Integration of Regenerative Shock Absorber into Vehicle Electric System

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Abstract of the Thesis

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For cars with combustion engine, fuel is wasted on powering electric devices and conquering resistant forces from the road while driving forward. Regenerative shock absorber can help to harvest kinetic energy from vehicle suspension and power on-car electric system. One innovative design of energy harvesting shock absorber with mechanical motion rectifier is used in this thesis to harvest power and to be integrated with existing vehicle electric system. Interfacing circuits are developed and tested to regulate unstable power and achieve input current control for damping adjustment purpose. The overall integration of car alternator, electric load and regenerative shock absorber is built as a demonstration platform. In experiments, the platform shows fuel saving when additional power is harvested from the shock absorber.

Dedication Page

For motherland.

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Acknowledgments

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I want to thank my parents for supporting me chasing my dream to study in the U.S. They always provide shelter and encouragement, though most of the time they are far away. I'm grateful to their dedication.

For other students in the research group, I would like to thank them for helping me with experiments and providing their thoughts. Sparks are important towards research and teamwork can help reduce difficulties and pressure.

Chapter 1 Introduction

1.1 Energy background

While most people are enjoying the benefits brought by new technologies of this modern era and keeping a positive view of mankind's future, the energy crisis, described by some researchers as the "greatest bottleneck" to our fast growing economy, may easily hold back people's perspective. Despite people's efforts spent in developing new forms of safe & clean energy for the past several decades, little change has been made towards the actual condition. Even today, in the second decade of the 21st century, fossil fuel is still the primary energy source for human activities. According to U.S. Energy Information Administration, in 2011, petroleum, natural gas and coal are the three major sources, making up 83% of overall energy consumption of U.S, shown in Fig. 1.

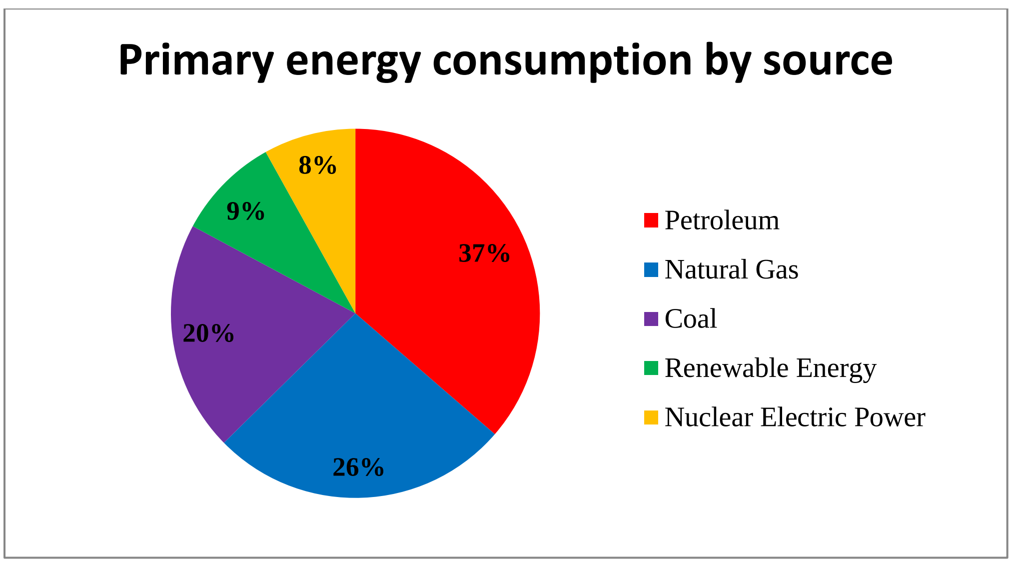


Figure 1 2011 U.S. primary energy consumption by source [1]

With heavy dependence on non-renewable energy and its strong effects on our environment, analyzing energy usage sectors and improve efficiency can be as important as finding alternative forms of clean energy. Another set of data from U.S. Energy Information Administration reveals the distribution of energy flow in different sectors, shown in Fig. 2.

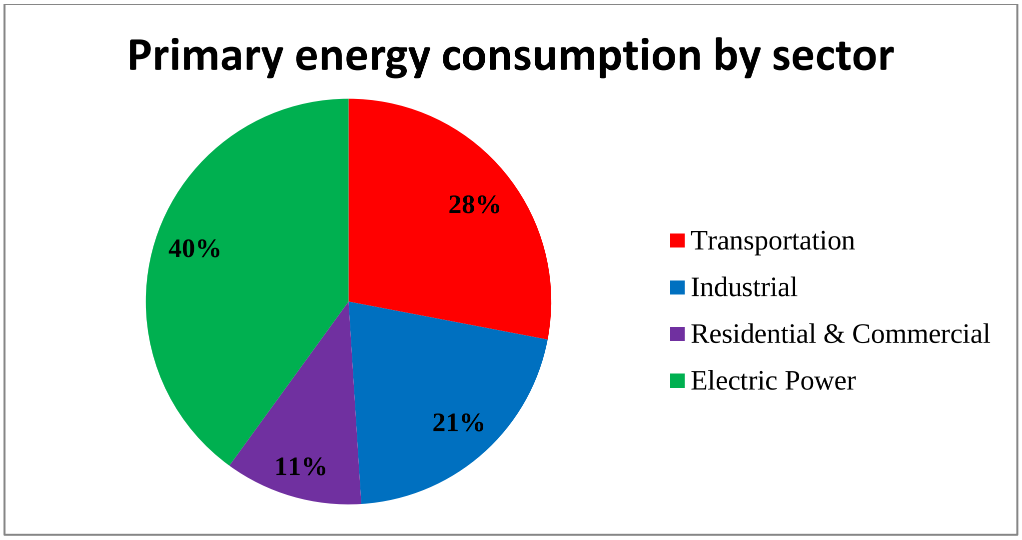


Figure 2 2011 U.S. primary energy consumption by sector [1]

From the figure we can see that 28% of energy is consumed by transportation, in which lies great potential of efficiency improvement. One good example is the well-known low efficiency of internal combustion engine used in most on-road vehicles. Considering engine thermal loss, drivetrain loss and other parasitic losses, only 17%-21% of fuel energy is passed to the wheels and actually drive the car to go forward while overcoming wind resistance and rolling resistance, etc. [2].

1.2 Related work

Paying closer heed to the wasted energy, some researchers have already come up ways to reduce energy loss or to harvest & recycle that part of energy. According to [3], typical temperature for vehicle exhaust can range from 200 to 650 degrees Celsius, showing a promising result of power extraction. In the reviewed articles, thermoelectric generators (TEG) are used on vehicle exhaust pipe for energy recovery. Shown in Fig. 3 is a waste-heat energy harvesting system prototype with TEG. The system is placed in the middle part of vehicle exhaust pipe and produces electricity as exhaust gas goes through. Due to the intrinsic properties of TEG materials, limited power could be transferred into electricity and further challenges of material development await researchers.

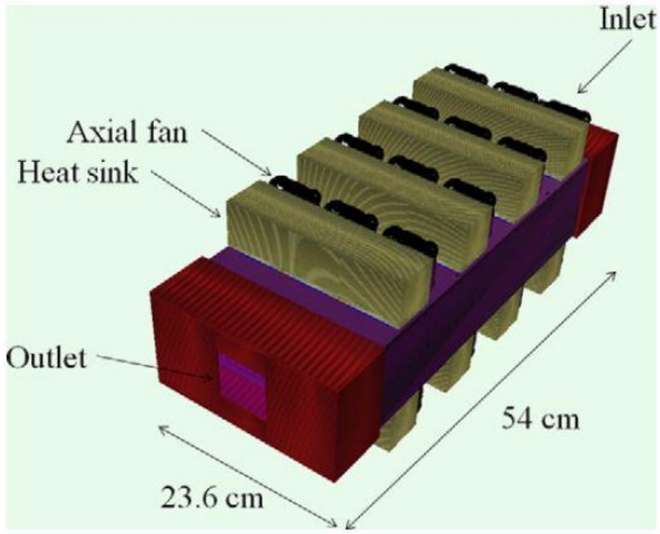


Figure 3 Waste heat energy harvesting system with TEG [15]

Kinetic energy, which usually exists in vehicle suspension system, is another form of energy that can be harvested during daily driving. The spring-damper system in vehicle suspension filters out strokes on bad road conditions and provides adequate support to vehicle body for high-speed curving or abrupt speed change. Yet, the suspension system itself is unavoidably consuming power from the engine. The amount of energy dissipated in the suspension's damper utterly comes from the driving power of engine, or equivalently, the fuel. Some researchers have begun the investigation about the substantial influence of suspension system on vehicle fuel efficiency [4]. Based on modeling and road test results, Lei *et al* [5] concludes that potentially about 100-400 W power is available from shock absorbers of a mid-sized passenger car at 60 mph for good road (Class B) and average road (Class C) conditions.

Figure 4 Kinetic energy harvesting device tested on a vehicle [6]

Fig. 4 shows a kinetic energy harvesting devices tested on a Chevrolet Suburban. Part (a) shows the vehicle, part (b) shows the test equipment used and part (c) shows the mounting on the vehicle's suspension system. As the car drives electricity will be produced by the device.

Given the previous facts about energy potential in vehicle suspension, a promising device can be designed to replace the conventional suspension and provide energy harvesting and damping simultaneously.

1.3 Thesis structure

Background information is provided in chapter 1.

Chapter 2 introduces the regenerative shock absorber hardware design concept, prototype and previous test results.

Chapter 3 includes DC/DC converter topologies for achieving input current control and output voltage regulation. Circuit prototypes for component verification are also shown.

In chapter 4, structure and major parts in vehicle electric system are introduced. The regenerative shock absorber's on-car integration is also illustrated.

Chapter 5 shows experiment results and analysis.

Chapter 6 provides conclusion about this demonstration platform.

Chapter 2 Regenerative Shock Absorber with Mechanical Motion Rectifier

2.1 Vehicle suspension general information

Ever since Karl Benz invented the first gasoline automobile in 1885, various forms of vehicles have come to birth with the efforts from inventers and researchers. Along with their births come with different suspension systems, from single-purposed supporting springs to self-adjustable air suspensions, even with active controlled electromagnetic suspension. The prosperous development for those multi-style inventions is actually serving for two ultimate purposes: driving comfort and handling. As vehicles travel on the road, several factors influence their motion: excitation from road irregularities, forces from braking and accelerating, inertia forces on a curving lane, etc. They can all cause discomfort to the driver and add challenges in vehicle body control, especially for high speed condition in which inadequate maneuverability may lead to serious accidents. As stated before, among the numerous suspension systems, active suspensions provide the most satisfying result in both comfort and handling. Yet, due to the high cost in manufacturing and power consumption, they are only available on luxury cars and maintenance is still and issue to be solved. Therefore, the most widely used suspension on today's most cars is viscous shock absorber in parallel with suspension spring, offering a good balance between cost and performance. The working principle of viscous shock absorber is to reduce car body vibration by dissipating kinetic energy into heat, which then becomes total waste.

2.2 Regenerative shock absorber

As introduced in Chapter 1, there is great potential of harvesting energy in vehicle suspension, and theoretical research about regenerative shock absorber began more than two decades ago. Various designs of shock absorbers with different principles were developed and tested. Zhongjie *et al* [6] assorted the designs into two categories: designs based on varied linear electromagnetic generators and utilizing linear motion directly; designs converting linear suspension vibration into oscillatory rotation and using rotational DC/AC generators. The first type benefits from its simple structure and reduced complexity of dynamic analysis. In [7]

Karnopp proposed the design of using permanent magnetic linear motor as controllable mechanical damper. Changing the direction of energy flow, the designs can also be used as actuators and perform better control over the vibration. Martins *el al* [8] made some improvements to power electronics circuits, permanent magnetic materials and microelectronic systems, proving electromagnetic suspension to be feasible.

The second type, converting linear motion into rotation, usually includes mechanisms like ball-screw, rack-pinion or hydraulic transmission. Seemingly including unnecessary structures, there are also benefits in this second type. A comparative study is made by Gupta *et al* [9] between a linear and a rotatory shock absorber. The result revealed that larger energy density could be achieved in a rotatory shock absorber. With off-shelf and low-cost rotatory generators used, the shock absorber can be made compact and cost effective. However, before stepping into this choice, several problems shall be noticed. Mechanical mechanism reliability and vibration performance could be bad under irregular oscillations. For example, the ball-screw mechanism in [10] can provide high power density, but controlling is hard at high frequency due to high stiffness produced by large motion inertia. Even with active control, the structure is proved to have bad performance at high frequencies [11]. In the early prototypes of our research group, more critical problems were observed during experiments. The bidirectional oscillation produces large impact force, backlash and friction in the transmission system. The rack teeth were quickly worn out in experiments due to large impact force and that led to functional failure. Besides, taking energy storage into consideration, the AC voltage generated by the bidirectional rotation of generator would be hard to fir for storage devices such as battery or super capacitor. If bridge rectifier is used, then the voltage drop on diodes would induce power loss. Otherwise AC to DC converter shall be used and it also suffers from efficiency issue.

2.3 Regenerative shock absorber with MMR

So, the regenerative shock absorber used in this paper is designed with an innovative structure of “mechanical motion rectifier”, allowing bidirectional vibration to be converted into single direction rotation. This is not a simple alternative of conventional regenerative shock absorber. In [6] the new designed is described to significantly improve reliability by reducing impact forces and increase mechanical efficiency by reducing system friction. Besides, even in high frequency bidirectional excitations with irregular amplitude, the structure allows the motor to make unidirectional rotation at a relatively constant speed, thus increasing the mechanical to electrical power conversion efficiency.

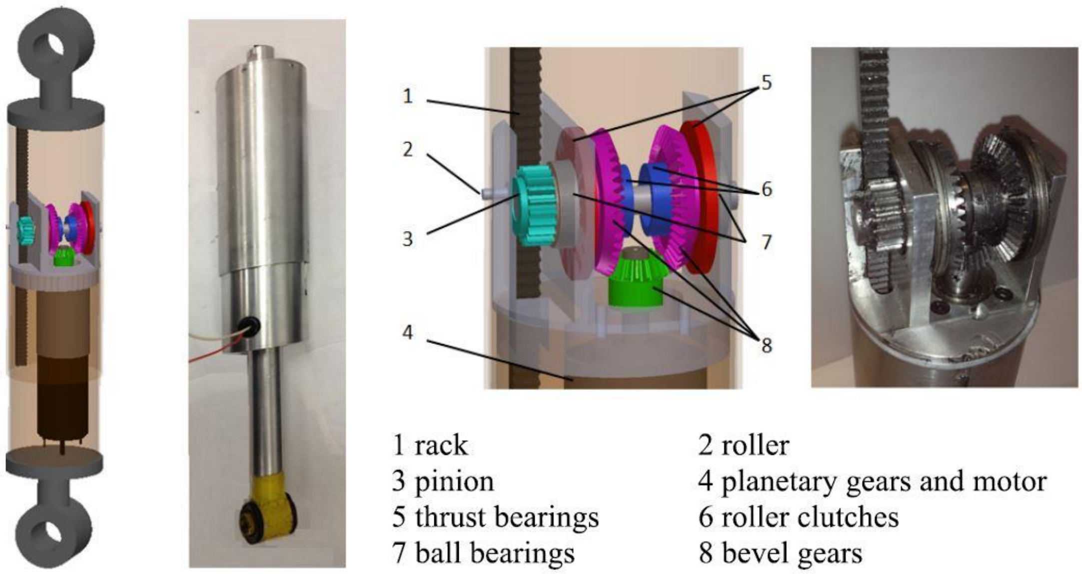


Figure 5 Comparison of 3D model and real prototype [6]

Fig. 5 shows the design made by our group members, both 3D model and actual prototype. The shock absorber is mounted between car chassis and wheels. When the car drives on road and is affected by excitation from road surface, vibration can be suppressed by the shock absorber and better driving comfort and handling can be provided. In this design, the shell consists of two cylinders. Inside the shell one pair of rack and pinion, one shaft and three bevel gears are used. The force from the top cylinder is first applied to the rack (black), and then passed to the pinion (cyan) that is engaged with the rack. Two roller clutches (blue) are mounted between the shaft (gray) and two bevel gears (purple). The shaft is driven by the pinion on one terminal and rotates in two directions. The small bevel gear (green) is connected with the motor's shaft and it's always engaged with the larger bevel gears (purple). When the rack moves up and down, the pinion and shaft rotate in two directions. Due to the engagement of one-way roller clutches, at the same time only one large bevel gear will be engaged and driven by the shaft; another bevel gear will be disengaged by the roller clutch [6]. Since the large bevel gears are located on opposite sides of the small bevel gear, the later one will only rotate in one direction no matter the outer cylinder moves up or down. This ensures the motor's single direction rotation.

The assembly of the pinion, shaft and bevel gears are mounted to the bottom cylinder. Between the top and bottom cylinders, Teflon rings are added to reduce the friction.

Since there are two statuses for the roller clutches: engaged and disengaged; the dynamics of this shock absorber is nonlinear. However, by looking into the force-displacement relationship, we can have a better understanding of the system's conditions at different moments.

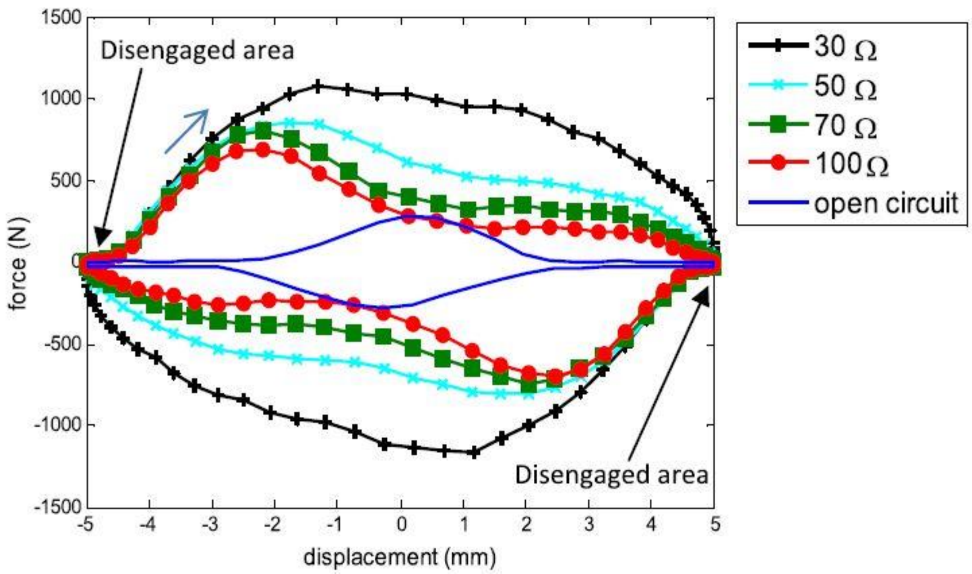


Figure 6 Damping loops with different electrical loads (1.5 Hz and 5mm excitation) [6]

Fig. 6 shows the shock absorber's damping loops under 1.5 Hz and 5 mm sine wave excitation with different electrical loads. Since the two axes are force and displacement, the loop area stands for the input mechanical work of the shock absorber in one cycle. When the shock absorber works with no electrical load (open loop condition), the loop area means input mechanical work is dissipated by mechanical loss, such as inner friction. Compared with other working conditions, the open circuit loop is relatively small, which means the structure can achieve high efficiency. Looking at loops with smaller resistance (i.e. from 100 Ohms to 30 Ohms), the force is significantly larger. This is resulted from the working condition of the motor. For a typical permanent magnetic DC brushed motor, when rotation speed is relatively constant, the motor's torque is proportional to the current that's flowing through the coils. In this case we assume the motor speed does not change much with different resistors, the smaller the resistance, the larger the current will be and thus resulting in a larger torque.

One other point to be noticed is the roller clutches' disengaged area. As we can see from the figure, before displacement reaches the maximum value, the force decreases to almost zero, meaning that no mechanical power is transferred to the shock absorber. This happens because the bevel gears connecting with the motor have higher angular velocity than the shaft that's connected with another side of the roller clutches. This condition makes the roller clutches to disengage and no torque is transferred to the motor.

2.4 Characteristics of electric power from shock absorber

With the understanding of shock absorber's working principles, we can take a closer look at its energy extraction. Fig. 7 shows the output voltage of shock absorber under 5 Hz and 5 mm excitation, powering a 100 Ohm resistor. The RMS of voltage is 33.825 V, ranges from 25 V to 40 V. The electric power produced is 11.44 W.

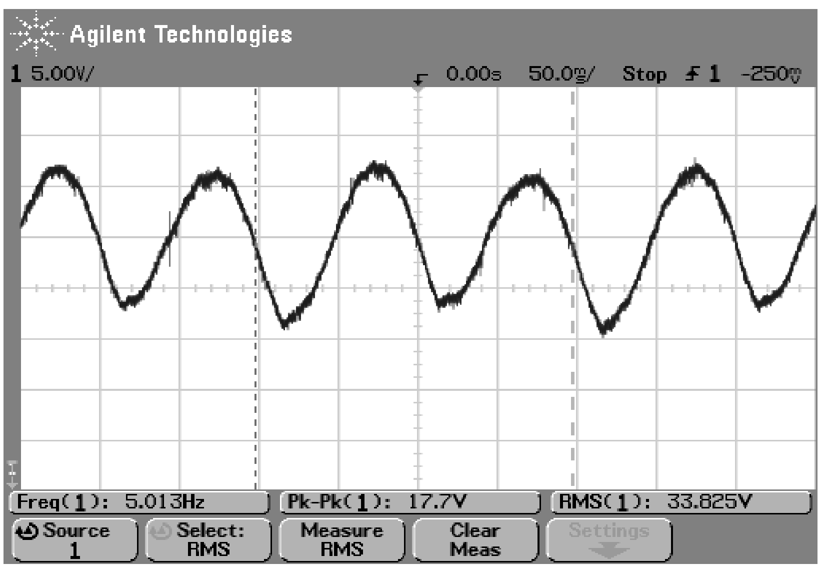


Figure 7 Output voltage of shock absorber with 100 Ohm load (5 Hz 5 mm excitation)

Mechanical to electrical frequency relationship can be easily observed. If the system is implemented without MMR, the DC motor's output voltage would just follow the input excitation. In this design, the MMR helps to convert AC output to DC voltage and thus the frequency of waveform will just look like doubled. The rising slope of output voltage means the shock absorber's roller clutch is engaged, mechanical power is being transmitted into electric power. After the speed of bevel gears is lower than the central shaft, both roller clutches will be disengaged and output voltage will decrease due to power consumption on the load. Depending on different excitation conditions and different loads, the output voltage waveform of shock absorber will look different. From the above figure we can easily notice that the original voltage produced by the shock absorber is neither steady nor regular, so it could not be directly applied to normal energy storage units, such as car battery. In this case, interfacing circuits are needed to better handle the incoming power and provide power transmitting function.

Chapter 3 Power Electronics Circuits for Suspension Energy Harvesting

3.1 Major requirements for power electronics circuits

With the help of mechanical motion rectifier, the DC motor used in the regenerative shock absorber will only provide DC voltage no matter the shock absorber moves up or down. It reduces some problems for the next stage. However, as shown in Chapter 2, original output voltage waveform of regenerative shock absorber can be very unstable, making energy storage and utilization difficult. This puts some requirements for the interfacing electric circuits. In this situation, DC/DC converters can be a good media in transmitting power from the shock absorber to the next stage. As the name indicates, those converters change power from one voltage level to another level, could be lower, equal or higher. In terms of power electronics, there are three major challenges for the converter:

(a). The converter should be able to stabilize the incoming power and provide steady output voltage. When the car drives on different road conditions, irregular excitations will be transferred to the shock absorber, making the motor inside working with various speed and torque. So the output power of the DC motor can be random. In order to handle that power and properly convey energy to the next stage, the interfacing circuit should automatically adjust the working condition of itself to cope with the input. In this way, power electronics circuits with closed-loop self-control shall be used. Besides, for a good response time, the circuit should be able to switch at high frequency. Most commercial DC/DC converters on the market can fit this requirement. Since the output voltage may be lower, equal or higher compared with the input voltage, buck-boost converter can be a good choice. Fig. 8 shows the schematic of a typical buck-boost converter.

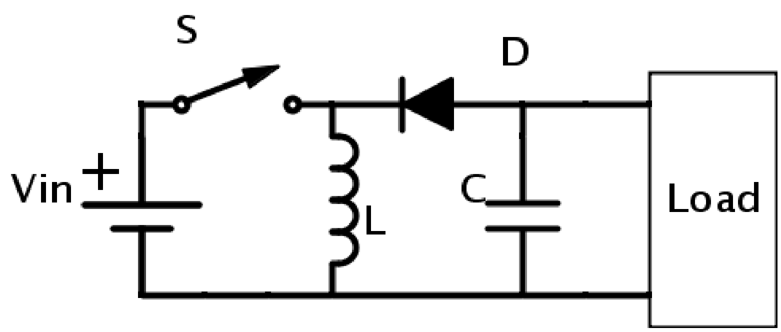


Figure 8 Buck-boost converter

Switch S controls the charging and discharging process of inductor L. When the switch is closed, input charges the inductor. When the switch opens, the energy stored in L will be transferred to the load. Capacitor paralleling with the load is not a must, but it will usually smooth the output voltage waveform and provide better output quality. When the converter works in continuous mode (the current in inductor never reaches zero), the in/out voltage relationship can be expressed as:

$$\frac{\boldsymbol{V_o}}{\boldsymbol{V_i}} = \frac{\boldsymbol{-D}}{\boldsymbol{1-D}}$$

V_o stands for output voltage, V_i is input voltage. D is the duty cycle of switch S. By changing the duty cycle, we can maintain a constant output with different input conditions.

(b). The circuit should be able to control input current (achieve damping control). The torque of motor is closely related with the current flowing through it. When the DC motor is used as a generator, it can be modeled as follows:

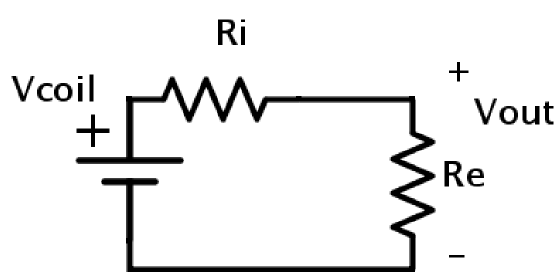


Figure 9 Equivalent circuit of motor as generator

The following equations can be listed:

$$\boldsymbol{V_{coil} = I \times (R_i + R_e)}$$

$$\boldsymbol{\omega = K_e \times V_{coil}}$$

$$\boldsymbol{T = K_t \times I}$$

V_{coil} is the inner coil voltage of the motor, also known as back EMF (electromotive force). R_i is the motor's inner resistance (terminal resistance), R_e is the external resistance (load resistance). I is the current flowing through the motor, ω is the angular velocity of motor, T is the motor's torque. K_e is the motor's speed constant (typical unit rpm/V) and K_t is the motor's torque constant (typical unit Nm/A). When the motor rotates at a constant speed, the output voltage will remain relatively steady. By changing the external resistor's value, the current flowing through the motor will be changed, thus affecting the torque. With torque varied, different damping can be provided by the shock absorber.

To harvest energy, the shock absorber should be connected with a DC/DC converter. Since the converter switches at frequencies much higher than the mechanical excitation, the converter can be regarded as a variable resistor from the side of motor. However, this resistor is a "lossless" resistor. It does not dissipate energy as heat; it only transfers power to the next stage. By properly controlling the switch operations in the DC/DC converter, equivalent resistance control and power transmission can be achieved at the same time. Take the buck-boost converter shown in Fig. 6 as one example. When the converter operates in discontinuous or marginal mode (current stored in inductor will be depleted after each switching cycle), the following relationships exist:

$$\boldsymbol{V_{in} = L\frac{di}{dt}}$$

V_{in} is input voltage, L is inductance and i is current flowing through inductor. Since the converter's switching frequency is much higher than varying speed of input voltage, the input can be assumed to be constant during each switching period. In this manner, with a duty cycle of D, after the switch is open, total current stored in the inductor will be:

$$\boldsymbol{I = \frac{di}{dt} \times DT}$$

T is the switching period and the change rate of inductor's current can be derived from the previous equation. Since the converter works in marginal or discontinuous mode, the current in inductor reaches zero before the next switching cycle begins. So the average current for one switching cycle can be expressed as:

$$I_{avg} = \frac{D^2 T V_{in}}{2L}$$

With a constant input voltage V_{in}, the equivalent input resistance is:

$$R_{eq} = \frac{V_{in}}{I_{avg}} = \frac{2L}{D^2 T}$$

Since inductor is a constant value for a fixed circuit, changing duty cycle D and switching period T can make the equivalent resistance controllable. When the shock absorber is excited with external mechanical force, the amount of mechanical energy is a fixed value. After the system loss of shock absorber and conversion loss of DC motor, there is also fixed value for electric power. Then the current flowing through the motor can just be controlled by changing the equivalent resistance of DC/DC converter.

(c). The circuit should have high efficiency and good reliability on a wide input voltage range. Typical DC/DC converters can provide power conversion with efficiency at about 95%, some even higher. For example, the LTC 3789 high efficiency synchronous 4-switch buck-boost controller can provide efficiency up to 98% [12]. Shown in Fig. 10 is the efficiency and power loss curve for this converter.

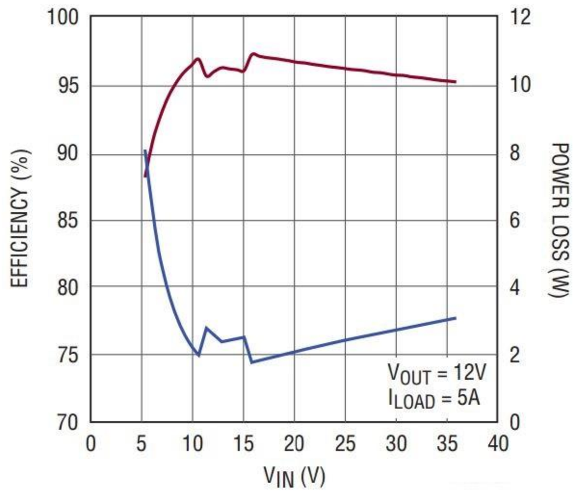


Figure 10 Efficiency and power loss of LTC 3789 [12]

The figure shows that peak conversion efficiency of 98% only happens when input voltage is 16 V. For other conditions, the efficiency can drop to as low as 88%. Although this type of conventional DC/DC converter can be used to harvest energy from the shock absorber, it is not an optimal solution. Based on previous test results of shock absorber, when excitations similar to road condition are given to the shock absorber, its open loop voltage can be from 0 to 80 V. Even with load applied, this still requires a large range of converter's operation.

3.2 Circuit topologies suitable for energy harvesting

Based on the three major requirements, various circuit topologies were developed and discussed. Since the shock absorber will be used to charge car battery and be integrated into existing car electric system, the specified requirements for the converter can be: 4V to 80 V input; 14.5 V output; 200 W maximum power; enable input current control together with output voltage regulation; high efficiency and good reliability.

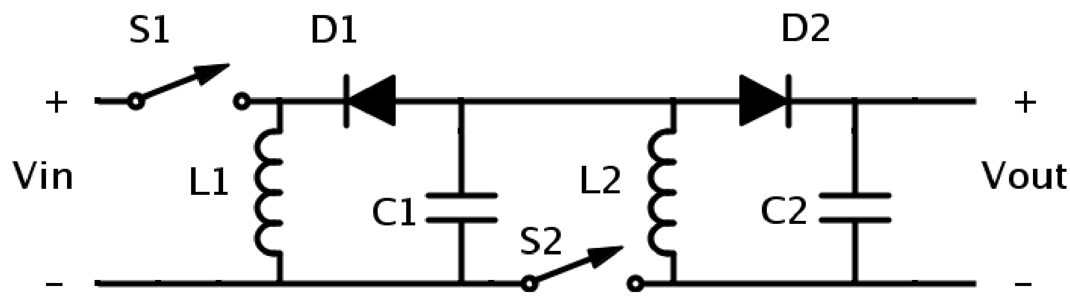


Figure 11 Cascaded buck-boost converter

One topology of cascaded buck-boost converter is shown in Fig. 11. The circuit is actually two buck-boost converters with the second one vertically mirrored to have a switched polarity. S1 and S2 can be transistor switches to block current from both directions. C1 is used as intermediate energy storage, providing buffer to the previous stage and next stage. The two stages serve different functions. The first stage, with switch S1, inductor L1, capacitor C1 and diode D1, mainly controls the input current. Based on previous derived equation of equivalent input resistance of buck-boost converter, controlling the duty cycle and switching frequency of S1 can change the resistance of the input port. Of course as the duty cycle is changed, the output voltage of stage 1 will be changed accordingly. In order to properly charge the final storage unit, the second stage is needed to regulate the unstable voltage from the buffering capacitor. So the duty cycle and switching frequency of switch S2 is aimed for leveraging the voltage. In this circuit, there are two independent control variables for two switches. As the energy go through two stages, it will flow through two diodes and therefore voltage drop is unavoidable. This direct assembly of two buck-boost converter can perform certain functions, but still requires further improvement.

One problem that may exist in the cascaded buck-boost converter is the extreme duty cycle of two switches. Since the first stage only controls the input current, the duty cycle of switch S1 can be random, leaving the intermediate capacitor with unstable voltage. Regarding this unfriendly input voltage, switch S2 will have to operate in a wide range, possibly below 10% or above 90% in some cases. This may cause the current flowing through the transistor switch and the voltage applied on the switch approaching the standard value, inducing efficiency reduction and energy loss. If in some special conditions that the switch has to be operated during a long period of time, the lifetime of the switch will be greatly reduced and thermal failure will be a critical issue.

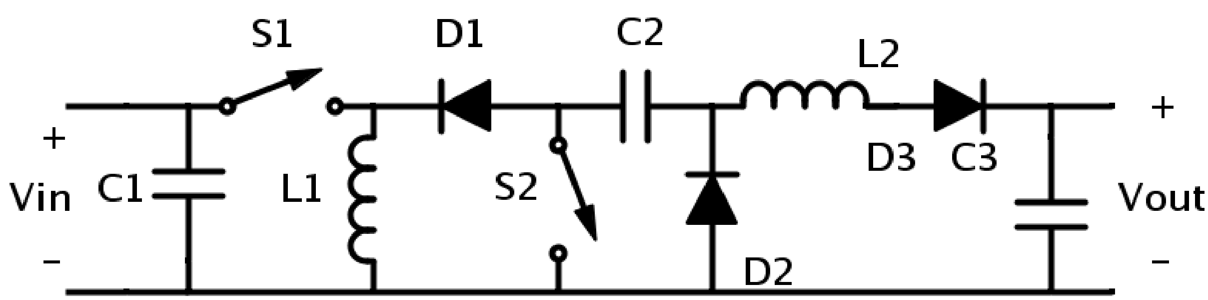
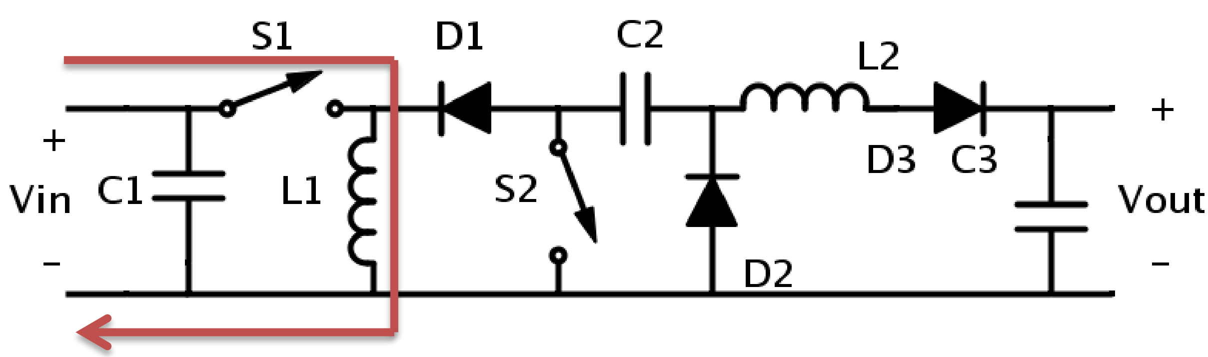
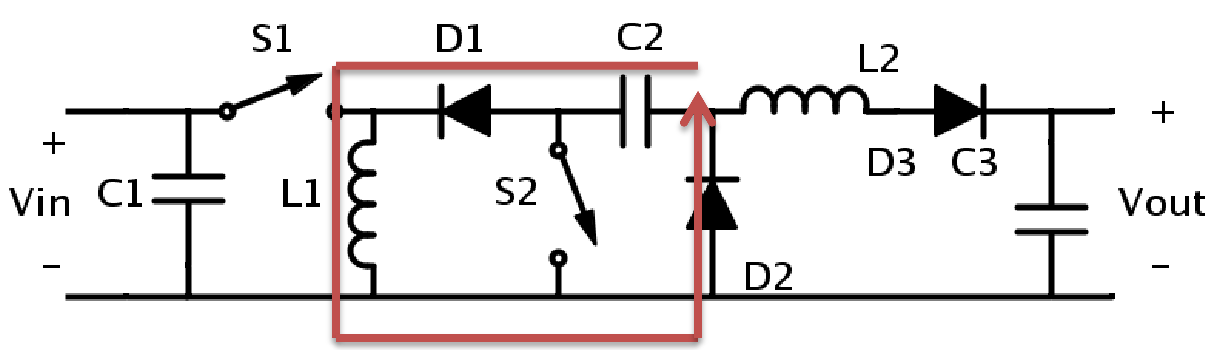


Figure 12 Hybrid DC/DC converter

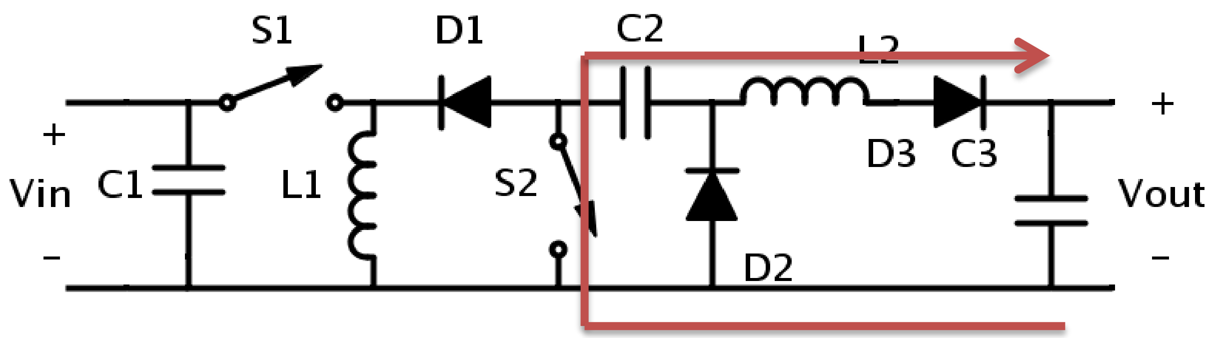
Shown in Fig. 12 is another DC/DC converter topology developed by me. The working principles of this hybrid converter can be illustrated in following figures.



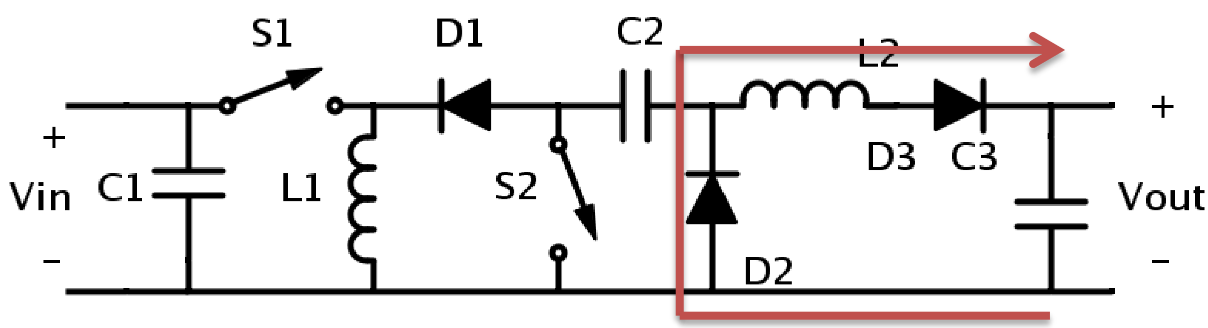
(a) Input charging inductor L1



(b) Inductor L1 charging capacitor C2



(c) Capacitor C2 charging inductor L2 and output



(d) Inductor L2 continues to charge output

Figure 13 Operating status of hybrid converter

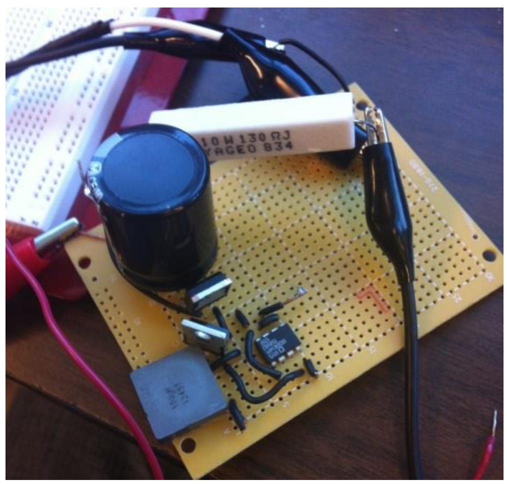
In Fig. 13 (a) the input first charges the inductor L1 as switch S1 is closed. Capacitor C1 is used to further help stabilize the input voltage from shock absorber. After a short period, L1 will be charged with some energy and then switch S1 opens. Then in Fig. 13 (b) the inductor will start to charge intermediate capacitor C2 through 2 diodes, D1 and D2. Capacitor C2 isolates the first stage and second stage, providing buffer to the energy. After the amount of energy in L1 is fully released to C2, switch S2 closes. In Fig. 13 (c) capacitor C2 charges the inductor L2 and output through one diode. In Fig. 13 (d) when switch S2 opens, the inductor L2 will continue to charge the output. Capacitor C3 is used to stabilize the output voltage.

For this converter there are still some issues to be solved. Switch S1 mainly functions to control the input current, which adds uncertainty to the voltage stored in capacitor C2. In this case, switch S2 controls the output voltage. However, due to the special topology of this circuit, switch S2 shall not be closed until all energy of L1 is released. This adds constraints to the operation of S2. Besides, S2 should not be closed when S1 is closed, otherwise there will be a short circuit for the input side. In this manner, the control algorithm of S2 is to be complicated and the output voltage may not be efficiently controlled within a given range.

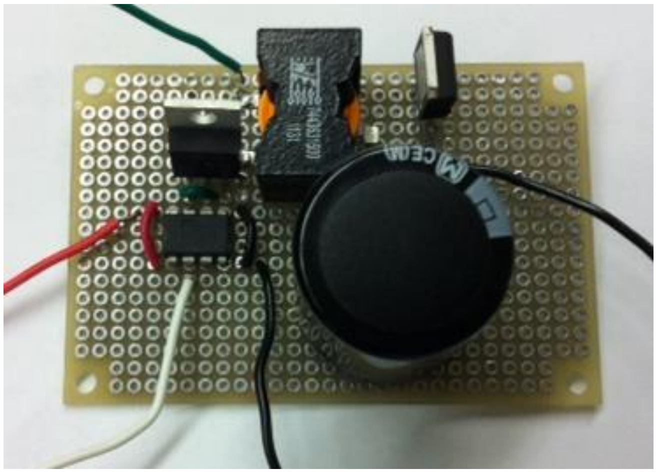
Comparing this circuit with cascaded 2 stage buck-boost converter, they have same number of switches, inductors and capacitors. However, the hybrid DC/DC converter requires one more diode, which may certainly reduce the efficiency of this circuit. As a brief conclusion, it is challenging to design an interfacing circuit for the shock absorber to have stable output voltage and enable input current control.

3.3 Circuit prototypes for verification

In order to verify the components to be used for circuits with more complex functions, two circuit prototypes were built, one boost converter and one buck-boost converter.



(a) Boost converter prototype



(b) Buck-boost converter prototype

Figure 14 Prototyping circuits

Parameters for the components to be used in the prototypes were first calculated based on the power estimation from shock absorber: 100W maximum power and 0 to 80V voltage. Switching frequency shall be discussed first since it affects the size of energy storage units such as inductor and capacitor. According to experiences about balancing between switching loss and component sizes, the frequency between 50kHz and 1MHz is reasonable. Due to the practical conditions of controller in our lab, 50kHz is chosen. Then the size of inductor shall be considered first before other components. During the charging process of inductor, input voltage can be assumed to be constant. So the following equation exists:

$$V_{in} = L\frac{di}{dt}$$

i stands for inductor's current, L for inductance and V_{in} for input voltage. The amount of current increased during the charging cycle is:

$$\Delta i = \frac{V_{in}}{L}DT$$

D for duty cycle and T for switching period. The current increment, Δi should not exceed the saturation current of the inductor. For real inductors, the saturation current, internal resistance and heat performance vary from each other. So that is only partial requirement for the final selection. Simulations can help to select the parameters faster.

After calculation, the results were verified with MATLAB Simulink simulations. Shown in Fig. 15 is the circuit model in MATLAB.

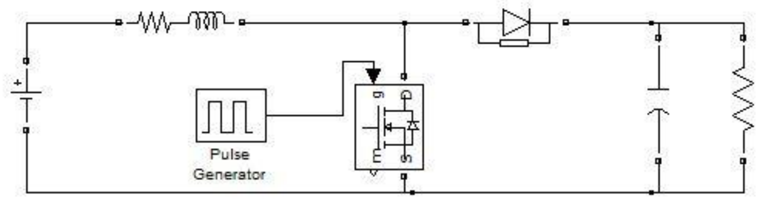


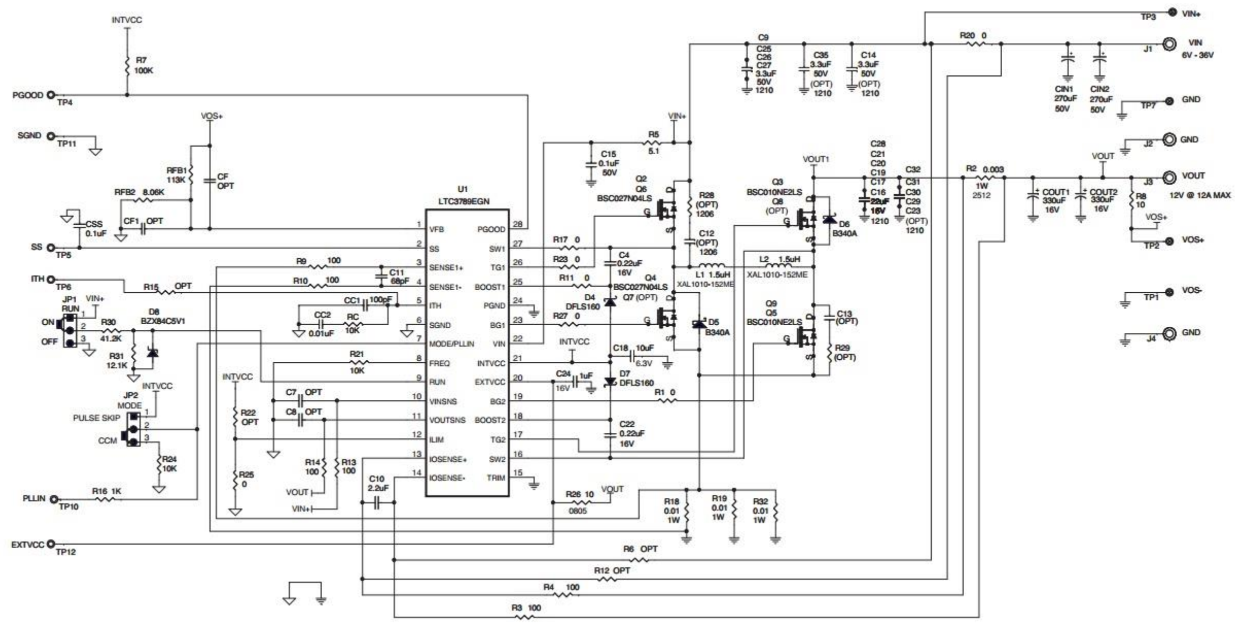
Figure 15 Simulation model of boost converter in MATLAB

For the two converters, switching frequency is set around 50kHz, reducing the size of inductor but still maintain a relatively low switching loss. In the experiments of testing the prototypes, several problems occurred and some components were replaced by parts with better performance.

3.4 DC/DC converter used in experiments

In our previous experiments, two commercial DC/DC converters were used to harvest power generated from the shock absorber. One is LTC 3789 EGN Circuit 1757A, the other is LTC 4000 Circuit 1721A. Both are buck-boost converters, with different in/out specifications.

(a) LTC 3789EGN 1757A top view



(b) LTC 3789EGN 1757A schematic diagram [12]

Figure 16 LTC 3789 EGN 1757A

With input voltage from 6V to 36V, the converter is able to generate 12V output voltage with maximum current at 12A. Typical switching frequency of the switches range from 200kHz to 600kHz. With this high switching frequency, the shock absorber's output voltage can be regarded as relatively constant during each switching period.

The LTC4000EGN Circuit 1721A has similar view of 1757A, and schematic diagram is shown below.

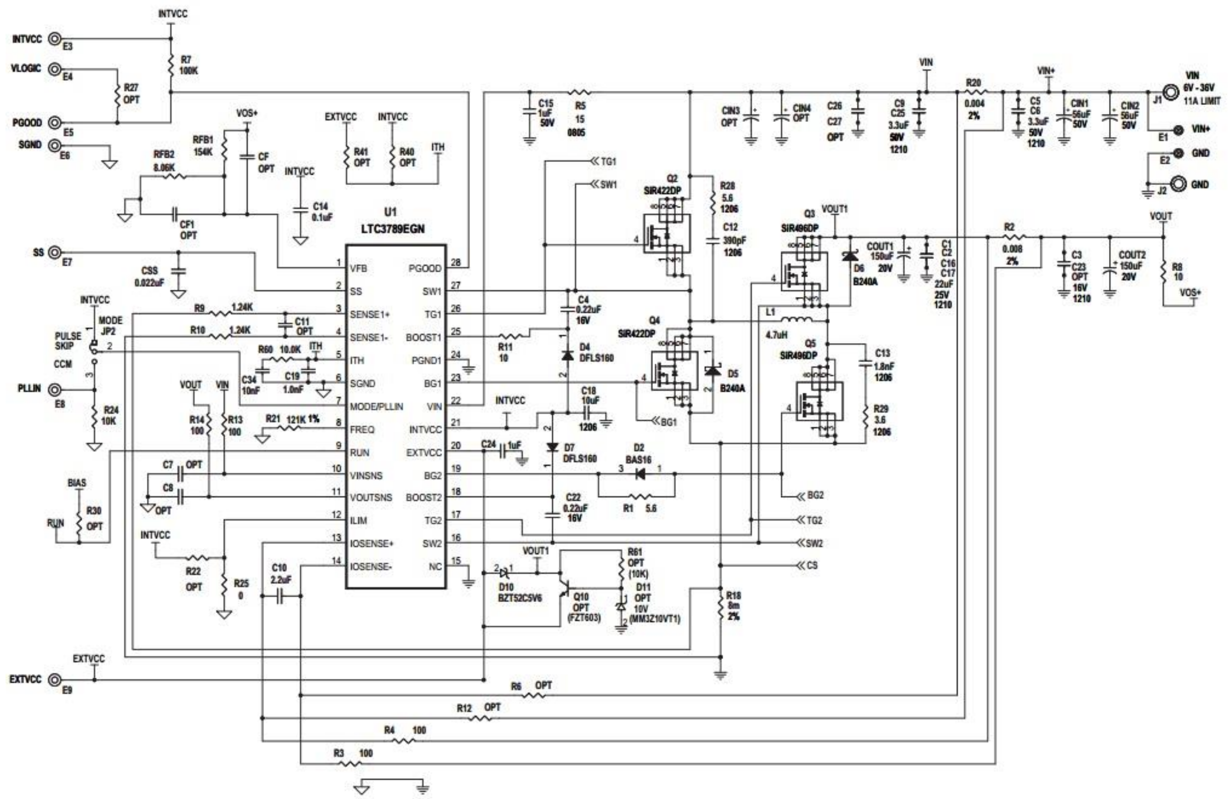


Figure 17 LTC4000EGN 1721A schematic diagram [13]

The LTC4000EGN 1721A can provide a higher output voltage at 14.6V, more suitable for future car battery charging. Input voltage range is same, 6V to 36V. This converter is used in tests to charge the car battery together with vehicle alternator.

Chapter 4 Integration into Vehicle Electric System

4.1 Vehicle electric system overview

In order to achieve the goal of fuel saving, the shock absorber needs to be integrated with existing electric system on cars. Before bringing up the whole structure, it is essential to take a look at the electric system of a typical car. Internal combustion engine is the ultimate power source for all on-car equipment. Fig. 18 shows how the engine (crankshaft) drives different equipment with belt transmission on a BMW 3 series car.

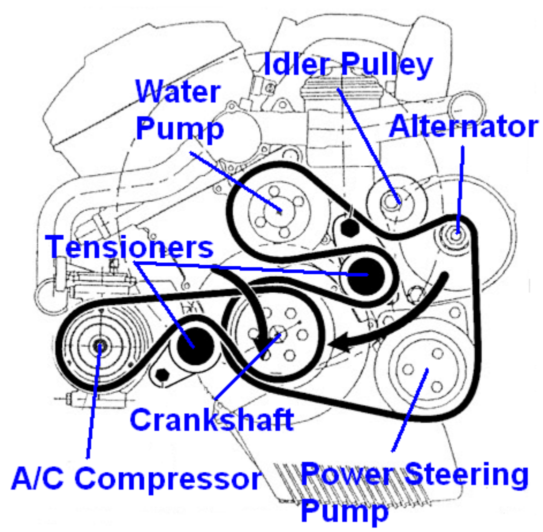


Figure 18 BMW E46 belt diagram [14]

As it can be seen from the figure, car engine drives the alternator, which generates electricity for all on-car devices. Same as the A/C compressor, alternator consumes horsepower from the engine. Most people may have the experience that during summertime when air conditioning is often used, fuel consumption is slightly higher than normal. Same principle applies to the alternator. With more electric power drawn from the alternator, the engine will also consume more fuel.

The alternators used on vehicles are typically induction generators, not permanent magnetic ones. This provides the alternator a self-adjustable power output under different engine speed, which is controlled by the driver, not the need of electric loads. Shown in Fig. 17 is the connection diagram of a typical car alternator. The three coils X, Y and Z stand for the output coils of alternator, which provides three phase AC voltage. The output voltage is then rectified by a full-bridge rectifier and charges the car battery. The inductor Lm functions as the induction coil inside the alternator, which provides magnetic field with the power from car battery. As introduced before, the alternator is driven by the car engine’s crankshaft with fixed belt transmission. In this manner, as the driver operates the car in different conditions, the alternator will be driven with different speed.

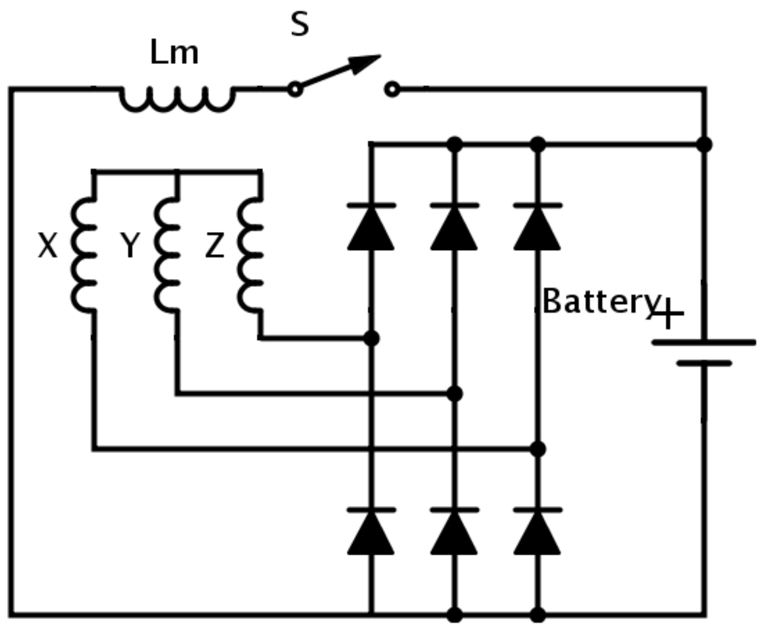


Figure 19 Car alternator connection diagram

Switch S in Fig. 19 is an electrical switch that is controlled in a feedback loop. The voltage of alternator’ output coil is the control input and target. As the engine goes faster and drives the alternator with a higher speed, the voltage created in the coils will be higher assuming the current flowing through the induction coil Lm stays relatively constant. Then this change is detected by the system and average connection time of switch S will be reduced. That reduces the average current flowing through the induction coil and the generated magnetic field will be weakened according to Ampere’s law. This change leads to a constant voltage production of the alternator.

There is one more benefit for connecting the battery to the output of the three phase full bridge rectifier. Due to the large energy storage ability of battery and its chemical nature, the output voltage will be maintained on a relatively constant level. Output noise can also be reduced as small voltage spikes can be absorbed by the battery at no costs.

4.2 Integration concept

Understanding the principles of car alternator, we can imply a method to reduce the fuel consumption of engine: by reducing the electric power of alternator, which leads to mechanical power reduction for the combustion engine. Since on-car electric devices still need relatively same power supply, additional power source can be introduced into the system. The following figure shows how the shock absorber can be integrated together with existing on-car electric system.

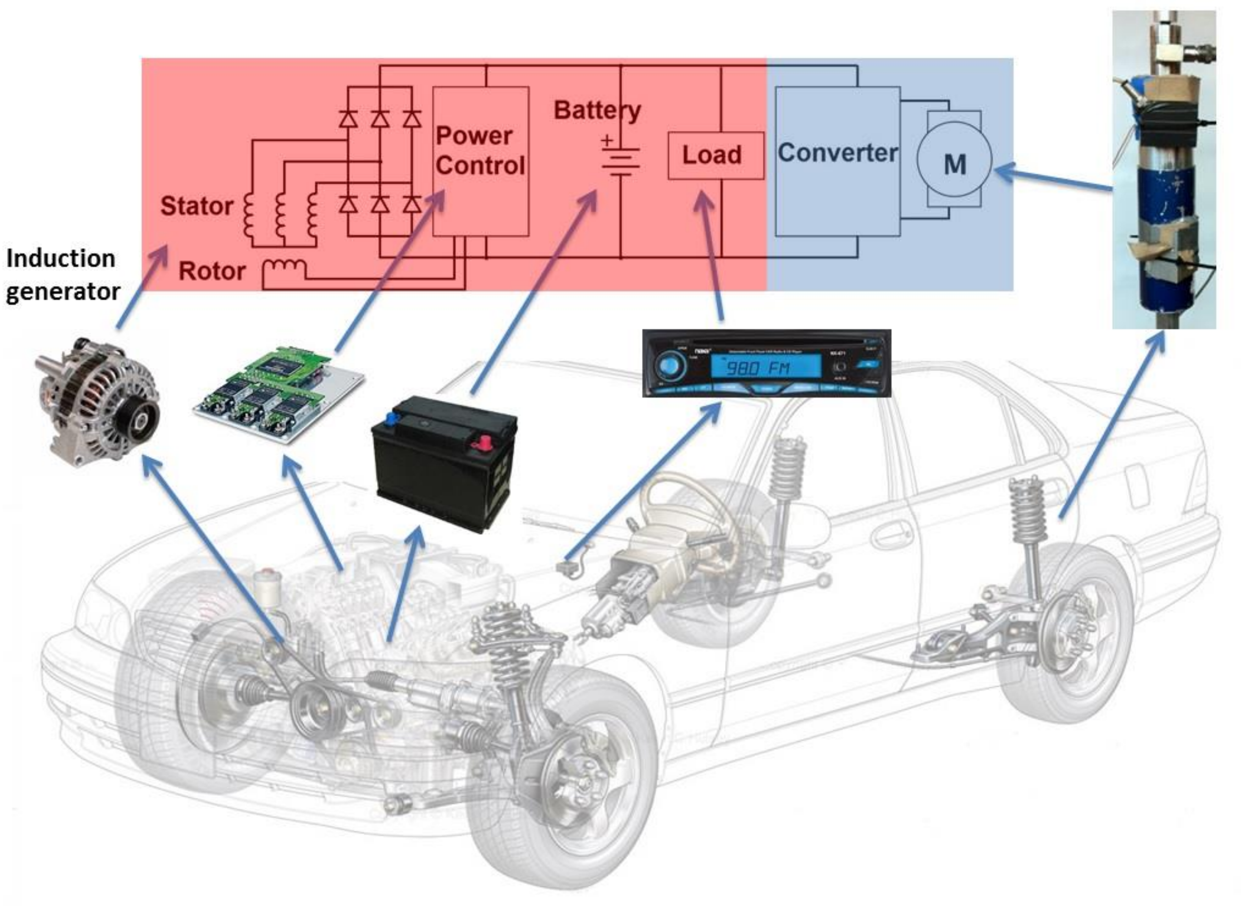


Figure 20 Integration of regenerative shock absorber

The area on the left side with red color resembles existing electric system and the area on the right side with blue color stands for the regenerative shock absorber and its circuits as additional power source. Starting from the alternator, electricity is generated when the engine runs and drives the alternator with some speed. After three-phase full bridge rectifier, the electricity then flows into the alternator (for the case without additional power supply). The magnetizing current flowing through induction coil is controlled according to the output voltage of output coils. In this conventional operating process, fuel is consumed from the engine and transferred into kinetic energy. Then electricity is generated.

With the help from right side, the regenerative shock absorber, free energy can be harvested from random road excitations. After power regulation (such as DC/DC converter), the energy can be used to power electric load. Thus the power comes from the alternator can be reduced. Recalling the equation for mechanical power in rotational systems, we have the equation as:

$$\boldsymbol{T} = \boldsymbol{\tau} \times \boldsymbol{\omega}$$

τ stands for torque and ω resembles angular speed. Compared with conventional cars without the additional power supply, the rotational speed of alternator is the same since in both cases the alternator is driven by the engine via belt. However, as the alternator's power reduces, when the battery's voltage is the same, current flowing out of the alternator reduces. According to motor's theory, the mechanical torque on alternator reduces. This helps in reducing the torque on engine and can lead to fuel saving for the combustion engine.

One example can be given to illustrate the benefit of energy recovery. One single head light of a regular car is around 55W. For the regular alternator with 1.2kW power output, the head light itself consumes 4.58% of the total electric power. However, if additional 30W power is harvested during regular driving by one shock absorber, then only 25W of the head light's power comes from the vehicle alternator, which means a 2.5% reduction out of the total power. With 4 shock absorbers working together, more energy can be saved.

Chapter 5 Experiment Results

5.1 Regenerative shock absorber test

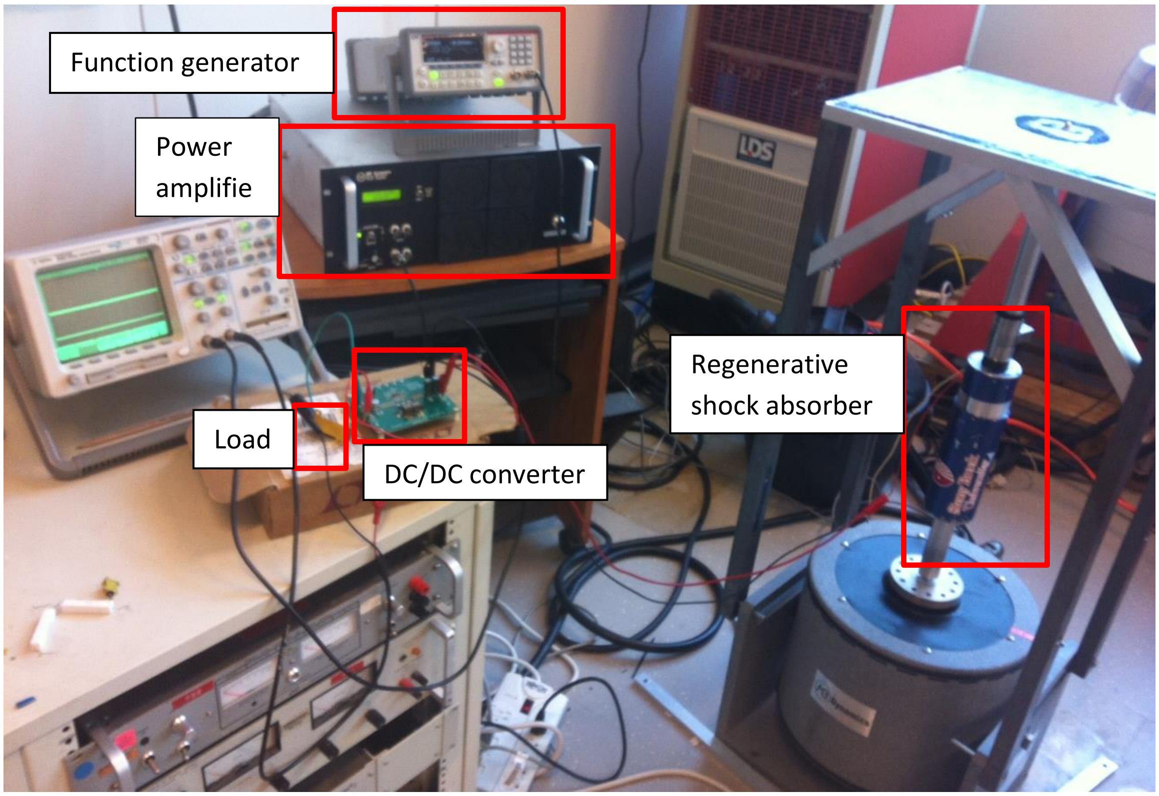


Figure 21 Regenerative shock absorber test setup

The test setup for regenerative shock absorber is shown in Fig. 21. The function generator provides input signal as excitation. Usually signal is sine wave and frequency is set between 0.5 Hz and 10 Hz to simulate the vibrations that car suspension may experience during regular driving. Then the signal goes into a power amplifier, MB Dynamics MB 1000VI. This voltage-controlled power amplifier provides necessary driving power to its attached shaker. The power rating for the amplifier is 1000 W and the shaker is permanent magnetic type, capable to offer 250 lbs. force. As is shown in the figure, the shaker's terminal is attached to the shock absorber through an adaptor on the bottom. The shock absorber is fixed to the top plate of shaker frame via one force sensor and adaptor. One laser displacement sensor is mounted on the top cylinder of regenerative shock absorber to provide information about its movement. As the shaker moves, the shock absorber will produce electricity to its output and by using a DC/DC converter or directly connecting a power resistor we can know the amount of energy generated from it.

The force sensor used in the experiments is Honeywell RM model sensor. The full load of sensor is 2000 lbs. With a 10 V DC supply, the sensor can provide a linearity of 24.224 mV at full load.

Since the voltage provided by force sensor is on mV level with small number, it can be easily affected by external noise. In our test environment with cooling fan for shaker and motor + alternator running, the electromagnetic noise induces severe noise in our detected signals. So a pre-amplifier, or filter with amplifying function, is used in the test.

Shown in the following figure is a Model SR560 low-noise preamplifier. It has two input channels and can achieve high gain or low noise amplification.

Figure 22 Low-noise preamplifier

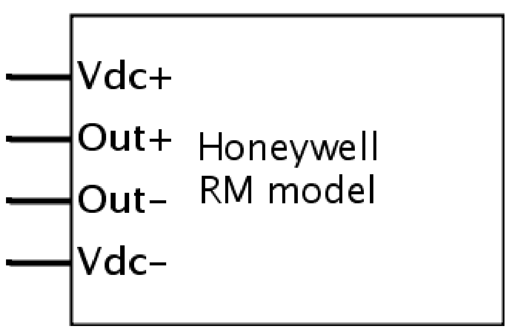


Figure 23 Force sensor pin diagram

In the above figure, it is shown that there are 4 terminals for the force sensor. In order to better eliminate noise, differential input is used for the preamplifier. So the “Out+” of force sensor goes into channel one of preamplifier and “Out-” goes into channel two. This provides better result than using a single channel.

For the cutoff frequencies of preamplifier, a few things shall be noted. Since the system’s vibration frequency is between 0.5 and 10Hz, the bandwidth of preamplifier shall be broader than that. However, there is strong electromagnetic noise in the test room, so 60Hz power supply frequency shall be removed from the signal. Thus a band-pass filter with cutoff frequency of Hz and 30Hz is used and the following figure shows the frequency response of that filter.

Figure 24 Frequency response of preamplifier

From the figure it can be seen that the preamplifier gives steady response for low frequencies from 1 to 10 Hz and the amplitude decreases for higher frequencies. 60Hz’s response is lower than one half of the response in test range. So this setting fits the experiment requirement. After proper filtering and amplifying, the force signal can be read on oscilloscope or data acquisition card.

Figure 25 Laser displacement sensor

The laser displacement sensor used is optoNCDT1401, shown in Fig. 25. It provides voltage output according to different displacement. The working range of the sensor is 50 mm to 150 mm and it would give output voltage between 1 V and 5 V. The relationship is shown in the following equation:

$$\boldsymbol{D = V \times 25 + 25}$$

V is the voltage output of sensor, in Volts. D is the actual distance between the laser source and the reflection surface, in millimeter.

The data acquisition system we used is National Instruments NI USB-6008 8 inputs, 12-bit, 10kS/s multifunction I/O, shown in Fig. 26. It can conveniently display real-time data and store with scaling.

Figure 26 NI USB-6008 data acquisition card

5.2 Vehicle integration test

For the vehicle electric system, the setup is shown as follows.

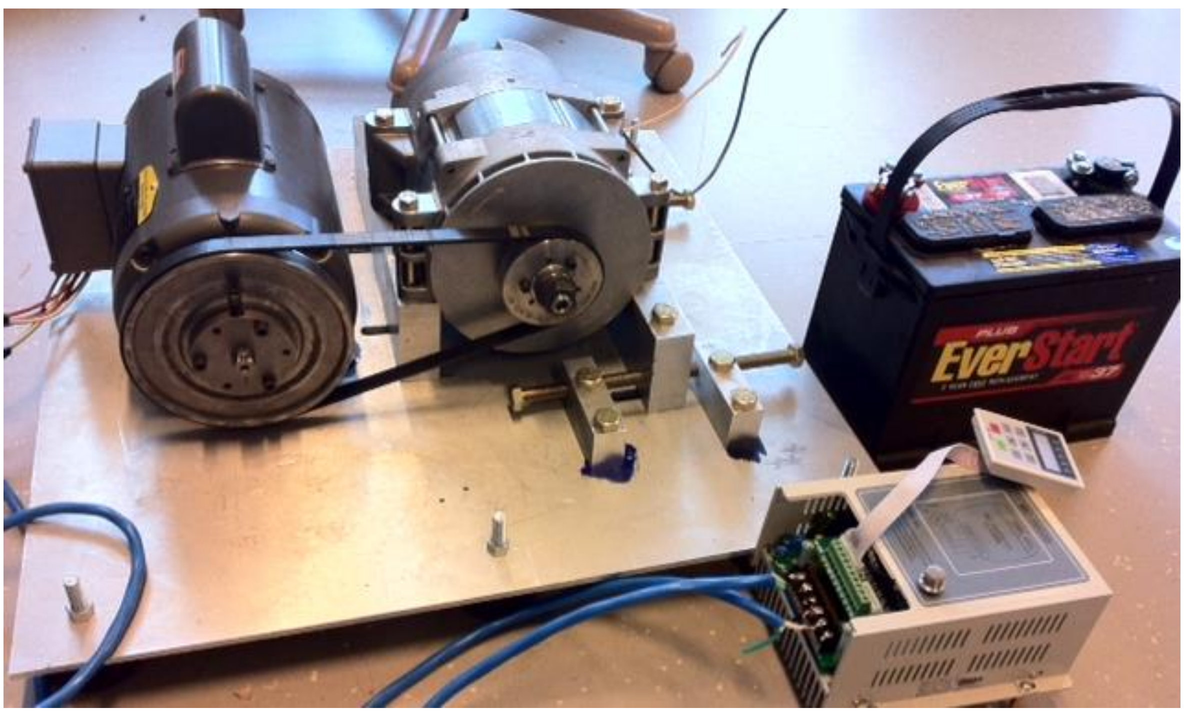


Figure 27 Car electric system assembly

Since it's difficult to monitor the operating condition and fuel consumption of internal combustion engine, and acquiring accurate data is another big challenge, an AC motor is used to mock up the combustion engine. On the left side of Fig. is Baldor L1317 AC motor. It's a 2 horsepower single phase motor with high/low voltage connections. Rated speed is 3450 RPM. Parallel with the motor is a belt driven, Leece Neville 4000 series truck alternator. The alternator works for 12V vehicle system and can provide maximum current of 200 A. With output voltage of 14V, the alternator's maximum power is 2800 W. Looks like the driving motor's power is smaller than that, however, in our experiments the alternator will not run with full power, only light duty electric loads will be given. So the 2HP (1.5kW) motor is capable to drive the alternator together with some electric loads. The output of the alternator connects with an EverStart 56-3N car battery. This helps storing the energy out of alternator and smoothies the output voltage as well. The motor controller we used is a single phase 3.7kW motor driver. It enables frequency and output voltage change according to user's setting. The overall schematic is shown as follows:

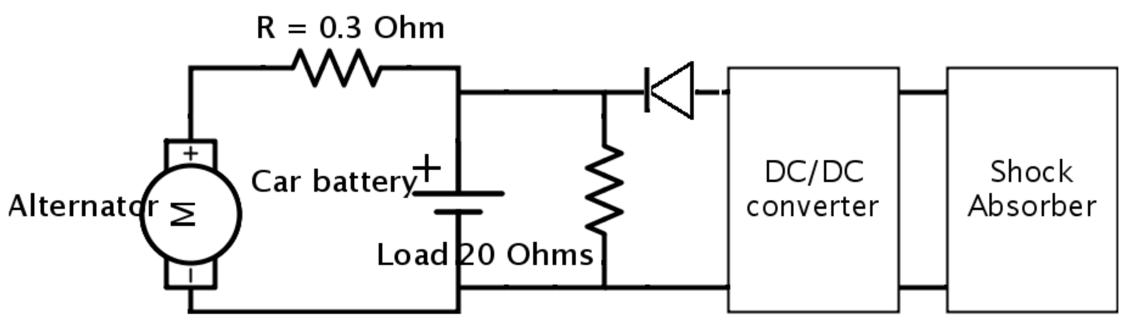


Figure 28 Connection diagram of energy harvesting platform

Since alternator is driven by belt and the electric system is isolated, the AC motor and its driver are not included in this diagram. The alternator provides most power towards the load and car battery. A small resistor with 0.3 Ohms value is used as current sensing resistor. Also it helps to limit the current flowing through the alternator to avoid high mechanical torque which would bring pressure to the motor driver and cause over heating problems. On the other side is the harvested energy. The regenerative shock absorber is driven by a shaker and conveys mechanical power into electrical. After a DC/DC converter, the voltage can be regulated and fit for charging the battery as well as powering electric load. One diode is applied at the output of the converter so that energy flow direction is guaranteed to be from the converter to battery. The electric load we used in the experiment is a 20 Ohms power resistor. The results are shown as follows:

Table 1 Experiment data of shock absorber and alternator powering battery and load

Frequency (Hz)	Alternator power (W)	Alternator power with shock absorber (W)	Shock absorber mechanical power (W)	DC/DC converter power (W)	Battery consumed power increment(W)
1	18.53	18.21	1.48	0.41	0.32
2	18.30	17.96	3.71	0.69	0.35
3	18.26	17.14	7.00	0.96	-0.16
4	18.17	17.06	12.93	1.37	0.26
5	18.17	16.67	12.13	1.65	0.15

"Frequency" means the excitation frequency of the shock absorber. Generally, given the same force and displacement, a higher frequency will produce a higher power output. In our case the force and displacement is not controlled, but mechanical power of shock absorber increases as frequency goes up. "Alternator power" means without exciting the shock absorber, the value of the original output power of car alternator when it's charging the car battery and powering one electric load with 20 Ohms. "Alternator power with shock absorber" in the third column means the power of alternator when both the alternator and the shock absorber are working. "Shock absorber mechanical power" is calculated from the force-displacement loop of shock absorber. Since the power of shock absorber will need to go through the DC/DC converter, the "DC/DC converter power" means the actual amount of power going into the circuit (battery + load). Ideally the reduction in power of alternator should be equal to the power provided by the shock absorber. However, the chemical properties of car battery bring an unstable condition for its electrical properties. So from the table we can see that even the shock absorber provides some electrical power, the alternator's power reduction is not that significant. But this set of data still is the proof of our car integration concept: bringing in the power of regenerative shock absorber will help reduce fuel consumption.

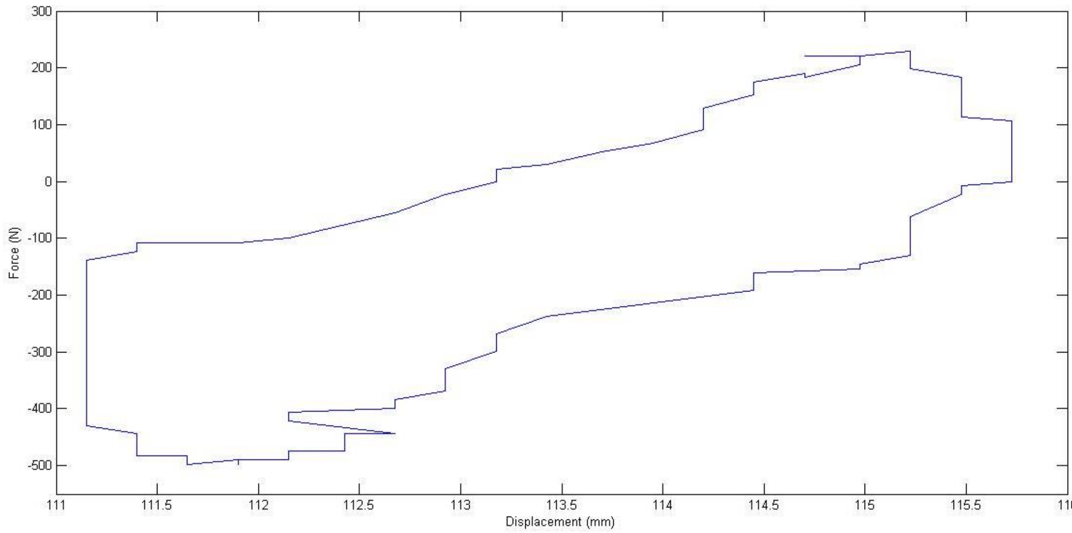


Figure 29 Force-displacement loop of shock absorber under 2 Hz excitation

The above figure shows the force-displacement loop of regenerative shock absorber when it's driven by a shaker and have output connected with DC/DC converter with electric loads. The travel distance and applied force on it is pretty limited, only with about 5mm displacement and 700 N force difference. Under this condition the mechanical power applied to the shock absorber is only 3.71 W. With a more powerful shaker the device can generate much more power. If we also consider the battery's condition to be fully charged during regular driving and thus no battery loss exists in the generated power, the overall system can achieve much higher performance. For example, with 20 W electric power generated from single shock absorber mounted on the suspension (80 W in total for all 4 shock absorber), and 500 W constant power consumption of a driving car, the regenerative shock absorber can help save 16% of electricity and thus by reducing the load of car alternator, even more fuel can be saved.

Chapter 6 Conclusion

This thesis introduces the need for increasing energy efficiency and recovery techniques. Then an innovative design of regenerative shock absorber with mechanical motion rectifier is shown in this paper as a method to help harvest kinetic energy in vehicle suspension system. The design concept is shown together with test results. Due to the intrinsic properties of kinetic energy, interfacing circuits are needed to help regulate power and enable input current control for damping adjustment purpose. Several DC/DC converter topologies are shown with comparison. Verification circuit prototypes are built and tested for measuring component performance. Then with AC motor and truck alternator mocking up the working condition of internal combustion engine and vehicle electric system, a demonstration platform is built to show how regenerative shock absorber can increase the fuel efficiency when integrated into existing vehicle electric systems. The test results clearly show the potential of regenerative shock absorbers to be used as additional power supply for on-car electronic devices for the purpose of reducing fuel consumption. Further improvements can be made towards the testing system, the converter topology and control algorithms. Using semi-active control can help the vehicle to have better dynamics performance while harvesting energy at the same time. By enabling bidirectional energy flow, active-control can be applied towards the suspension to have more intelligent response towards different road conditions.

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