A Design of SRM Controller using Microprocessor

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Abstract : This paper explains the study of controller design applied to SRM(Switched Reluctance Motor) 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. During initial period, SRM controller was designed to control respective target RPM (Revolution per minutes) and PID (Proportional Integral Differential) coming from the PC(Personal Computer) monitor program, and receiving clockwise and counter-clockwise rotation signal and target RPM coming from the front panel, and receiving the location of rotational element and RPM generating from the position censor during activation period.

1. 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. Our research is to design a controller controlling 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. Microprocessor only executes control algorithms, therefore, it requires fewer burdens to handle controller and designed to convert various types of μ - processor according to its function to increase the use of practical use.

2. Characteristics of SRM

2.1 Torque characteristics of SRM

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

$$W_c = \frac{1}{2} i^2 \cdot L \qquad (2\text{-}1)$$

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).

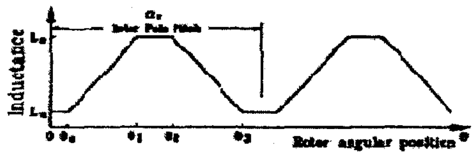
$$T_e = \frac{\partial W_c}{\partial \theta} = \frac{1}{2} i^2 \cdot \frac{dL}{d\theta} \qquad (2\text{-}2)$$

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 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 $\theta_s \sim \theta_1$, 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 $\theta_s \sim \theta_1$, and creates same amount of negative torque during decreased period.



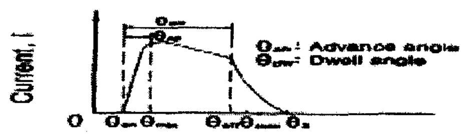
"Figure 2-1. Single phase inductance profile "

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

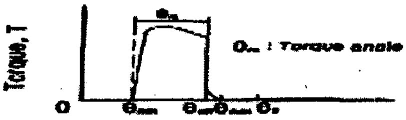
In order to prevent negative torque and obtain efficient electric torque, torque will be generated by adding torque created by exciting current of each phase, and three phase output torque T_{out} will be calculated according to equation (2-3).

$$T_{out} = \frac{1}{2} i_a^2 \frac{dL(\theta)}{d\theta} + \frac{1}{2} i_b^2 \frac{dL(\theta - 30°)}{d\theta} + \frac{1}{2} i_c^2 \frac{dL(\theta - 60°)}{d\theta} \qquad (2\text{-}3)$$

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



"Figure 2-2. Relationship between angle and electric current "



"Figure 2-3. Relationship between angle and torque"

Motive equation is same as (2-4).

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

where v is the stator voltage, λ is leakage magnetic flux.

Activate fixed angle ω, while assuming there is no resistance of winding core and magnetic non-sector characteristics of core,

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

energy flow at this time is shown in equation (2-6).

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

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 period, and effective torque generation period by switch. This angle is called torque angle.

3) $\theta_{max} \sim \theta_2$: Inductance maintains L_{max}, and falls under dead zone. It caused by difference in width between stator magnetic and rotor magnetic. This period is established 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_{min}. This period creates the negative torque and demagnetizing. Once electric current stream through this period, the energy created from magnetic as well as mechanical energy generated from negative torque will be converting 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.

2.2 Excitation characteristics of SRM

According to position angle of rotor and the type of exciting current by stator phase switch. α is the maximum overlapped angle, and value of this angle will be the least value of stator and rotor angle, and period beyond β is the decrease period of inductance, therefore, current must be completely wasted prior to β in order to deter negative torque, and value of β will be the maximum angle between stator and rotor angle. Preceding switch angle must be adjusted to establish electric current to obtain appropriate torque when the load changes. The characteristics of SRM torque control changes according to the type of voltage transmitted to phase winding core and type of switch signal and current, because phase current is generated by operational speed of electric motor. Generally, phase current of excitation should maintain steady level considering high efficiency operation and changed efficiency, and the design of butter and magnetic circuit is developed following this guideline. The value of this current can be measured by the phase current chopping to limit current or adjusting the switch angle.

2.3 SRM excitation control

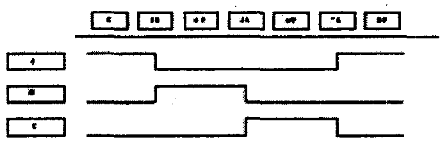
It is the control method by adjusting preceding switch angle in variable ways to establish steady current according to variable load during torque generation period. The required load current increases due to increased load torque. This method is to establish steady current all the time by setting up 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_{off} 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}($\theta_{min} \sim \theta_{off}$), and the other is to control dwell angle θ_{DW}($\theta_{on} \sim \theta_{off}$). 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. 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. 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

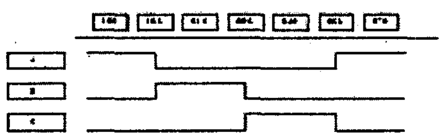
3. Design of SRM Controller

3.1 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 to 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. Figure 3-1 and 3-2 show on/off status during three phase revolution.



"Figure 3-1. Switch angle between 0° ~ 90° "



"Figure 3-2. Switch angle between 180° ~ 270° "

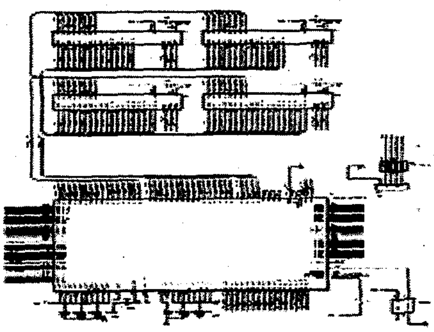
VHDL is designed to reduce the load of CPU and to practice precise PWM (Pulse Width Modulation) control. PWM generates the excessive amount of acoustic noise when the frequency is too low, therefore, high frequency should be used. 20KHz must be used because PKM couldn't receive frequency beyond 20KHz. When 20KHz frequency is directly applied to CPU, practical frequency is only 2.5MHz due to the fact that the CPU 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 CPU 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.

3.2 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 circuits 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.

3.3 CPU 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 to use 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.



"Figure 3-3. CPU circuit"

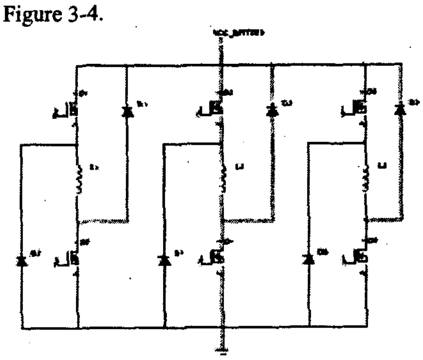
Figure 3-3 displays CPU circuit of controller devices. Oscillator is used to create clock, and convert 5MHz frequency to 20MHz frequency using internal PLL.

3.4 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) signals 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.

3.5 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 3-4.



"Figure 3-4. Three phase power drive "

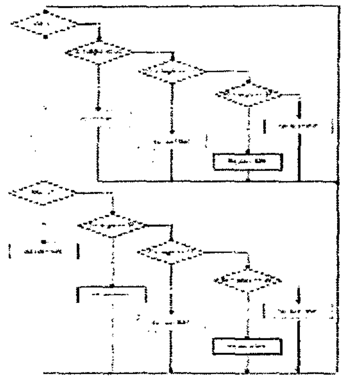
Power FET (Field Effect Transistor) is IRL1004 of International Rectifier. Configuration of power circuit should be made with low cost and has high capacity and easily attachable part in order to pursuit commercial use.

3.6 CPU program

CPU program receive input signal and assign PID into controller, then increase output power value to 10bit and transfer it to VHDL. Input signal consist of censor input signal, normal and reverse revolution signal, and speed setting signal. Also, PID and target rpm can be selected at the PC monitor program. It is difficult to calculate precise rpm when it is measured at 90 or 180 degree due to the fact that magnet ending point is not exactly 90 degree during manufacturing phase of censor, therefore, rpm should be calculated after one complete revolution

3.7 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 has 80MHz frequency and PWM frequency is 20KHz. 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 recognizes 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.



"Figure 3-5. Controller module flow chart "

3.8 PC Monitor program

PC monitor program establish PID and rpm via controller, and receive current speed which able to save it as a file Figure 3-6 describe the designed controller outfit and test set.

4. Experimental results and considerations

4.1 SRM controller experiment

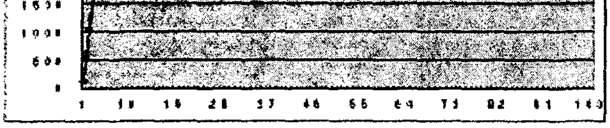
24V was used to verify the performance of designed controller, and testing was performed at the load free condition. Response time at the 1000, 2000, 3000, 4000 rpm and excessive response characteristics are consolidate with rpm data and graphics according to the number of revolutions. Table 4-1 display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

"Figure 4-1. Test set configuration "

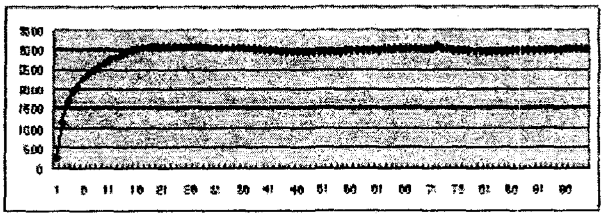
"Table 4-1 Speed characteristics waveform at 1,000 rpm "

Number of revolution	rpm	number of revolution	rpm	number of revolution	rpm	number of revolution	rpm	number of revolution	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

Figure 4-2 and 4-3 display characteristics waveform when target rpm reaches at 2,000 and 3,000



"Figure 4-2. Speed characteristics waveform at 2,000 rpm"



"Figure 4-3. Speed characteristics waveform at 3,000 rpm"

4.2 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 4-1, 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

5. Conclusions

In this paper, VHDL is used 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 μ-processor. 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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