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Research Article

Design and Implementation of a High-Voltage Generator with Output Voltage Control for Vehicle ER Shock-Absorber Applications

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A self-oscillating high-voltage generator is proposed to supply voltage for a suspension system in order to control the damping force of an electrorheological (ER) fluid shock absorber. By controlling the output voltage level of the generator, the damping force in the ER fluid shock absorber can be adjusted immediately. The shock absorber is part of the suspension system. The high-voltage generator drives a power transistor based on self-excited oscillation, which converts dc to ac. A high-frequency transformer with high turns ratio is used to increase the voltage. In addition, the system uses the car battery as dc power supply. By regulating the duty cycle of the main switch in the buck converter, the output voltage of the buck converter can be linearly adjusted so as to obtain a specific high voltage for ER. The driving system is self-excited; that is, no additional external driving circuit is required. Thus, it reduces cost and simplifies system structure. A prototype version of the actual product is studied to measure and evaluate the key waveforms. The feasibility of the proposed system is verified based on experimental results.

1. Introduction

In a vehicle suspension system, the shock system is installed between the carriage and the tires. The shock system mainly consists of springs and a shock absorber. When the car is driven on an uneven road, the springs provide support between the carriage and the tires. The shock absorber reduces the oscillation energy in the springs and prevents the energy produced from vertical oscillation from being transferred to the carriage. This improves stability and comfort during the drive. There are advantages and disadvantages of having a shock absorber with different damping factors. If the damping factor is high, then more protection is offered when controlling the car and turning the car; however, with a lower damping factor, more comfort is provided to the passengers. If the shock absorber is able to continuously adjust the damping force, optimal suspension could be achieved when driving the car.

To improve the stability when driving, major motor companies currently use methods including gas springs controlled by microcomputers, digital control systems, or active oil pressure control system to build controllable suspension systems for different road conditions. The system structure and the control mechanism can be quite complicated. To overcome the disadvantages mentioned above, electrorheological (ER) fluids are used as the working fluid in shock absorbers [1–3]. The intensity of electric field is used to control the behavior of the ER fluid, as well as to adjust the damping factor in the shock absorber [4–7]. This is a simple method. ER fluids are formed of electrically polarizable suspended particles. Suspension fluids can be made by a variety of materials: silicone oil, cooling oil, kerosene, and so forth. Suspended particles can include macromolecule materials such as ion-exchange resin, starch, and microfiber granules. When changes in the external electric field occur, ER fluids can transform between a liquid state and solid

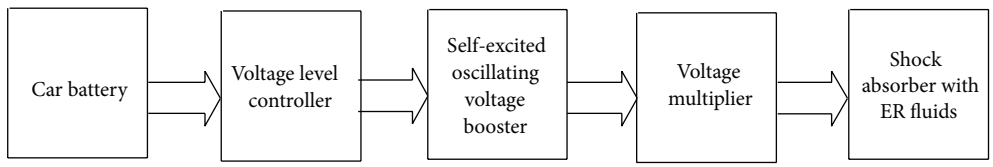


Figure 1: System diagram of the proposed high-voltage generator to supply ER shock absorber.

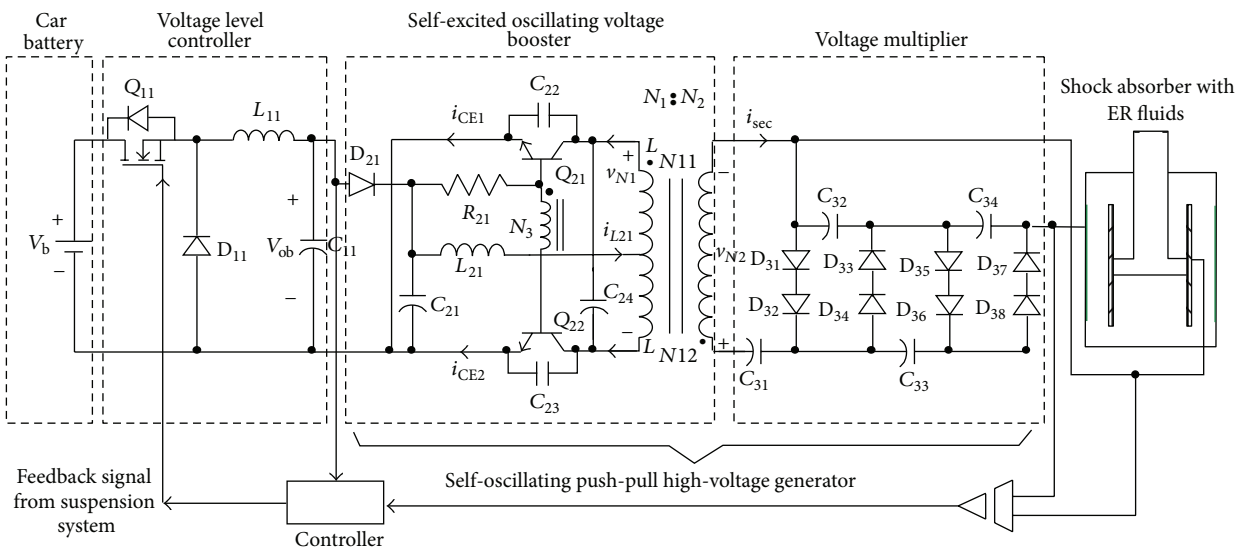


Figure 2: Main power circuit of the proposed high-voltage generator to supply ER shock absorber.

state within a few milliseconds. The transformation process is reversible. ER fluids can be applied in the clutch, hydraulic pump, robotic arms, oscillation damper, and so forth and seem to be a promising trend for future motor applications [8, 9].

Switching-mode power converters are widely used to process electricity energy. For example, buck type is adopted for stepping down input voltage [10–13], while push-pull configuration is suitable for dc/ac applications [14–19]. In our study, we use a self-excited high-voltage generator to create a high-voltage dc electric field to control the physical property of the ER fluids. The input dc power source for the high-voltage generator is from the car battery. As previously stated, no external dc power source is required. In addition, a dc/dc buck convertor is used to adjust the input dc level for the high-voltage generator. This replaces the conventional linear power supply. The proposed shock absorber with the high-voltage generator has the following advantages: low cost, simple structure, linear control, and high efficiency for power transformation.

2. System Structure

The system diagram for the proposed self-excited high-voltage generator for shock absorbers with ER fluids is shown in Figure 1. It mainly includes car battery, voltage level controller, self-excited oscillating voltage booster, voltage multiplier, and shock absorber with ER fluids. The voltage level controller transforms the voltage from the car battery within a controlled output range of 0 to 12 volts. A buck converter is used in our study. The self-excited oscillating voltage booster has a push-pull converter structure. It takes the dc voltage from the buck converter and drives the power transistor using self-excited oscillation. Thus, dc voltage is therefore transformed into ac. A high-frequency transformer is then used to increase the voltage. The voltage multiplier, instead of active-type voltage booster so as to lower cost and volume [20, 21], converts the ac from the high-frequency transformer into dc potential. Then, the output voltage of the voltage multiplier is supplied to the shock absorber. The main power circuit of the proposed high-voltage generator is shown in Figure 2.

3. Operation Principle

As shown in Figure 2, the buck-type voltage level controller reduces the 12 volts from the car battery to a desired voltage level by controlling the duty ratio of the active power switch component, Q_{11}. Using volt-second balance criterion, at steady-state operation, the relationship between the input voltage of the buck convertor, V_b, and the output voltage, v_{ob} (voltage across capacitor C_{11}), can be obtained as

$$d = \frac{v_{ob}}{V_b}, \tag{1}$$

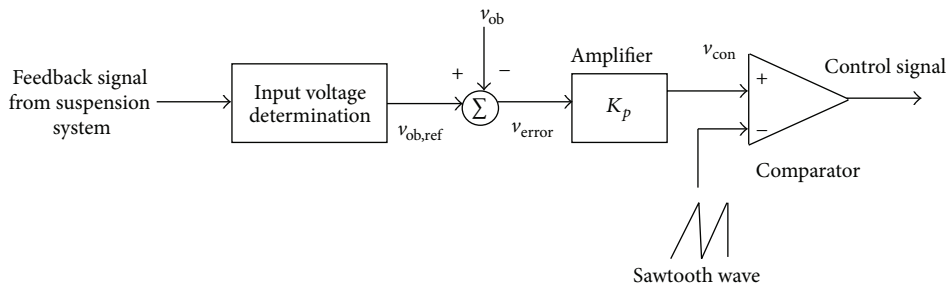


Figure 3: The control block diagram of the voltage level controller.

where d is the switching duty cycle. It is observed from (1) that voltage across C_{11} can be changed by controlling the switching duty cycle. This in turn adjusts the intensity of the electric field of the ER shock absorber. As shown in Figure 3, feedback signals from the suspension system determine the reference input voltage of the self-excited oscillating voltage booster, $v_{ob,ref}$. We then compare the reference voltage with the actual voltage, v_{ob}. After magnifying the errors, we can obtain the controlling signal, v_{con}. This controlling signal, v_{con}, is compared with a sawtooth waveform to determine the controlling signal for the active switch, Q_{11}. If we suppose the peak value of the sawtooth waveform is V_{sp}, then

$$v_{ob} = \frac{V_b}{V_{sp}} v_{con}. \tag{2}$$

Since V_b and V_{sp} are constant, from (2) it can be observed that v_{ob} and v_{con} are proportional to each other. In the voltage level controller, the voltage ripple Δv_{ob} is generated on C_{11} when the active switch is switching. If the voltage ripple is too large, a significant impact on the high-voltage generator will occur. Therefore, the switching frequency, f_s, for the voltage level controller must be much greater than the oscillating frequency, f_o, of the self-excited oscillator. In addition, C_{11} should be greater than $C_{11,\min}$, which is determined by

$$C_{11,\min} = \frac{(1 - d_{\min})}{f_s^2 L_{11}} \left(\frac{v_{ob}}{\Delta v_{ob}} \right)_{\max}. \tag{3}$$

The self-excited high-voltage generator consists of two parts: the self-excited oscillating voltage booster and the voltage multiplier. The self-excited oscillating voltage booster derived from a Royer-type resonant oscillator [22]. With the feature of iron saturation in the transformer, it alternately drives two power transistors and converts dc into ac. Then, with the use of a high turns ratio transformer, the booster steps up the voltage. The voltage multiplier adjusts the secondary output voltage of the transformer into dc voltage and stacks voltage to a high level. The high-level voltage is transmitted through the electric poles to the shock absorber. The time that both Q_{21} and Q_{22} conduct simultaneously is very short and is negligible. Therefore, the self-excited high-voltage generator can be divided into the following two primary working modes.

Mode 1 $[t_1\text{-}t_2]$. Transistor Q_{21} is on and Q_{22} is off. The voltage across Q_{21}, v_{CE}, is zero. Inductors L_{21} and C_{23} are resonant. The voltage of C_{23} is a sinusoid wave. Output voltage from the high-frequency generator is a negative half-wave.

Mode 2 $[t_1\text{–}t_3]$. The high-frequency transformer saturates. Coil N_3 drives transistor Q_{22} but Q_{21} is off. The voltage across Q_{22}, v_{CE2}, is zero. The inductance of the high-frequency transformer resonates with the capacitors, C_{24} and C_{22}. The voltage across C_{22} is a sinusoid wave. The output voltage from the high-frequency generator is a positive half-wave.

According to the operation of the proposed high-voltage generator, the secondary current i_{sec} can be expressed as

$$i_{sec}(t) = K_1 \sin\left(\omega_p t + \varphi\right) + \frac{nC_{31}}{2\left(n^2 C_{31} + C_{23}\right)} i_{L21}, \tag{4}$$

where

$$n = \frac{N_2}{2N_1}, \tag{5}$$

$$\varphi = \tan^{-1} \frac{i_{L21}}{2\left[n v_{C_{23}}(0) - v_{C_{31}}(0)\right]} \cdot \sqrt{\frac{n^2 C_{31} L_{N2}}{C_{23}\left(n^2 C_{31} + C_{23}\right)}}, \tag{6}$$

$$K = \sqrt{\frac{n^2 C_{31}^2 i_{L21}^2}{4\left(n^2 C_{31} + C_{23}\right)^2} + \frac{C_{31} C_{23}\left(n v_{C_{23}}(0) - v_{C_{31}}(0)\right)^2}{L_{N2}\left(n^2 C_{31} + C_{23}\right)}}. \tag{7}$$

In (7), L_{N2} stands for magnetizing inductance looking into the secondary of the high-frequency transformer. Figure 4 shows the corresponding waveforms for both working mode 1 and working mode 2, including the transistor base currents i_{B1} and i_{B2}, the collector-emitter currents i_{CE1} and i_{CE2}, and the collector-emitter voltages v_{CE1} and v_{CE2}.

4. Experimental Result

A prototype is built to assess the feasibility of the proposed structure. The related data and waveforms are measured and evaluated. In order to avoid the skin effect which causes temperature increase in the high-frequency transformer as well as the surrounding components, a multiwire-wound transformer is used to lower the operating temperature and to increase current capacity. In addition, if the turns of the

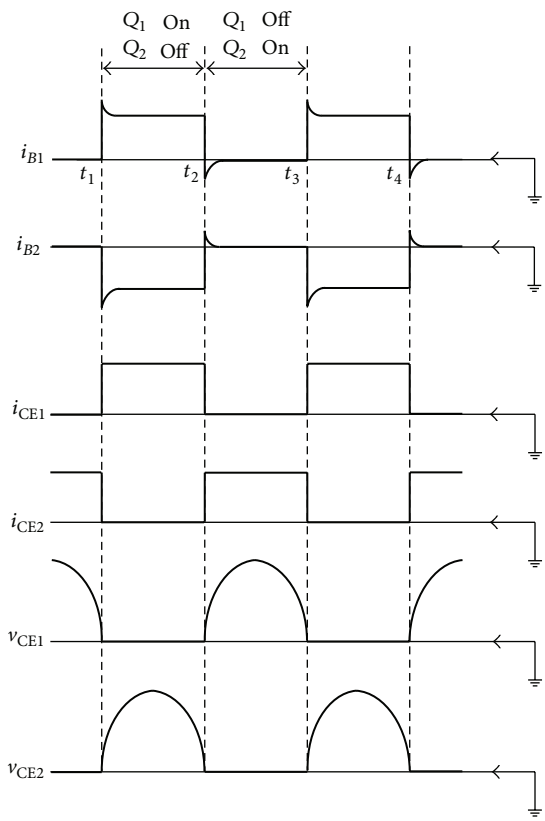


Figure 4: Conceptual key waveforms of the proposed high-voltage generator for ER shock absorber.

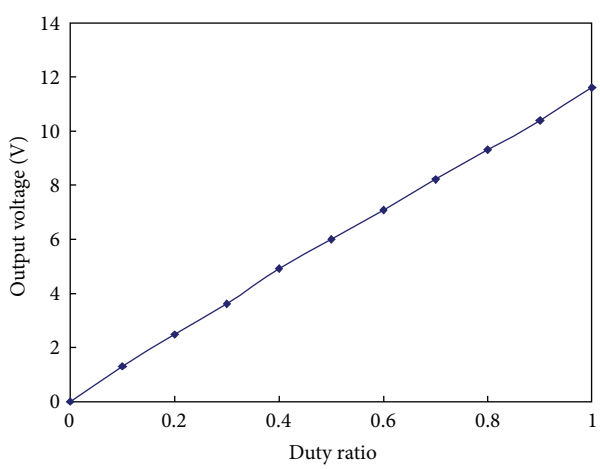


Figure 5: Measured result: relationship between output voltage and duty ratio of the voltage level controller.

transformer winding increase, transformer wire resistance will increase, which increases the temperature of the transformer. This can also be alleviated by using the multiwire-wound transformer.

In order to verify that the output voltage of the voltage level controller can be linearly adjusted by controlling the duty ratio of the active switch Q_{11}, the relationship between the duty and output voltage is measured, which is shown in

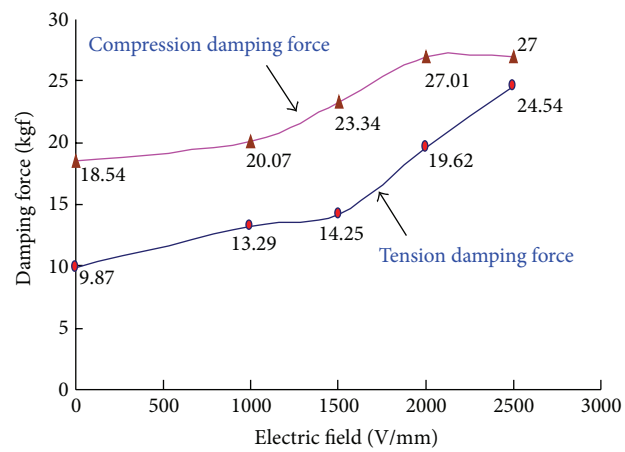
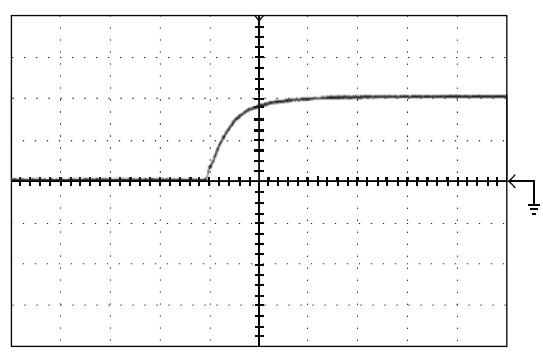


Figure 6: Measured result: relationship between damping force and intensity of electric field.



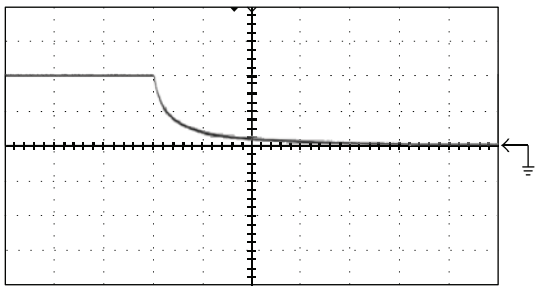
(2 kV/div, time: 1 ms/div)

Figure 7: Measured waveform while output voltage changes from 0 V to 4 kV.

Figure 5. It can be observed that we can linearly adjust the output voltage by changing the duty cycle. In Figure 6 the relationship between the damping force in the shock absorber with ER fluids and the intensity of the electric field is shown. The corresponding desired voltages for the electric poles are between 0 to 4 kV. Figure 7 shows the dynamic response when voltage supplied on the electric poles in the shock absorber was changed from 0 and 4 kV. As changed from 4 kV to 0 V, Figure 8 shows the corresponding response. From Figures 7 and 8, it can be seen that the self-excited high-voltage generator proposed in this study can rapidly step up or down voltage, supplying the suspension system with the desired damping force. Figure 9 shows the relationship between the input voltage and the output voltage of the self-excited high voltage generator. It reveals that the supply voltage on ER shock absorber can be linearly changed by adjusting the input voltage.

5. Conclusion

In tradition, ER-absorber driver is carried out by linear power supply, which has the apparent drawbacks of low efficiency,



(2 kV/div, time: 1 ms/div)

Figure 8: Measured waveform while output voltage changes from 4 kV to 0 V.

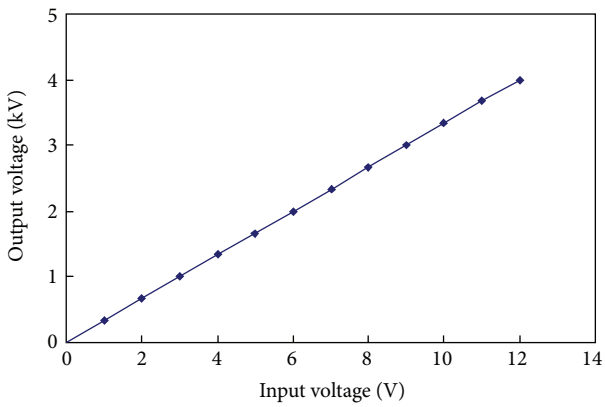


Figure 9: Measured results: relationship between output voltage and input voltage of the voltage booster.

large volume, and heavy weight. In this paper, switching-mode technique is applied to the design for ER driver and a self-excited push-pull-based high-voltage generator is proposed. In the proposed ER driver, a controlled voltage output can be obtained in order to control the damping force in a shock absorber. The high-voltage generator is powered by car battery. That is, no additional dc power supply is required. A buck converter is used to control the input dc level of the voltage booster. With the control of the duty ratio of the buck converter, we can obtain a high output voltage proportional to the duty ratio, which simplifies voltage control mechanism. The proposed system has the main advantages of having simple structure, low cost, easy control, high reliability and rapid response and being a compact product. A hardware prototype is constructed to verify the feasibility of the proposed ER high-voltage driver.

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