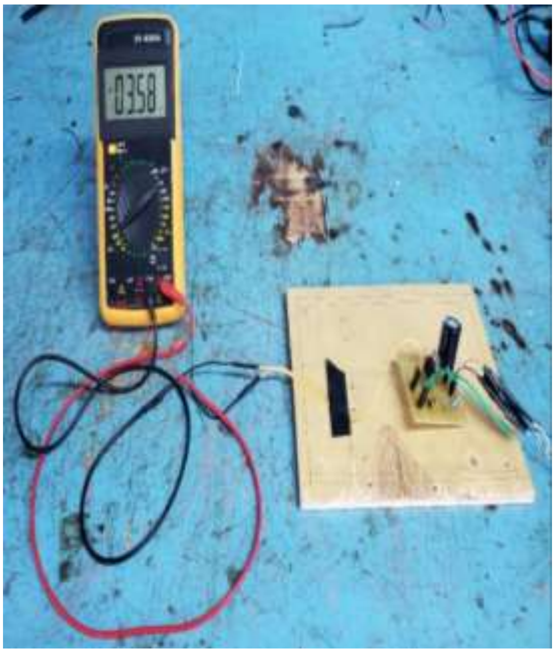
Generated Power Analysis

The motor (in generator mode) while rotating provided the following power characteristics across the terminals:

- Short-circuit Current: 0.1-0.9A
- Open-circuit Voltage: 0.3-1.2Vdc

After connection through the **DC-DC Boost converter**, the following was observed about the regenerated power:

- Short-circuit current: 0.6A
- Open-circuit Voltage: 3.58Vdc (*Figure. 3)*
- The output power was able to power an 30Ω LED light load *(Figure. 4)*
- The output power was able to charge the 3.3V battery bank *(Figure. 4)*



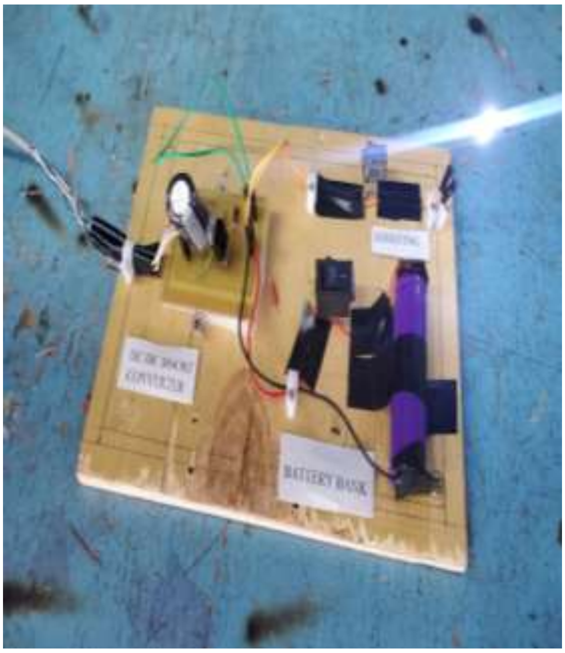


Figure 4: Generated open-circuit voltage after Boost converter   Generated power used for lighting

Energy Computations

In line with the objective of the study, there is a need to analyse the amount of energy that has been recovered through the regenerative braking process and compare with the energy input.

Input Energy Computation

During ascent and descent, the motor driver was supplied with 12V, 2A DC from an AC-DC power supply. The motor was supplied with power for 10s (time required to raise lift).

Using a Duty Cycle of 0.5 for speed regulation, the motor terminals were supplied with:

$$V_{out} = Duty\ Cycle * V_{in}$$
$$= 0.5 * 12V$$
$$= \mathbf{6V\ (average\ voltage)}$$

Power drawn by the motor:

$$Power = Voltage * Current$$
$$= 6V * 2A$$
$$= \mathbf{12W}$$

Energy used by the motor during ascent:

$$Energy = Power * lifting\ \ time$$
$$= 12W * 10s$$
$$\underline{= \mathbf{120J}}$$

Recovered Energy Computation

After various losses such as the stator losses and boost converter losses, the output power was calculated as power across the 30Ω load LED during lighting.

During descent the output power is given by:

$$Power = (load\ current)^2 * load\ resistance$$
$$= 0.683^2 * 30\Omega$$
$$= \mathbf{14W}$$

Energy recovered during descent is given by:

$$Energy = Power\ * LED\ on\ time$$
$$= \ 14W * 2s$$
$$\underline{= \mathbf{28J}}$$

Energy Recovery Factor

In order to find a good approximation of the energy that can be recovered on existing vertical lifts, the **Energy Recovery Factor** can be computed to gain an appreciation of the potential of regenerative braking technology.
The energy recovery factor can be computed by:

$$Energy\ recovery\ factor = \frac{Energy\ recovered}{Energy\ Input} * 100\%$$

$$= \frac{28J}{120J} * 100\%$$

$$= 23.33\%$$

$$\underline{= \mathbf{23}\%}$$

III. Conclusions

It is worth mentioning that the aim of the project has been met which is “To design a regenerative braking system for vertical lifts”. The project allows for energy recovery in electrical form while leading to higher efficiency and reduced utility costs.
The following objectives were successfully achieved:

- ***To recover a significant of the kinetic energy of a vertically moving object as electrical energy***
  Through switching from motor-mode to generator mode quickly during vertical movement, it was possible to capture 23% of the kinetic energy as electrical energy. This was made possible by allowing the momentum of the moving object to rotate the rotor of the motor and so harnessing electrical power through electromagnetic induction.
- ***To condition the electrical energy produced to a storable form***
  Through careful calculation and sizing, an appropriate DC-DC Boost Converter was designed to raise the extracted 0.7V DC voltage to the required 3.58V DC voltage level in order to charge a 3V battery.
- ***To power electrical loads from the extracted electrical energy***
  After disconnecting the storage device (battery), it was possible to power a 30Ω LED during the regenerative braking process.

There is great potential for the system to be integrated to vertical lift systems such as building elevators and mine hoists, ultimately reducing their utility and operational costs. With an energy recovery factor of 23% as shown in the results, this can lead to reduced electricity bills by 23% for the mining industry and corporate buildings.
However, it is important to note that the design is yet to cater for safety when it comes to human transportation. This implies that further design aspects such evacuation systems, stability mechanisms and emergency stops should be considered for the system to accommodate human transportation.

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