A Controller Design for SRM using VHDL

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Abstract—SRM (Switched Reluctance Motor) has not been put into practical use since it has been developed in mid 19th centuries, but the switching element using semi-conductor was developed in 1950's which made possible to produce small size staffing motors. The research activities have been lively conducted regarding SRM since 1960's, nowadays, more research activities are being carried out focusing on developing small home appliances such as vacuum cleaners and washing machines. This thesis explains the study of controller design applied to SRM concept. This controller executes controller algorithms via μ - processor to increase stability and precise measurement, and VHDL (Very high speed integrated circuit Hardware Description Language) is designed to generate SRM driving signal.

Index Terms – VHDL, SRM, PID controller, MCU

I. INTRODUCTION

Large capacity switching element was developed as a result of rapid development of semi-conductor being used for power generation, therefore, many power converting devices are developed using this technology. Based on this background, the research activities are carried out to use reluctance torque as a power generation which has been underdeveloped due to lack of existing switching technology. Based on these research activities, SRM will be designed for practical use. Original use of reluctance torque being used as power source of electric car in mid 19th centuries. At that time, manual and mechanical switching methods are used, so it was far from being used as practical use. Since then, alternating current motor has been relying on direct and alternate device using mutual torque created from two magnetic fields. The switching element using semi-conductor was developed in 1950's, and being utilized as small staffing motors.

Active research activities regarding SRM have been carried out in the mid 1960's. These activities achieved great success capable of competing against direct current motor, alternating current induction motor, and brushless DC motor. The first reference to the term Switched reluctance was made in 1969 when the initial disk type switched direct motor consisted of axial air-gap developed by Nasar. Recently, many research institutes and universities found great interest in SRM. In Korea, and continue to study the possibilities of utilizing SRM in electric home appliances, industrial equipment, and towing electric motor of electric car. Nowadays, SRM puts to practical use in small type motor operating 500W and below such as washing machines and vacuum cleaners. This research is aim to design a controller for 1.2 KW SRM motor. The stability of switching element has been the key issue in the development of SRM, and the use of high-priced switching element makes SRM difficult to be put into practical use. Therefore, our research is focused on using low-priced switching element, and securing stability using VDHL as well as simplifying the circuits and using high frequencies which able to perform precise control. Microcontroller only executes control algorithms, therefore, it requires less burden to handle controller and designed to convert various types of μ - processor according to its function to increase the use of practical use.

II. CHARACTERISTICS OF SRM

A. Torque characteristics of SRM

SRM general torque can be represented by the equation described in equation 2-1.

$$W_c = \frac{1}{2} i^2 \bullet L \tag{2-1}$$

i indicates the phase winding electric current, L is the inductance. single phase torque, T_e can be obtained from a differential equation of co-energy against the rotor position angle. Equation is described in 2-2.

$$T_e = \frac{\tau W_c}{\tau \theta} = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{2-2}$$

It was learned that SRM generating torque is proportioned to the square of electric current, and proportioned to the slope of inductance against position angle.

Torque can be generated regardless directions of phase electric current since torque is proportioned to the square of electric current, and the position angle of rotor is created from negative torque which is reverse direction because torque value can be changed in accordance with slope of inductance, therefore, switch excitation should

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be made according to the position angle of rotor to deter negative torque.

When traditional inductance profile of double-phase doubly salient SRM is displayed, there is an increase $\theta_0 \sim \theta_1$, decrease $\theta_2 \sim \theta_3$, and fixed period $\theta_1 \sim \theta_2$ against the position angle of rotor as described in figure 2-1

If fixed exciting current is running through the phase winding electric core, it generates positive torque during increase period $\theta_0 \sim \theta_1$, and creates same amount of negative torque during decreased period.

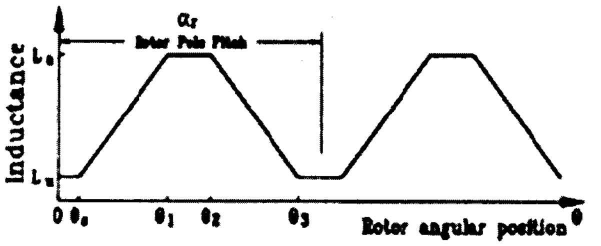


Fig.2-1 Single phase inductance profile

Therefore, fixed excitation offset the positive torque, and axial torque of electric motor will become 0, and can't obtain electro-motive force. It is necessary to practice continuous excitation by obtaining information about position angle of rotor in order to prevent negative torque and obtain efficient electric torque. Torque will be generated by adding torque created by exciting current of each phase, and three phase output torque T_{out} will be calculated according to equation 2-3.

$$T_{out} = \frac{1}{2}i^2\frac{dL(\theta)}{d\theta} + \frac{1}{2}i_b^2\frac{dL(\theta-30^\circ)}{d\theta} + \frac{1}{2}i_b^2\frac{dL(\theta-60^\circ)}{d\theta} \quad (2\text{-}3)$$

Inductance, phase current, and torque caused by switch during actual switch excitation will be shown as figure 2-2, 2-3, and 2-4.

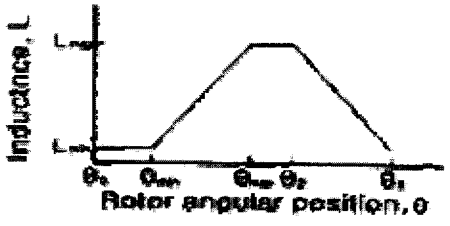


Fig. 2-2 Relationship between rotation angle and inductance

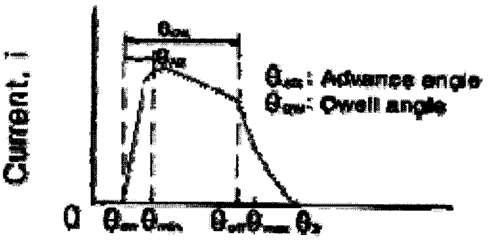


Fig. 2-3 Relationship between angle and electric current

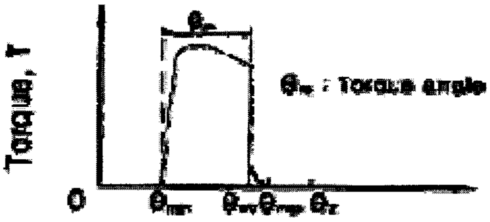


Fig. 2-4 Relationship between angle and torque

Motive equation is same as equation 2-4.

$$V = \gamma i + \frac{d\lambda}{dt} \quad (2\text{-}4)$$

Where v is the stator voltage, λ is leakage magnetic flux. ω is activate fixed angle, while assuming there is no resistance of winding core and magnetic non-sector characteristics of core,

$$V = L\frac{di}{df} + i\frac{dL}{d\theta}w \quad (2\text{-}5)$$

Energy flow at this time is shown in equation 2-6

$$Vi = \frac{d}{dt}\left(\frac{1}{2}Li^2\right) + \frac{i^2}{2}\frac{dL}{d\theta}w \quad (2\text{-}6)$$

When SRM is activated as electric motor, part of input will be converted to a mechanical output $\frac{1}{2}i^2\left(\frac{dL}{d\theta}\right)\omega$, and rest of them will be saved as a magnetic energy, however, part of magnetic energy $\frac{1}{2}Li^2$ will be converted to mechanical output, and the other part will be converted to power resources during this period when the switch is on

1) $\theta_{on} \sim \theta_{off}$: it is the period when inverter switch is on, and also known as dwell angle.

2) $\theta_{min} \sim \theta_{off}$: it is the actual torque generation and effective torque generation period by switch. This angle is called torque angle.

3) $\theta_{max} \sim \theta_2$: Inductance maintains L_{max} , and is decreased below dead zone. It caused by difference in width between stator magnetic and rotor magnetic. This period is made to reduce negative torque at the next inductance decrease period ($\theta_2 \sim \theta_3$).

4) $\theta_2 \sim \theta_3$: Inductance will be decreased by sector until L_{max} . This period creates the negative torque and demagnetizing. Once electrical current stream through this period, the energy created from magnetic as well as mechanical energy that generated from negative torque will be convert into power source. This is what we called regenerative motive, and also being utilized as braking torque. This allows four phase activation using circuit rounding switch, and one of the main important characteristics of SRM.

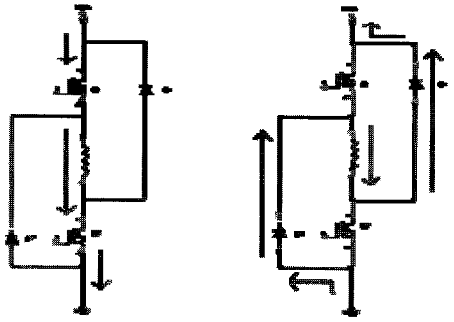
B. SRM excitation control

It is the control method by adjusting preceding switch angle in variable ways to establish steady current according to variable load during torque generation period. The required load current increases due to increased load torque. This method is to establish steady current all the time by setting up proportioned θ, even though load changes. Preceding switch angle can be controlled by extracting load current, and this can be accomplished by configuring simple feed back circuit. It is necessary to control switch off angle θ[illegible] to enhance the efficiency at the same time to control the preceding switch angle which allow maintaining steady current according to variable load. There are two types of control to control the switch off angle. One is to control torque angle θ_{TQ}(θ[illegible] ~ θ[illegible]), and the other is to control dwell angle θ_{DW}(θ[illegible]~ θ[illegible]). Torque angle θ_{TQ} is the angle to connect switch during increased inductance period, and this is the effective period to produce torque. To control torque angle θ_{TQ} in a steady manner regardless of load is the same as to maintain effective torque period constantly. Under the condition where magnetic saturation is not existed, It is a good way to maximize the θ_{TQ} beyond the limit where disappearing electric current is not affected by negative torque, and maximize maximum output by reducing the torque ripple. Saturation point moves up when load current is increased as shown in figure 2-8, therefore, electric current increases at the saturation point before the switch is off. Increased current due to saturation causes the loss of core and take longer time to use electric current which reduce its efficiency. SRM produces torque according to the changes of inductance, therefore, there is a decreased inductance area existed to produce negative torque. If load current is too large to handle and takes long time to process, the current may be streaming into negative torque area, and the negative torque produce excessive amount of acoustic noise causing unsteady operation, therefore, it has characteristics to limit maximum output by controlling maximum load current to prevent negative torque. Efficiency will be reduced if increase of current occurred due to excessive saturation as the stator and rotor increases and load current is too large during torque production period, therefore, it is good idea to turn the switch off prior to the saturation point. Saturation point will move up as the load current increases, enhancement of efficiency can be expected by adjusting θ_{AD},at the same time, reduce the size of θ_{TQ} to prevent current from increasing at the saturation area. Specific control of dwell angle θ_{DW} is the method to control θ_{DW} which the value by designating increased value of θ_{AD} and decreased value of θ_{TQ} in a steady manner. General switching method of SRM is to turn the switch off within a given time after switch was on according to the position angle of rotor. If the dwell angle θ_{DW} is preset, the only requirement is to adjust the angle of preceding switch, therefore, switch control program becomes much simpler to operate compare to θ_{TQ} control method which has to adjust θ_{DW} in variable ways. Once dwell angle θ_{DW} is preset, switch off angle θ[illegible] will move up, and does not allow for used current to move to negative torque area, therefore, there is no maximum current limit due to saturation which allow to produce maximum output with operational safety. Current resource excitation method which has superior mechanical and magnetic capabilities will be best suited for excitation of SRM. Current resource excitation is the ideal excitation method which produces steady torque and no negative torque

III. DESIGN OF SRM CONTROLLER

A. Characteristics of SRM controller design

SRM is a doubly salient machine which independent phase windings on the stator and a solid laminated rotor, therefore, it is easy to manufacture. It is less efficient than BLDC but its performance is superior than other motors, therefore, it is treated as future generation motor. The electrical motor we have used for this research is 6 stator 4 rotor (6/4 SRM). Stator is placed on simple windings, and there is no windings on the rotor, therefore, stator current will be on or off according to the position of rotor. Due to this control, it is easy to obtain characteristics similar to the speed and torque of direct electric motor. Three-phase turn the switch on or off depending on the position of rotor. the on/off angle makes big differences, however, this thesis have set the switch on at 45 degree prior and off at 15 degree prior, therefore, there is no overlapped angle. In addition, according to classic invert method we have used for our research, voltage will flow direction shown in figure 3-1 (a) during phase on, and figure 3-1 (b) during phase off. Our circuit use both MCU and VHDL to increase its efficiency and control characteristics. VHDL is designed to reduce the load of MCU and to practice precise PWM (Pulse Width Modulation) control. PWM generates the excessive amount of acoustic noise when the frequency is too low, therefore, high frequency should be used. 20KHz must be used because PKM couldn't receive frequency beyond 20KHz. When 20KHz frequen-cy is directly applied to MCU, practical frequency is only 2.5MHz due to the fact that the MCU clock is 20MHz and it is divided by eight, therefore, it is difficult to perform precise control because it flex 125, but if VHDL is used, 50MHz frequency would be used and be able to flex 2500 which allow to perform precise control of motor. In addition, it gives fewer burdens to MCU to generated PWM. CPU receives current rpm from sensor, and calculates its output value, and transmits to VHDL using parallel communications, then VHDL generates PWM by reading angle from the sensor, and create appropriate phase according to current angle to activate SRM.



(a) (b)

Fig. 3-1 Direction of SRM power supply when the switch is on or off

B. Design of power supply circuit

Power supply circuit is mainly divided into driving power supply and control circuit power supply. The power supply of these two circuit are 24V, and the large capacity condenser is mounted to reduce the voltage generated from driving power supply. Control circuit power supply use PS3-24-5 (DC-DC converter) manufactured by POWER PLAZA to reduce voltage from 24V to 5V for the practical use.

C. MCU circuit design

The µ - processor used by controller is C167CR and additional element consisting 256KB Flash ROM and 128KB SRAM are configured in 16 bit de-multiplexed mode. VHDL allows using 72 inputs and output port of C167CR. Using this advantage, quick delivery of signal can be made by connecting output value and control signal using parallel connection, and use MAX232C driver to interface data between PC monitor program using RS232 serial communications. When there is a need to download program into controller devices, download directly into a flash memory. Controller device uses C167 bootstrap mode to download program directly into a flash memory. Switch is used to select between bootstrap mode and normal execution mode.

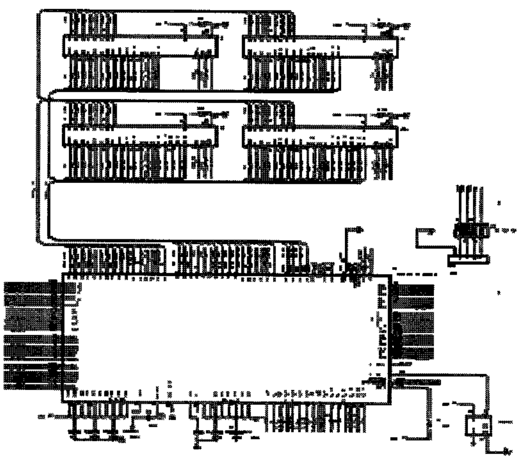


Fig. 3-2 MCU circuit

Figure 3-2 displays MCU circuit of controller devices. Oscillator is used to create clock, and convert 5MHz frequency to 20MHz frequency using internal PLL.

D. Sensor structure and circuit design

Sensor always is able to acknowledge the absolute angle. Existing angle should not be affected by outside sources such as power supply. In the case of increasing sensor, angle can be acknowledged at the first revolution when the power is on. SRM may suffer critical damages such as element damage, therefore, absolute encoder is needed rather than increasing encoder, however, high cost of absolute encoder leads to low economic efficiency, therefore, encoder using hall sensor can be used. Hall sensor generates 1(high) signal when N pole is approaching, and generate 0(low) signal when S pole is approaching. Sensors are manufactured and utilized based on this principle. First, fix the cross point between N and S pole to the rotor 0 degree using 4 pole magnet, and fix hall sensor to 0, 30, 330 degree on the case, then set the angle control to be on prior to 45 degree and off prior to 15 degree. Sensor input can be accomplished using hall sensor. Attach a 4 pole magnet to the SRM axle, and attach four hall sensors to the case with 15 degree interval. Four hall sensors generate 6 values and total of 24 values are created because there are four magnets, therefore, control can be made in 15 degree interval.

E. Power inverter circuit design

Power inverter types consist of asymmetric bridge converter, classic inverter, bifilar-winding converter, split-source converter, and switched-shared converter. we created converter using asymmetric bridge converter method. The method of asymmetric bridge converter is shown in figure 3-3.

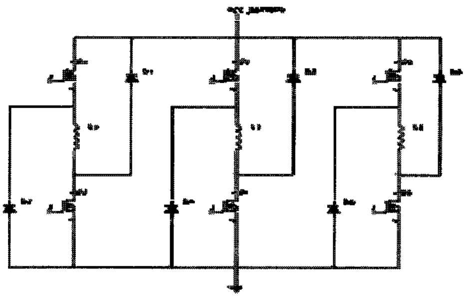


Fig. 3-3 Three phase power drive

Power FET (Field Effect Transistor) is IRL1004 of International Rectifier, and basic specifications are as follow;

V_{DSS}=40V(Drain-to-Source Breakdown Voltage)

$R_{DS(on)}$ =0.0065Ω(Static Drain-to-Source On-resistance)

I_D =130A(Continuous Source Current)

Three will be used as one pair using parallel connection due to low I_D in IRL1004.

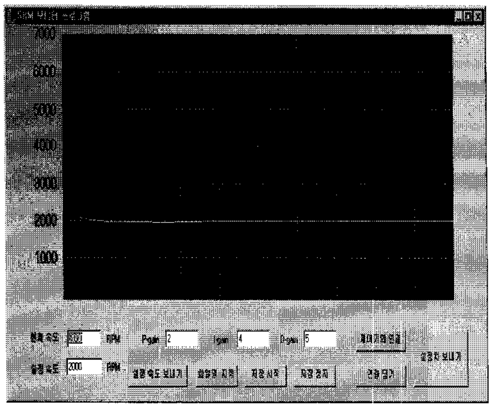
Power Fast Recovery Epitaxial Diode is DEEI 60 manufactured by IXYS, and basic specifications are as follow: I_{FAVM}= 60A, V_{RRM}=600V, t_{rr}=35ns

Configuration of power circuit should be made with low cost and has high capacity, and easily attachable part in order to pursuit commercial use.

F. VHDL program.

VHDL consists of PWM driving module and controller module. PWM driving module output is based on phase excitation signal generated from control module and output value generated from CPU. Control module creates phase excitation signal using sensor, control signal from CPU, and sensor input signal. PWM driving module usually monitor clock signal, and increase counter by one when clock signal drops from 1(high) to 0(low). Oscillator we used for our research has 80MHz frequency, and PWM frequency is 20KHz, therefore, 20KHz frequency can be obtained once the clock counts 4,000, and PWM capacity becomes 4,000. If clock continues to count exceeding 4,000, counter variable can be reset to 0, and let it repeat endlessly, then produce a simple circuit based on 20KHz high frequency and 4,000 counters and be able to use efficiently. In order to activate PWM properly, counter variable compares the output values from CPU as counter increases, and when the counter variable value is less than output value, initiate power signal to turn PWM on using excitation signal generated from PWM driving module. When the counter variable is greater than output value, generate 0 signal to all output ports to turn PWM off. The PWM made from this method is designed to change output number when CPU output value changes even if one cycle has not completed. There are three input signals coming from normal and reverse revolution signal and sensor. If signal transmits to normal and reverse revolution signal, it recognize the input signal of sensor and reading current angle. Once acknowledge current output value, transmit appropriate phase excitation signal to PWM method module. It determines when to initiate normal, reverse, and stop revolution once signal has received. Output value and control signal will be processed in parallel mode. PWM standard frequency is received at the outer crystal, and out controller use 80MHz. Also signal is received at the sensor using 80MHz.

G. PC monitoring program



RPM Pgain 2 Igain 4 Dgain 5

2000 RPM

Fig. 3-4 monitoring program activation screen Figure 3-5 describes the designed controller outfit and test set.

PC monitoring program establish PID and rpm via controller, and receive current speed which able to save it as a file. In figure 3-4, activation screen for monitoring program is shown.

Fig. 3-5 test set

IV. SRM EXPERIMENTATION

A. SRM controller test

24V was used to verify the performance of designed controller, and testing was performed at the load free condition. Response time at the 1000, 2000, 3000, 4000 rpm and excessive response characteristics are consolidate with rpm data and graphics according to the number of revolutions. Table 4-1 displays data when target rpm reaches at 1000, and figure 4-1 displays its characteristics waveform.

Table 4-1 speed characteristics data at 1,000 rpm

Number of revolution	rpm	No. of rev.	rpm	No. of rev.	rpm	No. of rev.	rpm	No. of rev.	rpm
1	214	11	1001	21	998	31	1000	41	999
2	876	12	1000	22	999	32	1000	42	1000
3	1082	13	998	23	1001	33	1000	43	1000
4	1091	14	997	24	1001	34	998	44	1000
5	1082	15	997	25	1001	35	998	45	1000
6	1070	16	996	26	1002	36	998	46	1001
7	1053	17	996	27	1002	37	997	47	1000
8	1038	18	996	28	1001	38	997	48	1000
9	1022	19	998	29	1001	39	998	49	1002
10	1007	20	998	30	1000	40	999	50	999

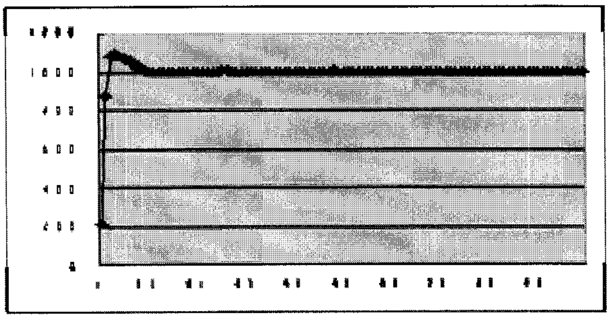


Fig. 4-1 speed characteristics waveform at 1,000 rpm

Figure 4-2 displays its speed characteristics waveform at 2,000 rpm.

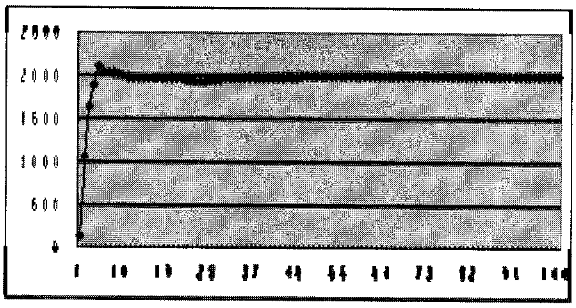


Fig. 4-2 speed characteristics waveform at 2,000 rpm

Figure 4-3 displays speed characteristics wave-form at 3,000 rpm.

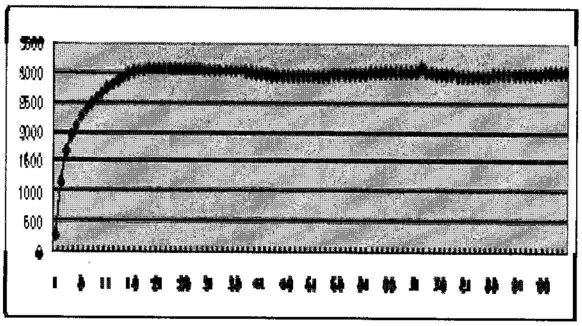


Fig. 4-3 speed characteristics waveform at 3,000 rpm

Figure 4-4 displays speed characteristics wave-form at 4,000 rpm.

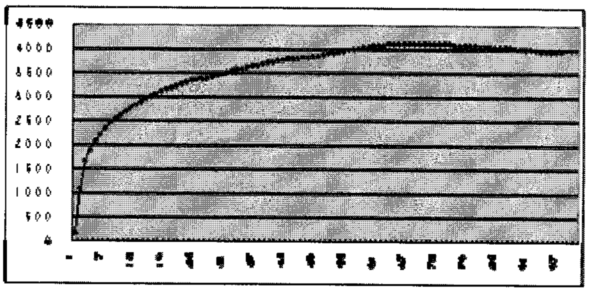


Figure 4-4 speed characteristics waveform at 4,000 rpm

B. Considerations

When the target rpm need to be fixed at low rpm, adjust PID to coordinate excessive response and normal time, however, this thesis found out that normal time was long during high rpm and excessive response was little big during low rpm after adjusting PID to satisfy speed characteristics within wide speed range. According to table 4-2, excessive response came out 9% at 1000 rpm, and normal time is 0.617 seconds, 7 revolutions. Excessive response came out 6%, and normal time is 0.59 seconds, 5 revolutions at 2000 rpm. Excessive response came out 2%, and normal time is 0.52 seconds, 12 revolutions at 3000 rpm. Excessive response came out approximately 2%, and normal time is 1.16 seconds, 41 revolutions. Our controller PID achieved satisfied result at 2000 rpm, and be able to obtain better results by adjusting PID and fix the target rpm between 1,000 and 3,000 rpm.

Table 4-2 controller characteristics

rpm	excessive response	response time	response revolutions
1000	9%	0.617second	7
2000	6%	0.59second	5
3000	2%	0.52second	12
4000	2%	1.16second	41

V. CONCLUSIONS

SRM structure is simple and efficient electric motor which able to support in large operational area. Especially, it has large torque at low speed, great towing characteristics, and low cost of production, therefore, it can be applied to various area in the future in Korea. Our research used VHDL to reduce the load off μ-processor which controls the controller, at the same time, precise control of PWM and stability was achieved by utilizing high speed of VHDL and special characteristics of parallel process, in addition, reduce the unit cost of controller by using low cost MCU. SRM's response time is longer than usual due to low torque at high rpm. This is the weak point, however, this weak point was improved by adjusting PID, and achieved satisfied results at 2000 rpm regarding response speed and excessive characteristics. In the future, we anticipate that control characteristics can be enhanced by adding excitation angle control function.

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