Performance and economic analysis of a plug and play regenerative brake for improving energy efficiency for traction elevators

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Abstract. This paper presents performance and economic analysis of a plug and play regenerative brake for improving energy efficiency for traction elevators. The proposed regenerative brake recycles the energy loss of a dynamic brake and feeds into the grid while an elevator inverter is operating in the braking mode. According to field measurement of energy consumption, it reveals that the efficiency can be improved as much as 18%. The prototype of a regenerative brake 12 kW, 400V, 3φ is developed and tested on an elevator simulator. It is shown that it can transfer energy out of a DC capacitor before the dynamic brake kicks in. Further, an economic analysis is provided to carry out the payback period and the present worth equivalent to confirm economic feasibility.

1. Introduction

Traction elevators driven by electric motors are typically composed of several components, such as a car, sling, elevator machine, electric motor, inverter, control equipment, counter weight, hoist way, guide rail, and pit as shown in figure 1 [1]. In the present, induction motors fed by pulse width modulated (PWM) inverters are commonly used to control speed and position of elevators. They are capable of controlling speed from zero to the rated speed accurately regardless of load variations. For instance, the elevator under study employs a three-phase induction motor rated at 12 kW /230V /50Hz/ 4 Poles driven by a three-phase PWM inverter.

When elevator inverters operate in the braking mode, the kinetic energy accumulated in the elevator car is transformed to electrical energy and stored in the inverter’s DC capacitors. If voltage across the inverter’s DC capacitor becomes higher than the upper limit, the stored energy will be dissipated in the form of heat by the dynamic brake, which is a group of power resistors connected in series with an IGBT switch. When this switch turns on, the DC capacitor voltage will drop rapidly. It will turn off if the DC capacitor voltage is less than the lower limit. This method has a drawback that the dissipated heat will cause temperature rise in a machine room and shorten lifetime of electronic control devices. In some cases, air conditioners are installed to bring down the room temperature, which results in a loss of electrical energy.

In the past, recovering the energy loss had not gained interest due to high costs of regenerative inverters [2]. At present, advances in power semiconductor technologies and digital microcontrollers have significantly contributed to economic costs of the regenerative inverters so that they can be made commercially available [3-6]. However, their performance and economic feasibility have not been reported.
This research proposes a plug and play regenerative brake which is placed in parallel to the existing elevator inverter without altering and re-commissioning the original control configuration. The energy consumption of the elevator under study is measured at various loads. The prototype of the regenerative brake is developed and tested on the elevator simulator. The experimental results confirm that the proposed regenerative brake can substitute the original dynamic brake and can supply electrical energy back to the grid safely. The economic analysis of cost/benefit of the device is also presented.

2. Electrical energy measurement

The electrical energy of the elevator is measured at various loads ranging from no-load to full-load capacity using the power quality analyzer, Fluke 435 in figure 2(a), (b). The electrical energy loss in a dynamic brake is measured by the electrical energy measurement device which is developed specifically for the load having discontinuous voltage and/or current in figure 2(c), (d). The measuring device comprises a differential high voltage probe with bandwidth of 50 MHz and voltage gain of 10mV/V to measure the voltage across the dynamic brake resistor and a current clamp with bandwidth of 200 kHz and output voltage gain of 100 mV/A. That is, the maximum measured voltage of 1,000 V and the maximum measured current of 100 A yield the signal output of 10 V.

All measured signals must be filtered and amplified by signal conditioning circuits before they are supplied to a data acquisition card (PCI-6013). Labview 2013 software is used for configuring the simultaneous 50 kHz sampling rates and calculating the kWh electrical energy. The sampled voltage and current signals are multiplied to calculate the electrical power and the electrical energy can be obtained from integration of the calculated electrical power. In addition, the developed software is capable of recording data such as voltage, current, power, energy in a text file.

Figure 3 illustrates the consumed energy and electrical energy loss in a dynamic brake at various loads. At 500 kg load being the same mass as the counter weight, the elevator consumes the same amount of energy when it moves up or down between the 1st and 5th floor. figure 4 shows electrical energy loss in the dynamic brake’s resistors. It reveals that the elevator can operate efficiently when weight of the load and the counter weight are equal. According to the analysis as shown in figure 5, if the energy loss in the dynamic brake’s resistors can be recycled and fed into the grid, the energy efficiency can be improved by as much as 18%. Considerable friction loss in elevator machines, guide rails, and pulleys is a major cause that prohibits improving the energy efficiency much less than the theoretical limit (50%).
3. Plug and play regenerative brake prototype and testing

Figure 6 shows circuit configuration of the proposed plug and play regenerative brake. It is placed in parallel to the front-end diode rectifier of the inverter without altering the original control configuration. When the elevator’s inverter operates in the braking mode, the mechanical energy stored in the elevator car will be removed and transformed into electrical energy stored in the DC capacitor. Thus, it causes the capacitor voltage to rise abruptly. Then, the regenerative brake must transfer energy stored in the DC capacitor and feed it into the grid before the dynamic brake does. A blocking bridge diode is employed to control energy to flow only in one direction. Just in case, a galvanic isolation transformer is recommended in practice to prevent malfunction of the elevator control board or the regenerative inverter.

Figure 7 shows the experimental setup. The operation of a traction elevator under study is emulated by two induction motor drives (ABB ACSM204-1). The first induction motor drive is programmed to emulate operation of the actual elevator’s motor drive. The rotational speed is regulated to follow the speed profile of the elevator under study. The second induction motor drive exerts the load torque against the other that is considered as it were a passenger load. Both motor drives must work in synchronism by using a programmable logic controller (PLC S7-300). This method enables the developed elevator simulator to have similar speed and load torque characteristics to that of the actual elevator system.

Figure 8 shows the block diagram and speed/torque characteristics of the simulator. Figure 9 shows the input current of the regenerative brake while the elevator emulator is operating in the braking mode. The plug and play regenerative brake succeeds in recycling energy stored in the DC capacitor to the grid before the dynamic brake does. The DC capacitor voltage is well regulated at a constant 650V.

4. Economic analysis

The economic analysis and payback period is carried out by considering cumulative present worth (CPW) of all activities from the incoming and outgoing cash flows within an estimated lifetime of 15 years.
years (180 months) and comparing it with the minimum attractive rate of return (MARR). The present worth factor is calculated by the expression (1).

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PWF = \left( \frac{1}{1 + MARR} \right)^m
\]

where the number of year is denoted by \(m\) and the MARR is the minimum rate of investment return, in which an investor makes a decision whether it is worth investing.

If an investor borrow money for this investment, the MARR should be greater than the lending interest rate. If the investor uses his own cash instead, then the MARR should be greater than the deposit interest rate. This analysis chooses the MARR of 0.5\% per month based on general inflation rate of 0.38\% in June 2016 from the Bank of Thailand. It is assumed that at the end of the 15\textsuperscript{th} year, the salvage value will be zero, the maintenance cost approximates 1,000 Baht/year with additional 100 Baht increasing each year. Then, the installation of the regenerative brake will improve the overall efficiency of the elevator by 15\%. If the device were installed with the existing elevator rated 1,000 Kg load at Building 1 of the Faculty of Engineering, Mahidol University, the electricity costs will be reduced
approximately by 1,200 Baht/month. The electricity price per kWh increases 5% each year. According to the information, the cumulative sum of present worth equivalent can be calculated and compared with the investment in low risk 15 year bonds with 2.8% yearly interest rate and the discount yield rate of 2.38%.

Table I shows the calculation of the cumulative sum of present worth equivalent in the first 12 months. Starting at the 1st month, the cumulative sum is negative because of the outgoing cash flow of 125,000 Baht or the initial investment. Afterwards, the cumulative sum of present worth equivalent increases as a result of the electricity cost saving presented in the incoming cash flow. Figure 10 shows that present worth equivalent becomes positive in year 10. The cumulative sum of the present worth equivalent for the 15 year lifetime is 53,538 Baht.

In comparison, an investor could use his/her initial fund of 125,000 Baht to invest in low risk bonds for 15 years, such as “The 2016 3rd State Railway of Thailand Bond” with the fixed interest rate of 2.8% or 3,500 Baht yearly. Table II shows the cumulative sum of present worth equivalent when combining the interest with the repayment of principal at maturity with the adjusted discount rate, the present worth equivalent of this bond investment is 6,517.6 Baht.

From the economic analysis, it can be concluded that the installation of the regenerative brake device to improve the efficiency of the elevator is worthwhile, and the investment return is 8 times greater than the investment in low risk bonds at the same duration of 15 years.

| Year | Outgoing cash flow | Incoming cash flow | Total cash flow | Present worth factor | Present worth equivalent | Cumulative sum of the present worth equivalent |
|------|-------------------|-------------------|-----------------|----------------------|-------------------------|-----------------------------------------------|
| 1    | -125,000          | -125,000          | 0.99502         | 1,492.53             | -123,507.47             | -125,000.00                                  |
| 1    | 1,500             | 1,500             | 0.99007         | 1,485.11             | -122,022.37             | -123,507.47                                  |
| 1    | 1,500             | 1,500             | 0.98515         | 1,477.73             | -120,544.64             | -122,022.37                                  |
| 1    | 1,500             | 1,500             | 0.98025         | 1,470.38             | -119,074.64             | -120,544.64                                  |
| 1    | 1,500             | 1,500             | 0.97537         | 1,463.06             | -117,611.21             | -119,074.64                                  |
| 1    | 1,500             | 1,500             | 0.97052         | 1,455.78             | -116,155.43             | -117,611.21                                  |
| 1    | 1,500             | 1,500             | 0.96569         | 1,448.54             | -114,706.90             | -116,155.43                                  |
| 1    | 1,500             | 1,500             | 0.96089         | 1,441.34             | -113,265.56             | -114,706.90                                  |
| 1    | 1,500             | 1,500             | 0.9561          | 1,434.15             | -111,831.41             | -113,265.56                                  |
| 1    | 1,500             | 1,500             | 0.95135         | 1,427.03             | -110,404.39             | -111,831.41                                  |
| 1    | 1,500             | 1,500             | 0.94661         | 1,419.92             | -108,984.47             | -110,404.39                                  |
| 1    | -1,100            | 1,500             | 400             | 0.94191             | 376.76                  | -108,984.47                                  |

| Year | Outgoing cash flow | Incoming cash flow | Total cash flow | Present worth factor | Present worth equivalent | Cumulative sum of the present worth equivalent |
|------|-------------------|-------------------|-----------------|----------------------|-------------------------|-----------------------------------------------|
| 0    | -125,000          | -125,000          | 1.0000          | 125,000.00           | -125,000.00             | -125,000.00                                  |
| 1    | 3,500.00          | 3,500.00          | 0.9767          | 3,418.553            | 3,418.553               | 3,418.553                                    |
| 2    | 3,500.00          | 3,500.00          | 0.9540          | 3,339.001            | 3,339.001               | 6,757.554                                    |
| 3    | 3,500.00          | 3,500.00          | 0.9318          | 3,261.300            | 3,261.300               | 10,018.854                                   |
| 4    | 3,500.00          | 3,500.00          | 0.9101          | 3,185.408            | 3,185.408               | 13,304.262                                   |
| 5    | 3,500.00          | 3,500.00          | 0.8889          | 3,111.281            | 3,111.281               | 16,415.543                                   |
| 6    | 3,500.00          | 3,500.00          | 0.8683          | 3,038.880            | 3,038.880               | 19,454.423                                   |
| 7    | 3,500.00          | 3,500.00          | 0.8480          | 2,968.163            | 2,968.163               | 22,422.586                                   |
| 8    | 3,500.00          | 3,500.00          | 0.8283          | 2,899.092            | 2,899.092               | 25,321.678                                   |
| 9    | 3,500.00          | 3,500.00          | 0.8090          | 2,831.628            | 2,831.628               | 28,153.306                                   |
5. Conclusion
This paper presented the performance and economic analysis of the regenerative brake to improve efficiency of traction elevators. The electric energy consumption and energy loss in the dynamic brake at various loads were measured and analyzed. If the energy loss in the dynamic brake can be recycled and fed back to the grid, the efficiency can be improved as much as 18% when the elevator carries no load or full load. The prototype of the regenerative brake was developed and tested with the elevator simulator. The test results confirmed viability of the method, and the economic analysis proved its investment worthiness. In comparison, its return from the energy saving is 8 times greater than the investment in low risk bonds with the same yield duration.

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