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Energy Saving Through Regenerative Braking in Diesel Locomotive with Super-capacitors

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ABSTRACT: The aim of this paper is to build an energy storage system for regenerative braking, with use of dc to dc converter, and testing rig to perform testing for dc drive with dc motor with the super capacitor bank against diesel locomotive (WDM2) regenerative braking profiles. A bank of was constructed along with a bidirectional DC to DC converter allowing practical testing of two of the four possible bank configurations. An average of 55% and 63% end to end efficiency was found for the two configurations respectively when tested fewer than two modes of regenerative braking profiles. It was found that capacitor banks with a higher maximum voltage i.e. more cells in series were more efficient as there were lower input and output currents and most of losses were restricted to the converter.

Keywords: Super capacitor, chopper, regenerative braking, diesel locomotive.

I. INTRODUCTION

Energy consumption is 90% for traction and 10% for auxiliary supply in diesel locomotive. Braking energy is 40% of energy consumption. Up to 40% of the relating power of diesel locomotive capable of returning energy to the power supply can be regenerated during braking and that this energy can be used to feed diesel locomotive which are accelerating at the same time. The energy generated by braking condition would simply be converted into waste heat by its braking resistors if no other diesel locomotive is accelerating at exactly the same time. Such synchronize braking and accelerating cannot be coordinate, the energy storage system stores the energy generates during braking and discharges for other electrical uses. The energy storage system creates optimum conditions for energy regeneration. The energy storage system is able to store and discharge energy extremely quickly, consequently enabling a complete exchange of energy between diesel locomotive, even if they are not braking and accelerating at precisely the same time. The energy storage system reduces primary energy consumption without affecting transport capacity and punctuality. In addition, the energy storage units can stabilize the system voltage. For this purpose we evaluate the Super-capacitors as storage devices for regenerative breaking in diesel locomotive. Super-capacitors are high capacitance capacitors with a large power density. A lot of attention has been given in the last decade to using Super-capacitors in electric diesel locomotive to overcome the deficiencies of batteries especially when it comes to harnessing and releasing the power generated in regenerative breaking. As Super-capacitors have much higher power densities than batteries, the devices can successfully absorb the power produced by the regenerative braking, which is normally over a short time interval. To achieve this with batteries, large battery banks need to be installed which are costly, inefficient and heavy. This paper is going to focus on the charging and discharging of Super-capacitors banks in regenerative breaking profiles. The aims of the proposed paper are to Design a scaled down capacitor bank for regenerative breaking. i.e. size a capacitor bank based on the scaled powered requirements. Design a DC to DC converter to regulate the output of the capacitor bank and allows both charging and discharging of the capacitors. Test the capacitor bank and DC to DC converter by charging and then discharging the setup in line with different mode of regenerative breaking profiles.

II. SUPER-CAPACITORS

Super-capacitors , also known as ultra-capacitor s, electric double layer capacitors and electrochemical double layer capacitors, are capacitors with high capacitance and high power density, with commercially available capacitances up to 5000 F and power densities up to 20kW/Kg. They are also used to supplement battery power for power intensive applications as a means to extend battery life. Improvements in design and material technology are allowing Super-capacitors to be used in much higher power applications such as UPS and hybrid cars [35]. Modern Super-capacitors have many advantages over traditional capacitors and secondary batteries such as lithium ion batteries such as: [18]

- They can provide high amount of power in a short period of time.
- As no chemical reactions take place the cycle life is over 500,000 cycles. The manufacture Panasonic states an unlimited number of cycles for their gold cap series [5]. On the other hand rechargeable batteries usually degrade in a few thousand cycles [3]. This results in a device that can out last the product it was designed for and requires lower maintenance.
- They have very good temperature operational characteristics and can operate as low as -40C°,

- where batteries have poor performances at low temperatures. This makes them suitable to assist batteries in low temperatures as the batteries can trickle charge the capacitors and the capacitors can then provide enough current to start a motor in a car.
- As long as the capacitor's voltage and current ratings are not exceeded, the capacitors cannot overcharge.
- They have high efficiencies of up to 95%.

The first stage in the design process was to determine the size of the Super-capacitors bank. There were a number of considerations to take into account, such as voltage range, cost, flexibility, current and energy limitations, and lead time. The number of cells was selected to be 10 as it offered the most flexible bank configuration. By selecting 10 cells 4 different parallel/series arrangements could be made. The capacitor size was selected as 20F. This value was chosen because when parts were sourced, it was the largest size available in the quantities required.

The energy storage system operates in two modes:

In energy saving mode, it absorbs the energy generated by braking and stores it until the storage unit can feed it back into the power supply system at a later point when vehicles are accelerating. As a voltage stabilizer, its energy content is constantly kept at a high level and it discharges when the system voltage falls below a specified limit.

These equations were placed into a specification of a capacitor such as current rating and voltage.

$$\frac{dE(t)}{dt} = \frac{-CE(t) \pm \sqrt{C^2 E(t)^2 - 4R_{ESR}C^2 p}}{2RC^2} \quad \ldots (1)$$

$$\frac{di(t)}{dt} = -\frac{i(t)}{C\left(R - \frac{E}{i(t)}\right)} \quad \ldots (2)$$

Where E is the terminal voltage, C is the cell capacitance, R and RESR is the capacitors equivalent series resistance (ESR) and p is the charging power. A minimum bank voltage is calculated from the constant discharge power and current rating. Then using equation 1 in a while loop the equation is resolved until the number of cells is high enough so the finial discharge voltage of the cell is greater than the minimum voltage.

III. SUPER-CAPACITORS MODELLING

There are several propositions of ultra-capacitor model representation [32]. The simplest of all is the classical equivalent circuit with the lumped capacitance, equivalent parallel resistance (EPR) and equivalent series resistance (ESR). Fig.ure 1 shows the classical equivalent circuit with the three parameters. Determination of these parameters provides a first approximation of an ultra-capacitor cell. The EPR represents the current leakage and influences the long-term energy storage. In multiple series connections of ultra-capacitor s, the EPR influences the cell voltage distribution due to the resistor divider effect. Showed that the EPR is related to the voltage decay ratio by,

$$EPR = \frac{-t}{\ln\left(\frac{V_1}{V_2}\right) C}$$

Where V_1 is the initial voltage, V_2 is the final voltage and C is taken as the rated capacitance.

Through experimental measurements of voltage decays of several ultra-capacitor s having various capacitance values, it was shown that the EPR effects could be neglected for transient discharge calculations. However, the EPR value is important when cell balancing of series connected ultra-capacitor s is considered. This parameter has not significantly dependent on the terminal voltage nor the charge rates. Hence the ESR can be considered as a non time dependent parameter. A three RC branch network with one branch having a voltage dependent capacitance.

Each branch of the circuit shown in Fig.1 has a different associated time constant. Containing R_i as the "immediate branch". This branch dominates the ultra-capacitor behavior in the order of a few seconds. The "delayed effect branch", with R_d has influential behavior in the range of minutes. The third branch is the "long-term" branch. This branch governs the long-term response of the circuit after periods exceeding ten minutes. Finally, the branch with resistance R_{Leak} represents the ultra-capacitor leakage current. The "immediate branch" contains a voltage dependent capacitor C_{i1} that reflects the voltage dependency of the cells double-layers capacitance. [32]

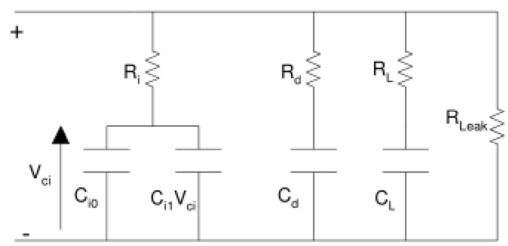

Fig. 1. Brach representation ultra-capacitor model.

IV. REGENERATIVE BRAKING

In an electric system which is driven only by means of electric motor the system consists of an electric motor which acts both as generator and motor. Initially when the when the system is cruising the power is supplied by the motor and when the there is a necessity for braking depending upon driver's applied force on the brake pedal the electronic unit controls the charge flowing through the motor and due to the resistance offered motor rotates back to act as a generator and the energy is energy is stored in a battery or bank of twin layer capacitors for later use.

Regenerative breaking provides high current over a short period with a high number of cycles. Super-capacitors have the ability to absorb all of this energy at a high efficiency, while batteries on the other hand can not readily absorb high current. The Super-capacitors can then be used to provide high current during acceleration. In addition, it can provide trickle charge for the batteries and can be used for other electrical loads, such as power steering. This increases the life of the batteries as there may be tens of thousands of regenerative cycles per year while a battery can only accept a few thousand cycles. Another factor which reduces the life of a battery is deep current draw, which can be avoided if the capacitors are used for high current loads. Therefore, using capacitors increases battery life and allows a smaller and lighter battery pack to be installed, and also helps the batteries operate at low temperatures. They also don't need sophisticated charging equipment and are low maintenance.

V. DC TO DC CONVERTER

A chopper is a static power electronic device that converts fixed dc input voltage to a variable dc output voltage. A Chopper may be considered as dc equivalent of an ac transformer since they behave in an identical manner. As chopper involves one stage conversion, these are more efficient [1]. Choppers are now being used all over the world for rapid transit systems. These are also used in trolley cars, marine hoist, forklift trucks and mine haulers. The future electric automobiles are likely to use choppers for their speed control and braking. Chopper systems offer smooth control, high efficiency, faster response and regeneration facility [1].

The power semiconductor devices used for a chopper circuit can be force commutated thyristor, power BJT, MOSFET and IGBT.GTO based chopper are also used. These devices are generally represented by a switch. When the switch is off, no current can flow. Current flows through the load when switch is "on". The power semiconductor devices have on-state voltage drop of 0.5V to 2.5V across them. For the sake of simplicity, this voltage drop across these devices is generally neglected [2].

As mentioned above, a chopper is dc equivalent to an ac transformer, have continuously variable turn's ratio. Like a transformer, a chopper can be used to step down or step up the fixed dc input voltage.

Average Voltage, $V_o = (T_{on}/(T_{on} + T_{off}))*Vs$

$= (T_{on}/T)*Vs$

$= \alpha Vs$

T_{on} = on-time.

T_{off} = off-time.

$T = T_{on} + T_{off}$ = Chopping period.

$\alpha = T_{on}/T_{off}$.

Super-capacitors operate on extra low voltages, while most hybrid electric vehicles, such as the operate their batteries at voltages of $202V_{DC}$, and the motor and generator runs off $500V_{AC}$. [22] to get 202 V_{DC} from a Super-capacitors bank requires 80 Super-capacitors to be placed in series. This may be impractical or increases the weight and cost by having a larger bank than required. Also, unlike batteries, capacitors lose their voltage quickly with the discharge of energy. For example, if a bank was reduced to half of its voltage it would have discharged 75% of its energy. Thus to allow better sizing of banks and allow for a higher discharge of energy a DC to DC converter is needed.

There are a vast number of different DC to DC converter topologies available, but in the regenerative braking application the converter will need to be able to increase the voltage for discharge, decrease the voltage of charging and be able to operate over a large voltage range. Two converters which satisfy this condition are the buck boost and full/half bridge converter Buck boost converters are able to increase or decrease the output voltage relative to the input voltage depending on how they are set up. While they have many advantages, such as having commercially available control chips, they are only unidirectional. This would result in a need for either two converters, one for charging one for discharging, or a switching arrangement that changes the input and output connections when charging/discharging is needed.

Full bridge dc-dc converters allow for bidirectional flow but the switching and control is more complicated. There are many topologies for full bridge and half bridge converters designed for Super-capacitors and fuel cells which are highly efficient. the device needs to be a bidirectional two quadrant converter, meaning that the converter needs to be able to switch current in both positive and negative directions offlow. The output voltage varies over a large range and considerations in inductor selection need to be made carefully.

As the aim of the system is to simulate a regenerative braking system, constant power needs to be delivered to the load, which makes voltage regulation inappropriate.

VI. EXPERIMENTAL SETUP

For engine analogy torque and speed profile are set for engine start running, braking and then running then stop condition. In MATLAB both the profile are set using speed and torque input blocks. DC6 model for two quadrant operation is chosen. Total simulation time is 4 seconds. Power input is isolated by a rectifier. The power supply is as usual used as in engine. The speed and torque profile adjusts the PI regulator that decides the IGBT operation. At starting of engine initial speed and torque is set the time is t = 0. Speed curve at the output follows a ramp shape that shows gradual incremental speed of engine up to 2 seconds. Now effective torque reduces during motion that also affects the current raise. Now speed is 400 rpm before undergoing braking. As per the speed profile during t = 2.75 braking starts and speed reduces to 100 rpm. Current curve follows negative transition that was detected to switch over the power and explained later. At 3.4 seconds motor speed is 100 rpm and then comes back in normal first quadrant operation until stop at t = 4 seconds. The braking mode can be observed between 2.75 to 3.4 seconds.

A comparator detects current I_A = 0 and operates the contactor between main power and charger. See Fig. 2 model more details [11].

MATLAB 7 version with simulink is used for simulation purposes under windows xp sp2 platform.

Fig.3 show armature current, Fig.5 voltage, braking available voltage and speed curve.

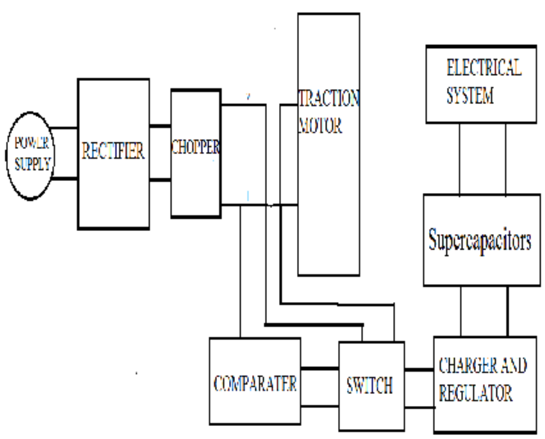

Fig. 2. Block diagram of experiment setup of system.

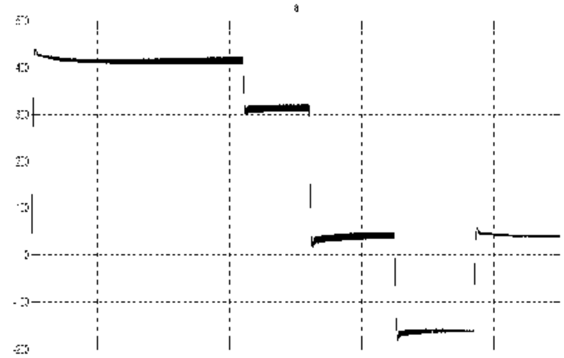

Fig. 3. Armature current curve for system.

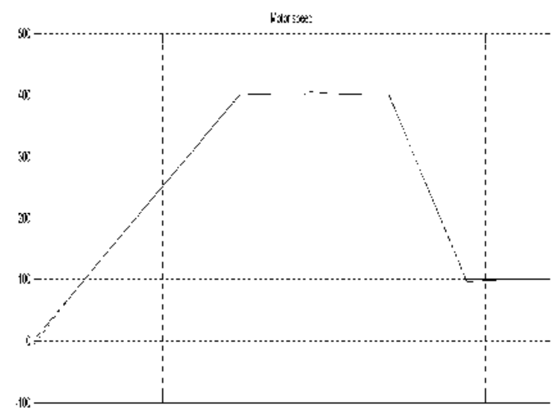

Fig. 4. Motor speed curve for system.

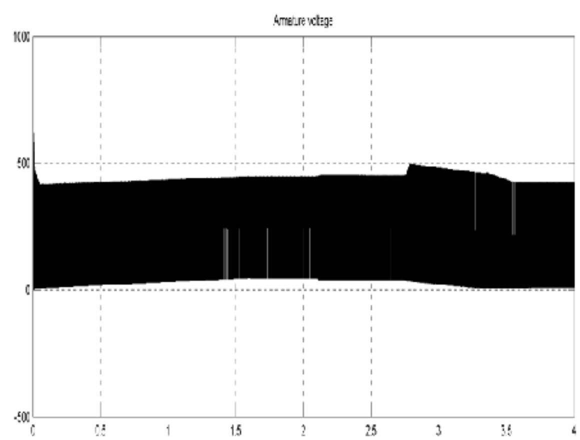

Fig. 5. Armature voltage curve for system.

VII. RESULT

The voltage is now available for charging the battery or any other storage like super capacitor. In the proposed model super capacitor are being used as storage. A PI based charger charges the super capacitor bank up to 400 V. At the time 2.75 to 3.4 seconds we observed charging voltage which can show Fig. 6.

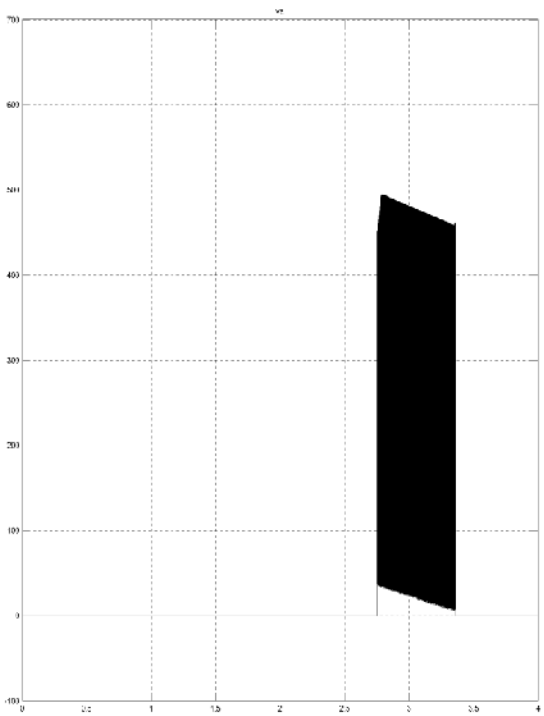

Fig. 6. Charging voltage curves for Super-capacitors .

VIII. CONCLUSION

The aims of this paper were to build a Super-capacitors bank, a DC to DC converter, and a testing rig to perform efficiency testing for various configurations of the super capacitor bank against electrical locomotive WDM2 vehicle regenerative braking profiles . Most of the aims of the paper were met. A DC to DC converter was built, a test rig was constructed and efficiency was tested for a bank configuration under two different braking profiles. While improvements in the operation of the converter would have been ideal to allow for more testing of the capacitor bank in different configurations, most of the aims of the paper were still met. Practical experiment agreed that the configurations with higher maximum voltages, i.e. more cells in series were more efficient as they had lower output and input currents, which meant lower i^2R losses in the circuit.

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