

Development of Electronic Control System for Small Hybrid Snow Thrower

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ABSTRACT

An electronic control system has been developed for a small snow thrower for general home use. The new system provides stable propulsion and smooth turning. Development focused on the major requirements of stable operational behavior in changing conditions and responsiveness to operator input. The new system has eliminated the need for variations in speed control, and even more complicated turning maneuvers can be conducted more easily. Both high torque and high speed are required from the drive motor, which employs a 12 V battery power supply. A brushless DC motor was utilized and flux-weakening control was adopted to enable these requirements to be balanced. The new control system achieves good performance, and the integration of components has resulted in a 10% reduction in the size of components compared to the current hybrid snow thrower.

1. Introduction

With the recent technology trend of hybrid systems, Honda has introduced a parallel hybrid system for the Integrated Motor Assist (IMA) system⁽¹⁾. Automobiles released for sale on the market have already adopted this hybrid system. The hybrid system has also been adopted by working tools such as the medium-sized snow thrower, which has been available on the market since 2000⁽²⁾.

Incorporation of the hybrid system to snow throwers has made the machines easier to control by reducing the operation load. These advantages are now being sought in small-size snow throwers.

Among the characteristics associated with snow throwers configured with a hybrid system are: adoption of a series

hybrid system that uses an engine for the snow clearing work and power generation and uses DC motors for axle driving only; use of drive motors powered by a lead acid battery for automobiles; use of minimal sensor data to allow for a simple and inexpensive system construction; driving with a continuous high load torque at low speed ranges; stable performance over changing load conditions including a variety of surface conditions; driving speed control in response to the work load; independent control of left and right mounted motors to achieve smooth turning maneuverability; and synchronized control of forward propulsion.

This paper introduces the control methods and the various device technologies used in the development of the small-size hybrid snow thrower.

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2. Development Goals

The goals set for this development were to further enhance the electrical control system of the current medium-size hybrid snow thrower by incorporating an even simpler operator interface in addition to achieving a level of stabilized performance response. Also, higher motor drive efficiency, overall system compactness, and lower costs were targeted in the development of the small-size hybrid snow thrower.

Figure 1 shows an electrical system concept.

2.1. Applications for Small Type Hybrid Snow Thrower

Conventional small type snow throwers configured with typical engine formats are approximately 60% in both weight and size compared with similarly configured medium-size snow throwers. While the small-size snow thrower is comparatively easier for an operator to maneuver, it exhibits considerable variation in behavior as conditional disturbances arise according to the work conditions. More specifically, the operator needs to exert frequent path correction movement to maintain forward propulsion and turning stability regardless of whether the machine is traveling or being engaged in work activity.

This development has quantitatively eliminated such factors and targeted good performance responsiveness and stable maneuverability.

2.2. Ease of Operation

Hybrid snow throwers configured with steering systems control turning operations (during decelerated speeds) with left and right mounted drive motors by assigning the target speed to each drive motor independently. On medium-size snow throwers, the target speed is derived from an analog signal initiated by the speed lever as shown in Fig. 2.

While the operator is able to arbitrarily control the turning speed according to the degree of control exerted on the speed lever, stable turning motion is dependent on the operator.

The need for controlling speed deceleration with a speed lever has been eliminated in the new system as shown in Fig. 3. To achieve ease of operation, On/Off push switches have been adopted to automatically control acceleration and deceleration according to the targeted turning requirement.

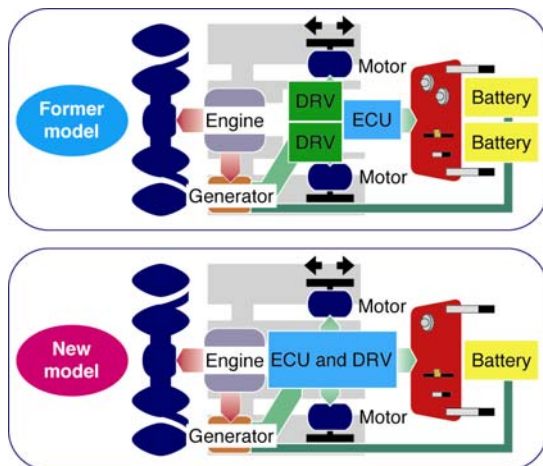


Fig. 1 Electrical system concept for hybrid snow thrower

2.3. Motor Drive

The existing medium-size hybrid snow thrower is configured with 24 V motor driven power sources to provide the required running torque during work conditions and satisfy the adopted brush motor characteristics. The system's power source is also 24 V. This configuration therefore necessitates the adoption of two 12 V batteries. However, one battery is preferable when considering a design of a small-size snow thrower. Achieving a 12 V DC power source system would enable the installation of the battery to the limited space of a small-size snow thrower. Also, general in-vehicle electrical devices could be used in the configuration, which would contribute to the overall cost reduction.

However, adopting the 12 V motor drive has created a challenge in achieving the required motor speed and torque. A snow thrower requires gearless speed change capability from a stationary position to the highest running speed to accommodate work requirements at low and medium speed ranges as well as movement at higher speed ranges. A motor shaft speed of 2 500 rpm is required for the gear ratio demand to provide the necessary torque during work operations.

To address this challenge, a brushless motor as shown in Fig. 4 was utilized to achieve high efficiency and variable speed control at the lower 12 V-voltage level. This has achieved a highly efficient drive system with a broad speed range.

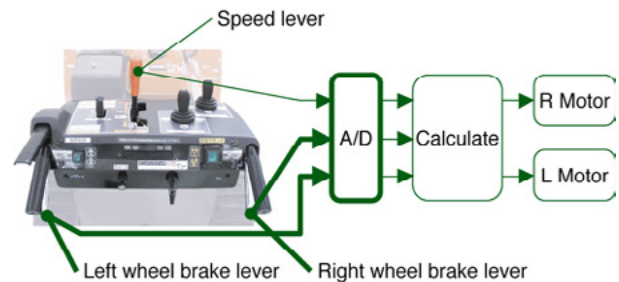


Fig. 2 Control panel of former model

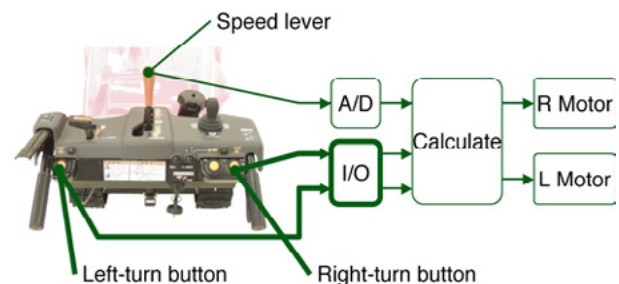


Fig. 3 Control panel for new model

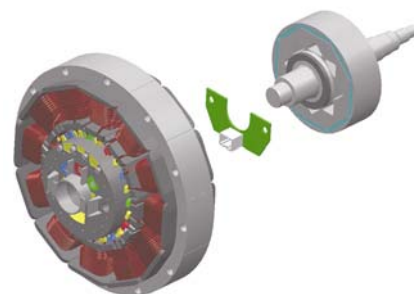


Fig. 4 Brushless DC motor

2.4. Compact Configuration

Multiple controlling devices including man-machine interface components, system controls, relays for initiating driving of devices, and motor driving devices were required to achieve a hybrid system configured with independent left and right mounted motor drives. A 10% reduction in size compared with the previous configuration was targeted through the integration of these devices. The integration of the devices has eliminated electrical connection between the devices, increased wire harness reliability, and reduced overall system cost.

3. System Controls

In integrating the multiple devices, the Electronic Control Unit (ECU) and motor driver (hereafter referred to as DRV) used in the medium-size hybrid snow thrower have been configured to control the main functions as follows:

- ECU – total system control and interface
- DRV – motor drive with load control

Microcomputer chips (hereafter referred to as CPU) are used selectively to regulate processing as follows:

- One high-performance CPU for integrated data processing
- Multiple common CPUs for individual processing

Applying the latter CPU configuration to the system formulates a master-slave method of control. The signal interface between CPUs is mainly digital by means of the bus connectivity but analog interfaces are also employed. This configuration reduces the number of debugging checks by allowing distribution of CPU processing and also maintains system integrity when CPU inconsistencies occur. Figure 5 shows a block diagram of the electronic control unit.

3.1. Automatic Turning Control

To achieve ease of operation, automatic deceleration and acceleration in a smooth response without any unusual feeling of movement is required when the operator uses the push switches to initiate a turning operation. While the motor drive is operating, the snow thrower must evaluate the various possible drive conditions such as whether it is driving on a paved surface, moving over snow (especially when a crawler drive is employed the influence to the running movement is significant because of the large surface contact) or conducting snow-cleaning work. Such variable factors were set as parameters, and the targeted speeds, SPm and SPm' were obtained from model Eqs. (1) and (2). These represent the target speed for the left and right driving shaft respectively and are calculated in the master CPU.

The targeted forward speed is determined according to the target speed data of forward ACC input by the speed adjustment lever. The same target speed value is indicated to the two slave CPUs to perform the forward running motion.

The turning instruction command is entered with the R or L mounted push switches. This initiates a request for the target speed data of deceleration SPm and the target speed data of counter side deceleration SPm' and then executes automatic deceleration in a timed series control.

$$SPm = (a1 \times DECm \times ACC) - (a2 \times DECm' \times ACC) \quad (1)$$

$$SPm' = a1 \times DECm' \times ACC \quad (2)$$

- SPm : target speed data for deceleration
 SPm' : target speed data for counter side deceleration
 ACC : target speed data of forward
 $DECm$: speed reduction for deceleration (parameter)
 $DECm'$: speed reduction for counter side deceleration (parameter)
 $a1$: rate of deceleration contribution 1 (parameter)
 $a2$: rate of deceleration contribution 2 (parameter)

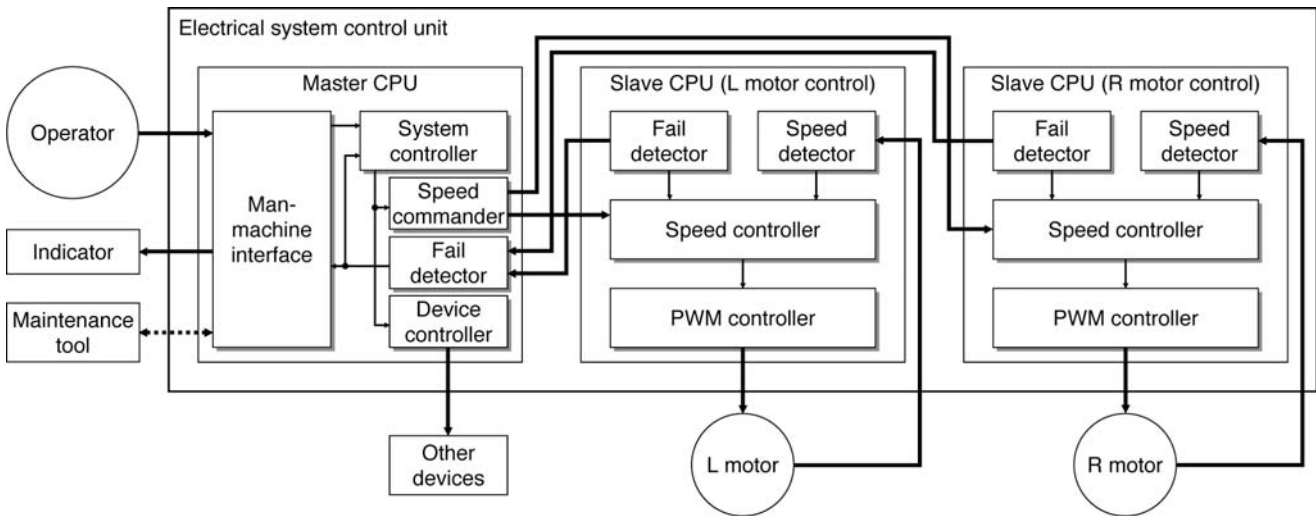


Fig. 5 System block diagram

Using *DECm*, the time series control and the rate of deceleration required for the automatic deceleration pattern after the push switch is activated are determined. The running speed when the push switch is activated and running load influence the location of the vehicle's center of gravity and produces a difference in running behavior and deceleration. In determining the deceleration pattern, these parameters are optimized through actual vehicle tests so that there would be no unusual feeling in behavior to the operator under each condition. Figure 6 shows a graph of the *DECm* MAP data.

$a1$ and $a2$ are independent parameters for the snow thrower's left and right mounted motor drive system. Turning of the snow thrower is carried out by slowing down the speed of the wheels on one side. Reducing the speed slightly on the counter deceleration side as well as on the deceleration side yields a smooth turning feel. The Map data is derived in the same way as that for *DECm*.

The *ACC* input on the actual snow thrower is operated by the acceleration lever positioned on a straight line. The total operation range comprises of the speed range of the forward motion, the stop position (neutral position) and the reverse motion. This data is converted into analog signal and inputted into the model equation. However, the mounting tolerance of the analog potentiometer and other factors create reading variation on individual units. In order to retain reliable operation of this system in respect to such variable factors, the *ACC* calculation has also been set to a model pattern where the initial operation is to compensate for such deviations.

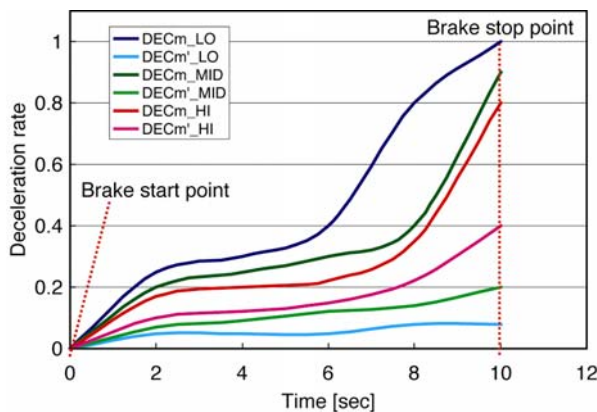


Fig. 6 DECm MAP data

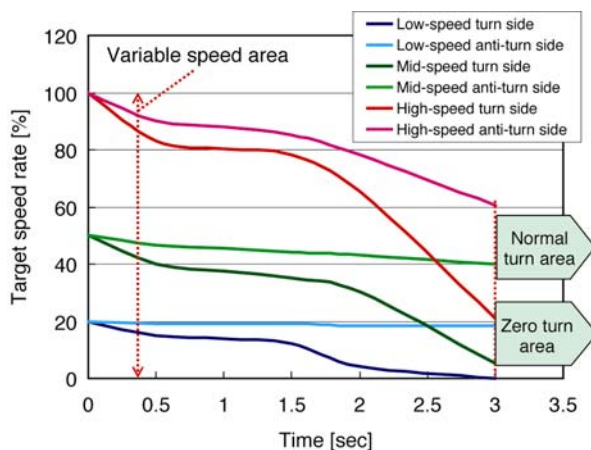


Fig. 7 Brake timing chart

Figure 7 shows a deceleration curve obtained from Eqs. (1) and (2) when each of the parameters is fixed. This yields a correlative output according to each of the running conditions.

These results are illustrated in the automatic turn control image as shown in Fig. 8.

3.2. Motor Drive Control

The maximum torque for the driving motor required by the small-size snow thrower is 4.5 Nm; the maximum motor speed is 2 500 rpm. Figure 9 shows the relationship between the motor speed and motor torque required for the driving motor. Control must be implemented to quickly reach the target speed calculated by the master CPU without any noticeable disruption of movement, ensuring a desired level of operational ease. Also, a stable speed control is required while the system is conducting snow-clearing work at low speeds under a 12 V power source.

In resolving these issues the following controls have been implemented to satisfy configuration demands of the small-size snow thrower:

- Motor speed control
- Switching of high-side with low-side
- Phase change by force
- Cancellation of zero start synchro control

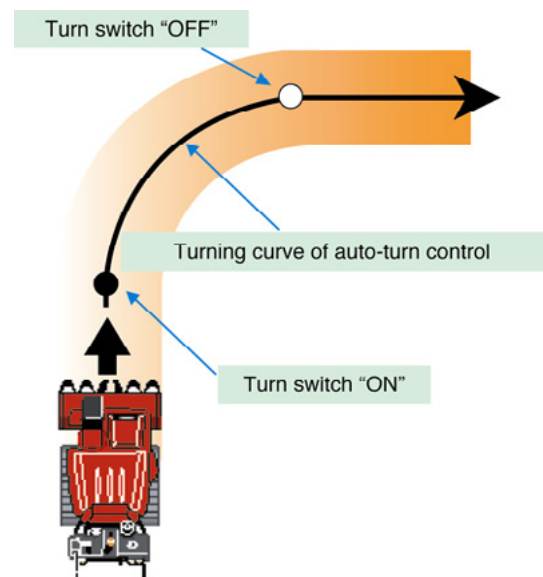


Fig. 8 Turning curve line of auto-turn control

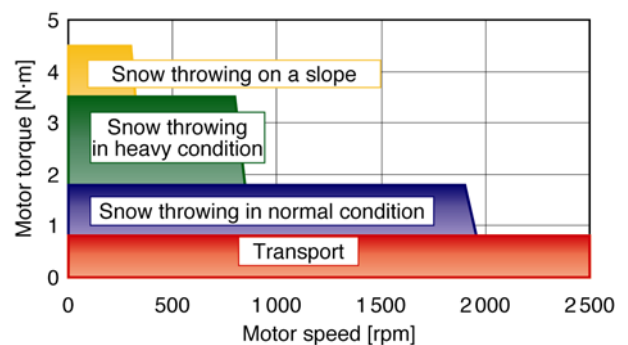


Fig. 9 T-N curve of brushless DC motor

3.2.1. Motor speed control

As mentioned earlier, this system comprises three CPUs. The calculation for target speeds that regulate the vehicle speed in response to the operator's control input is conducted by the master CPU, which determines the SP_m and SP_m' parameters for the R and L motors. The two slave CPUs for controlling the left and right mounted motors provide speed feedback in accordance with the values calculated by the master CPU and provide follow-up control to changes of the vehicle's speed due to the surface conditions and workload. Each slave CPU executes control regulation independently without any interference to one another. This configuration is able to assign the highest priority response to change the vehicle speed. Additionally, the resulting imbalance in the right and left motor speeds has been addressed by assigning synchro control to the master CPU that responds after receiving motor speed data in real time from each slave CPU.

The slave CPUs carry out feedback control with the PI method control function and use the feed forward control for the targeted speed to achieve quick responsiveness and prevent speed overshooting in response to variations in vehicle speed and target speed. Figure 10 shows a slave CPU control block diagram. Figure 11 shows target speeds and Map data for feed forward control speeds.

The integral coefficient for feedback control as shown in Fig. 12 provides Map data for deceleration and acceleration values and provides a stabilized response across the range of speeds.

3.2.2. Switching of high-side with low-side

To provide the necessary running torque for driving the vehicle powered with a 12 V source, an increase in current is required. With switching elements (hereafter referred to as FET), a larger capacity configuration is preferred in order to accommodate occurrences of heat generation by switching

loss and withstand current. However, a larger capacity FET would be physically larger and more costly. This development has enabled the adoption of a small capacity FET by implementing a motor drive with an improved switching efficiency rate that has reduced the level of heat loss and provides a reliable safeguard.

The motor drive is configured with a bridge circuit three-phase motor on the high side and low side. The motor drive controls equalization of FET loss balance. The issue of heat generation in real mode operation has been solved as shown in Fig. 13 where the difference in temperature on the high side and low side does not exceed $\Delta t=20$.

3.2.3. Phase change by force

The maximum torque required while the unit is running or when conducting work operation is 4.5 Nm. However, if the crawler becomes locked while the machine is running, there are situations when the lock cannot be released even when maximum torque is reached. In such situations, the system will conduct a series of protection processes when either the master CPU detects the locked condition or a slave CPU detects an over voltage reading. However, there is a need for the working unit to run continuously even though the crawler remains in the locked position. When an over voltage is detected in the conventional machine, more power is required for retry action. This is not possible however in a 12 V system. Furthermore, the crawler locked condition causes continuous electrical input to the same single phase and carries a large flow of current flow. This eventually leads to over voltage output. Therefore, the method is employed in which a phase change control is forcibly exerted to cause the lock to be released and send electricity to a new phase. Figure 14 shows the torque level during a crawler lock condition.

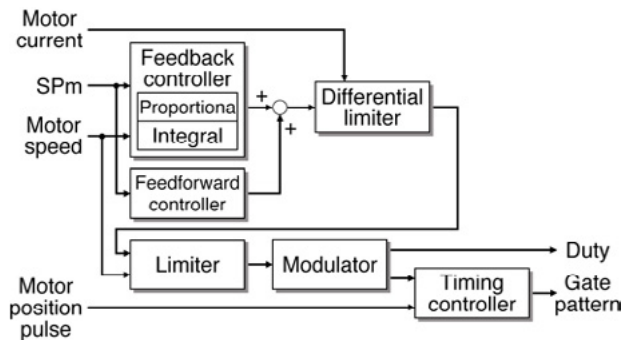


Fig. 10 DRV control block diagram

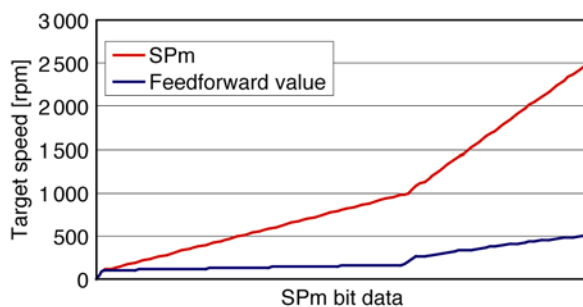


Fig. 11 Feedforward value

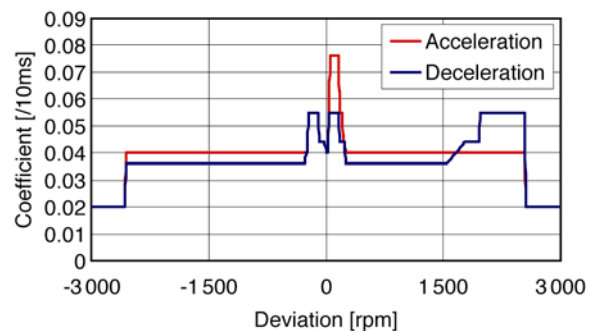


Fig. 12 Integral coefficient MAP

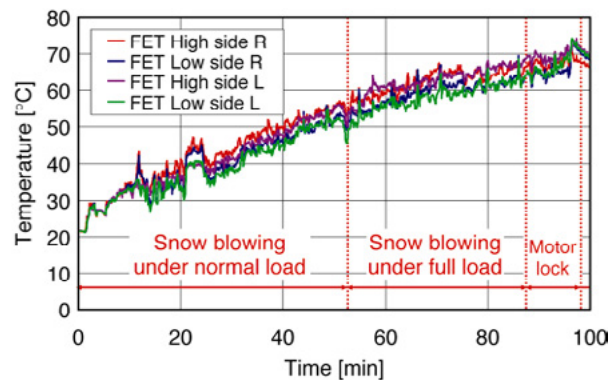


Fig. 13 Result of measurements temperature of drive FET

3.2.4. Cancellation of zero start synchro control

With the implementation of the 12 V DC power source, there are cases where the motors are powered with an impressed voltage level of 3 V when running at low speeds. When the applied voltage for the target speed is so low, the start response of the forward propulsion synchro control, which reliably compensates for the speed difference in the independent left and right mounted motors, deteriorates.

It was discovered that not synchronizing the left and right motors at the drive startup provides a better initial response. Consequently, it was decided to cancel the synchro control of the left and right motors until a speed was reached wherein the machine's forward propulsion motion was not adversely affected. This process was removed immediately after an initial speed was reached. Testing of whether this had any negative influence on the synchro control while the machine was running has shown that this is not a concern. The process has been applied only from the initial zero speed up until the machine begins to move. Normal processing has otherwise been applied at deceleration of forward speeds and when the unit is being turned.

The results gathered from this section have been effectively applied to the working machine where the drive is running at high resistance with crawler work activity.

4. Hardware Configuration

The previous section dealt with the counter measures applied to the system software. This section will discuss hardware related issues and countermeasures.

Over voltage resulting from the application of regenerative braking current is characteristic of hardware configured around a 12 V DC power source. This development has successfully determined the circuitry

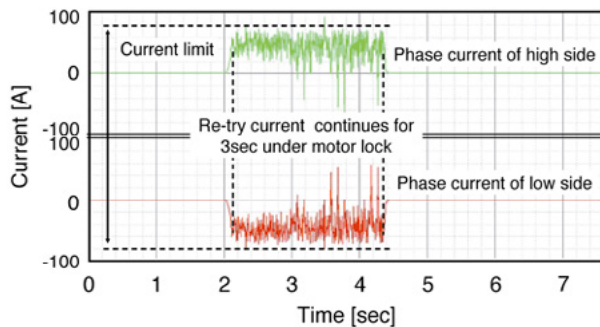


Fig. 14 Results of lock current measurements

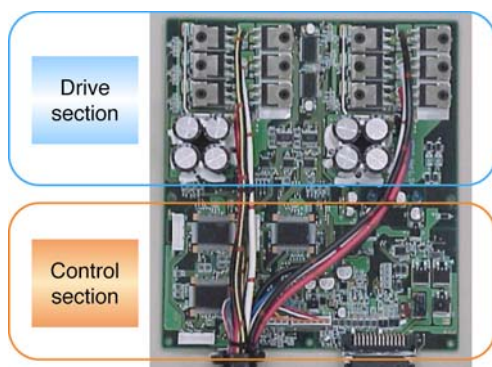


Fig. 15 Circuit board of ECU/DRV unit

voltage specification from the peak voltage levels applied to the controller and driver components respectively. Protection of over voltage level occurrences has also ensured voltage reliability. Figure 15 shows the circuit board for the ECU/DRV unit.

4.1. Integrated Circuit Board

The large scale integration layout has been applied on a print circuit board consisting of four glass epoxy layers. The pattern line of power ground (hereafter referred to as GND) was taken into consideration in the board design to prevent any negative influence on the controller when conducting large current flow switching at the motor drive. Each GND was adapted to a common configuration to minimize the pattern surface area. The CPU GND however was configured separately and the GND location is set close to the connector pattern in conjunction with the common condenser with surge-suppression elements. This has also succeeded in maintaining GND noise integrity.

4.2. Control Power Source Configuration

The device is integrated in a single unit construction wherein multiple power sources are configured on the same circuit board. The following power source configurations have been integrated to achieve a small power source construction:

- Shared motor drive power and DRV control power sources
- Independent system control power source

After establishing the startup time difference for each power source regulator, the hardware was configured so that the master CPU would start before the slave CPUs when the power is initiated.

4.3. Input/Output Line

As shown in Fig. 16, the signal and device power interface lines have been designed as a direct coupler on the circuit board. This has eliminated the need for a wire harness in the unit, improving reliability and reducing cost. The battery power source input line and motor drive output power line have been connected to the circuit board via a direct cable. This has eliminated the need for a circuit board pattern for power lines to carry large current flow. Improving the efficiency of the circuit board layout pattern and minimizing the overall line length have reduced the overall circuit board surface area and 10% reduction in the volume compared with the previous device configuration was achieved.

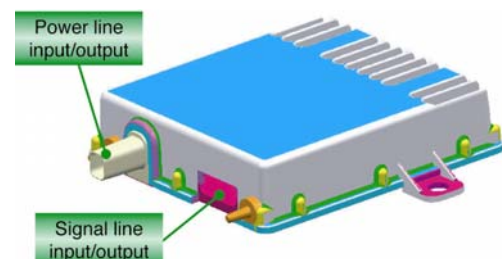


Fig. 16 Overview of ECU/DRV unit

Table 1 Major specification of hybrid snow thrower

Items	Former hybrid model	New hybrid model
Type	Medium	Small
L × W × H [mm]	1650 × 920 × 1340	1500 × 725 × 1155
Outfitted weight [kg]	265	163
Snow-clearing width [mm]	920	710
Snow-clearing height [mm]	580	510
Maximum snow-clearing volume [ton/h]	80	60
Drive system	Dual drive for DC motor	Dual drive for brushless DC motor
Speed control	Pulse Width Modulation (PWM) control with unipolar drive	Pulse Width Modulation (PWM) control with bipolar drive
Motor reduction gear ratio	61 : 1	36.4 : 1
Maximum speed [m/sec]	0.78	0.8
Maximum motor speed [rpm]	3000	2500
Maximum motor output [N·m]	4.5	4.5
Turning	Manual operation with analog switches	Automatic control with digital switches
Power source	12V battery ×2	12V battery
Control device	Electronic Control Unit (ECU) Motor Driver (DRV) ×2	Unified controller

5. Unit Test Results

Figure 17 shows an overview of the hybrid small-size snow thrower used in the evaluation testing of the running speed response from the time the machine is started through its maximum running speed and for the evaluation of user feeling while the machine is in work mode. Table 1 lists the major specifications of the small-size hybrid snow thrower. The successful developments carried out for the hybrid small snow thrower have enabled the introduction of a new snow thrower model that offers significant enhancements over previous models including the adoption of an electronic control system and the improvement of snow-cleaning efficiency by 30% over conventional mechanical small-size snow thrower. Furthermore, the full cover construction has reduced the machine's working noise level and overall mechanical vibration. The results of the actual working test conducted on this small-size hybrid snow thrower clearly demonstrate a level of performance that satisfies the running requirements for small-size snow thrower units.

5.1. Snow Thrower Running Speed Response

Influences to the motor speed control for driving the snow thrower unit include: 1) changes initiated by the operator to speed operation, 2) surface changes ranging from tiled surfaces having a low friction coefficient (μ) to a partially melted snow surface having a high μ value, 3) changes in snow removal performance according to the work load. Figure 18 shows the time variables associated with the motor speed response in relation to the motor's



Fig. 17 Overview of hybrid small snow thrower

actual speed and the internal variable SP_m (the target speed calculated by the master CPU). The graph shows the response characteristics of the actual motor speed against the optimal target speed SP_m under different load conditions when the speed control by an operator ranges from the initial low speed to the maximum speed.

Even with the previously described changes, the unit was able to achieve a linear response to deliver a highly satisfactory level of operational ease.

5.2. Performance Behavior of the 12 V DC Power Source Configuration

The following results were observed in the actual unit test conducted on the 12 V DC power source configuration where voltage drops during high load runs and changes in drive speed caused by fluctuating primary voltage due to varying work loads were measured:

- Lowest voltage level when voltage dropped during performance run 11.4 V
- Deviation in rated speed for varying voltage levels $\pm 6\%$

These results indicate that the voltage level did not exert any influence to the system controls or responsiveness and also shows that the performance levels were well within the permissible rated speed range.

5.3. Stability During Turning Operation

Maintaining stability when performing turning operations is essential particularly when exposed to a range of variables during snow-cleaning work. Figure 19 shows an analysis of the yaw rate. These results confirm that a stable yaw rate was achieved during turning operation without creating any noticeable disruption of movement to provide an overall favorable level of responsiveness.

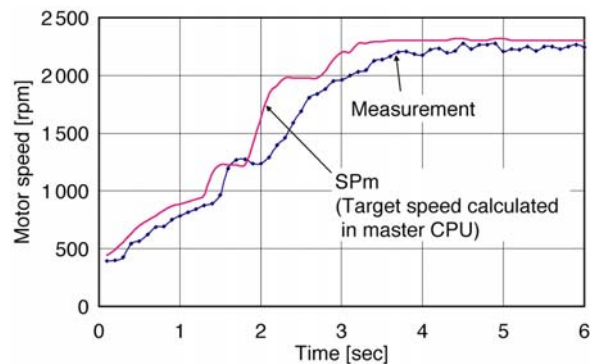


Fig. 18 Response time graph for different load characteristics

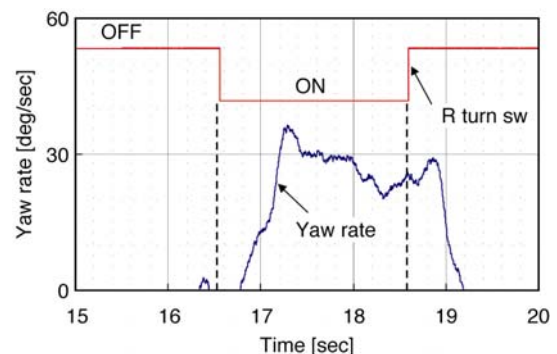


Fig. 19 Response time graph of vector curve

6. Conclusion

The development of an electronic control system for a small-size hybrid snow thrower has yielded the following:

- (1) Automatic turning control that provides stable turning performance with automatic speed deceleration and acceleration, which is operated by an easy to use push switch.
- (2) Motor speed control provides stable control even with variable factors including load condition and fluctuation of voltage. Additionally, switching control of high-side with low-side, phase change by force and cancellation of zero start synchro control have achieved the necessary running torque and speed with a 12 V drive power source, enabling complete system configuration under the 12 V DC power source.
- (3) Integrated circuit board and miniaturized control power source configuration; direct coupler configuration for input/output lines and shared cable connectivity on the circuit board - have reduced the volume of the control unit by 10% compared with the control device employed in the medium-sized hybrid snow thrower.

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