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Regenerative Brake of Brushless DC Motor for Light Electric Vehicle

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Abstract — This paper proposes a new and simple while cost-effective method for light electric vehicles regenerative brake with BLDC motor (Brushless DC Motor). The power stage topology of this electric vehicles' motor controller is similar to traditional BLDC motor controller. There is not necessary to use additional power converter, such as a boost converter, or other electric energy storage system for regenerative braking. During the regenerative braking, only PWM schemes of the inverter are changed, the kinetic energy of the vehicles will be converted to electrical energy and then returns to the battery pack. In order to achieve both better rider's comfort and improved regenerative energy returns to battery pack, this paper proposes a novel regenerative current sensing and control method. On the regenerative braking period, the controller performs two control loops, the winding current control loop and output DC-Link current control loop. To implement the regenerative DC-Link current control loop, there is no need to mount additional sensor to measure the output current sensor. Finally, some experiment on a BLDC controller with new control strategy, described above, is demonstrated.

I. INTRODUCTION

There are millions of LEV (Light Electric Vehicles), such as electric bicycle or electric tricycle, on the road in China. The convenience and low cost makes the number of LEVs growing dramatically in the last decade. The growth of LEVs is one of the most obvious, since there are plenty of express companies in China. In many large cities in China, LEVs are used as delivery vehicles for express. The battery packs on the most of delivery LEVs can cover only 50km for the best traffic condition. While most of delivery LEVs are driving on busy city where drivers have to start and stop frequently. Traditional LEVs using machine braking system which means lots of kinetic energy are converted to heat and dissipate. In the heavy traffic condition of a busy city, regenerative braking will be a better option than mechanical braking.

To implement regenerative braking, several ways are feasible, such as using additional boost converter, ultracapactior, or only changes the switching sequence of the inverter. Apart from changes the switching sequence of the inverter, other options are too complex and not cost effect [1][2].

Generally, three goals need to be achieved for regenerative braking on electric vehicles, riding comfort, maximum regenerative energy and low cost. Riding comfort can be achieved by implementing constant electric braking torque. For realize constant electric braking torque, a winding current closed-loop is necessary. On the other hand, traditional lead-acid battery pack on delivery LEVs has a maximum charged current limit [3]. So, in order to achieve maximum regenerative energy, charging current also need to be regulated. Since we need to regulate two different current and two different current are both bidirectional, normal thought is implement two current sensor on the BLDC motor controller. But mounting two current sensors are too expensive to accept. Therefore, traditional commercialized BLDC motor controller with regenerative brake only has a motor armature current closed loop [4][5], the DC-link current is not regulated. From the perspective of conservation of the power during regenerative brake period, if only perform a single motor armature current control loop, it means that the regenerative power will decrease in response to the motor speed. Also, the output charge current flow on the DC-link transmission line declines following the motor speed.

As a result, in order to achieve the measurement both motor winding current and charge current which flow on the DC-Link transmission line with single current sensor, the dynamic property of DC-Link transmission line need to be analyzed.

This paper proposes a method to imitate the DC-Link transmission line property so that we can derive the current which back to the battery precisely from a single current sensor. In other word, the analysis of DC-Link transmission line and the way to derive DC-Link current from a single current sensor is the most important task. This paper also provides a control strategy to regulate those currents and this can be done in traditional cascade control strategy. Simulation and experiment result verifies the points in this paper.

II. REGENERATIVE BRAKING COMMUTATION BY SINGLE-SWITCH STRATEGY

Normally, the maximum speed LEV cannot higher than no-load speed on flat road. The EMF (Electromotive Force) of motor is not enough to induce current back to the battery. In this case, the inverter needs to operate at boost mode to pump up EMF to a higher voltage in order to charge the battery. In this paper, single switch strategy is used to boost the EMF.

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Fig.1 illustrates the armature current path when switch on and off [6].

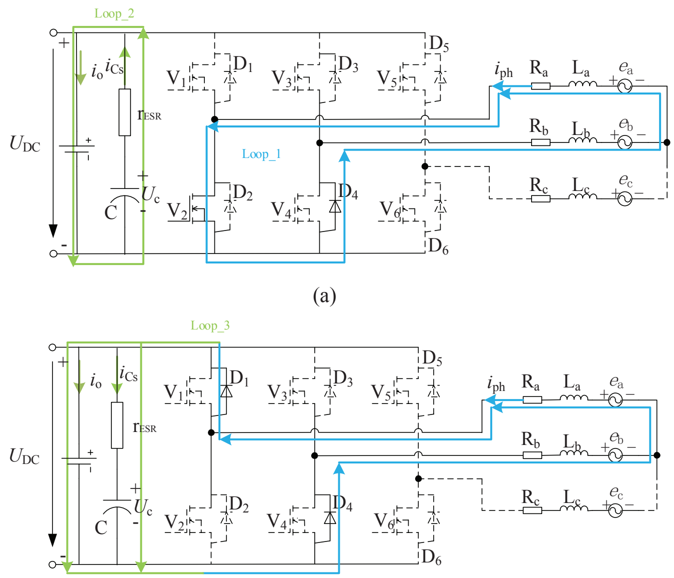


Fig. 1. The current of the single-switch Strategy switching on regenerative braking : (a) Current path as the switch V2 is on, (b) Current path as the switch V2 is off

According to the principle of the volt-second balance and the principle of the capacitor charge balance, where D is the dutycycle and $D + D' = 1$, the charging voltage U_{dc} can be described in terms of D', the internal resistance R of the armature, and the equivalent load resistance R_b, i.e.

$$\frac{V_{dc}}{V_{emf}} = 2 \cdot \frac{1}{\left(D'+2\frac{K}{D'}\right)} \tag{1}$$

Where K is defined as R/R_b [1].

III. Modeling of DC-Link Transmission Line & Analysis

DC-Link transmission line between a battery and BLDCM drive controller in a traditional LEV (Light Electric Vehicle) are not just a pair of wire which transfers electrical current unimpededly [7][8]. Furthermore, the DC-Link electrolytic capacitor has its parasitic ESR (Equivalent series resistor). So, the real equivalent circuit of the DC-Link transmission line is not as ideal as demonstrated in II. In fact, these parasitic components of DC-Link transmission line play a key role to make the chopping current flow through the inverter to be a DC current.

A. DC-Link Transmission Line Small-signal Modeling

DC-Link transmission line simplified equivalent circuit is shown at Fig.4. U_{DC} is the battery pack voltage, L_p & r is the parasitic inductor & resistor of DC-Link transmission line. r_{ESR} is the ESR of electrolytic capacitor.

Perform Kirchhoff's Current Law to node A, we can get equation (2):

$$i_1(t)+i_2(t)+i_3(t)=0 \tag{2}$$

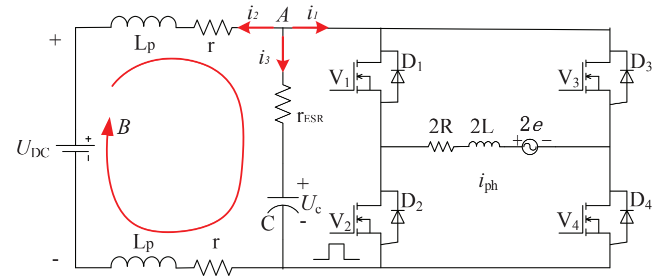


Fig. 2. DC-Link transmission line equviIent circuit with parasitic components. (Red arrow defines the current flow direction on three different branchs.

Perform Kirchhoff's Voltage Law to loop B, we can get equation (3):

$$-\left(2L\cdot\frac{di_2(t)}{dt}+2ri_2(t)\right)+\frac{1}{C}\int i_3(t)dt+r_{ESR}i_3(t)=U_{DC} \tag{3}$$

Assuming the initial current $i_1(0)=i_2(0)=i_3(0)=0$, and initial voltage of the capacitor $v_c(0)=0$.

Applying Laplace transform to (2) & (3), we get (4) & (5) in s- domain:

$$I_1(s)+I_2(s)+I_3(s)=0 \tag{4}$$

$$-2L\cdot s^2 I_2(s)-2r\cdot sI_2(s)+\frac{1}{C}I_3(s)+r_{ESR}sI_3(s)=0 \tag{5}$$

From (4) & (5), we can get the transfer function about $I_1(s)$ & $I_2(s)$:

$$G(s)=\frac{I_2(s)}{I_1(s)}=\frac{r_{ESR}Cs+1}{2LCs^2+(2r+r_{ESR})Cs+1} \tag{6}$$

B. Analysis of Transmission Line Transfer Function

According to the experiment result of an electric drive system of LEV, the parameters of transfer function (6) are listed below: C = 470μF*5 = 2350μF, L = 1.674μH, r_{ESR} = 0.005Ω, r = 0.01Ω.

Therefore, the transmission line transfer function can be written as (7):

$$G(s)=\frac{5e-6s+1}{2e-9s^2+2.5e-5s+1} \tag{7}$$

The frequency response of this transfer function is demonstrated by bode plot in Fig.3. As the bode plot shown, there is a zero at $-2e5$, and two poles at $-6.25e3 \pm 2.15e4i$

which corresponding to 31.8 kHz, 3.56 kHz. Actually, G(s) is a second order low pass filter. At the 10 kHz point, G(s)'s gain is about -20dB. This reduces the pulse current, caused by 10 kHz PWM modulation, flow into the inverter exactly.

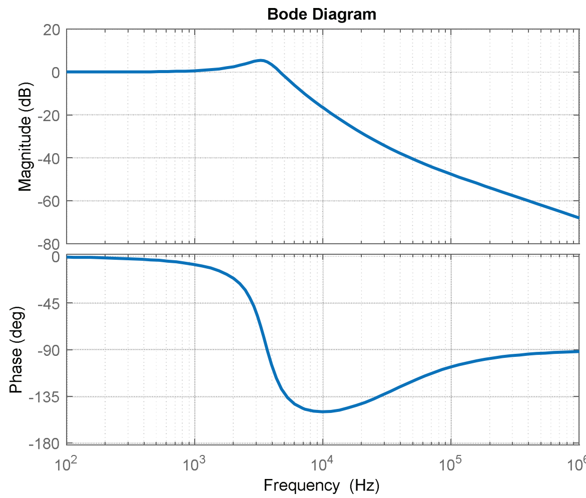


Fig. 2. Bode plot of the DC-Link transmission line transfer function

IV. RC Low Pass Filter Design For Simulate the DC Transmission Line Property

A. Using RC Low Pass filter to Achieve Similar Frequency Response of DC-Link Transmission Line

After the analysis above, DC-Link transmission line is nothing but a second-order low pass filter which can remove the pulse current at PWM frequency component flow into the inverter. According to the bode plot of the transfer function, the input current with frequency below 1 kHz has 0dB gain and a little bit phase shift. It means that if we can construct a simple low pass filter which attenuates above the PWM frequency component with about -20dB and 0dB gain at frequency below 1 kHz with slight phase shift, we can derive the current signal of DC-Link from the signal of the current sensor which located between electrolytic capacitor and inverter.

A RC circuit is a simple and feasible circuit to realize the low pass filter that mentioned above. RC circuit is a one-order low pass filter with one pole at:

$$f_c = \frac{1}{2\pi RC}$$

This one-order low pass filter has a slope with -20dB/Dec above f_c, so in order to achieve the same attenuated gain that DC-Link transmission line have, the R & C can be set to the calculated value below: $R = 1\text{k}\Omega$, $C = 0.1\mu\text{F}$.

The bode plot of the RC low pass filter is shown in Fig.3. It is obvious that gain, below 1 kHz, is 0dB and has a little phase shift. On the other hand, the attenuation at 10 kHz is almost the same with DC-Transmission line transfer function.

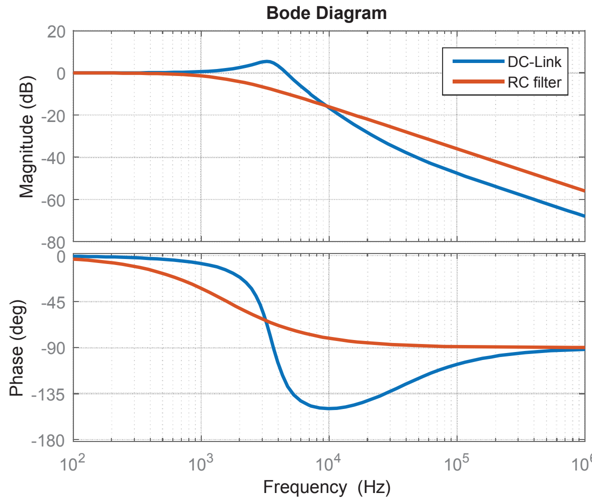


Fig. 3. Bode plot of the DC-Link transmission line transfer function vs RC low pass filter transfer function

B. Simulation of RC Low Pass Filter Performance

SimPowerSystems of MATLAB is used to simulate the whole system of BLDC motor regenerative braking controller with DC-Link transmission line and well-designed RC Low filter, as shown in Fig.4.

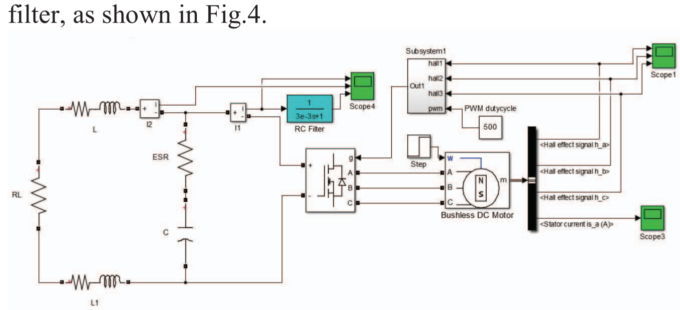


Fig. 4. Schematic of Simulation in SimPowerSystems

In Fig.5, the simulation result shown that two different sources of current which comes from the real DC-link current and current signal from RC filter coincides with each other. It is clearly demonstrates that the designed RC Low pass filter has almost the same dynamic response with DC-Link transmission line.

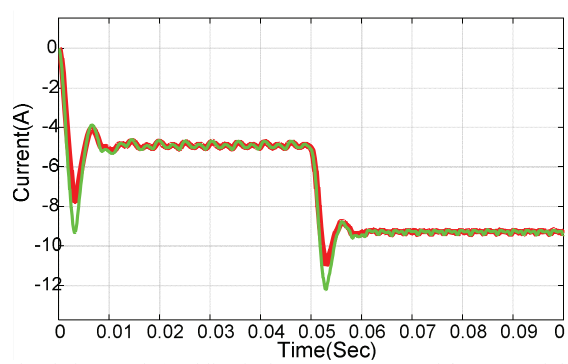


Fig. 5. Simulation result (Red line is the current measured from DC-Link(I2), Green line is measured from the output of RC low pass filter (I1))

V. SYSTEM STRUCTURE & CASCADE CONTROL LOOP

This regenerative braking control system consists of a half-bridge three-phase voltage source converter, microcontroller, breaking signal input, Hall signal input, bus current sensor, a brushless DC motor with trapezoidal back-EMF and Lead-acid battery pack as shown in Fig.6.

The DC-link Current Regulator and Phase Current Regulator blocks are typical PI controller. DC-link Voltage Protection unit performs over voltage protection. The protection is activated at the DC-link voltage above 75V. PWM modulator receives Hall signals from the BLDC motor for commutation.

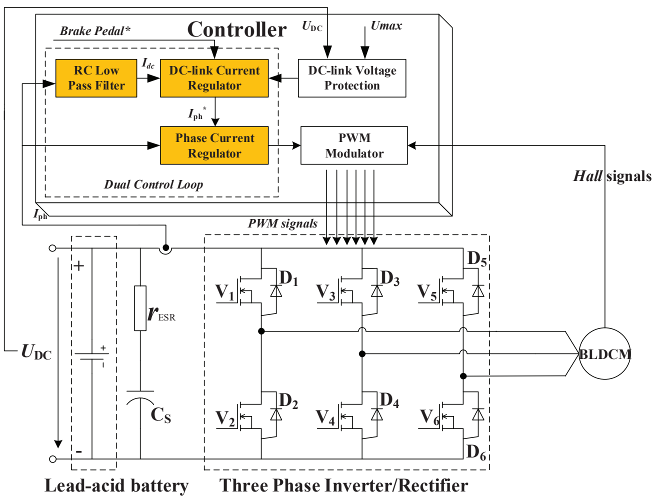


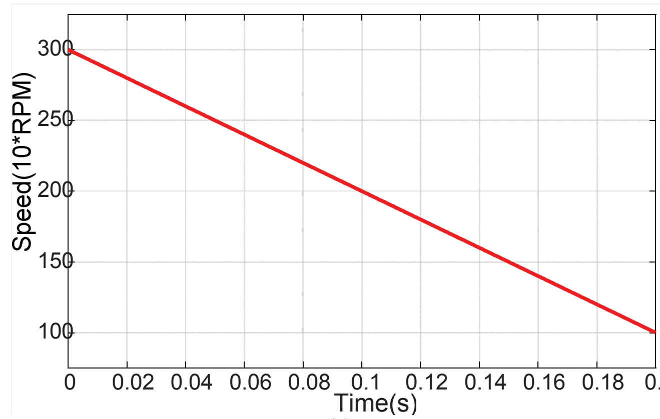
Fig.6 Control system structure.

The cascade current closed control loop has the ability to maintain both DC-link current which return to the battery pack and BLDC motor armature current. This cascade current closed loop contains the outer-loop and inner-loop. The outer-loop reference is the Brake Pedal* and feedback is the I_{dc}. The inner-loop reference is the I_{ph} which comes from the output of outer-loop and the feedback directly connected to the current sensor.

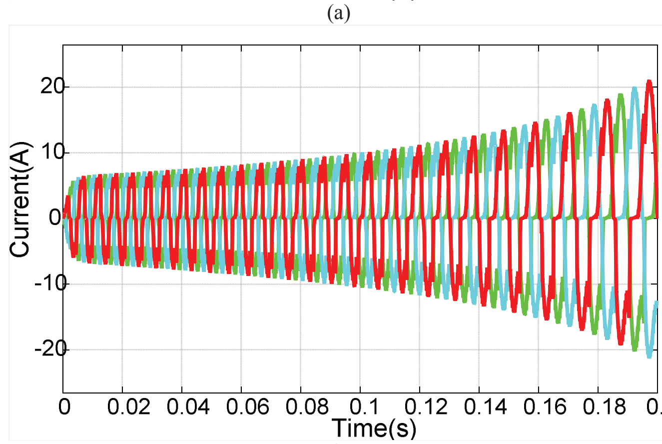
This control method, however, can achieve the maximum charge current to the battery without compromising the electric braking ability. During the braking progress, the speed of the vehicle begin slowing down, the outer-loop maintains the maximum battery charging current all the time, at the meantime, inner-loop receives the reference signal from outer-loop to control the motor armature current to reach the target braking force as large as possible.

Simulation results are shown in Fig.7, Fig.8. The simulation compares two different control methods, one is dual loop, and the other is single armature current loop. This simulation assume that the maximum charge current of the battery is 5A and the speed of the BLDC motor has a linear drop from an initiative speed for simulating a real braking progress approximately.

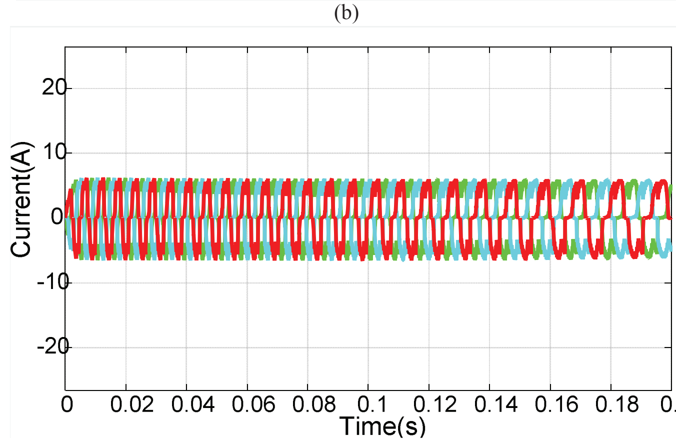
From Fig.8 (b), we can see that the three phase current increases gradually in response to the speed drop. While, in Fig.8 (c) which only have a single armature current loop, the three phase current are only maintained at a small value.



(a)



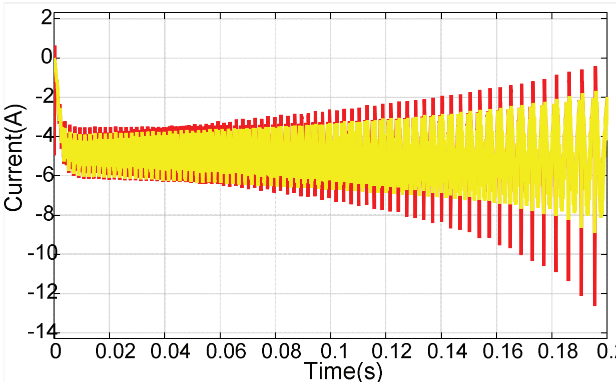
(b)



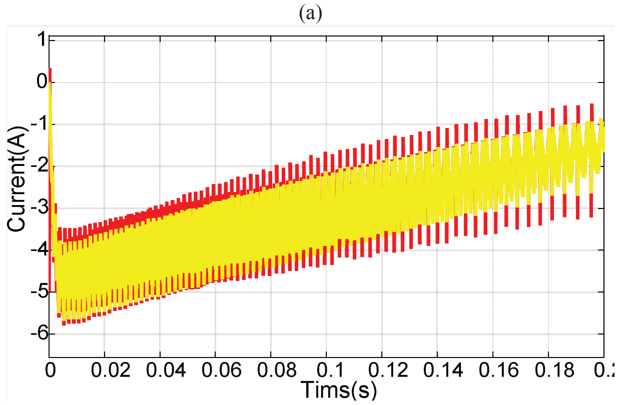
(c)

Fig.7. BLDC motor speed & three phase current (a) Motor speed (b) Dual loop control condition, (c) Single armature current loop control condition (Three color lines are three different phase current waveforms)

DC-link current average value keeps to the maximum charge current with proposed dual loop control strategy all the time, as shown in Fig.8 (a). But the system with only a single armature current control loop cannot maintain its DC-link current, the DC-link current gradually decreases following the speed of vehicle. This means the charge current can only reach its maximum value at the beginning of braking.



(a)



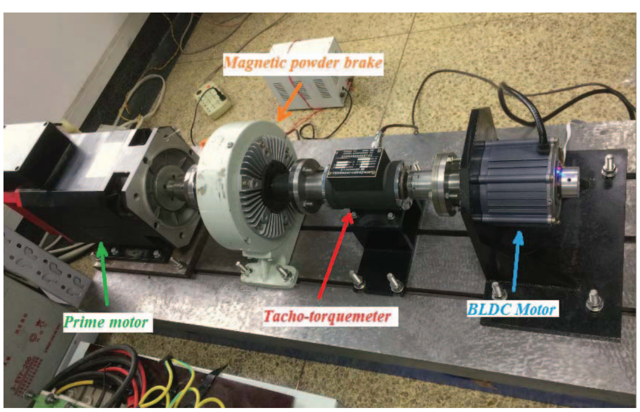
(b)

Fig.8. DC-link current waveform comparison (a) Dual loop control condition, (b) Single armature current loop control condition(Red lines are real DC-link current waveforms, yellow lines are current signals from RC low pass filter)

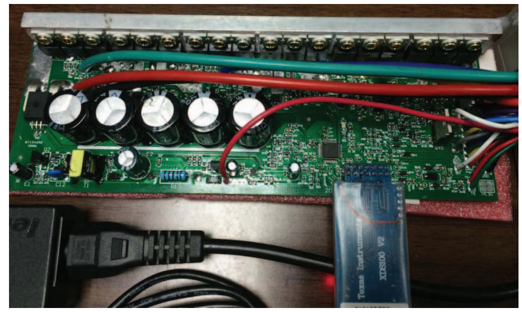
VI. EXPERIMENT

The experiment hardware platform shown in Fig.9 (a) includes a commercialized 800W/60V BLDC motor which winding induction is 820μH and resistance is 28.57mΩ, a servo AC induction motor as the prime motor, a tacho-torquemeter and 60V/38AH lead acid battery pack.

With a TMS320F28020 DSP as the central control unit, a laboratory experimental prototype motor controller for a LEV is developed (Fig.9 (b)). The bus current is detected by Hall Effect-Based linear current sensor which has a ±150A detection range .



(a)



(b)

Fig.9 Experiment platform & Developed controller

Fig.10 is the current waveforms of real DC-link current and raw current signal from current sensor. Two zero Amp reference is above these waveforms, which means they are current return to the battery pack. The current signal from current sensor is 10 kHz pulse current which envelop is the real armature current flow through the motor winding. Furthermore, the tested current level is similar to the simulated current level.

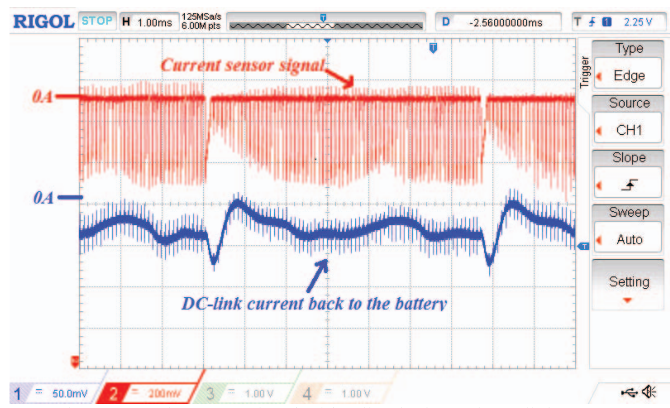


Fig.10 Experiment result (The blue line is the real DC-link current, the red line is the raw current signal from current sensor)

Fig.11 is the current waveforms of real DC-link current vs current signal derived from designed RC low pass filter. Compared with these two waveforms, current signal derived from RC low pass filter is almost the same with the real DC-link current.

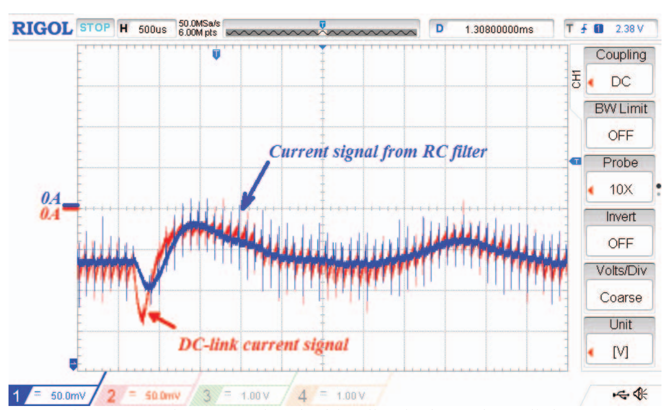


Fig.11 Experiment result (The blue line is the real DC-link current, the red line is the current signal derived from designed RC low pass filter)

From the experiment which mention above, we are sure that the DC-link current can be measured reliably from designed RC low pass filter. The dynamic property is similar to DC-link transmission line which can be guaranteed. Dual loop current control design is similar to traditional cascade closed loop, so the details are not discussed in this paper.

VII. CONCLUSION

The simulation and experiment result illustrates the feasibility and accuracy of RC low pass filter design methods mentioned above. The dynamic response of designed RC low pass filter is similar to DC-Link transmission line, so it can be used to obtain DC-Link current which back to the battery pack precisely. Using both armature current which reconstructed from current sensor and DC-Link current as two cascading closed loop feedback is possible. Therefore a more efficient and cost effective regenerative brake control system can be implemented to a BLDC motor driver of LEV.

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