A study on Regenerative braking system with matlab simulation

Debajit Kumar Sandilya
Assam Engineering College
Guwahati, India
sandilyadebajit@gmail.com

Bubumani Kalita
Assam Engineering College
Guwahati, India
kalita.bubumani@gmail.com

Siddhartha Goswami
Assam Engineering College
Guwahati, India

Shweta Chakraborty
Assam Engineering College
Guwahati, India

***Abstract*— Braking is a process in which a mechanical or electrical device inhibits motion. It is often necessary to brake the motor rapidly and smoothly according to a given speed schedule. Braking torque may be applied by electrical or mechanical methods or combination of both. For both of these processes, a retarding torque is required, which may be supplied mechanically or electrically. Electrical methods are more precise than mechanical methods, where accurate and smooth control of the stopping instant is possible. In electrical braking the kinetic energy of the rotating parts of the equipment gets converted into electric energy. The methods of braking employed in electrical drives can be classified as regenerative, plugging and dynamic braking. In this study, we have discussed the advanced regenerative braking of an electric vehicle and the operation is performed with the help of a brushless DC motor. A comparative study has been carried out by considering various motor drives and we finally concluded that the BLDC motor is the most suitable one for performing regenerative braking operation. The proposed scheme is implemented using MATLAB and the results are illustrated. The results thus obtained are analyzed and using the results, further study is carried out to determine the regenerative power of the proposed system. The PID control is one of the most suitable methods which have been adapted in our scheme to have a fine transition between mechanical and electric braking. The implementation of the PWM technique to the inverter is performed using PID control to maintain the constant braking torque. Thus it is possible to recover energy using our recommended RBS. The extension of the project work carried out here will be to test the circuit on a prototype vehicle.**

***Index Terms*— Regenerative, BLDC motor, PID control, PWM control, power inverter**

I. INTRODUCTION

A. Braking:

Braking is a process in which a mechanical or electrical device inhibits motion. It is often necessary to brake the motor rapidly and smoothly according to a given speed schedule. Braking torque may be applied by electrical or mechanical methods or combination of both. The speed and accuracy of stopping operations improves the productivity of a system and reliability of the product. While operating electrical drives, it is often necessary to stop the motor quickly. For both these processes, a retarding torque is required, which may be supplied mechanically or electrically. In mechanical process, the braking action is performed by the frictional force between the rotating parts and brake pads. On the other hand, in electrical braking, a braking torque which opposes the motion of a rotating member is developed during braking operation. Electrical methods are more precise than mechanical methods, when accurate and smooth control of the stopping instant is possible. Braking torque is also needed over some parts of the duty cycle and for emergency braking in respect of some applications such as cranes. Reversal and speed control of drives may also be undertaken by means of electric braking. The kinetic energy of the rotating parts gets converted into electrical energy in case of electric braking.

B. Types of braking:

Braking in ac systems: The methods of braking employed in an induction motor drive can be classified into: a) Regenerative braking, b) plugging or reverse current braking, c) Dynamic or DC Rheostat braking.

a) Regenerative braking: If the rotor speed becomes greater than the synchronous speed, the relative speed between the rotor conductors and air gap rotating field reverses. This reverses the rotor induced emf, rotor current and component of the stator current which balances the rotor ampere turns. Consequently, the phase angle between the stator phase voltage and stator phase current becomes greater than 90 degrees. Thus power flow reverses, resulting in regenerative braking.

b) Plugging or reverse voltage braking: When phase sequence of the supply of the motor running at a speed is reversed by interchanging the connections of any two phases of stator with respect to supply terminals, operation shifts from motoring to plugging. Reversal of phase sequence reverses the direction of rotating field.

c) Dynamic or rheostat braking: It is obtained when the motor is run on a single phase supply by disconnecting one phase from the source or leaving it open or connecting it with another machine phase. When connected to a 1-phase supply the motor can be considered to be fed by positive and negative sequence three- phase set of voltages. Net torque produced by the machine is the sum of torques due to top positive and negative sequence voltages. When rotor has a high resistance, the net torque is negative and braking operation is obtained.

Braking in dc systems: The braking in DC systems are again classified into three categories: (a) Regenerative braking, (b) Dynamic or rheostat braking, (c) Plugging or Reverse voltage braking

a) Regenerative braking:
DC shunt motor: Regenerative braking is possible when an adjustable speed motor (a motor which operates at rated condition with a weak field current) is used. Before bringing the motor to rest the field excitation is increased to the permissible maximum value due to which the speed of the motor falls to a minimum value and the KE released from the rotor is fed back to supply.
DC series motor: Current and flux both increase with speed in dc series motor. Therefore it is not possible to get e.m.f greater than terminal voltage by this means. Also there is no way possible to make the field current greater than armature current in simple series motor. Hence regeneration is not practicable in DC series motor.

b) Dynamic braking:
DC shunt motor: The retarding torque varies linearly with speed in case of DC shunt motors. The motor characteristics slope depends upon the total resistance of the armature circuit. Braking torque here can be obtained at very low speed.
DC series motor: In case of DC series motor, the interconnection of the armature winding and the field winding is to be taken into account to ensure that the direction of current in the field remains unchanged in spite of the change in current in the armature winding. Only then, the self-excitation of series generator will take place.

c) Plugging or reverse current braking:
DC shunt motor: In plugging of DC shunt motor, the motor is reconnected to the line with reverse polarity. The motor now produces a torque opposite to that of rotation. Therefore, reverse current braking is employed to get either a quick reversal or a rapid stop. In order to stop the motor, it is necessary to employ some means to disconnect the motor from the supply at the time when it passes through zero speed.
DC series motor: Different constant torque loads acting on the motor develop various magnitudes of plugging. Plugging torques varies significantly with changes in load torque; i.e. with changes in motor speed before plugging.

II. BRAKING IN ELECTRIC VEHICLES

Braking Systems in electric vehicles can be of different types. For example, conventional friction brakes are used in some vehicles. In those systems, continuous braking is applied which in turn produces the necessary friction to stop the wheels from rotating and thereby slowing down the vehicle. In conventional braking systems, a considerable amount of energy is wasted as the braking pads get heated up. Another type of brake system is the Anti-Lock Brake System. Here, continuous braking is not applied, but a non-continuous braking pattern is employed which slows down or stops the vehicle when needed. This system is more efficient than the conventional braking system and indeed gives superior performance. Here, we can cite one more type of efficient braking system, which is called the regenerative braking system. An electric motor is used in regenerative braking system. When the driver applies the brake pedal in an electric vehicle, the mechanism then tends to drive the motor in the reverse directing by producing a torque in the opposite direction and thus slows down the vehicle. During braking the motor works as a generator giving back energy to the battery and slowing down the vehicle at the same time. Any other circuit can also be used to divert the motor current during braking so that the vehicle slows down. Such types of systems also recharge the battery and help in braking. But regenerative braking systems cannot be used solely because it only causes the vehicle to slow down and does not completely stop the vehicle. Therefore, such systems are used in conjunction with conventional friction brakes or Anti-Lock Braking System.

Choice of motors used:

BRUSHED DC: The properties of the motor depend on the composition of the material, the number of coils wound around and the density of the coils. In a brushed DC, the field is a permanent magnet and the rotor is an electromagnet. The commutator is charged by the brushes to the reverse polarity, which in turn causes the rotor to rotate. By reversing the polarity of the brushes, the direction of rotation can be altered. Efficiency is very less here.

INDUCTION TYPE: When the speed of the motor is more than the synchronous speed, relative speed between the motor conductors and air gap rotating field reverses, as a result the phase angle because greater than 90° and the power flow reverse and thus regenerative braking takes place. If the source frequency is fixed then the regenerative braking of induction motor can only take place if the speed of the motor is greater than synchronous speed, but with a variable frequency source regenerative braking of induction motor can occur for speeds lower than synchronous speed. The major advantage of this type of braking is that the power generated is usefully employed and the major disadvantage is that the for fixed frequency sources, braking operation cannot be performed below synchronous speeds. Speed control of induction motors is quite difficult.

BLDC: Efficiency is a primary selling feature for BLDC motors. As in case of BLDC motor, the rotor is the only bearer of magnets, hence it does not require any, i.e. no commutator, no connection and no brush is required for the operation and hence there is no sparking produced in the process. In place of these, the motor employs control circuitry. In order to determine the position of the rotor at different times, a hall sensor is used along with the controllers. They come in single and 3 phase.

Following are some generalizations regarding trade-offs between the three motor technologies. Although examples that will defy some of the mentioned parameters can be cited, our objective here is to present the nominal values for electric vehicles.

In terms of efficiency, we have for

Brushed DC- Motor (80%), DC controller (94%, passive fly back), NET (75%)

BLDC: Motor (93%), inverter (97%, synchronous fly back or hysteretic control), NET (90%)

Induction: Motor (91%), inverter (97%, synchronous fly back or hysteretic control), NET (88%)

In terms of service, we have for

Brush-DC: Periodic replacement for brushes and bearing are required

BLDC: No replacement of bearing is required

Induction: Same as in the case of BLDC MOTOR

In terms of specific cost (cost/ kW), inverter included

Brush-DC: The cost is low

BLDC: The high power permanent magnets are indeed expensive

Induction: The cost is moderate in this case.

In terms of Heat rejection, we have for,

Brush-DC: The removal of heat is difficult

BLDC: Heat rejection is comparatively is easier. Magnets on the rotor have low-moderate eddy current induced heating

Induction: Windings on stator make stator heat rejection straightforward. The current induced in the rotor can be cooled by oil when implemented in high power applications.

For Torque/speed behavior,

Brush-DC: It has infinite zero speed torque, but the torque drops down gradually with increasing speed.

BLDC: The motor has a constant torque up to base speed and power is constant up to the maximum speed. Automotive applications are viable with a single ratio gearbox.

Induction: Here the torque remains constant up to base speed and the power is constant up to maximum speed. Automotive applications are viable with a single ratio gearbox. The torque builds up after some delay when current is applied.

- Miscellaneous:

Brush-DC: At high voltages arcing can be problematic. Regenerative braking is tricky and requires a more complex speed controller.

BLDC: BLDC motors are ideal for low power applications. Regenerative braking comes essentially for free.

Induction: Cost is low and implementation for automotive application is cheaper. Regenerative braking comes essentially for free.

Considering various parameters, it can be concluded that the BLDC motor is best suited for Regenerative Braking operation. Hence, BLDC motor is widely used in braking of electric vehicles.

Properties:

For successful operation of regenerative braking system, it should have the following properties:

1. Efficient energy conversion.
2. Energy storage with a high capacity per unit weight and volume.
3. Power rating should be high allowing large amount of energy to pass through in a short duration of time.
4. Smooth delivery of power from the regenerative system.
5. The absorption and storage of energy during braking should be in direct proportion to the braking operation and the delay and the losses should be at least over a wide range of speed and torque.

III. OBJECTIVE

The objective of the project is to study regenerative braking used in electric vehicles and to prepare a mathematical model of the system with the help of MATLAB and SIMULINK.

MOTIVATION

An electric vehicle is an ideal alternative to the IC engine vehicles (run on petrol/diesel). As the consumption of fossil fuels is increasing at a prominent rate, so alternative sources of energy have to be utilized to maintain a balance and at the same time, reducing the effect of using these fossil fuels on the environment. In this scenario, an electric vehicle can provide many benefits as they are environment-friendly and to maximize the benefit, the electric vehicle should have the latest braking system installed as braking is a crucial element to every vehicle. Regenerative braking systems provide the energy efficiency to an electric vehicle and at the same time make the vehicle safer and easier to handle. Thus, it should be implemented in the vehicles. If such a braking system is incorporated in an electric vehicle, then this will not only increase the sale of electric vehicles but at the same time, will reduce the pollution rate. As the country is facing major problems with increasing pollution due to the plethora of vehicles in the major cities, increase in the use of electric vehicles will be beneficial to the society and to the environment.

IV. WORKING PRINCIPLE OF BLDC

BLDC motor is the one of the most preferred motors in electric vehicles, because the peak point efficiency is more and the cooling of the rotor is simpler. The motor can also operate at “unity power factor,” which means that the drive can operate at its maximum efficiency levels. The batteries are the most crucial component of BLDC motor driven system. So, the batteries in green cars should be as efficient as possible. Hence, a rechargeable battery is most efficient when it is maintained near to full charge.

The brushless DC motor isn’t without fault. It is currently more expensive to manufacture than its brushed counterparts. Also the magnetic field produced by the permanent magnets isn’t adjustable.

Regeneration during braking in BLDC motor:

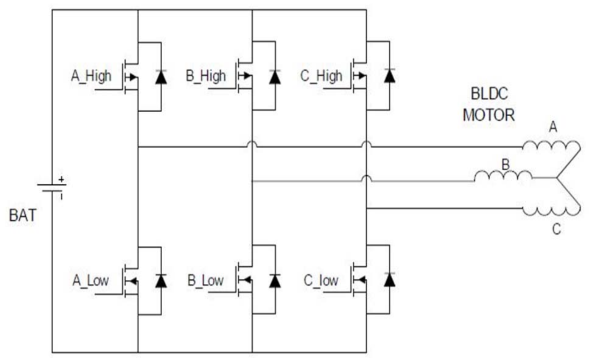

Fig.1. Power Inverter Circuit

Regenerative braking can be achieved by the reversal of current in the motor-battery circuit during deceleration and redirecting the current flow into the supply battery. The same power inverter circuit of Figure 1 can be used with an appropriate switching strategy. One simple and efficient method is independent switching in conjunction with pulse-width modulation (PWM) to implement an effective braking control.

During regenerative braking, current in the winding is reversed and supplied back into the battery. In this mode, all switches are turned off and the current can flow back through the freewheeling diodes. Figure 2 shows an example of the current flow when the winding pairs of the A and B phases are energized. In this example, the current can flow through the freewheeling diode of the high-phase high-side switch, A-High, through the battery and through the low-phase low-side switch, B-Low. To control the level of braking, the PWM duty cycle is varied, which essentially toggles the current flow between regeneration and coasting. The maximum level of regeneration occurs when the low-side switches are all turned off. Consequently, the duty cycle is varied from high to low. Therefore, by simply disconnecting the inverter circuit (power module) from the control source controlling the inverters' switching sequence (control circuit), regenerative braking will occur to its maximum potential. It is noted that the low-side switches are switched with PWM and the others remain off.

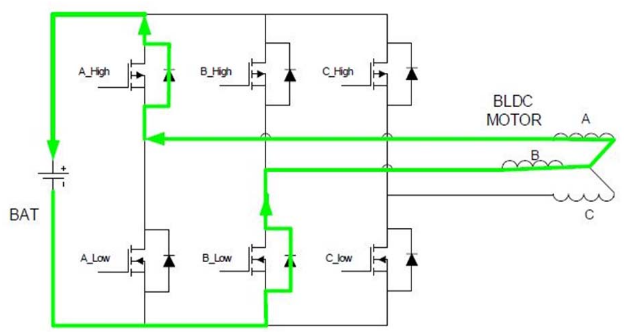

Fig.2. Regenerative Current Flow

BLDC MOTOR CONTROL: As the motor is brushless, the commutation is achieved electronically by controlling the conduction of switches in the arm of Inverter Bridge. The schematic of BLDC motor is shown. DC power supply is given as input to BLDC motor. To control the BLDC motor, the position of rotor must be determined, which decides the commutation. The voltage vector of BLDC motor is divided into six switches, which is in correspondence with the Hall Effect sensors' signal. The corresponding hall signals are given to the controller which generates gate signals. These PWM signals are given to the switches in the inverter which supplies the stator winding. Thus by taking the the help of Hall sensors, the motor is controlled by using any micro controller. Generally, a three phase motor uses six switches, two in each arm of the inverter. MOSFET or IGBTs are the most widely used components due to its low output impedance IGBTs are commonly used in high power applications.

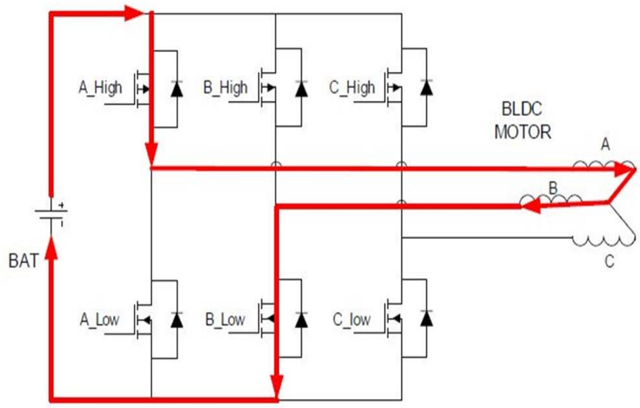

Fig.3. Motoring Current Flow

Speed Control: Commutation ensures proper rotor rotation of the BLDC motor, while the motor speed depends only on the amplitude of the applied voltage. The amplitude of the applied voltage is adjusted by using the PWM technique. The required speed is controlled by a speed controller. The speed controller is implemented as a conventional PI controller. The difference between the actual and required speed is input to the PI controller. Based on this difference, the PI controller controls the duty cycle of PWM pulses, which corresponds to the voltage amplitude required to keep the required speed.

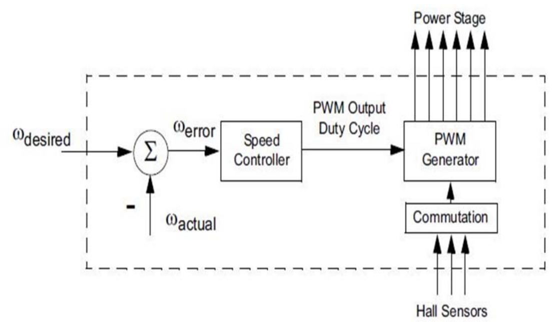

Fig.4.Speed control

Torque Control: For applications requiring the motor to operate with a specified torque regardless of speed, a current controller can be used, since torque is directly proportional to current. In this mode, the speed will be held at the value set by the speed reference signal for all loads up to the point where the full armature current is needed. If the load torque increases further, the speed will drop because the current-loop will not allow more armatures current to flow. On the other hand, when the load attempts to drive the motor above the reference value, this will automatically reverses the direction of motor current, causing the motor to act as a brake and feed back the regenerative power to the mains. The current controller is implemented as a conventional Proportional-Integral (PI) controller. The speed controller output goes to the current controller with measured DC bus current. The output obtained from the current controller will be controlling the duty cycle of the PWM pulses. The figure below shows the combination of both the controllers, i.e. the speed and current controller.

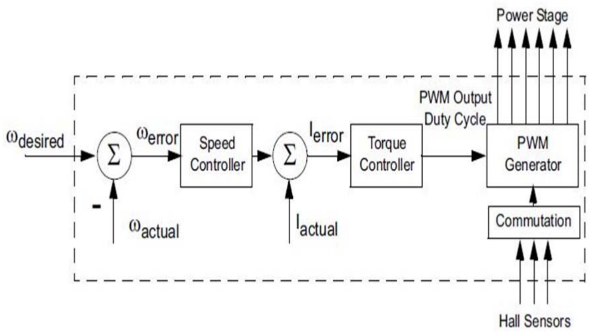

Fig.5. Speed and Torque control

In both Speed and Torque control processes, the controller uses one of two PWM techniques:

a. Unipolar PWM switching: This technique refers to the motor phases being switched in such a way that one of the phases returns current while the PWM modulation is happening in another phase, this is unipolar. Unipolar switching reduces electromagnetic noise and the DC bus ripple because there is less switching.

b. Bipolar PWM switching: This technique refers to the voltage passing through the two phases as being modulated with the PWM, both the input and output of current are being modulated. Bipolar switching is better suited for sensor-less approaches, where it is necessary to sense back electromagnetic forces (BEMF). The bipolar approach has the zero volt point at a 50% duty cycle; therefore there is more time to sense the BEMF.

Both unipolar and bipolar approaches can be either independent or complementary. Unipolar and bipolar approaches refer to the relationship of the two phases. The complementary approach refers to the relationship of the two signals controlling one phase. The independent approach applies to the PWM only on one side of the phase. The complementary approach modulates both sides. The complementary and independent approaches allow the control to address either a 2 or 4-quadrant operation.

V. MODEL SPECIFICATION and SIMULATION

Rated Voltage	300 V	Stator Resistance per phase	0.18Ω/phase
Rated Current	5 A	Stator Inductance per phase	0.0085 H /phase
Rated Power	2 HP	No. of Poles	8
Rated Speed	2000 rpm	Rated Torque	3 Nm

TABLE: Specifications of the model

In the Matlab model we have used an Electric vehicle with BLDC motor drive having a rated voltage of 300 V. The rated current of the motor is 5 A. We have estimated a power output of 2 HP at an rpm of 2000, which is also considered as the reference speed of the motor. The Stator Resistance per phase and the Stator Inductance per phase are 0.18 Ω /phase and 0.0085 H/phase. The no. of poles of the motor circuit is 8. Also the torque output is around 3 Nm. From the Matlab simulation model, we have got the behaviors of motor speed, generated voltage, braking torque and the state of charge of the battery. From the data obtained from the curves we have also got an approximate idea of generated power output. The behavior of the motor during braking can also be studied from the simulation and also the way the polarity of voltage changes with braking.

The flowchart for the motor speed control is added below:

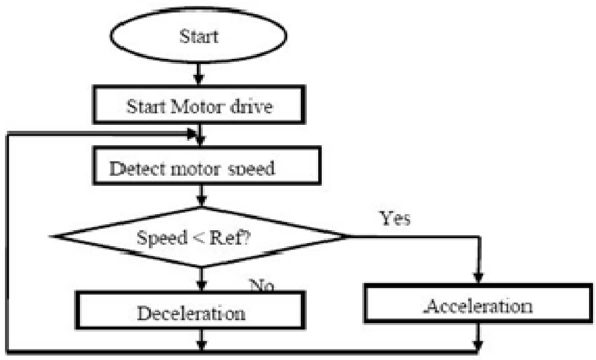

Fig.6. Control flowchart of the model

For the BLDC motor specifications shown in the table above, the simulation is carried out and the results are shown below

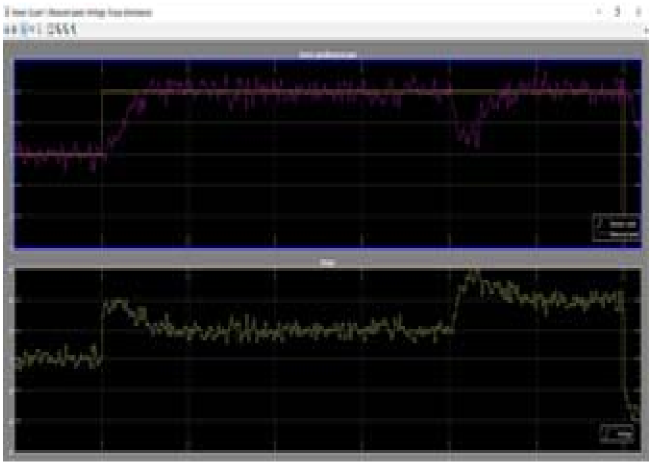

Fig.7. Measured speed and generated Voltage characteristics

VI. CONCLUSION

In this project, we have discussed the advanced RBS of an electric vehicle and the operation is performed with the help of a Brushless DC motor. A comparative study has been carried out by using various motor drives and we finally concluded that the BLDC motor is the most suitable one for performing regenerative braking operation. The proposed scheme is implemented using MATLAB and the results are illustrated. The results thus obtained are analyzed and using the results, further calculations are carried out to determine the regenerative power obtained from the proposed system. The PID control is one of the most suitable methods which we have adapted in our scheme to have a fine transition between mechanical and electrical barking. The PWM technique is implemented to the inverter using PID control to maintain the constant braking torque. Thus it is possible to recover energy using our recommended RBS. By using the submitted RBS, the safety of the vehicle is also ensured.

SCOPE FOR FUTURE WORK

The extension of the project work carried out here will be to test the circuits on a prototype vehicle. Also, the capacitor bank can be replaced by ultracapacitors when the system works on a higher voltage level. Ultracapacitors are costly but they can store 20 times the energy stored in conventional batteries and the energy loss is less. Ultra capacitors, when used in an actual electric vehicle which may be working around a 300 Volt DC battery supply, prove to be cost effective as well as capable of providing a superior performance.

REFERENCES

[1] S. K. Pillai, A First Course on Electrical Drives; New Age International Publishers; 2nd edition

[2] G. K. Dubey, Fundamentals of Electrical Drives; Narosa; 2nd edition

[3] R. Krishnan, Electric Motor Drives: Modeling, Analysis, and Control; PHI

[4] Stefán Baldursson, "BLDC Motor Modeling and Control – A Matlab/Simulink Implementation"; Institutionen för Energi och Miljö; May 2005

[5] Module11: Regenerative Braking; NPTEL–Electrical Engineering – Introduction to Hybrid and Electric Vehicles

[6] M. Krishnamurthy, J Leon, A Gonzalez, G. Niu and M. J. Acero, "Case Study of an Electric-Hydraulic Hybrid Propulsion System for a Heavy Duty Electric Vehicle", SAE Technical Paper 2016-01-8112, September 2016.

[7] Boretti, A. and Al-Zubaidy, S., "E-KERS Energy Management Crucial to Improved Fuel Economy," SAE Technical Paper 2016-01-1947, 2016, doi: 10.4271/2016-01-1947.

[8] Li, J., Tan, G., Ji, Y., Zhou, Y. et al., "Design and Simulation Analysis for an Integrated Energy-Recuperation Retarder," SAE Technical Paper 2016-01-0458, 2016, doi: 10.4271/2016-01-0458.