Jarrad Cody, Özdemir Göl, Zorica Nedic, Andrew Nafalski, Aaron Mohtar
University of South Australia

REGENERATIVE BRAKING IN AN ELECTRIC VEHICLE

ODZYSKIWANIE HAMOWANIA W POJAZDACH ELEKTRYCZNYCH

Abstract: Electric vehicles have been attracting unprecedented attention in light of the volatile market prices and prospect of diminishing supplies of fuel. Advances in battery technology and significant improvements in electrical motor efficiency have made electric vehicles an attractive alternative, especially for short distance commuting. This paper describes the application of Brushless DC (BLDC) motor technology in an electric vehicle with special emphasis on regenerative braking. BLDC motors are being encountered more frequently in electric vehicles due to their high efficiency and robustness; however a BLDC motor requires a rather complex control to cope with the reversal of energy flow during the transition from motoring regime to regenerative braking. In an electric vehicle, regenerative breaking helps to conserve energy by charging the battery, thus extending the driving range of the vehicle. There is a number of different ways to implement regenerative braking in a BLDC motor. This paper describes the Independent Switching scheme for regenerative braking [1] as applied to a developmental electric vehicle at the University of South Australia.

1. Electric vehicles and regenerative braking

In recent times, electric vehicles (EVs) have received much attention as an alternative to traditional vehicles powered by internal combustion engines running on non-renewable fossil fuels. This unprecedented.focus is mainly attributable to environmental and economic concerns linked to the consumption of fossil-based oil as fuel in internal combustion engine (ICE) powered vehicles.

With recent advances in battery technology and motor efficiency, EVs have become a promising solution for commuting over greater distances. Plug-in EVs utilise a battery system which can be recharged from standard power outlets. Since performance characteristics of electric vehicles have become comparable to, if not better than those of traditional Internal Combustion Engine (ICE) vehicles, EVs present a realistic alternative.

Regenerative braking can be used in an EV as a way of recouping energy during braking, which is not possible to do in conventional ICE vehicles. Regenerative braking is the process of feeding energy from the drive motor back into the battery during the braking process, when the vehicle's inertia forces the motor into generator mode. In this mode, the battery is seen as a load by the machine, thus providing a braking force on the vehicle.

It has been shown that an EV, which uses regenerative braking can have an increased driv ing range of up to 15% compared with an EV, which only uses mechanical braking [2].

A rare case when regenerative braking can not occur is when the battery is already fully charged [3]. In such a case, braking needs to be effected by dissipating the energy in a resistive load.

Mechanical braking is still required in EVs for a number of reasons. At low speeds regenerative braking is not effective and may fail to stop the vehicle in the required time, especially in an emergency. A mechanical braking system is also important in the event of an electrical failure. For example, if the battery or the system controlling the regenerative braking failed, then mechanical braking becomes critical.

It is common in electric vehicles to combine both mechanical braking and regenerative braking functions into a single foot pedal: the first part of the foot pedal controls regenerative braking and the final part controls mechanical braking. This is a seamless transition from regenerative braking to mechanical braking, akin to the practice of 'putting the brakes on' in a conventional ICE vehicle.

2. BLDC motor

Principally, a brushless DC (BLDC) motor is an *inside-out* permanent magnet DC motor, in which the conventional multi-segment commutator, which acts as a mechanical rectifier, is replaced with an electronic circuit to do the commutation. [6]. Consequently, a BLDC motor requires less maintenance and is quite robust [7]. A BLDC motor has a higher efficiency than a conventional DC motor with brushes [6]. However, a BLDC motor requires relatively complex electronics for control.

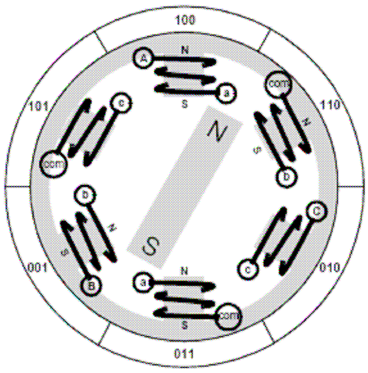


Fig. 1. Permanent Magnet BLDC Construction [4]

In a BLDC motor permanent magnets are mounted on the rotor with the armature windings being hosed on the stator with a laminated steel core, as illustrated in Figure 1. Rotation is initiated and maintained by sequentially energising opposite pairs of pole windings, which are said to form *phases*. Knowledge of rotor position is critical to correctly energising the windings to sustain motion. The rotor position information is obtained either from Hall Effect sensors or from coil EMF measurements.

3. BLDC motor control

Two separate modules (stages) are required in order to control a BLDC motor: a power module and a control module.
A BLDC motor requires a DC source voltage to be applied to the its stator windings in a sequence so as to sustain rotation. This is done by electronic switching using an inverter as shown in Figure 2. The inverter circuit employs a half *H-Bridge* for each stator winding [8].

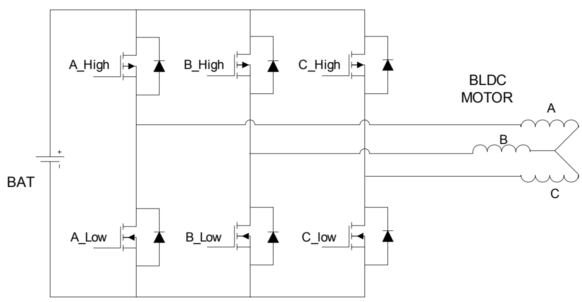


Fig. 2. Power Inverter Circuit (Adapted from [10])

In the case of a BLDC motor with three pairs of stator windings, a pair of switches must be turned on sequentially in the correct order to energise a pair of windings. This commutation sequence is shown in Table 1, with NC (*Not Connected*) designating the pairs of stator windings (phases) which are not energised during this commutation step. Table 2 shows the corresponding switching sequence.

Table 1. Forward Commutation Sequence

Forward/Clockwise Motoring Commutation Sequence						
Step	**Hall A**	**Hall B**	**Hall C**	**Phase A**	**Phase B**	**Phase C**
1	1	0	0	-V	+V	NC
2	1	0	1	NC	+V	-V
3	0	0	1	+V	NC	-V
4	0	1	1	+V	-V	NC
5	0	1	0	NC	-V	+V
6	1	1	0	-V	NC	+V

Table 2. Forward Switching Sequence

Forward/Clockwise Motoring Inverter Operation			
Step	**PWM Switch**	**ON Switch**	**OFF Switch**
1	B_High	A_Low	Remaining
2	B_High	C_Low	Remaining
3	A_High	C_Low	Remaining
4	A_High	B_Low	Remaining
5	C_High	B_Low	Remaining
6	C_High	A_Low	Remaining

Figure 3 illustrates the current flow from the inverter circuit at the first commutation step to energise the winding pairs of phases A and B.

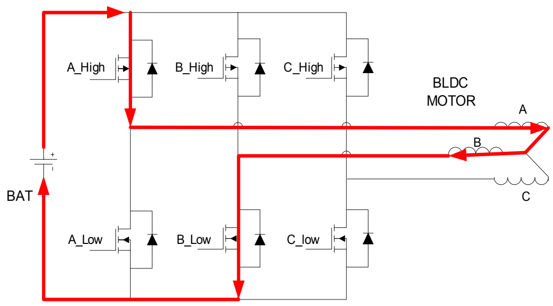


Fig. 3. Motoring Current Flow for a Commutation Sequence (Adapted from [10])

A similar strategy can be applied to achieve reversal of the sense of rotation, as shown in Tables 3 and 4.

Table 3. Reverse Commutation Sequence

Reverse/Anticlockwise Motoring Commutation Sequence						
Step	**Hall A**	**Hall B**	**Hall C**	**Phase A**	**Phase B**	**Phase C**
1	1	0	0	+V	-V	NC
2	1	0	1	+V	NC	-V
3	0	0	1	NC	+V	-V
4	0	1	1	-V	+V	NC
5	0	1	0	-V	NC	+V
6	1	1	0	NC	-V	+V

Table 4. Reverse Switching Sequence

Reverse/Anticlockwise Motoring Inverter Operation			
Step	**PWM Switch**	**ON Switch**	**OFF Switch**
1	A_High	B_Low	Remaining
2	A_High	C_Low	Remaining
3	B_High	C_Low	Remaining
4	B_High	A_Low	Remaining
5	C_High	A_Low	Remaining
6	C_High	B_Low	Remaining

A number of switching devices can be used in the inverter circuit; however MOSFET and IGBT devices are the most common in high power applications due to their low output impedance [6].
A microcontroller is commonly used to read rotor position information from the Hall Effect sensors and determine which phase to energise, switching the appropriate device as depicted in Table 1. Alternatively, phase EMFs can be monitored to determine the rotor position in sensorless applications.

4. BLDC regenerative braking

Regenerative braking can be achieved by the reversal of current in the motor-battery circuit during deceleration, taking advantage of the motor acting as a generator, redirecting the current flow into the supply battery. The same power circuit of Figure 2 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 [9].
In *independent switching*, all electronic switching devices are *off* while applying regenerative braking. The bottom switching devices are *on* for the 120 degree portion of the cycle, corresponding to the flat top part of the phase EMF, as illustrated in Figure 4. All top switches are kept turned *off*.

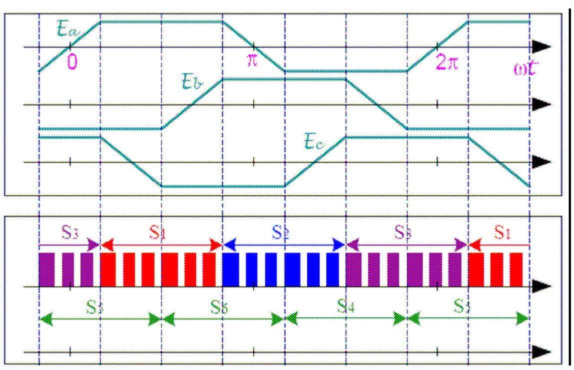


Fig. 4. BLDC EMF with Corresponding Switch Sequence [9]

PWM is used to control the level of regenerative braking by varying the duty cycle of the PWM.
Figure 5 shows the current flow path during coasting, during which there is no current exchange between the BLDC and the battery [9].

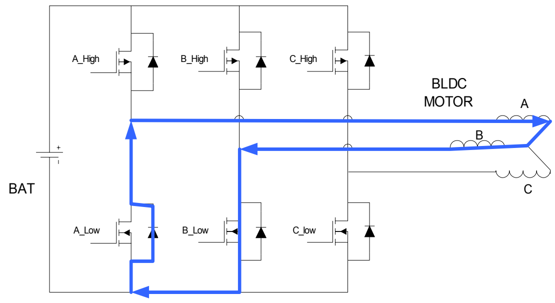


Fig. 5. Coasting Current Flow for First Commutation (Adapted from [10])

In this mode, the energised windings allow the current to flow through the *low*-side of the PWM switch and through the freewheeling diode of the *low*-side *high* phase switch. Thus no current flows from the BLDC machine to the supply battery.
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 6 shows an example of the current flow when the winding pairs of the A and B phases are energied. 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.
Table 5 below shows the switching sequence applied during regenerative braking with independent switching. It is noted that the *low*-side switches are switched with PWM and all other switches remain *off*.

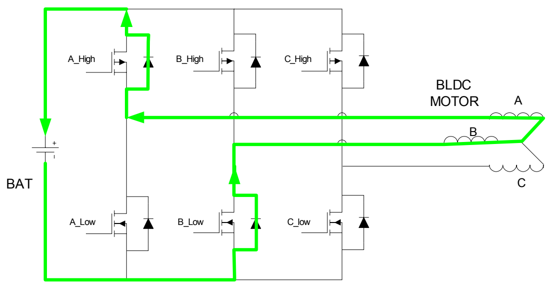


Fig. 6. Regenerative Current Flow for Step 1 of Commutation (Adapted from [10])

The switching steps are controlled by the control stage measuring the Hall Effect sensor readings, similar to the motoring process.

Table 5. Forward Regenerative Switch Sequence

Forward/Clockwise Regenerative Inverter Operation			
Step	**PWM Switch**	**ON Switch**	**OFF Switch**
1	A_Low	NIL	Remaining
2	C_Low	NIL	Remaining
3	C_Low	NIL	Remaining
4	B_Low	NIL	Remaining
5	B_Low	NIL	Remaining
6	A_Low	NIL	Remaining

Regenerative braking can also be applied whilst the vehicle is in *reverse* as shown in Table 6. The same method is used as in the forward mode; however the phases are energised differently and thus require a different switching sequence as shown in Table 6. This switching sequence is determined by the control stage and by the use of a forward/reverse switch interface.

Table 6. Reverse Regenerative Switch Sequence

Reverse/Anticlockwise Regenerative Inverter Operation			
Step	**PWM Switch**	**ON Switch**	**OFF Switch**
1	B_Low	NIL	Remaining
2	C_Low	NIL	Remaining
3	C_Low	NIL	Remaining
4	A_Low	NIL	Remaining
5	A_Low	NIL	Remaining
6	B_Low	NIL	Remaining

5. Application

A commercially available BLDC motor has been selected to replace the currently used conventional DC motor in the developmental electric vehicle of the University of South Australia, known by the acronym TREV, from *Two-person Renewable Energy Vehicle*. TREV is shown in Figure 7.

Fig. 7. TREV Electric Vehicle

Based on the motor controller presented in [8], a simple control stage, that uses a Microchip dsPIC30F4012 microcontroller [11] has been built and tested.

The *control stage* controls the motoring in forward and reverse modes, with the PWM control linked to a 5kΩ potentiometer to control the motor speed. The control can select between *forward* and *reverse* by the use of a three way switch with the sequence of reverse, neutral and forward.

The control stage employs *independent switching* for regenerative braking control. The stage controls the PWM of the *low*-side switches with another 5kΩ potentiometer. The potentiometer sets the level of braking for regenerative braking. The extent of battery recharging was measured on the input terminals of the power module during tests (Figure 8).

A commercial power stage was chosen and purchased for TREV's drive system, after having verified the control concept with test bench measurements, using a simplified version of the power stage constructed in-house.

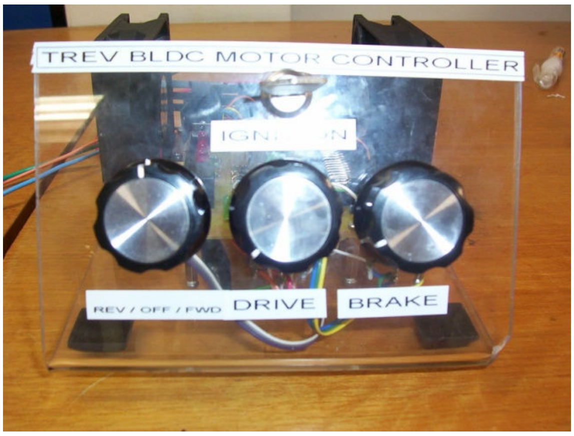


Fig. 8. TREV Control Stage

The final drive system implemented in TREV includes a brake pedal, which combines regenerative braking action with mechanical braking action. Using a 5kΩ potentiometer, the first portion (1/3 of the brake pedal) controls the level of regenerative braking; the remainder controls mechanical braking. Acceleration is controlled by another 5kΩ potentiometer connected to the acceleration pedal.

6. Conclusion

The regenerative braking system described in the paper hss been successfully type-tested. The system employs the *Independent Switching* strategy to control the flow of current during various stages of the cruise profile. The work is in progress to fit TREV with the commercial BLDC motor and a commercial power supply together with the controller developed in-house.

7. Acknowledgements

The authors gratefully acknowledge the invaluable contributions to the TREV project of Dr Peter Pudney, Senior Research Fellow, Centre for Industrial & Applied Mathematics University of South Australia.

8. References

[1]. Cody J, 2008, "Regenerative Braking Control for a BLDC Motor in Electric Vehicle Applications", Honours Paper in Bachelor of Engineering degree, University of South Australia, School of Electrical and Information Engineering.

[2]. Ford R. 2007, "Regenerative Braking Boosts Green Credentials, Railwaygazette", http://www.railwaygazette.com/ features_view/article/2007/07/7577/regenerative_braking_boosts_green_credentials.htm, viewed: 23rd June 2008.

[3]. "Regen Braking" Q4D Sales Information Web Page, http://www.4qd.co.uk/fea/regen.html, viewed: 15th Aug 2008

[4]. 2002 Brown W. , "AN857 Brushless DC Motor Control Made Easy." Microchip Technology Inc, available from http://www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=1824&appnote=en012037, viewed: 15 August 2008.

[5].Rashid M. H., 2004, "Power Electronics: Circuits, Devices and Applications" Prentice Hall, 3rd Edition

[6]. Emadi, A., 2005, "Handbook of Automotive Power Electronics and Motor Drives", CRC Taylor & Francis.

[7]. "3-Phase BLDC Motor Control with Hall Sensors Using MC56F8013: Targeting User Guide." Freescale Semiconductors

[8]. Mohtar A., Nedic Z., Machotka J., 2008. "A compact and affordable BLDC motor controller for a microelectronics remote laboratory", International Conference on Embedded Systems and Applications, ESA 2008, Las Vegas, Nevada, USA, pp.75-80.

[9]. Su, G J., McKeever J.W. Samons K.S., "Design of a PM Brushless Motor Drive for Hybrid Electrical Vehicle Application.", http://www.ornl.gov/~webworks/cpr/pres/107923_.pdf, viewed: 15th August 2008

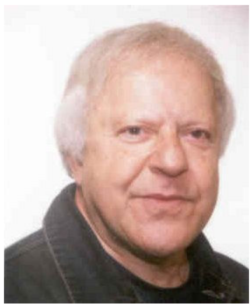
[10]. Chen, J-X., Jiang, J-Z.and Wang, X-J., 2003, "Research of Energy Regeneration Technology in Electric Vehicle." Shanghai University Press, Volume 7, Number 2.

[11]. Microchip Technology Inc., 2007, dsPIC30F4011/4012 Data Sheet, http://ww1.microchip.com/downloads/en/ DeviceDoc/70135.pdf

Authors

The authors are with the School of Electrical and Information Engineering, University of South Australia, Adelaide, South Australia, Australia.

Jarrad Cody received his BEng degree in Electrical and Mechatronic Engineering in 2009 from the University of South Australia (UniSA), Adelaide, Australia. During his time in study he worked on the University's Two Seat Renewable Energy Vehicle (TREV) project. Since completing his studies late 2008 he has worked as a Hardware Design Engineer at BAE Systems Australia on the Airborne Early Warning and Control (AEW&C) project.
E-mail: codjs001@students.unisa.edu.au



Özdemir Göl has had extensive experience as an engineering educator in addition to his substantial industrial experience. His academic career has included teaching and research in electrical engineering at universities in Turkey, Australia, France, Belgium Switzerland, Finland and Greece. He holds the degrees of MESc, ME and PhD, all in electrical engineering. He is cur-

rently Associate Professor at the University of South Australia. His research interests have been focussed on electrical machines and drives, and include modelling and simulation of electrical machines using numerical methods, design optimisation of electromagnetic devices and condition monitoring of electrical machines. He is the recipient of several national and international awards for excellence in research, teaching, engineering education and community service. He is the author and co-author of some 300 publications.
E-mail: ozdemir.gol@unisa.edu.au

Zorica Nedic received her MESc degree in electrical engineering, specializing in electronics, from the University of Belgrade, former Yugoslavia. She obtained her ME in electrical engineering (control) in 1997 from the University of South Australia (UniSA), Adelaide, Australia. She worked for six years as a design engineer at the Institute Mihajlo Pupin in Belgrade. Since 1991, she has been working as a lecturer in electrical engineering at the UniSA. She is currently studying for her PhD degree at the UniSA in the field of modelling biological vision.
E-mail: zorica.nedic@unisa.edu.au

Andrew Nafalski's career includes assignnments in academic and research institutions in Poland, Austria, Wales, Germany, France, Japan, USA, Canada, and Australia. He holds BEng(Hons), Grad DipEd, MEng, PhD and DSc degrees.
He is Chartered Professional Engineer and Fellow of the Institution of Engineers, Australia, Fellow of the Institution of Engineering and Technology (UK), Senior Member of the Institute of Electrical and Electronic Engineers (USA) and Honorary Member of the Golden Key International Honour Society. He is currently a Professor of Electrical Engineering at the University of South Australia in Adelaide. His major research interests are related to electromagnetic devices, magnetic materials and technologies as well as innovative methods in engineering education. His teaching areas cover analysis and design of electrical circuits and devices, electromagnetic compatibility and information technology. He has published over 300 scholarly works in the above fields He has been leader of some 40 technical and educational research and development projects. He has received numerous national and international awards for excellence in research, teaching, engineering education and community service.
E-mail: andrew.nafalski@unisa.edu.au

Aaron Mohtar received his BEng degree in electronics and microengineering in 2006 from the University of South Australia (UniSA), Adelaide, Australia. He is currently studying for his PhD degree at UniSA with a focus on remote laboratories in microelectronics fabrication. Since 2004, he has been involved in teaching electronics, microprocessor and microcontroller courses at the School of Electrical Information Engineering within UniSA. His interests include energy efficient commuting, robotics and biomedical devices.
E-mail: aaron.mohtar@unisa.edu.au