A New Electric Brush Cutter

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Abstract: - To integrate power electronic control technology into the most mechanical mechanism of conventional internal combustion engine type has made it possible to design and implement a new electric brush cutter with blade rotation speed control and electronic circuit protection functions. The mechanical power source of tradition mechanical grass cutter is based on a two or four strokes petrol engine. To obtain some very attracting advantages such as low vibration and acoustic noise, free of air pollution and low using cost, a DC motor is used as the mechanical power source of new electric type brush cutter. In addition, a Li-ion battery and electronic control board designed for DC motor speed control and circuit protection purposes were included as well. Designing ideas and the working principle of respective circuit in electronic control board will be explained. The performances of the proposed electric brush cutter were validated through extensive experiments and a laboratory scale implementation.

Key-Words: - Internal combustion engine, Electric brush cutter, DC motor, Li-ion battery

1 Introduction

Traditionally, the internal combustion engine type has been used to drive the mower requiring the human operation. It, however, may suffer from the drawback such as both time and energy consumption. Based on the modern concept, the development of modern system should consider manpower saving and avoid excessive energy consumption. Unfortunately, many systems such as traditional lawn mowers consume more power and result in greenhouse effect. This problem should be resolved by the academia and industry [1],[7-12].

In the past decade years, almost the main mechanical power source of blade of the conventional brush cutter was driven by two or four strokes internal combustion engine. Has larger instantaneous output mechanical power of engine makes that each type of engine is suit for many types of customer tools. Especially, many applications needs larger mechanical power output. The fuel of general internal combustion engine is gasoline and engine oil. As we known, the economic is increasingly development in the world, the total necessary quantity of fuel such as gasoline is certainly increased and the using days of fuel is shortened as well [2-6]. More fuel is used, more air pollution is made. Warm effect become a critical problem in the world, the average temperature in earth is increasing year by year. More and more people realize this series problem [6]. Some real actions should be done right away. To overcome the expensive using cost and the carbon dioxide released problems, there have been concerned by many countries in the recent years. In the manufacturing fields of the brush cutter, several types of new brush cutter were made based on electric power. According to the different application fields, the supplying electric power of brush cutter may be alternating current or direct current source and stand alone or not etc. [4].

This paper aims at developing a new electric brush cutter associated with high performances such as low noise and vibration, easy move and start, less malfunction and compact. The mechanical power of the internal combustion engine in conventional brush cutter is replaced by a DC brush motor (abbreviated as DC motor) here. To use electric power as the supply source of the brush cutter, therefore, it is almost free of carbon released and low electric energy is dissipated in normal operation process. No air and environmental pollution problem like internal combustion engine used will be happened again. The needed electric energy of this new electric brush cutter is mainly supplied with a rechargeable lion battery. Through the measuring estimation, the charging cost of battery per using time is generally lower than that needed by the internal combustion engine type. Several superior functions are included in the new electric brush cutter which never be found in conventional engine type, for example, high-speed and power-saving mode selection, status display, clockwise and counter-clockwise control, continuous speed setting control, the over-current and over-temperature detection of motor and proper protection abilities. Most of above-mentioned function should be not found or implemented in the conventional internal combustion engine brush cutter. For convenient carrying out experiments, a prototype of the electric brush cutter has been completed in our laboratory. The feasibility and overall performances of the developed electric brush cutter are validated through experiments.

The basic arrangement of this paper was divided into six sections. Section 2 develops the mathematical model of the proposed electric brush cutter, including the control modules, microcontroller, voltage regulator, sensory circuits and status display. Section 3 compares the mechanical structure features between internal combustion engine and electric type brush cutter. More descriptions concerning proposed electric brush cutter will be explored. In the section 4, the designing functional structure of electronic control board, detailed circuit design and its working principle of each sub-circuit in electronic control board will be examined. Section 5 presents the experimental results and their discussions. The conclusions are given in section 6.

2 Mathematical Model

For a permanent-magnet brush DC motor, the flux intensity generated in stator is a constant value. The blade or motor speed of the proposed electric brush cutter can only be controlled by changing the value of its applied average armature voltage. If the safe operation of electric brush cutter is always required; the blade speed must be often controlled under the rated motor speed in itself. The larger applied average armature voltage there is, the quicker the blade rotation speed will be. As depicted in Fig. 1, the electric magnetic torque is generated by motor should be kept constant value through controlling the current value flowing into the armature of motor at a constant value. The transient response of the electric brush cutter can be described by electrical and mechanical parts, respectively [7],[8-15]. Fig. 2 is a typical equivalent electrical circuit of a motor and included mechanical load. The mathematical model of the electric brush board can be established by using this figure.

2.1 Electrical model

In order to dynamically change the motor speed, the motor will be triggered by PWM signals by switching the power switch on or off. The dynamic electrical response of the electric brush cutter can be described by using the Kirchihoff's voltage law (KVL) and written as follows:

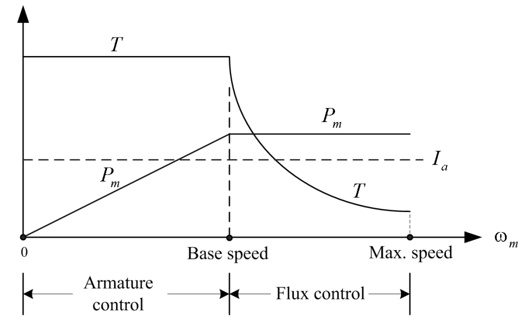


Fig. 1. Armature-voltage and field-flux control under rated torque and power.

$$U = R_a i_a + L_a \frac{di_M}{dt} + K\omega_m \tag{1}$$

where the meaning of those symbols shown in Equ. (1) are explained in the following:

U : the applied armature voltage of motor;

R_a : the armature's resistance of motor;

L_a : the armature's inductance of motor;

i_M : the motor current;

K : the emf constant of motor;

ω_m : the speed of the blade.

2.2 Mechanical model

In theory, the mechanical transient response described by employing the Newton's second law is given as follows:

$$J\frac{d\omega_m}{dt} = T - T_M - B\omega_m \tag{2}$$

where the torque T_M is torque applied to the load, which depends upon the blade type and lawn status. The generated electrical torque T is related with the current flowing into motor and can be given as:

$$T = Ki_a \tag{3}$$

Equation (3) can be substituted into Equ. (2) and then the result is given as follows:

$$J\frac{d\omega_m}{dt} = Ki_a - T_M - B\omega_m \tag{4}$$

The parameters B and J are called as the equivalent viscous coefficient and inertia moment of the brush cutter. The mechanical time constant of the DC motor can be written by the following formula:

$$\tau_m = \frac{J}{B} \qquad (5)$$

Generally speaking, the mechanical time constant is much larger than the electrical time constant. This is the reason why the speed or the applied voltage of the motor can be changed by a high frequency switching signal (PWM) through power switch.

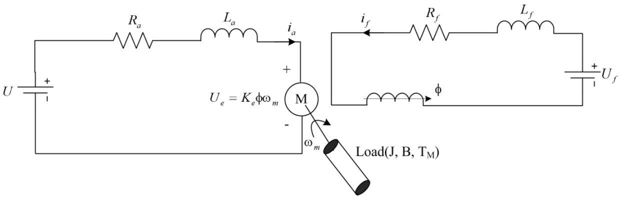


Fig. 2. Separately excited DC motor or permanent-magnet type DC motor (if the value of flux intensity ϕ is constant).

2.3 Power distribution of input power

In case of the input power of electric brush cutter is P_{in}, part of this power will be dissipated in each of electric circuit and mechanical mechanism by different loss forms. The remaining power is then used to output or drive the blade to work. For brevity, the relation of the input electric power and other loss powers can be expressed as follows (refer to Fig. 4):

$$P_{in} = P_o + P_1 + P_2 + P_3 + P_{out} \qquad (6)$$

where,

P_o: the power loss occurred in permanent-magnet DC motor (between point A and B);

P_1: the power loss occurred in between DC motor and coupling mechanism (between point B and C);

P_2: the equivalent power loss occurred in the mechanical transmission shaft tube(between point C and D);

P_3: the equivalent power loss occurred between two sides of gear box(between point D and E);

P_{out}: the power used as for working the brush-cutter blade (after point E);

According to equation (6), if the operating efficiency is hope to be improved, the power loss occurred in transmission process should be reduced as possible as.

3 Description of Electric Brush Cutter

Fig. 3 shows a typical structure of an internal two strokes engine brush cutter. The blade of the brush cutter is driven by a two strokes engine. The output mechanical power of engine is transmitted to the final terminal or blade through a coupling mechanism, shaft tube and gear box. In order to dynamic change the operating speed of engine, some mechanical control switches such as throttle trigger lockout engine stopping device, acceleration and deceleration operations and so on are arranged on a bike handle. In general, there is a suspender carried by operator shoulder will be combined with the brush cutter by using a hook. The blade (nylon rope or multi-tooth metal plate) is driven by the petrol engine through some mechanical devices such as coupling mechanism, shaft tube and gear box.

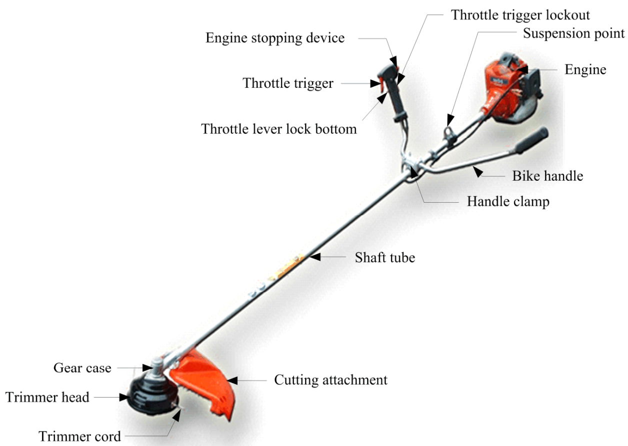


Fig. 3. Typical appearance of two stokes engine type brush cutter.

Fig. 4 shows the sketch of the proposed electric type brush cutter. Most of the mechanical mechanism is used in engine type of brush cutter is still be applied to the electric type brush cutter. But the mechanical power source is replaced with a motor. In order to have an independent operating ability, a rechargeable battery is employed as the independent electric power source of motor and other electronic circuits. The operation speed of blade is controlled by an electronic control board. To improve the operating safety, convenience and reliability of system, circuits with protection and display function are included in the electronic control board too. Note that the later two items are not sketched in the Fig. 3, but can be found in Fig. 4.

Every module cooperates each other and executes a grass cutting task [12],[16-20].

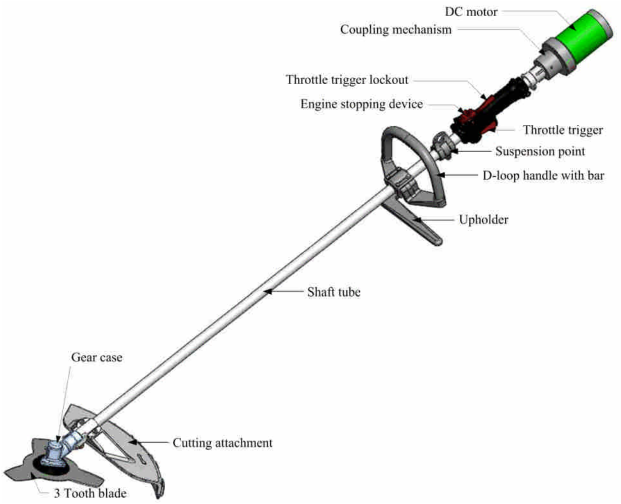


Fig. 4. Sketches the appearance of the proposed electric brush cutter.

3.1 DC motor

As mentioned earlier, the blade of the petrol engine type brush cutter is generally driven by an internal combustion two or four strokes engine. It is replaced by a permanent-magnet DC motor in electric brush cutter. Taken the manufacturing cost and compact size into consideration, a permanent-magnet and brush type DC motor is adopted. The magnetic intensity of the permanent-magnet DC motor is constant. So that, the rotation speed of the driven DC motor or the blade of the brush cutter should be controlled by the generated magnetic field intensity in the rotor or armature of the DC motor. Generally speaking, the complexity of the speed controller for the permanent-magnet DC motor is generally easier than the other types of motor and it is cheap. So that it is adopted as the driven motor of the electric type brush cutter.

3.2 Rechargeable battery

Because the proposed electric brush cutter is to have independent operation ability, Li-ion rechargeable battery has some superior features such as high volume energy rate, allowable cyclic charging times and energy density; it is very suit for electric type brush cutter used as its power source. The mechanical size is compact and the total weight is light as well. Especially, the repeat charging times is over one thousands times in theory, therefore, the using cost is cheaper than other types of rechargeable battery. The discharging rate is allowed to be over its rated current. Here, a Li-Ion rechargeable battery with capacity, 4.3 Ah, is used as the power source of the proposed electric brush cutter under the default using total time and operating rated current.

3.3 Electronic Control Module

In addition to the DC motor and rechargeable battery, the other one important device is the electronic control board. As shown in Fig. 5, it indicates that the structure of an electronic control board can be partitioned into some important portions, such as voltage regulator, sensory circuit, internal power supply, status display, speed selection, operation mode selection, and PWM (pulse width modulation) signal generator and driver and so on. The remainder of this section describes the operation of the electronic control module. The detailed circuits of electronic control board will be discussed and described in the next section.

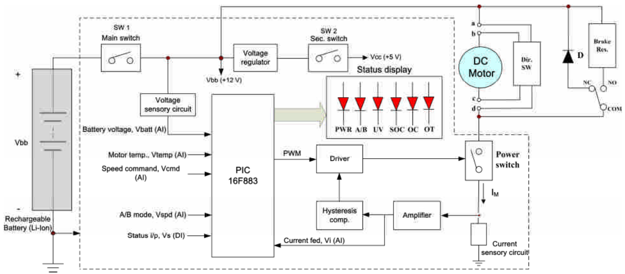


Fig. 5. Sketches the functional block configuration.

Fig. 5 indicates that the electronic control board is developed based on a single chip, PIC 16F883. The applied average voltage of the DC motor is controlled through a voltage buck converter which includes rechargeable battery, main switch, DC motor, power MOSFET, and a current sensor or low resistor. The output voltage of rechargeable battery is dynamically sampled by single chip. There are two purposes are taken into consideration. The first purpose is used to detect the remaining power capacity of battery; the second purpose is used to judge whether occurs under-voltage condition or not. Furthermore, a resistor with very low resistance, 10 $m\Omega$ is employed to detect the current flowing to the DC motor and feedback to single chip for judging if the over-current condition occurs.

4 Controller Design and Operating Principle

If the brush cutter would be confirmed work with high-quality, the different rotation speed and torque will respond to different blades. As the change of radius and dense degree of the grass, the required rotation speed of brush-cutter blade would be different too. The final output speed of blade is decided by operator's experience. In addition to the speed of blade should be changed dynamically, the protection of circuits or components and operating status display are also included in the electronic control board. Take the manufacturing cost into consideration, more complicate control approaches are not adopted here [13-16].

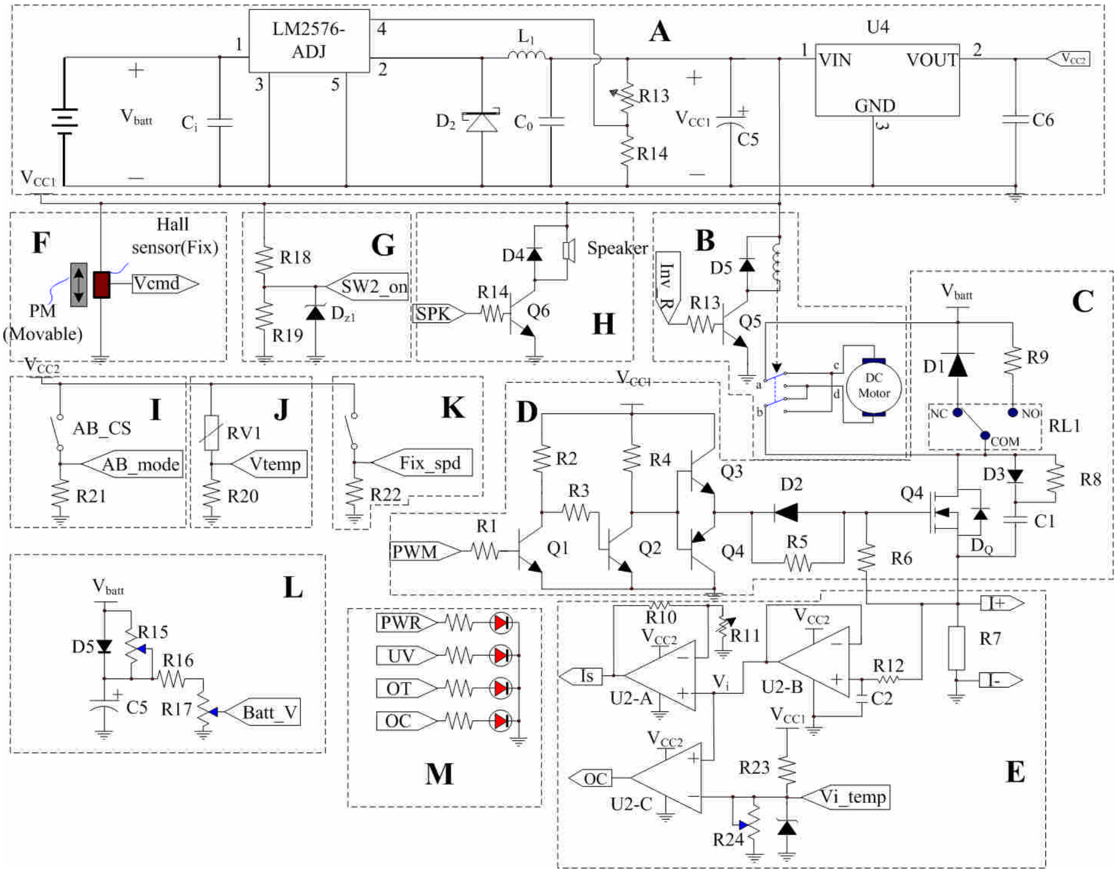


Fig. 6. Diagrams the complete electronic control board.

As mentioned above, the mechanical power driving source of the proposed brush cutter is a DC motor. The speed expression of the DC motor can be given as:

$$n = \frac{u - I_a R_a}{K_E \phi} \tag{6}$$

where, n represents the rotation speed ; ϕ is the magnetic flux generated by the permanent magnet which is install on the stator of DC motor. From the representation of the equati0n (6), the rotation speed of the DC motor can be directly controlled by means of changing the value of the externally applied average voltage. In order to achieve this purpose when the full voltage is supplied by the Li-ion battery, buck converter and pulse width modulation technology are used. By changing the working duty cycle of converter, the output average voltage of converter is then changed and given as

$$u = \delta V_{batt} \tag{7}$$

V_{batt} represents the output voltage value of the rechargeable battery. δ is the working duty cycle of buck converter.

The control kernel of the electronic control board is developed based on a single chip, named as PIC16F883. It is not included in the Fig. 6. Fig. 6 shows the detailed peripheral circuits included in the electronic control board. In addition to the hardware circuits, another important part is the firmware which is designed and programming inside the single chip. In the following, the designing ideas and operating principle will be introduced and described for each sub circuits included in the electronic board.

(1) Voltage regulator

The electric power of the new brush cuter is supplied with a rechargeable Li-ion battery. Its rated supplying voltage is 36 V and capacity is 4.3 Ah.

Although the rated voltage of Li-ion battery is 36 V, the voltage value after even charged is often over than the rated voltage value of itself. It is often even over 40 V. To copy with the necessities of dynamically changing the supplying voltage value of battery, the real applied average voltage or the rotation speed of DC motor is obtained by controlling the duty cycle of buck converter designed in electronic control board. In addition, two DC power source such as +12 V and +5 V are designed to supply with the control and protection circuits on the electronic control board.

As shown in part A of Fig. 6, the output voltage of battery is connected to the input of a voltage regulator IC, LM2576. The output voltage value of the LM2576 can be regulated by user. There is a noticeable requirement is the input voltage must be controlled within allowable voltage value. Due to peripheral circuits is very simple and inexpensive. Furthermore, another low DC voltage source +5 V is regulated directly from the +12 V by using a linear regulation integrated circuit LM7805. Because the DC power source +12 V is obtained from the output voltage of battery by means of switching approach, the power loss is much lower than that of a linear method used, although the larger voltage difference between output and input of regulator exists.

(2) Rotation direction control

At present, the used type of DC motor belongs to a separately DC motor. If the rotor rotation direction of DC motor is required to change, it is only necessary to change the armature applied voltage polarity of the DC motor. As can be seen in part B of Fig. 6, two electromagnetic DC relays are used to achieve this purpose. It is worthy of paying more attention to change the contacts of relay for changing the rotor rotation direction should be completed before applying voltage to the DC motor. Otherwise, those contacts of relay would be possibly destroyed due to the high temperature arc. At least, the using life of relay contacts is then shortened.

(3) Braking circuit

In order to improve or strengthen the operating safety, it is necessary to design a braking circuit which is embedded in electronic control board for quickly stopping the rotor rotation of DC motor. Basically, the DC motor itself is a typical feedback system. The polarity of induced voltage across the armature of DC motor is same as that of externally applied voltage (that is battery voltage). If the rotation speed of DC motor reduces gradually, the induced voltage ($nK_E\phi$) would be down as well. Finally, DC motor stops due to no any rotation kinetic energy. As diagrammed in part C of Fig. 6, the armature of DC motor is switched from a wheel diode to a resistor with low resistance by using an electromagnetic DC relay RL1 when the applied battery voltage source is broken. The remaining rotation kinetic energy of DC motor would be dissipated or transmitted into heat form at the low-resistance resistor. The needed braking time for stopping the DC-motor rotor is effectively shortened.

(4) Driving circuit

In the buck converter, the power MOSFET is belong to a voltage-controlled device. The MOSFET will be turned on or off is decided by the applied gate driving voltage value is +12 V or 0 V. The working power voltage source of most of circuits designed on electronic control board is +5 V. There is a less power loss will be dissipated on the power MOSFET if their gate trigger voltage is high as possible as in theory. Only the applied voltage must be lower than allowable rated voltage value of the used power MOSFET. As shown in part D of Fig. 6, not only the gate turn-on voltage is +12 V, but also is the push-pull driving circuit of power MOSFET used to promote the driving ability.

(5) Current sensor and amplifier circuit

Part E of Fig. 6 shows a resistor with low resistance R7 ($10\,\mathrm{m}\Omega$) in series of the armature of DC motor is set as a current sensor for dynamically sensing the motor current. To avoid effecting on the action of DC motor, the resistance of current sensor should be designed very low. The default rated working current of DC motor only has 10 A. Normally, the voltage-drop value across the current sensor is very small as well. Before this voltage is read by single chip, it should first be amplified by circuit. In order to reduce the load effect, the voltage drop across the current sensor or resistor R7 is amplified by a voltage follower. And the current signal is further amplified by a voltage amplifier which is composed of a U2-B and some other passive components. Here, U2-C and neighbouring some passive devices are formed as a voltage comparator. The output of U2-C, OC, will be changed from low voltage level to high voltage level when the sensed motor’s current is over the default current value. The OC signal is used to break the power MOSFET by hardware. In addition, this amplified current signal is an analogy signal. This signal is read by single chip dynamically. According to this dynamic current value, the working duty cycle of buck converter or the applied average voltage of DC motor will be real-time commanded to adjust by single chip.

(6) Speed command

To copy with the users' custom, the operating methods of electric type brush cutter will be designed the same as those of applied in internal combustion engine type brush cutter. Although the appearance and operating method is designed as similar as, the driving feature is much different from the engine type brush cutter. Part F of Fig. 6 diagrams acceleration and deceleration mechanism is composed of a hall sensor and a permanent-magnet. The hall sensor is fixed inside the acceleration and deceleration mechanism. The permanent-magnet can be moved by following a linear line. The induced voltage value across the hall sensor is proportion to the displacement of the permanent-magnet. The output induced voltage value across the hall sensor will be real-time read by single chip. When the single chip reads the induced voltage of hall sensor and realizes the equivalent meaning, it commands to change the rotation speed of DC motor later.

(7) Secondary power switch

In addition to the main or primary power switch, there is a secondary power is set. The designing purpose is the user of electric brush cutter who sometimes hopes to stop temporally. As can be seen in part G of Fig. 6, the resistors R18 and R19 are formed as a voltage divider. The output voltage of resistor R19 is copy with the digital level. Single chip only needs to read the voltage level across the resistor R19. The dynamic status of electric brush cutter is obtained by single chip.

(8) Speaker

A speaker shown in Fig. 6 will alarm when malfunction condition occurred. In order for the operator or equipment is avoided to be harmed or destroyed. For example, any malfunctions like under-voltage, over-current or waiting time too long and so on occurs, the speaker will be commanded by single chip begins to alarm for warning the operator. Generally, the operator should be required to stop working right away and check the reasons why malfunction occurs.

(9) A/B mode selection

To satisfy with different user's operating custom and the different grass condition when works with electric brush cutter, the different rotation speed of blade is required. In addition, power-saving purpose is another important controlling purpose generally for using electric brush cutter to execute the grass cutting work. Part I of Fig. 6 indicates a toggle switch AB_CS is designed for setting the working mode of electric brush cutter. By means of reading the setting of AB_CS switch, the anticipated operating mode is obtained by single chip.

(10) Temperature detection of DC motor

Most of generated heat of rotor or armature of DC motor will be dissipated through the air gap between the rotor and stator. The heat dissipated efficiency is worse than that of the armature designed in the stator such as blushless DC motor. In order to protect the DC motor from destroyed due to over-heating occurred, there is a temperature sensor, RV1, is installed on the motor surface to detect the temperature of DC motor whether the over-heating condition occurs or not. In case of the overheating condition of DC motor occurred, however, the system would be commanded to be stopped right now for protecting the circuit and device from being destroyed. Part J of Fig. 6 shows a temperature sensing device which the equivalent resistance value across two terminals of device is dependent upon the surface temperature of DC motor. In general, the sensed resistance is inverse proportional of the detecting surface temperature of DC motor. It is an analogous signal of detected equivalent temperature. More detected signal voltage Vtemp, less the surface temperature of DC motor is. The single chip reads the temperature voltage by using an analogous input pin.

(11) Fix-speed setting function

Taken the user can easily custom the operation and power saving into consideration, there is a fix-speed setting switch is designed on the acceleration and deceleration mechanical mechanism. When the radius of grass is thinner, low rotation speed of blade is necessary. Of course, the supplying power of battery can be effectively reduced due to low power is necessary for complete the grass cutting work. As shown in part K of Fig. 6, a fix-speed is set according to the grass condition. Later, the operator continues the grass cutting work by employing a fixed rotation speed of blade.

(12) Sensory circuit of battery voltage

Part L of Fig. 6 includes a voltage sampling circuit of rechargeable battery. Rechargeable battery is in series with DC motor and power MOSFET. These devices are formed as a close loop circuit or named as buck converter. When the power

MOSFET is turned on, the DC motor is applied DC voltage. Because of the inrush current of DC motor, the terminal voltage value will down momentarily. This larger voltage drop phenomenon across the battery is temporal. In case of the DC motor enters into a stable operation, the current value flowing into the armature of DC motor almost becomes a constant value. In general, the stable current of DC motor during normal operation process is always lower than that of inrush current during starting process. In order to avoid reading an error status related to the battery, the single chip embedded on the electronic control board of controller, as shown in Fig. 6, will not read the voltage value across the battery during the starting process until to stable operation process. Fig. 6 indicates that battery will charge the capacitor C5 in case of its voltage across the battery is larger than the voltage drop value across C5. On the contrarily, the voltage across C5 will discharge by way of a resistor R15 with bigger resistance. Due to a discharging time constant, the discharging speed of the voltage across C5 is very slow. Therefore, the effect of voltage momentarily down upon the reading and judging results of single chip within DC motor starting process is controlled as possible as.

(13) Status displaying circuit

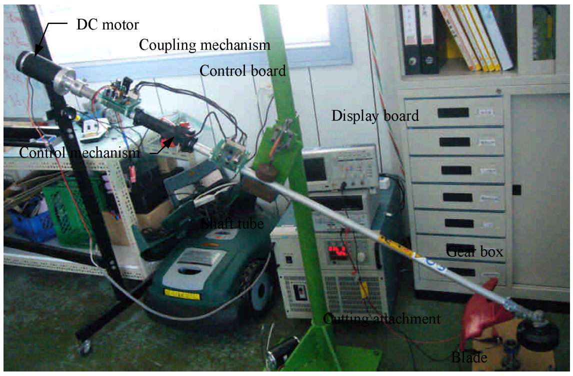
When the operator is operating electric brush cutter, the controller should provide the similar functions like conventional internal combustion engine brush cutter. For example, on the point of view of the operator, he or she can change the rotation speed of blade of electric brush cutter dynamically. However, the basic characteristic of the electric brush cutter is still different from the petrol engine type one. In order to provide enough operating information concerning the dynamical operation of electric brush cutter with operator, the controller or the electronic control board will inform any operating message of operator by using LED indicators and speaker, as shown in part M of Fig. 6.

5 Experimental Results and Discussions

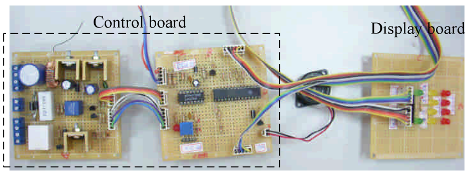
In order to validate the feasibility and reliability of proposed electric brush cutter, a prototype of electric brush cutter has been done in our laboratory. A rechargeable battery Li-ion with rated voltage 36 V, rated current 15 A is used as the power source of electric brush cutter. One permanent-magnet DC motor with 350 W is used as the mechanical power source takes place of the original two or four strokes internal combustion engine. Because of light weight, high discharging coefficient, more cyclic using times, better temperature characteristic and high energy density, Li-ion battery is used as an independent DC electric power source of circuit here.。

5.1 Implementation of prototype

Generally speaking, the price of Li-ion is more expensive than the other types of rechargeable battery. The total manufacturing cost of the electric brush cutter is then increased. However, the cyclic charging and discharging times of Li-ion is superior to other types of rechargeable battery within its allowable using life. Therefore, the using cost when the Li-ion used is much lower than that of conventional two or four strokes engine type brush cutter. In other words, the original increasing cost for buying the expensive electric brush cutter can feedback very soon. Fig. 7(a) and (b) show the prototype pictures of electric brush cutter and the electronic control board, respectively.



(a)



(b)

Fig. 7. Completed prototype pictures (a) electric brush cutter (b) electronic control board.

5.2 Operation process of single-chip software

Fig. 8 shows the operation process of the single chip designed in the electronic control board. The left side of Fig. 8 is the initial self function testing process of the electric brush cutter. In case of the output voltage of the rechargeable battery is applied to the electronic control board, the speaker first is alarmed three times, and then "PWR" indicator lighted. The program will continue to detect the secondary switch whether is turn off or not within three minutes. If the secondary switch is still not turned on during three minutes, the single chip embedded on electronic control board automatically enters into sleep mode for power-saving consideration and waiting for renew operation. On the contrarily, the single chip reads all the settings of operator. The electric brush cutter begins to work by soft starting action. During all working process, the single chip will dynamically read the battery voltage and the motor current. By means of sampled data, the single chip will give new PWM signal with different duty cycle. The electric brush cutter will always attempt to keep a special operation condition with constant motor current or torque. In order for safe operation purpose, the single chip will always detect the temperature of motor surface, the output voltage of battery and the value of flowing into the DC motor. Once abnormal condition generates, the system will be stopped immediately and begins to alarm with a speaker and some LED indicators.

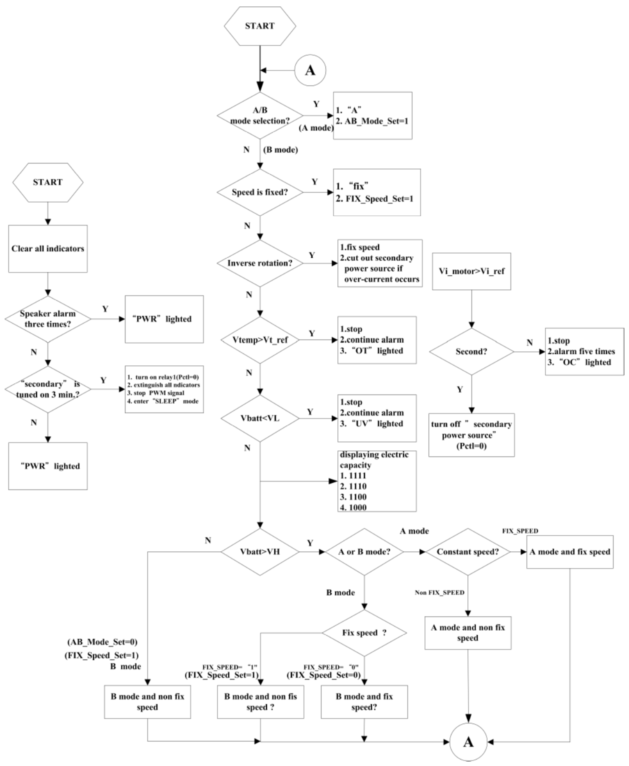


Fig. 8. Operation process of the single chip.

The controller will judge the remaining electric capacity of battery according to the output voltage across the battery. To satisfy with different operator of electric brush cutter, the electric brush cutter can be operated to be run by means of fix or variable blade speed. The operation mode is decided by the output voltage value of battery is then possibly operated at high-speed or power-saving mode.

5.2 Measurement of a DC motor

The basic working performance of the DC motor is tested first before it is combined with other devices. If the DC motor is applied to a different voltage values, in theory, there is a corresponding output current flowing into DC motor and rotation speed of motor's rotor will be changed and recorded case by case. Finally, the recorded currents and rotation speeds responding to the applied voltages are diagrammed by those curves, as shown in Fig. 9. Fig. 9 depicts the change of current value is almost proportional to the change of the externally applied average voltage value of the DC motor. Meanwhile, the rotation speed of DC motor is also increased as well. To observe the Fig. 9, assumed that the DC motor is applied to a special voltage +24 V and the current flowing into the armature of DC motor is 15 A, the output stable rotation speed of is about 5500 rpm. Apparently, the real time rotation speed of motor is not satisfied with the required working conditions of load. In other words, the required rated load current is too high to be used. The phenomenon of the experimental results represents that the working efficiency of the tested motor is worse under the required working conditions. Normally, high temperature would be occurred to the DC motor due to the high power loss dissipated in DC motor.

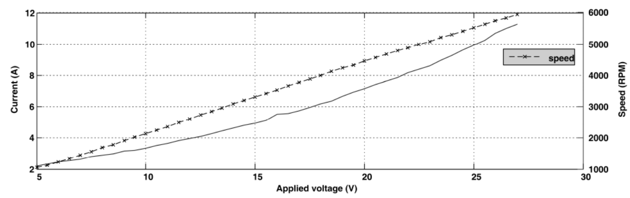
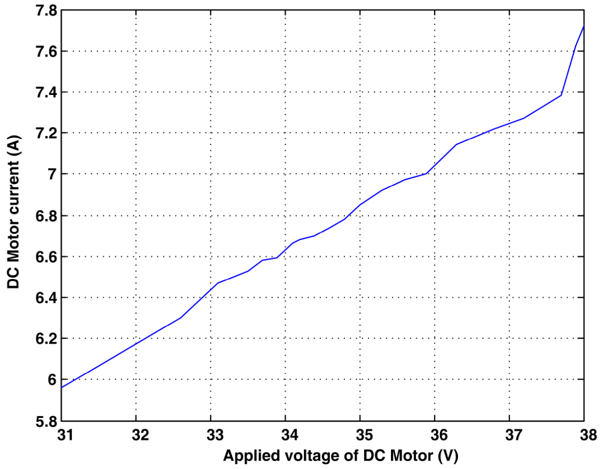


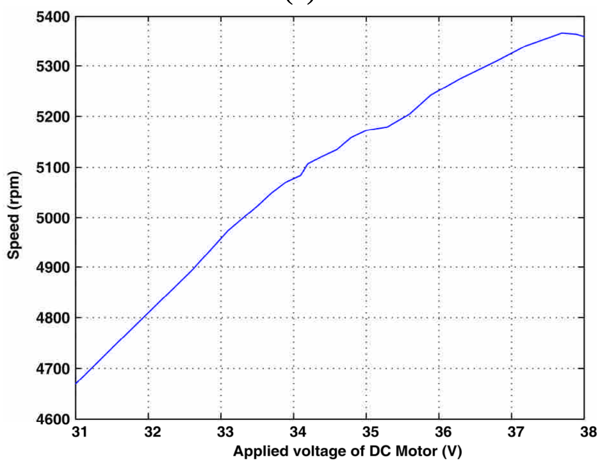
Fig. 9. Tests the electric characteristic curves of a single DC motor.

5.4 Performance tests of the prototype

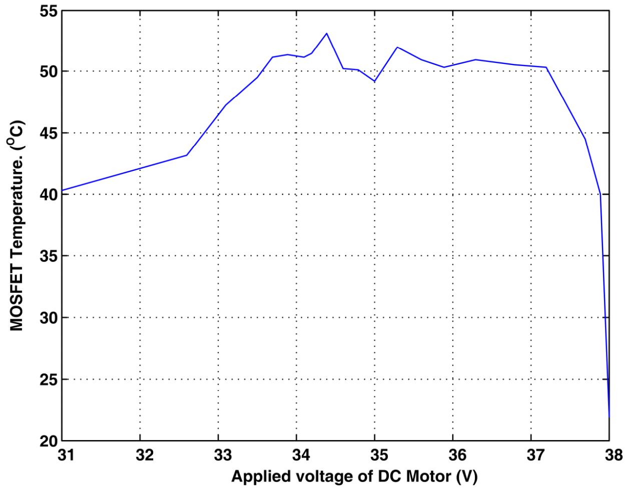
During the complete working process, the output voltage value of the rechargeable battery is nonlinear proportional to be reduced gradually as the reserved electrical energy is dissipated. To obtain a constant speed of electric cutter blade, the working duty cycle of power transistor have to be adjusted dynamically according to the remaining energy of battery. Fig. 10(a) shows the voltage value is decreased, the current value flowing into the armature of DC motor is reduced as well. Of course, the rotation speed of blade is decreased too, as shown in Fig. 10(b). Fig. 10(c) indicates the relationship between the applied voltage of DC motor and the generated heat of sink of MOSFET. The temperature of power MOSFET would be not changed suddenly. It is almost kept on a constant allowable temperature during all the working process. In general, the electric energy of rechargeable battery is inputted to the system and converted into mechanical output energy for providing required work of blade. During this energy converting process, it is normally to waste or loss some power energy on each device. Part of input power must be dissipated by the rotor of DC motor. Mechanically, there is an air gap exists between the rotor and stator of motor, the heat transmission efficiency becomes then bad. For protecting the using safety of motor, the temperature of motor is monitored during all the working process, Fig. 10(d) shows the temperature curve which directly measured on the surface of the DC motor. Although the temperature becomes high when the using time is increasing, finally, it will be almost located at a constant temperature value due to the temperature balance between inside and outside of motor space. This represents that the DC motor can be used under safety condition. However, as mentioned earlier, if the dynamic temperature of any device included in electric cutter is over their rated value, the system controller would first command to be stopped running for protection reason.



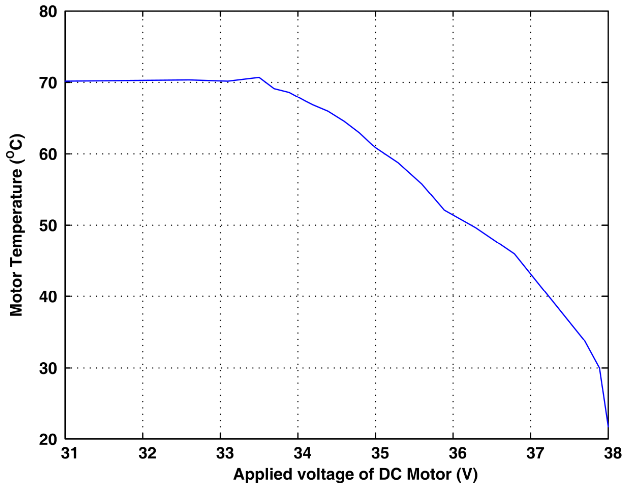
(a)



(b)



(c)



(d)

Fig. 10. Measuring results aims at prototype (a) applied voltage to motor current (b) applied voltage to rotation speed (c) applied voltage to MOSFET temperature (d) applied voltage to surface temperature.

When the operating status of cutter is changed from the stable standby condition to suddenly being applied to cut grass, the electric brush cutter required to generate more electromagnet torque for overcoming the increasing load torque. Fig. 11 diagrams the required stable standby current is about 6.5 A. If the electric cutter begins to execute cutting grass work, the required motor current will be suddenly increased. However, the motor current is always limited below 10 A. As mentioned above, a reversible rotation function is designed in the developed electric brush cutter. This function will possibly be required by many operators. When the blade is wrapped by grass, this wrapped blade may be released by using this function and recovered to normally operation. Therefore, the operator even need not stop working for trouble shooting even if the wrapping condition occurs. Fig. 12 indicates the reverse motor current will suddenly increase under the 50 percentage of full voltage of power supply. The shown current waveform of motor in Fig. 12, the inverse maximum current is about 6 A, although the applied voltage is only half of the voltage of power supply.

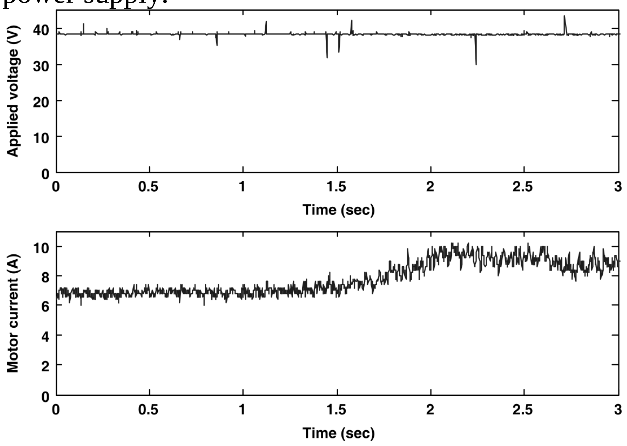


Fig. 11. Demonstrates the applied voltage and current change when the operating condition from standby status to cutting grass.

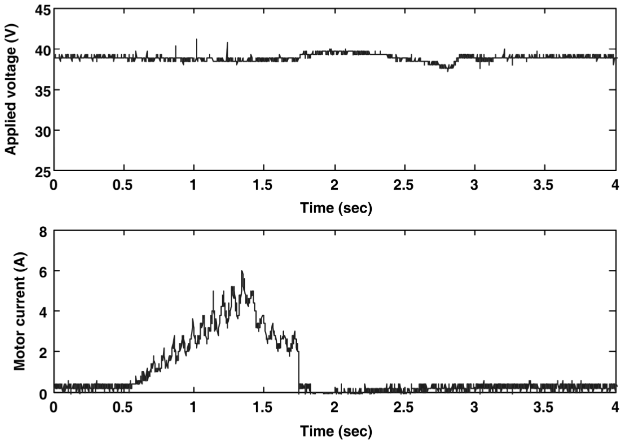


Fig. 12. Indicates the applied voltage and motor current when electric brush cutter begins reverse rotation.

6 Conclusion

The conventional engine type brush cutter has some critical disadvantages such as high noise and vibration, emission CO_2 and expensive using cost contrast to proposed electric brush cutter. The developed shoulder-type electric brush cutter with speed variable feature, therefore, it is suitable to be used in each type of grass. Although most of the mechanical mechanism of the electric brush cutter is the same as the conventional petrol engine type one, however, the bigger different point is that mechanical power is supplied with a permanent-magnet brush DC motor. The rotation speed of the blade or DC motor is controlled by adjusting the working duty cycle of the buck converter. Lots of new operating functions without existing in conventional engine types are included in the developed electric brush cutter. In addition, a controller is designed for controlling the rotation speed of blade and protection peripheral devices is introduced for protection from damaging. Naturally, the proposed electric brush cutter would be very suitable for people who want to execute the cutting work at home.

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