切換式磁阻電動機驅動系統
之效率提昇策略

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摘　　要

論文中提出一新式之基於分析模式推導結論的切換式磁阻電動機驅動系統之效率提昇策略，而此效率考量和控制方法乃由該電動機之模式而產生應用想法，其乃於獲知等效磁化電感對時間之變化之下，藉著調置相電流命令與電壓間之比例而實現其作動之功能；此效率提昇策略在本論文中經由探討後，構成實用上可行之效率提升方法，其是運用此電動機參數間之連結關係而能於驅動之操作時，由設定之調動規則，在不超過輸出性能需求所設定之範圍下執行命令，而經步階數值之更動，調置電流命令值來搜尋驅動系統運作下可能存在的效率提昇數值。

在完整之效率提昇之控制架構中，考量等效磁化電感為電流與該馬達轉子轉動位置之函數下，先採用模糊類神經網路來求算出電流、位置和該電感之映射關係，再運用模糊類神經網路，近似地計算出與輸出轉矩相關之電感對位置偏微分量；此外，數種需求之參數的新式估測和測量之架構與方法，包含有電阻值、電感值、互感值、轉矩值和轉速值，亦於本論文中提出，而提供其與效率提昇架構之整合和合併之可能考量；本論文也提出一類神經網路，在驅動系統未飽和運作下，乃為輸出性能判斷之核心單元，而於高比例飽和運作之系統中，則與前述模糊類神經網路共組性能判斷之雙核心。此外，於高性能切換式磁阻電動機驅動之考量下，二類就納入電阻值變動或互感影響下之性能提升架構，亦運用電流補償之做法於此論文中進行探討。

驗證所提出之相關論點之研究平台，乃針對可能運用於電動機車與洗衣機的切換式磁阻電動機而組構二系統，其實驗與模擬結果皆部份驗證了所提出架構之效能；此二式切換式磁阻電動機驅動系統實驗平台顯示了於五分之一，二分之一和全載之額定功率下，在效率提升上分別展現了百分之三點五、百分之五和百分之七點一，以及百分之三、百分之二點二和百分之五點一的效率提昇程度。

An Efficiency Improvement Strategy for Switched Reluctance Motor Drives

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ABSTRACT

A new control concept, the strategy of efficiency improvement for switched reluctance motor (SRM) drives applying derivation results based on analysis model, is proposed in this dissertation. The presented efficiency consideration and its control approach are inspired and originated from an SRM model, whereas can be realized by regulation of the ratio of the phase current command to voltage within derivatives of equivalent magnetic inductance with respect to time. Moreover, the efficiency improvement strategy is further discussed for constructing the applicable driving scheme in practical usage, operating based on the assigned regulation rule for searching the upgraded efficiency that may exist for the SRM drives by step-type variation of current command. The linking relation of parameters of SRM's model is utilized to execute commands under operation of SRM drives while no exceeding to the setting ranges according to the outputted performance requirement.

For the overall control scheme of the efficiency improving mechanism, a fuzzy neural network (FNN) system is applied to approximately compute the partial derivative of the equivalent magnetic inductance profile for the SRM with respect to the rotor position and current, while the inductance is obtained firstly by the mapping scheme of the FNN for relations among the position, current, and the inductance as well. In addition, several new estimation schemes and measurement approaches for getting the needed parameters, including the parameters of resistance, inductance, mutual inductance, torque, and speed, are also presented for considerations of the integration and combination to the efficiency improving schemes for extending its feasibility. Furthermore, an artificial neural network (ANN) is presented to establish the core unit with outputted performance judgment capability for under-saturation operation, as well as one of the dual-core operation with the FNN's scheme for high-portion saturation working. Besides, two performance enhancement schemes that can deal with the variation of the resistance or take the mutual inductance into account by current compensation are discussed for the high-performance SRM dives.

The research platforms for verification related to these issues are implemented applying two SRMs for possible applications of electrical bikes and washing machines, respectively. Simulation and experimental results partly demonstrated the validity of the capability of the proposed strategy with efficiency improvement up to 3.5 %, 5 %, and 7.1 % for one application target, and 3 %, 2.2 %, and 5.1 % to the other practice, both under the testing of ratio of 0.2, 0.5, and 1, rated power of the applied SRM drives.

誌謝

總覺得，人生即似是一齣在時間舞台上的戲，角色的扮演與戲份的安排，乃依據自我的人生理想與規劃所撰寫之生命劇本而決定；這一段博士學位之研究與學習過程，除了使我進一步地朝向教育實踐的理想而邁進外，更於生命的觀閱上，得到寶貴經驗的累積，謝謝在這段過程中所出現過的所有人、事、物，給了我無限的觀點啟發和想法之引導，讓我可以在人生的航程中，獲得猶如羅盤與星辰所提供的方位資訊，可以破浪前行而不憂偏離目的，可以享受開發新大陸的冒險經歷，而不懼迷失回行之航道。

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Nomenclature

W_r :	motor speed
V_{dc} :	DC bus voltage of the driving circuit
i:	current
V:	voltage
T_e:	outputted torque
T_l:	loading torque
B_m:	viscous coefficient
J_m:	rotor moment of inertia
Eff:	efficiency
t :	time
Suffix x:	general phase representation
Superscript A,B,C,D	specific phase representation
a,b,c,d:	
P_{in}:	input power
P_{out}:	output power
L:	equivalent magnetic inductance (inductance)
M:	*mutual inductance*
λ :	flux linkage
R:	phase resistance
i_{m1}:	the current flows through L_x
V_m:	the supply voltage
t_0:	initial analysis time for series type circuit
i_{st0}:	the current value flows through L_x at t_0
C_{m1}:	the adding capacitor
V_{m1}:	the voltage of C_{m1} for series type circuit
V_{st0}:	the voltage of C_{m1} at t_0
i_{m2}:	the current flows to the branch leg with L_x
i_m:	the supply current
t_{01}:	initial analysis time for parallel type circuit
i_{pt0}:	the current value flows through L_x at t_{01}
C_{m2}:	the adding capacitor for parallel type circuit
V_{m2}:	the voltage of C_{m2}
V_{pt0}:	the voltage of C_{m2} at t_{01}

Chapter 1 Introduction

Electric machine drives play a crucial role in many industrial, commercial, information processing, transportation and consumer product applications and usually represent a significant portion of the overall costs of the end-product they find themselves embedded in. In this drive scheme, motor is no doubt the most important element. The impact and improvement of computer related technology upon the development of electric machine drives is without equal. In this dissertation, for the applied electric machine, switched reluctance motor (SRM), the development overview based on motor design, control theory, and driving circuit can be illustrated as Fig.1-1. SRM drives rooted in the blossoming field of power electronics, have traditionally been dependent on power semiconductor and IC development driven mainly by the needs of high-volume computer, consumer electronics and telecommunications applications. In the 1990s, emerging high-volume automotive subsystem and applications for household appliance drives began spurring development of application-specific devices and solutions designed for drives.

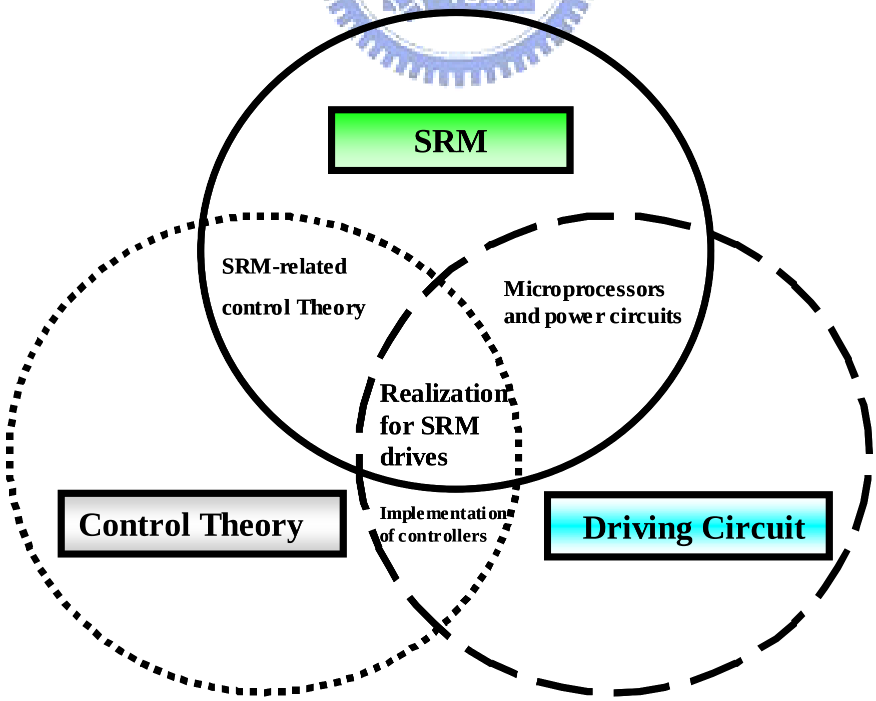


Figure 1-1: The overview of electric machine drives research focuses based on SRM.

Figure 1-1 shows the kernel intersection of drives realization and it is much efficient in development for recent technology supporting in latest two decades. SRM is characterized by high power density, high robustness with temperature up to 600 centigrade degrees, simple structure for low materials and manufacturing cost, and wide speed range, is double- salience that having no winding in its rotor. Because of the above advantages, the research for putting it into more extensive industrial and daily-life applications attracts a lot of attention recently. Though SRM takes advantages on several aspects, performance and related estimation methods still need more related efforts involved to make SRM apply to high precision servo-level applications. However, SRM has drawbacks such as high non-linearity of coupling parameters relation, which is difficult to improve performance of controllers design, described in [31,67]. Obviously, the future research of SRM should not only focus on motor design, driving circuit development, and control strategies that applied, but also take the motor parameters estimation and identification into account, which all are the important requirements for various kinds of SRM drives. A comparative information of the popularly applied motors among DC brush motor, induction motor (IM), permanent magnet synchronous motor (PMSM), and SRM is arranged in Table 1-1. To date, induction motors have mainly been used for heating, ventilation and air conditioning (HVAC) applications, however, there is significant research being done worldwide for evaluation of such applications while an SRM is utilized. So far the overall cost involving the market-volume issue for SRM drives makes it uneconomical to expand their application to home appliances but it is the objective of this dissertation achieved by presenting an optimizing efficiency strategy to make the SRM own more advantages while considering it as applicable usage conforming to the strictly regulated energy saving with acceptable performance. The needed driving circuit to the SRM is similar to a brushless DC motor (BLDC) or AC vector variable frequency drive (VFD). Insulated gate bipolar transistor (IGBT) are typically used in an SRM drive's inverter section. As such, SRM drives product design today is focused on producing cost-effective custom designs for different SRM designs under development for specific applications. Based on our experience within this research and discussion according to the visiting information from TECO Corp., SAMPO Technology Corp., and DELTA Electronics, Inc., the requirement to enhance the functionality of the SRM drives is one important gap to make them with more attention to consider the feasibility to putting them into present high-volume applications, no matter in household usage or industrial practice. The current trend in SRM drives' development is to design the drive to meet the specific requirements such as efficiency improving, being a useful way to discuss the controller operation mechanism to the drive and may contribute a lot for some specific applications.

Besides, under some survey information during the evaluation phase of this research, a topic that can be clearly found is the need for energy conservation and higher efficiency is global. It affects both products and processes. It spans industrial, commercial and consumer applications. It may be driven both by government mandate and by the need for greater productivity in order to be competitive in increasingly-global markets according to industrial opinion. In addition, in our daily life, a product with better efficiency regulation capability is expected as well. So far, energy conservation and efficiency manifests itself in the drive market by increasing the demand for use of drives in fans, pumps and compressors used in building HVAC systems, industrial HVAC systems, water and wastewater pumping systems, building water delivery systems, chemical processing, utility equipment, material-handling equipment, household appliances, commercial refrigeration, etc.. A strategy that may result in a significant improvement in efficiency of the SRM drives is naturally becoming the driving force to proceed this research.

The design process for the topics discussed in the consideration of both traditional and advanced research and development related to design problems of products usually focused on the functionality. The needs (N), applying approaches(A), bringing benefits(B), and owning competitions(C), that is, so-called NABC analysis method, and the opinions can be concluded easily from the former description in needs, benefits, and competitions, hence, the approaches that construct the highly connected NABC chains should be devoted for researcher in this field. Based on author’s observation, an efficiency improvement strategy for SRM drives is needed and it motivates me to find a useful approach to achieve this goal. Moreover, the strategy can also drive development of more advanced control schemes to optimize performance for SRM drives is another expectation.

The important factor in electrical drives is high efficiency and low cost. The SRM has the rugged and simple structure in which no winding, no magnets and no brush on the rotor, thus, its manufacturing techniques is relative simple and the manufacturing cost is lower than the other machines, such as synchronous machine, DC machine, and induction machine. The SRM has had inherent advantages on those issues, but needs more feasible approach to promote its features for acceptance in applications. It can be observed that the number of SRM commercial product is still very small, and only few of these have volumes of more than 100,000 per year[54].

Table 1-1: The comparison for some motor in drive systems.

Types / Items	DC brush motor	IM	PMSM	SRM
Volume	×	※	○	◎
Cost of material	※	○	×	◎
Cost of manufacturing	※	○	※	◎
Reliability	○	※	※	◎
Speed range	※	○	※	◎
Power range	○	◎	※	◎
Robustness	※	○	※	◎
Efficiency	○	※	◎	○
Torque ripple	○	○	○	×
Noise	○	○	○	※
Position information	Without-applicable	Without-applicable	Needed	Needed
Driving circuit	Needed	Without-applicable	Needed	Needed
Main application	Servo	Servo/Power	Servo	Power

◎:Excellent ○:Better ※:Good ×:Inferior

1.1 Motivations and Objectives

Switched reluctance motor, the electrical machine utilizes reluctance torque, is gaining acceptance in variable speed applications worldwide. In electrical machines related research, one of the most challenging tasks is the complexity of the implementing for the efficiency control, mentioned in[1,3,13,14,41,48,50,56,57,59]. Only few have considered the efficiency improvement among the SRM drives studies issued on that by a simple control strategy for ease of practical applications. For the efficiency research, most efforts have been devoted to the SRM structure design and it can be clearly realized from [19,48,49,53], which is focused on the modified type and special design for motor phase number, flux path, and air gap parameters to achieve the efficiency improvement. The circuit topologies for SRM drives are also taken to be the research topics for the efficiency research, such as dual-decay converter, C-dump inverter, and modified (n+1) switch converter, which have been described in [56,57], respectively. Besides of that, the current profile via switching angle control is also applied to involve the efficiency related research opinions [18]. To integrate the considerations originate from a motor model research, a method that being proposed is the optimizing efficiency control which makes use of the parameter information based on the equivalent magnetic inductance, hereafter can be described as inductance, without losing the conventional performance requirement in a simple way. The optimizing efficiency control is a novel current command decision method for adding the efficiency regulation capability for the SRM drives[24,25,75,76]. In practice, the proposed optimizing efficiency strategy needs some information of parameters to form a control scheme with considerations of actual operation states. Thus, followings will also arrange the related research topics for parameters that may be needed or helpful to this efficiency improving approach. .

Inductance:

For improving the performance of SRM drives, several approaches had been proposed and focused on the inductance measurement related issues. The frequency of inducing signal would be useful to enhance the measurement precision, addressed in [6,12,33,34,36,37,60]. The position estimation using the information of inductance profile to excite the stator winding at appropriate instant is applied referred to [58,44]. Besides of that, the inductance information is also taken in SRM sensorless drives applying resonant method, linked control strategy design, and flux estimation, respectively, in [58,60,33,34].

Mutual inductance:

A method that provides dynamically analytical information reflecting accurate working properties of SRM is needed [4,10,11,24,26,27,29,54,55]. However, most analytical schemes are either based on the simplified model or sophisticated mathematical computations, which means elimination of some parameters that are not measurable during operation or complex analytical functions may be involved. Broadly speaking, the SRM adjacent phases have overlapping current conduction, and hence there exists mutual flux linkages between these adjacent phases that result in mutual inductance between the windings. Some researchers have been devoted to the related studies for the influence of the mutual inductance in SRM drives [30,54]. Thus, the practical SRM drives system applied in the applications, such as high-speed and high-performance drives, to contain identification scheme of all affection parameters, including the mutual inductance, has been the trend in drive technology as long as it allows an easy utilization relationship with the control system [29,54,55]. Besides of that, many control strategies have been utilized to try to achieve both the improvement of parameters estimation and drives performance [26,29,30,54,55].

Resistance:

In sensorless drive, the parameter of phase resistance, hereafter can be called resistance, plays a crucial role to the speed estimation [2,61]. The resistance of switched reluctance motor may change with temperature obviously, and it has been the goal to find the value under operation described in [61,65]. Especially in low-speed operation, the influence of the resistance may lead to a larger portion to the estimation of speed[31,65]. Generally speaking, direct measurement, one-point probe measurement, two-point probe measurement, linear four-point measurement, and nonlinear measurement can be applied in resistance measurement, however, it may not be accepted in practice for consideration of convenience of usage and cost related issues.

Speed:

Designs of Sensorless' SRM drives have eliminated the encoder in systems. Most sensorless methods monitor the current and voltage in each winding of the motor in order to estimate the inductance from which position can be inferred by the use of look-up tables. In order to reduce cost and increase reliability and minimize sensitivity to line voltage and temperature variations, new sensorless techniques are under development, such as Mavrik Motors (U.S.) staggered tooth design motor system. Other techniques shape an induced voltage in an inactive phase of the motor adjacent to an energized phase in order to estimate the shaft position of the motor's rotor. Related researches on the parameters identification and estimation for SRM have moved toward on-line estimation from off-line operation and computation described in [25,31]. Furthermore, there are more researches focusing on the combination of parameters estimation applied in sensorless drives discussed in [31,45].

Torque:

Many methods proposed for estimation of torque address fundamental issues about requirement of reflecting its accurate properties [38,41,52]. However, most analytical schemes are based on the simplified linear torque model and sophisticated mathematical computations may involve, or require large numerical tables for looking up [22,23,39,40,42]. Furthermore, the linear model contradicts the fact of high proportion magnetic saturation operation for SRM, which means that the neglect of nonlinear effect probably yield poor computation results. Likewise, during on-line operation, the model structures and parameters of SRM may differ from the standstill ones due to the related effects of saturation and losses, especially at high current, which makes the previous schemes practically difficult to implement and thus can only be accurately described by a nonlinear model **[**52,64,45**]**. Besides, some parameters of SRM are highly nonlinear functions of phase current, rotor position, and rotor speed. They are not measurable during operation, and are hard to be expressed with analytical functions **[**40,44**]**. Hence, a estimation model is needed herein to construct a torque model to improve the torque evaluation capability. Moreover, it is also expected that being with the information acquired and computed from the torque estimation model, it can be applied for further speed estimation based on the motor electromagnetic derivation and it is applicable for speed sensorless applications.

1.2 Technology Trends from Literature

To observe more information for SRM drives, some databases are chosen to depict the trend of the related research, which include INSPEC (an indexing service for physics, engineering, computer science, and related fields. It also can be said as the database for Physics, Electronics, and Computing), Explore of IEEE (Institute of Electrical and Electronics Engineers), USPTO Patent Full-Text and Full-Page Image Databases, esp@cenet, and JP-Patnet Industrial Property Digital Library.

1.2.1 Academic Research Statistics

Figure 1-2 shows the published papers related to switched reluctance motor drives from 1994-2001 in INSPEC database. It keeps to attract the research effort to being involved. Fig. 1-3 illustrates the states of the research topics during this statistic period. It can be told that the research for actual application, which is the issue with minimum paper amount, is the key to narrow the gap to actual market **[**69**]**. A cross-field research statistics is made as well, shown in Fig.1-4, in which there are 66 papers may include at least two main topics on motor orientated design, control, overall drives, applications, and so forth.

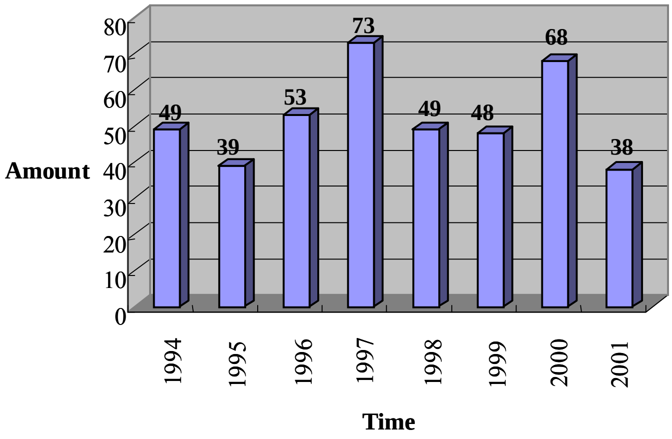


Figure 1-2: Information of paper amount statistic from INSPEC(time from 1994-2001).

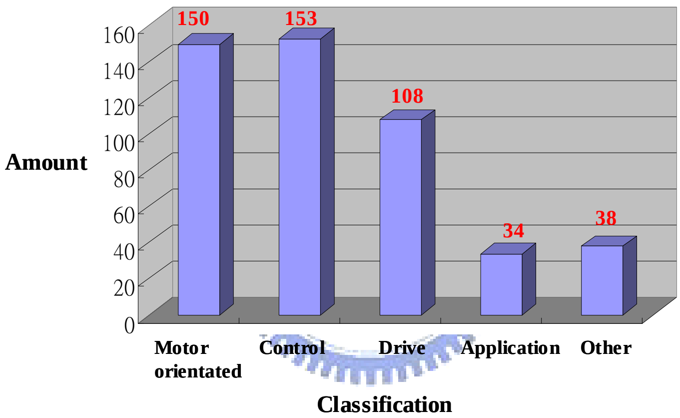


Figure 1-3: Information of research topics from INSPEC(time from 1994-2001).

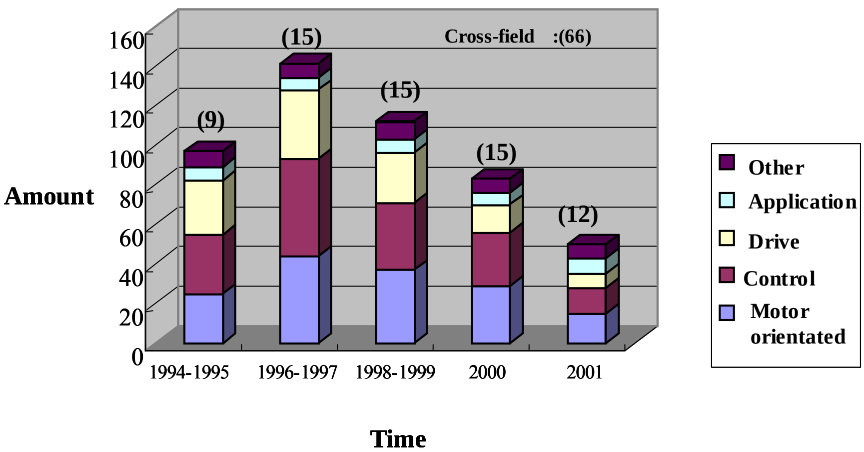


Figure 1-4: Information of cross-field research from INSPEC (time from 1994-2001).

By the similar analysis procedure, Fig.1-5 to Fig.1-7 illustrate the results of information from IEEE database. They obviously show the similar trends and development focuses. Fig.1-8 shows the amount order among the counties of the world. United States of America takes the leading role and Taiwan ranked in Top-10 in the time interval from 1994-2001. However, the drives of SRM exists a gap due to the relative less application with concerning issues in actual practice even the academic papers and published materials keeping growth, and most conferences related to electric drives include whole sessions on SRM .

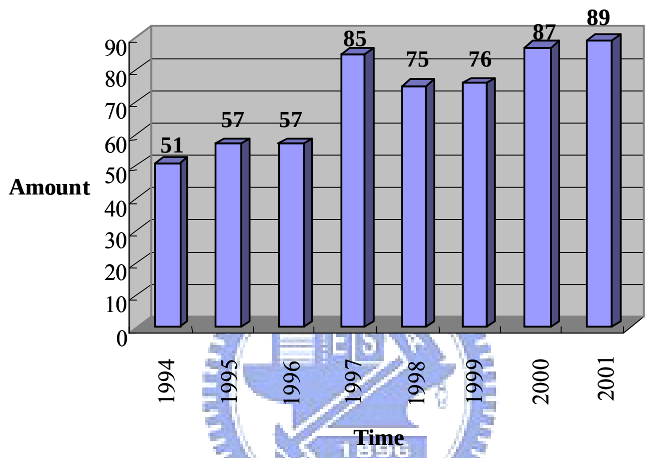


Figure 1-5: Information of paper amount statistics from IEEE(time from 1994-2001).

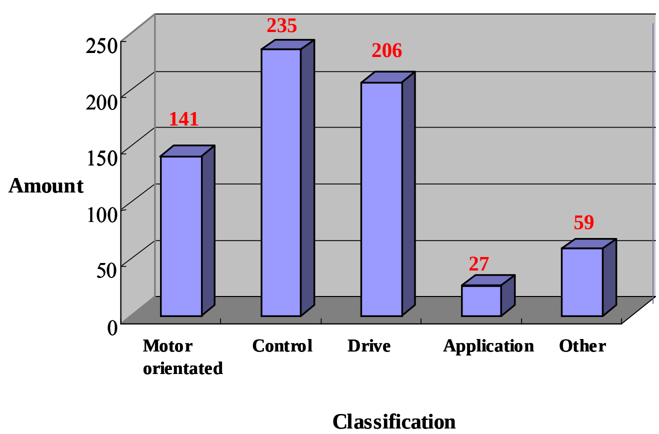


Figure 1-6: Information of research topics from IEEE(time from 1994-2001).

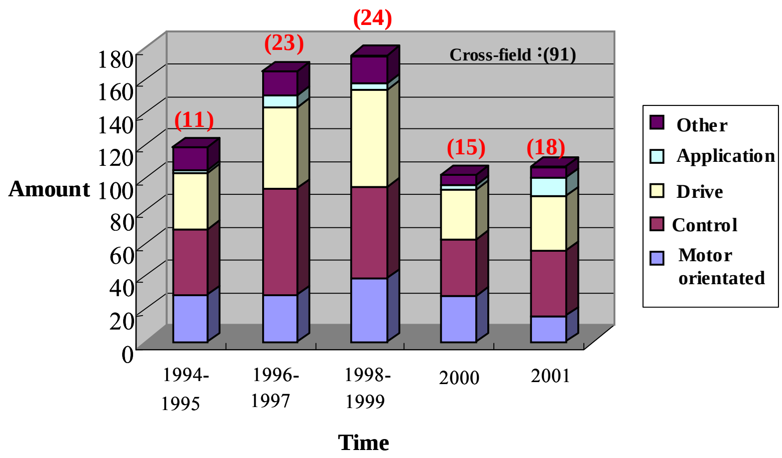


Figure 1-7: Information of cross-field research from IEEE(time from 1994-2001).

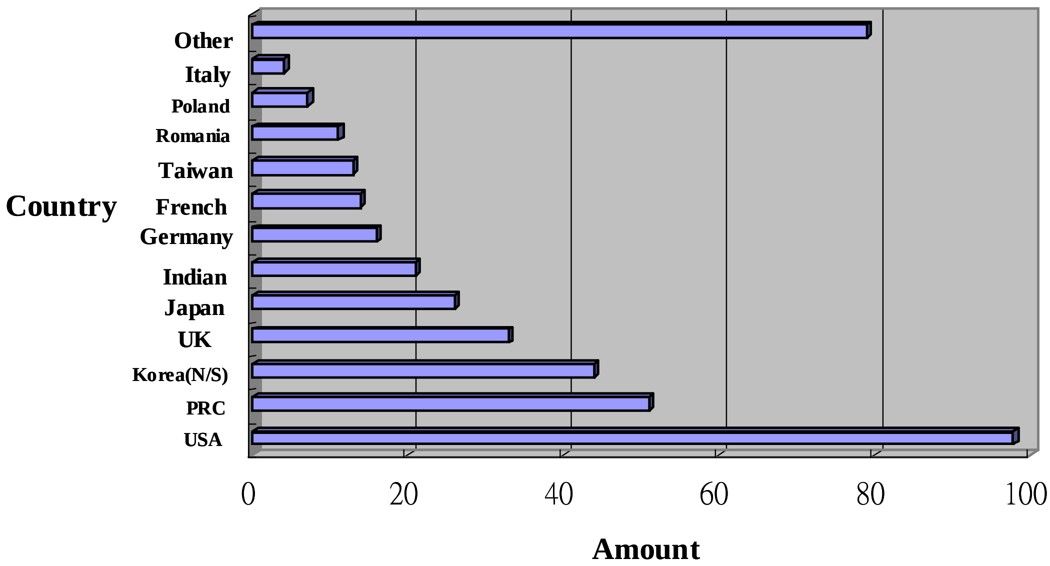


Figure 1-8: Information of paper amount based on countries from IEEE(time from 1994-2001).

For narrowing the discrepancy between research and application, a novel strategy to the efficiency topic should be one solution to breakthrough the bottleneck. From the statistic results from 2002 to 2005 based on IEEE data, arranged in Table 1-2, an interesting opinion can be concluded as that the efficiency-related topic is a field attracting research effort with a ratio around 10% of the totally published papers in each year, however, it worth more research to be devoted in that for shortening the application gap and apparently forming a research group conforming to today's energy requirement.

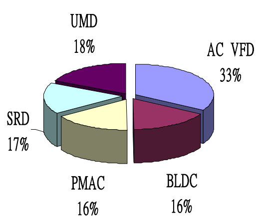
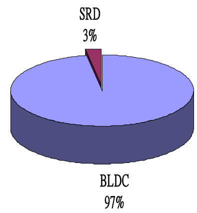
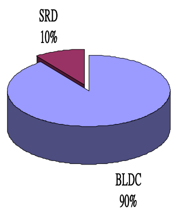
Table 1-2: Information of efficiency-topic paper.

Time	Paper amount	Efficiency-related paper amount	Ratio(%)
2002	215	27	12.6
2003	214	16	7.5
2004	209	17	8.1
2005	112	12	10.7

1.2.2 Patent Information

By the information of related seminar from DELTA Electronics, Inc., which was partly presented referring the information of "A Global Market Research and Industry Outlook Report on Electronic Motor Drives 2001-2005" by Drives Research Corporation of Laguna Hills, California USA, Table 1-3 arranges the portion of the usages in specific product markets, which depict the mainly applying usages for the issued patents.

Table 1-3: SRM-related markets' volume in 2005.

Applications	Clothes washer drum	Air conditioner fans	Refrigerator fans
Portions			

Note 1: SRD denotes SRM drives.

Note 2:PMAC is expressed for permanent magnet AC motor.

Note 3: UMD is expressed for universal motor dirves.

The power semiconductor technology on which SRM drives are based can be considered mature. IGBTs were introduced in the late-1980s. By the mid-1990s, most AC and brushless drives manufacturers had learned how to use, apply and control IGBTs or MOSFETs and were using them in their low-voltage drives systems.

Table 1-4 arranges some remarkable applications of SRM drives in the world for applications close to power source usage.

Table 1-4: Some application examples in product types.

Company/organization	Product type/ function	Features
Tridelta Industries Inc.	Floor cleaning machine. Electric bike.	Low start current. Multi-functions. Variable speed.
Emerson Electric Co.	High-volume rolling cylinder-type washing machine.	Higher efficiency. Without gear box.
Emerson Motor Co.	Vacuum pumping.	Speed range more than 31000 r/min. Life cycle more than 10000 hours. High speed ratio.
Ford Automobile Co.	Power steering.	High power density. Low cost.
AMC, Densei and Westinghouse Electronics Co.	Traction car.	High power.
Airplane's manufactures in UK	Flight brake plate actuator.	High power. High reliability.
Military of USA	Generator. Jet's petroleum pump.	High reliability. Conforming to military standard.

More information related to those products, it can be found by the following companies or web addresses as:

Emerson Electric(USA), Emerson Motor(USA)(www.srdrives.com), Tridelta Industries, Westinghouse(USA), Allenwest(UK), Densei(Japan), AMC(www.amc-inc.com), Motorsoft(www.motorsoftmotors.com), and so forth.

Example 1:

Switched Reluctance Motor	Traction Drives
AccuSwitch-3000 VSR Servo Controller	TracMotion-2000 VSR Traction Drive
HighPower VSR Servo Motors	TracMotion VSR Traction Motors

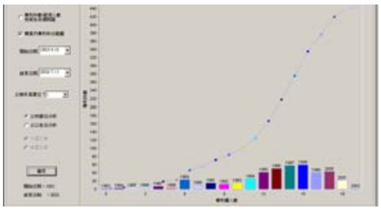
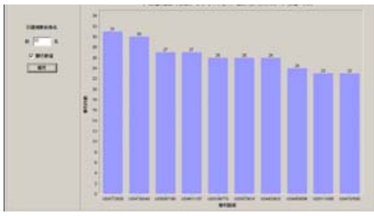
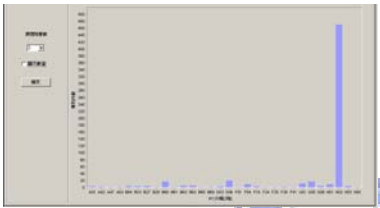
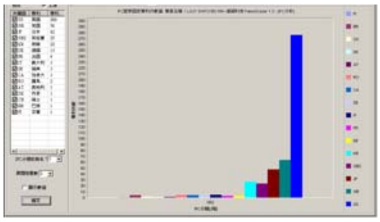
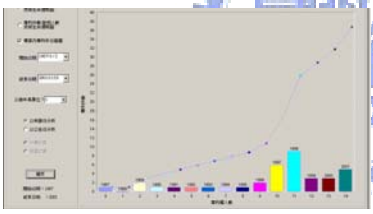
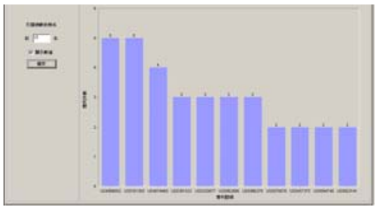
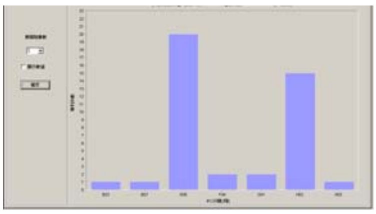
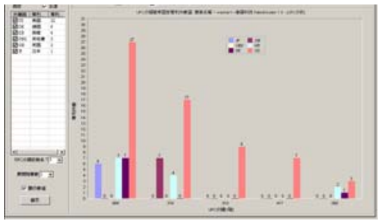
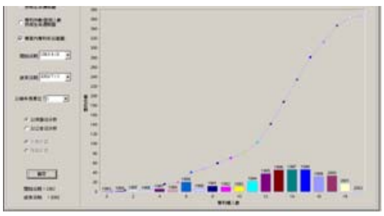
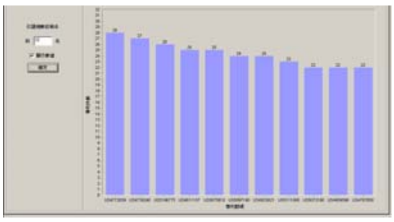
(Product information from AMC Web page)

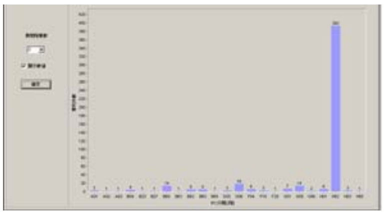
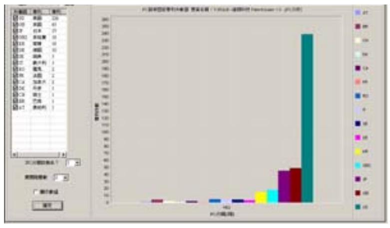
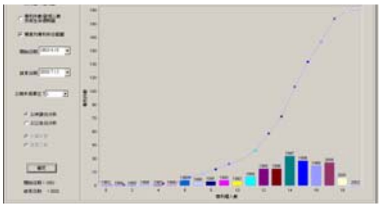
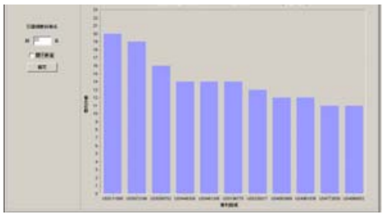
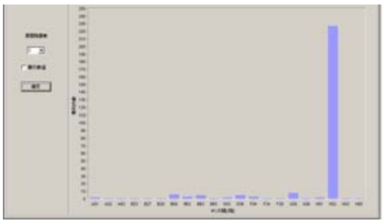
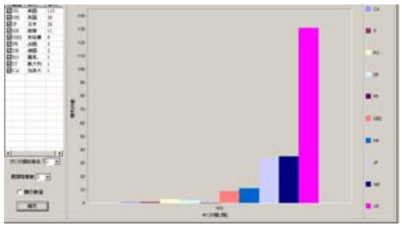
Example 2:

(Product information from Emerson web page)

High rate of filing patents exist especially in the United States, Europe, and Japan [67]. Followings will present some statistics information based on these regions. The statistic plots of US patents including life cycle of technology, the leading countries in patent issued amount, international patent classification (IPC), and the leading patents based on cited number, are arranged in Table 1-5.

Table 1-5: The statistic plots based on US issued patents (issued before 2003)

Main key words	Statistic plots using software of PatentGuider (Learning Tech. Co.)	
SRM	 Lift cycle of technology	 Leading cited patents
	 IPC classification	 Leading countries
Washing machines +SRM	 Lift cycle of technology	 Leading cited patents
	 IPC classification	 Leading countries
SRM + torque	 Technology lift cycle	 Leading cited patents

<table>
<tr><td></td><td>
IPC classification</td><td>
Leading countries</td></tr>
<tr><td rowspan="2">SRM
+
torque
+
noise</td><td>
Technology lift cycle</td><td>
Leading cited patents</td></tr>
<tr><td>
IPC classification</td><td>
Leading countries</td></tr>
</table>

Based on the patent information in the United States of America, it is clear that, the development of SRM and SRM drives is still laying in a growth phase for a long-term analysis for technologies. Besides, during the same ending time of 2003, patents issued by Japan related to keywords of SRM reach number of 321(the related items are collected in Appendix C), however, the strategy of motor design using interior permanent magnet (IPM) is the main stream. Meanwhile, there merely own 75 patents in Euro-patent database with the latest data collection date of May 2002 using the searching keyword of SRM. By the two statistic sources, system enhancement coming from control opinions still contribute less for SRM drives.

As the former mentioned high-volume rolling cylinder-type washing machine (brand: MAYTAG) using the SRM produced by Emerson Co.(specified as SRM 2 and the related information is given in Appendix A and Appendix B), the related introduction can be found in the web (http://www.srdrives.com/html/apps/emerson.htm) as shown in Fig.1-9.

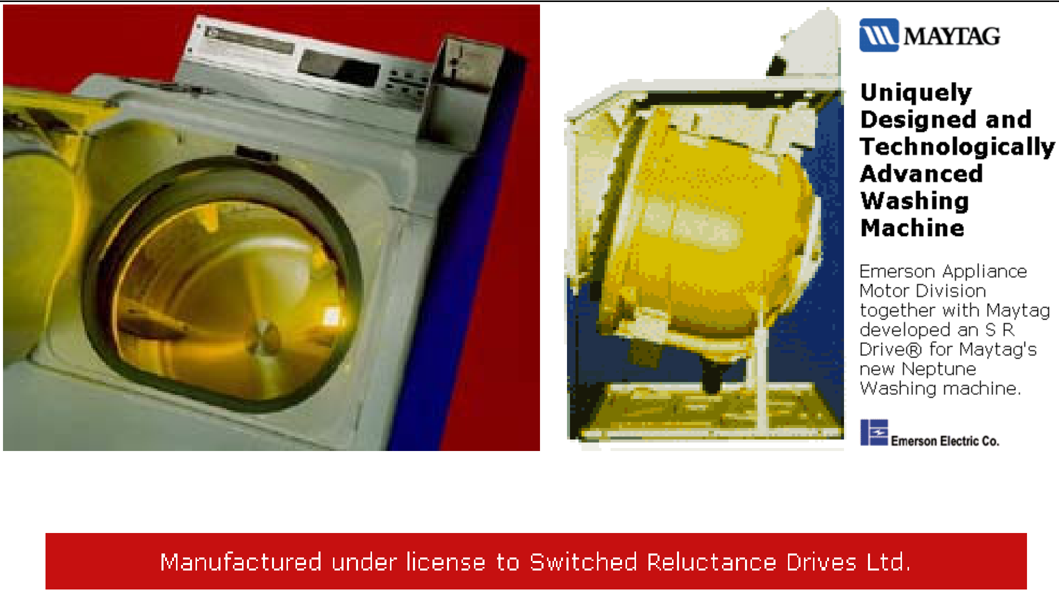


Figure 1-9: The product-type SRM drives with patent protection.

To observe more development trend and information of the leading company, Emerson Electric Co, Table 1-6 arranges the related patents (issued by US) for this product shown in Fig. 1-9.

Table 1-6:MAYTAG washing machine related patents

Number	Date	Title	Abstract
5,467,025	**November 14, 1995**	Sensorless rotor position measurement in electric machines	A sensorless rotor position measurement system comprises a digital processor (6) which receives signals from current and flux sensors (7, 8) of the current and flux associated with a phase winding of the machine. The measurement of the current and flux is enabled at a predicted reference rotor position. The measurements are compared with stored values of current and flux and an error between the actual and the predicted reference position calculated. The calculated rotor position can then be used to predict the instant the rotor will reach the next reference position.
5,637,972	**June 10, 1997**	Rotor position encoder having features in decodable angular positions	A rotor position encoder for an electric motor includes a discate member mounted to rotate with the rotor shaft. The encoder has a set of radially extending features formed with angularly evenly spaced leading edges and unevenly spaced trailing edges. The leading edges induce a signal in a sensor that corresponds to the relative timing of power switches for each motor phase, The trailing edges define a cyclical code by which motor controlling circuitry is able to determine the phase of rotation of the rotor and thus establish the correct power switch actuation sequence. An electric motor control system and methods of starting electric motors also provide significant advantages.
5,539,293	**July 23, 1996**	Rotor position	A rotor position encoder for an electric motor includes a discate member mounted to rotate with the rotor

		encoder having features in decodable angular positions	shaft. The encoder has a set of radially extending features formed with angularly evenly spaced leading edges and unevenly spaced trailing edges. The leading edges induce a signal in a sensor that corresponds to the relative timing of power switches for each motor phase. The trailing edges define a cyclical code by which motor controlling circuitry is able to determine the phase of rotation of the rotor and thus establish the correct power switch actuation sequence. An electric motor control system and methods of starting electric motors are also shown.
5,563,488	**October 8, 1996**	Control of switched reluctance machines	A control system for and method of controlling a switched reluctance generator to maintain stable control of the generator in the continuous current mode. This is achieved by sensing the load on the generator, the speed of the rotor and the position of the rotor with respect to each phase winding in order to derive switching command signals to maintain the volt-seconds applied to the winding in each phase period so as to inhibit progressive flux growth in the phase windings by actuation of the controller switches.
5,545,964	**August 13, 1996**	Control of switched reluctance machines	A control system for and method of controlling a switched reluctance generator to maintain stable control of the generator in the continuous current mode. This is achieved by sensing the load on the generator, the speed of the rotor and the position of the rotor with respect to each phase winding in order to derive switching command signals to maintain the volt-seconds applied to the winding in each phase period so as to inhibit progressive flux growth in the phase windings by actuation of the controller switches.
5,469,039	**November 21, 1995**	Control of switched reluctance machines	A control system for and method for controlling a switched reluctance generator to maintain stable control of the generator in the continuous current mode. This is achieved by sensing the load on the generator, the speed of the rotor and the position of the rotor with respect to each phase winding in order to derive switching command signals to maintain the volt-seconds applied to the winding in each phase period so as to inhibit progressive flux growth in the phase windings by actuation of the controller switches.
5,446,359	**August 29, 1995**	Current decay control in switched reluctance motor	A control circuit (10) for controlling the residual or tail current decay in a single phase or polyphase SRM winding when a phase is switched from active to inactive. A Hall-effect type sensor (30) senses rotor position of the SRM. Current flows through a winding (W) of the motor when the motor phase winding is active; and, current flow into the winding decays to zero when the phase becomes inactive. Semiconductor switches (22) direct current flow into the winding when the phase is active and then redirect residual energy in the winding between an energy recovery circuit and an energy dissipation circuit when the phase becomes inactive. A PWM signal generator (44) provides PWM operating signals to the switches to control current flow first into the winding and then between the recovery and dissipation circuits. A control module (42), or microprocessor (52) with a PWM output, is responsive to rotor position information for controlling operation of the PWM signal generator. The signal generator provides PWM signals having one set of signal characteristics when

			there is current flow to the winding and a different set of characteristics when there is not. This produces alternate intervals of zero voltage and forced commutation residual current decay while the phase is inactive. During the decay interval, both the PWM frequency and pulse duty cycle are variable to produce a current decay scheme which eliminates ringing and motor noise.
5,461,295	**October 24, 1995**	Noise reduction in a switched reluctance motor by current profile manipulation	Apparatus (10) for controlling the current profile (P2) in a single or polyphase SRM (M) during the active portion of a phase. Switches (S1, S2) are closed during an active portion of a phase to direct current flow into a winding (W). A Hall effect sensor (14) and other sensors are used to sense various operating parameters of the SRM. A PWM signal generator (16), or microprocessor (20) is responsive to the sensor inputs to provide PWM operating signals (G2) to at least one of the switches to control current flow to the winding. The operating signals modulate the switch(es) for switch operation to be controlled as a function of the signal characteristics of the operating signals. This allows the current supply to the winding to be in accordance with the current profile. According to the profile, current flow is initially rapidly increased from zero to a peak value (I.sub.p ') when the phase becomes active. The current is then allowed to decrease from this peak to a second and lesser value (I.sub.p) by the time the phase becomes inactive. Current decays from this second value to zero when the phase becomes inactive. The transition in the current profile which occurs when the phase switches from active to inactive is no longer an abrupt transition, but is rather a more moderate one. This smoother transition reduces the amount of ringing in the motor, which normally occurs when current flow into the winding ceases, thereby to reduce motor noise.
5,786,646	**July 28, 1998**	Method and apparatus for aligning a rotor position transducer	An improved method and apparatus for aligning and mounting a rotor position transducer element to the shaft of an electric motor. One embodiment of the invention is is an apparatus and method for aligning and mounting a RPT element in the form of a shutter assembly. Specifically, the shutter contains a perforated extended portion that surrounds the opening for the shaft. An annular clamp ring, made of metal or other suitable material slip fits over the protruded portion of the shutter. The clamp ring can also further comprise so-called "ears" or other non-annular portions that cause it not to be circular in cross-section. The clamp ring allows the shutter to be securely fastened to the shaft of the rotor without causing torsional force which could cause misalignment of the shutter with respect to the optical sensor, or misalignment of the rotor to the stator assembly, or both.

As shown in Table 1-6, control strategy plays a portion to the protection of the product development, but the concept to improve the efficiency still is lacked.

1.3 Contributions of the Dissertation

The main contributions of this dissertation are addressed by outlined items as follows:

1)The scheme of optimizing efficiency control which applies the parameter's linking relation is proposed.

2)The operation of efficiency regulation is realized by programming the ratio of phase current command to voltage within the inductance information under operation.

3)The FNN estimation scheme for parameters is constructed and integrated into the optimizing efficiency control scheme.

4)The mentioned parameters estimation schemes that can/may be integrated/combined into the proposed SRM drives are discussed as well as the analysis of the applicability of efficiency observer in future research.

5)The survey information of academic papers and issued patents of SRM and SRM drives are both presented in some statistics forms.

6)New approaches based on an artificial neural network (ANN) computation scheme related to parameters such as inductance, resistance, and outputted speed and torque are presented with capability of application of SRM sensorless drives and has been applied to providing the performance judgment information to the optimizing efficiency mechanism.

7)Two concepts of current command compensators operating under variations of resistance and existence of mutual inductance, which can enhance the capability of SRM drives including the proposed optimizing efficiency strategy, are presented.

8)Simulation models have been constructed for the SRM drives development.

9)Information and discussion on applicable drive schemes are arranged for reference of future research and emerging applications.

10)A verification system applying two SRMs is organized and realized by the platforms intended to demonstrate the SRM drives system in a efficient way.

Increased emphasis on energy conservation is leading researchers to look for better approaches to use energy efficiently. Usually, the drive for the need of more efficient power devices, results in the expense of higher cost, and complicating the cost-performance trade-off issues. The proposed optimizing efficiency strategy can deal with it within appropriate cost in hardware but with portable software concept that may be realized in a embedded system or module-like IC.

1.4 Organization of the Dissertation

The work presented in this dissertation has peoceeded according to the research procedure expreesed in Fig.1-10 and organized in eight chapters. These eight chapters are structured as follows:

Chapter 1 is entitled “ Introduction”. The details follow as the topics of 1.1 Motivations and Objectives, 1.2 Technology Trends from Literature, 1.2.1 Academic Statistics, 1.2.2 Patent Information, 1.3 Contributions of the Dissertation, and 1.4 Organization of the Dissertation, which arrranges the information for the states related to this research.

Chapter 2 is entitled ” Preliminary Concept and Applying Strategy”. It follows the sections of 2.1 Modeling of Switched Reluctance Motors, 2.2 Primary Classification for Switched Reluctance Motor Drives, 2.3 Utilizing Computation Scheme Based on Fuzzy Neural Networks, 2.3.1 Four-Layer Feedforward Fuzzy Neural Networks, 2.3.2 Partial Derivative Computation Scheme, and 2.4 Simulations and Analysis, which prensent the preliminary backgound for this research.

Chapter 3 is entitled ” Parameters Identification Approaches” . The new parameters' estimaiton or measurement approaches are derived and discussed in this chapter. It follows the sections of 3.1 Inductance Estimation, 3.1.1 Off-Line Scheme, 3.1.2 On-Line Scheme, 3.2 Resistance Estimation, 3.3 Mutual Inductance Estimation, 3.4 Speed and Torque Estimations, 3.4.1 Artificial Neural Network-Based Scheme, 3.4.1.1 Speed, 3.4.1.2 Torque, and 3.4.2 Fuzzy Neural Networks-Based Scheme.

Chapter 4 is entitled " Efficiency Control for Switched Reluctance Motor Drives" . The efficiency improvement mechanism and concept is introduced in this chapter. The operation and concpet of the optimizing concpet is disscussed in this chapter as well. The sections comes as 4.1 Traditional Dealing Opinions, 4.2 Reluctance-Based Analysis Concept, 4.2.1 Scheme with Inductance Information, 4.2.2 Scheme without Speed Information, 4.3 Power Relation for Optimizing Efficiency Planning, 4.3.1 Optimizing Concept, 4.3.2 Electrical Signals Planning, 4.4 Efficiency Regulation Capability, 4.5 Constant Efficiency Application, 4.5.1 Applied Speed Range, 4.5.2 Applied Torque Range, and 4.6 Efficiency Observer Application.

Chapter 5 is entitled " Performance Enhancement Study" . Two current command compensation schemes are described in this chapter. The details followed by 5.1 Compensation Rule for Resistance Variation, 5.2 Compensation Rule for Mutual Inductance Effect, and 5.3 Verifications.

Chapter 6 is entitled " System Implementation" . It follows the sections of 6.1 Introduction to Schemes and Functions, 6.2 Hardware Description, 6.2.1 Block Diagrams for Functionalities, 6.2.2 Efficiency Computation, and 6.3 Computer-Based Processing Structure. The system functionalities of circuits and the connections for schemes are described and illustrated.

Chapter 7 is entitled" Experimental Test and Analysis." It describes the sections of 7.1 Experimental Setup, 7.2 Experimental Results, and 7.3 Performance Comparison. Several experimental results are given in this chapter to validate the performance and feasibility of the proposed optimizing efficiency control strategy.

Chapter 8 is entitled ”Conclusions”. All achievements are summarized and the research conclusions are drawn herein. Some achievements are re-described in this chapter and it includes the sections of 8.1 Outlined Achievements and 8.2 Future Works.

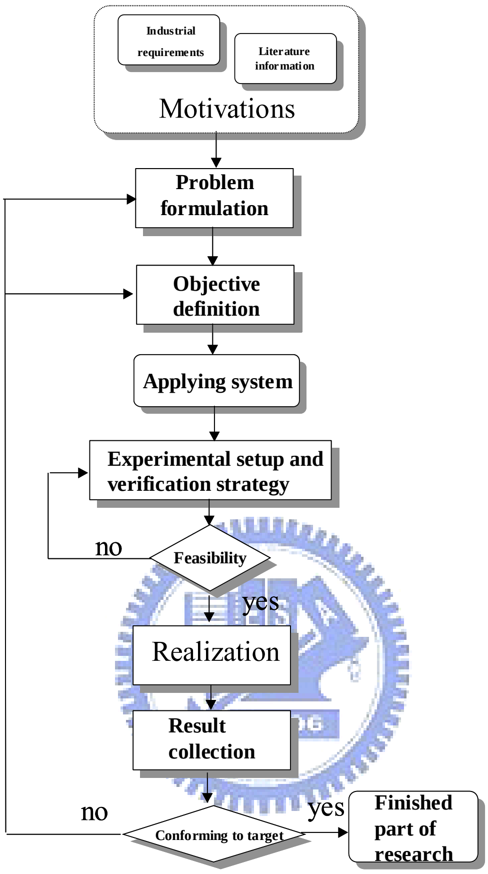


Figure 1-10: The operation flowchart of this research.

A systematic illustration for the dissertation, shown in Fig.1-11, that may help in further understanding for the purpose of organization of the research.

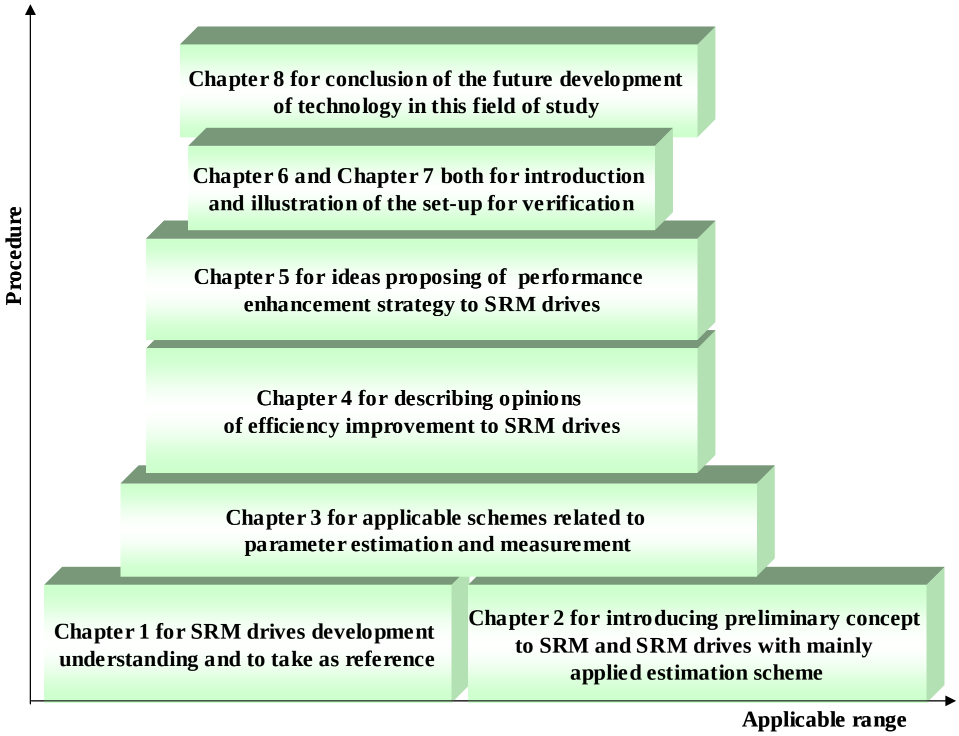


Figure 1-11: The illustration of the organization for this dissertation.

Chapter 2 Preliminary Concept and Applying Strategy

System modeling is a fundamental problem in system theory and many engineering problems as well as the important research topic in design and analysis of development tasks. A model with competence of obtaining the behaviour of the controlled plant is requested to support and enhance the control developments. In recent years, computational-intelligence techniques such as artificial neural networks, fuzzy logic, genetic algorithms, combined neuro-fuzzy approaches, and other nonlinear and biologically inspired techniques have become valuable tools to describe and help to upgrade variable control related indexes under plants with variable parameters effect, described in [5,25,42,41,52]. Fuzzy neural network (FNN), owning the adaptive mapping and fault-tolerant features, is usually a good choice for tackling the modeling problem. Because of highly nonlinear characteristics of the SRM, all the control schemes can not be avoided to deal with the control force related to these parameters, as classified in 1.1, even not fully considerable[7,8,15,17,21,22,23,40,63]. Normally, it may be realized by using a look-up table, i.e., the look-up table uses stored magnetic characteristics to provide the reference value, but it takes relative large space requirement to memory in processing unit. In addition, the fault tolerant capability is in lacked to such arrangement. As description above, FNN is taken to construct the mapping among inductance-related information, such as current, position, and torque, and introduced the applied scheme in this section as well.

2.1 Modeling of Switched Reluctance Motors

The machine shown in cross section in Fig.2-1 has eight stator poles and six rotor poles and is denoted as an 8/6 SRM. Each stator pole is surrounded by a coil, and the coils of two opposite stator pole are connected in series to form each of the four phase windings. The four phase windings are connected in sequence to a power converter that may be normally trigger either by a set of signals from shaft position sensor or various estimation-based strategies actuation method.

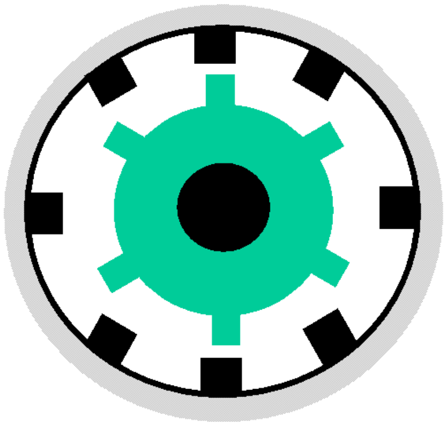


Figure 2-1: Cross section of an 8/6 SRM.

The direction of rotation can be driven to be either clockwise or counterclockwise by controlling the sequence of the current injecting to phase windings. To achieve high torque and power from a given frame size, most SR motors are operated so that the poles are significantly saturated when aligned and energized.

The reluctance of SRM changes with rotor position and phase current, which apparently affects the SRM's output. The phase voltage equation of SRM can be expressed in the form of

$$V_x = i_x \cdot R + \frac{d\lambda_x}{dt} \tag{2-1}$$

where suffix x means phase a, b, and c, or successive letters; V, i, R, and λ respectively denote phase voltage, phase current, resistance, flux linkage (product of phase current i and inductance L).

To find an expression for the motor torque production, the energy relation is firstly written as the field energy, which can be arranged as Eq.(2-2):

$$W'_{fld}(i,\theta) = i \cdot \lambda - W_{fld}(\lambda,\theta) \tag{2-2}$$

where θ, W_{fld}, W'_{fld}, are the rotor position, field energy, and co-energy, respectively. The field energy and co-energy are nonlinear functions as pairs of parameters (current i, and rotor position θ) and (flux linkage λ, and rotor position θ).

To consider further of the electromagnetic relation, the expression of

Eq.(2-3) can be depicted as:

$$i = \frac{\partial W_{fld}(\lambda,\theta)}{\partial \lambda}\Big|_{\theta=constant} \tag{2-3}$$

And, the expression for instantaneous torque production per phase can be written as Eq.(2-4):

$$T_{fld} = \frac{\partial W'_{fld}(i,\theta)}{\partial \theta}\Big|_{i=constant} \tag{2-4}$$

where T_{fld} means instantaneous torque.

The equations illustrated above will be utilized to establish the SRM output torque estimation model without assumption of linearly magnetic operation and certainly the nonlinear effect is taken into account.

To derive further, if taking the phase current as the control input, the parameters relation can be rearranged based on Eq.(2-1) and to be derived in the form of

$$\frac{di_x}{dt} = \frac{1}{L_x}(V_x - R\cdot i_x - w_r \cdot i_x \cdot \frac{\partial L_x}{\partial \theta}) \tag{2-5}$$

where w_r denotes rotation speed.

From the relation between inductance variation with respect to rotor position, the derivation of torque expressed in Eq.(2-4) can be equivalently depicted as:

$$T_{fld} = (i^2/2)\cdot {}^{\partial L_x}\!\!/_{\partial \theta}\,\Big|_{i=constant} \tag{2-6}$$

Then, the further derivation result can be given as:

$$\frac{\partial L_x}{\partial \theta} = T_{fld}/(i^2/2)\,\Big|_{i=constant} \tag{2-7}$$

Based on the information of torque value given by Eq.(2-4), the speed estimation can be achieved by the relation of rearrangement of Eq.(2-5) as:

$$w_r = ((-L_x \frac{di_x}{dt} + V_x) / i_x - R)) / (\partial L_x / \partial \theta) \tag{2-8}$$

The torque generation of SRM can be illustrated as Fig.2-2.

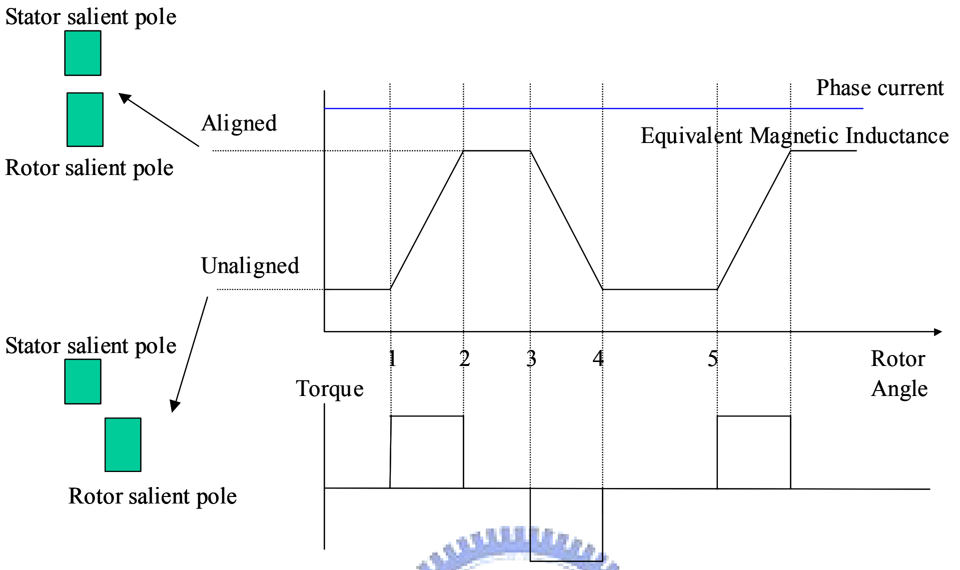
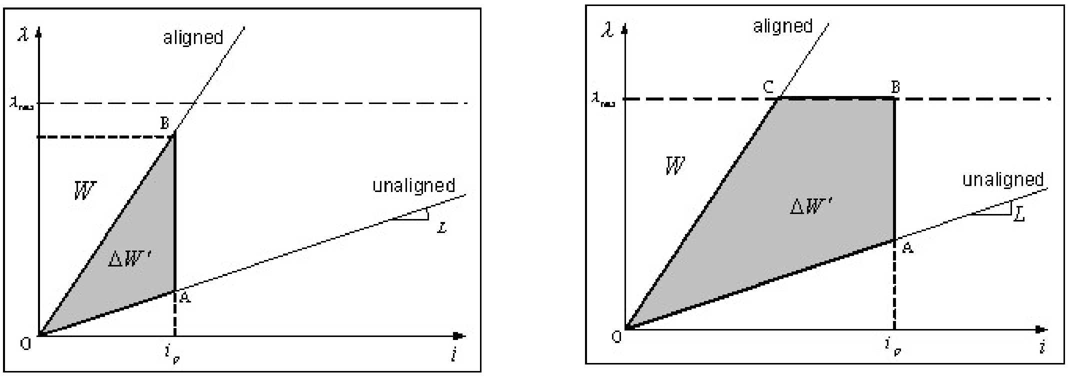


Figure 2-2: The torque-current-inductance relation.

To explain the work operation cycle, Fig. 2-3 shows the simple illustration of the magnetizing under saturated and unsaturated statuses.



(a) (b)

Figure 2-3: The work plots for the magnetizing of the operation: (a)Unsaturated magnetizing; (b) Saturated magnetizing.

2.2 Primary Classification for Switched Reluctance Motor Drives

For drives schemes of the electric machines, information of mechanical output, such as torque and rotation speed, is crucial and highly required. Figure 2-4 shows the conventional drive scheme of the SRM. To obtain the torque and speed values by estimation algorithms is the objective of this model.

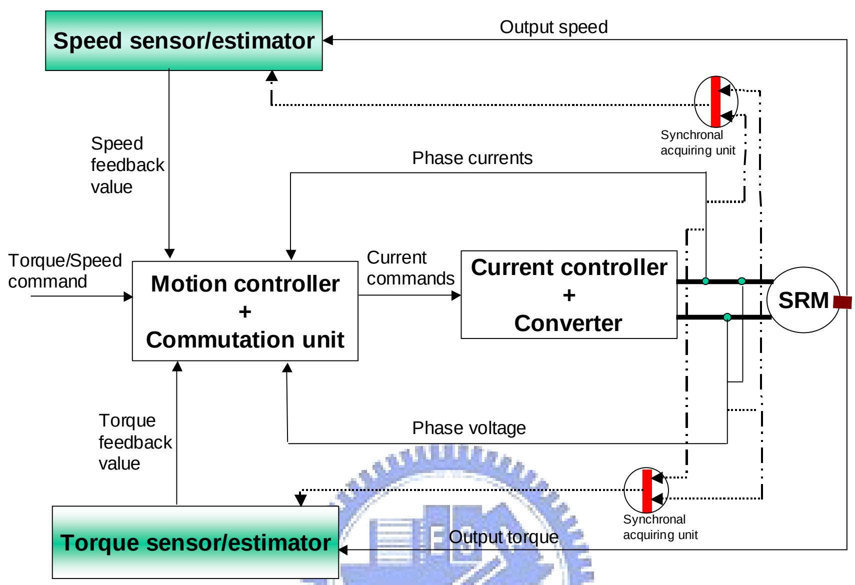


Figure 2-4: The conventional SRM drive scheme.

The primarily applying driving circuits include Bifilar converter, Miller converter, C-dump converter, split converter, bridge converter ,etc. which all proposed by the current flow concept according to the requirements[32,43,47].

Basically, the design and analysis concept that related to the converter can be illustrated as Fig. 2-5.

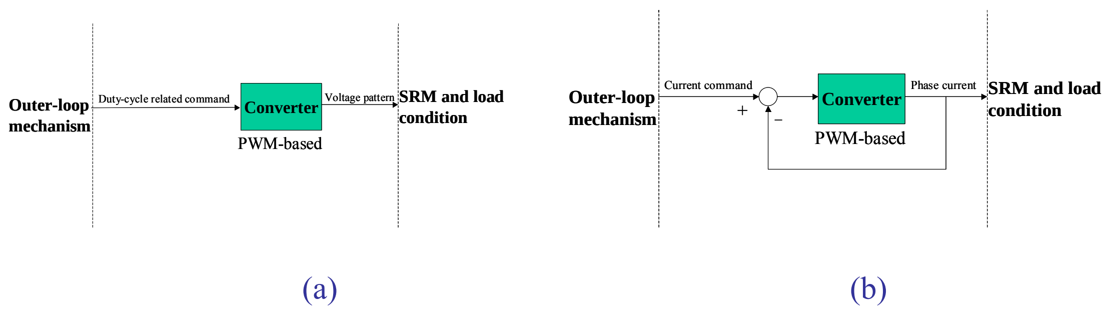


Figure 2-5: The simple analysis scheme for the drives based on circuit functions:(a) Voltage-controlled scheme;(b) Current-controlled scheme.

2.3 Utilizing Computation Scheme Based on Fuzzy Neural Networks

FNN is featured by the learning capability of the neural networks with the simplicity of fuzzy logic, which is useful for nonlinear mapping, learning capability, and not time-consuming. FNN's techniques have been used in control and identification of sophisticated systems. The FNN that applied to construct the relation among of current, inductance, and torque are given in this section and the details follow.

2.3.1 Four-Layer Feedforward Fuzzy Neural Networks

The proposed FNN-based scheme, shown in Fig.2-6, that owns the parameter mapping as well as performance evaluation capability, using linking relation of SRM's parameters. The analytical method is based on obtaining the difference between the information from actual motor and counterpart model and then to activate the FNN's weight updating procedure. After setting up the items of input and output for the network, the mapping and estimation can start and operate.

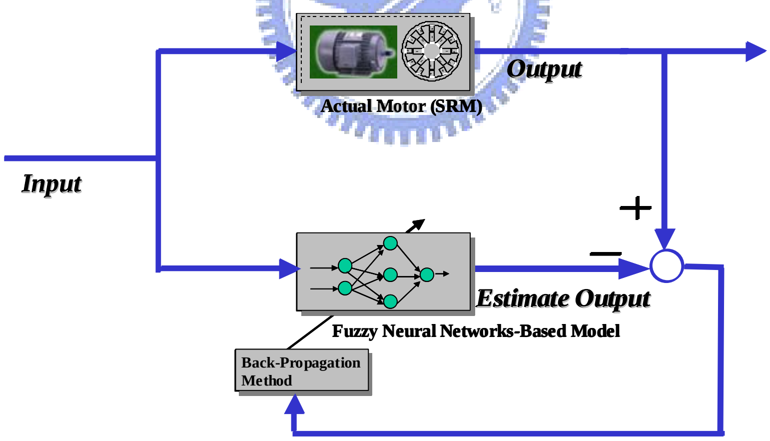


Figure 2-6: The FNN-based training scheme.

According to the development experience of high performance SRM drives, the pre-measured/on-line flux linkage λ related information, such as the relation between the inductance and electric properties, is needed. It is based on this opinion then the estimation flow can be illustrated as Fig. 2-7 within appropriate sets of bound(1) and bound(2) for both of accuracy consideration and computation action.

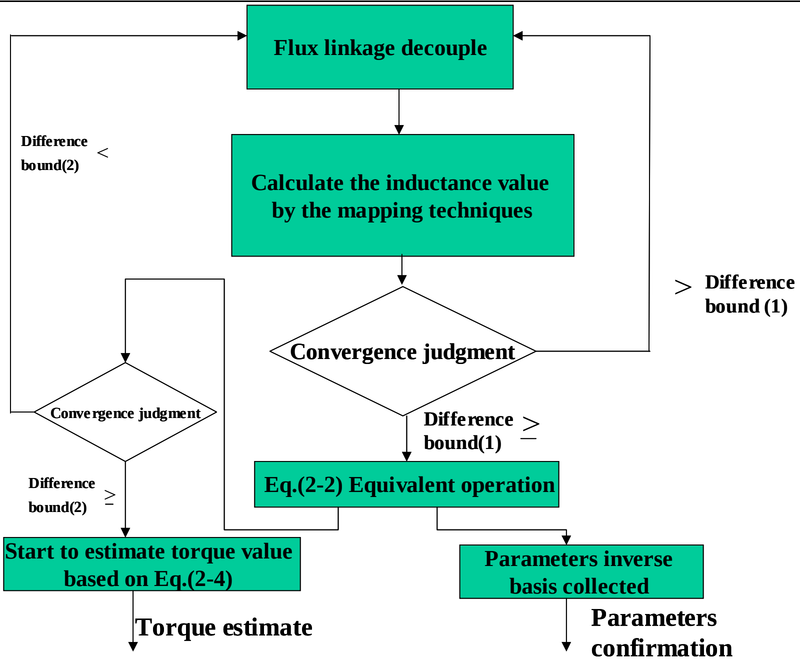


Figure 2-7: The operation flow of estimation.

The network computation algorithms of this FNN-based model applied for torque estimation and can provide for speed computing will be introduced in this section.

The network structure adopted in this proposed FNN-based model is shown in Fig.2-8. The four-layer structure is distinguished by its direct construction of fuzzy rules without other adjustment [7,8].

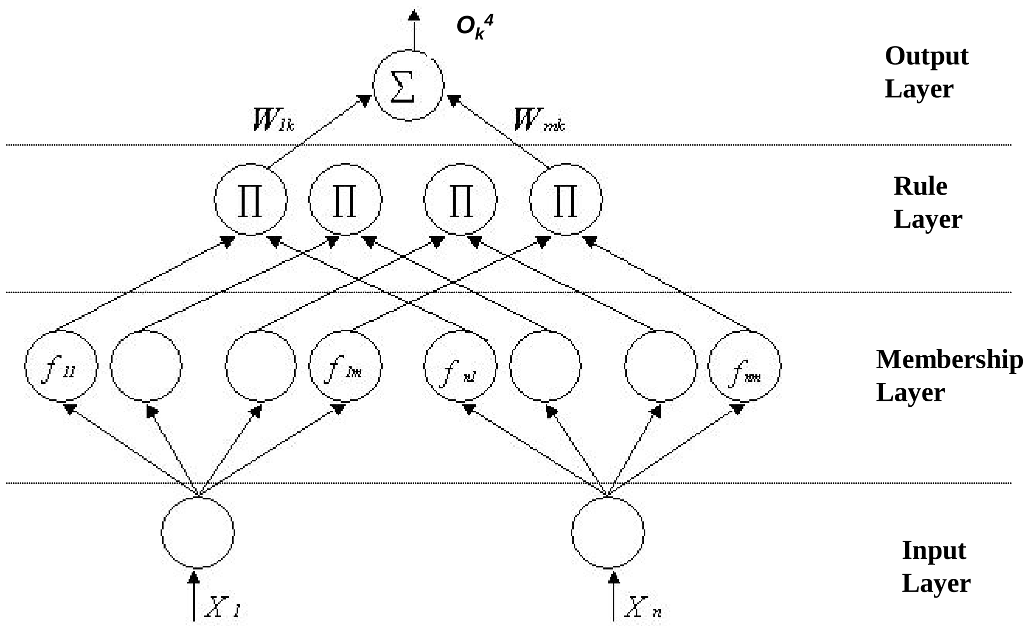


Figure 2-8: The applied four-layer schematic representation for the *k*th output.

Two denotations for ease of explanation are expressed as the aggregation function $g^c(.)$, and the nonlinear activation function $f^c(.)$, respectively; meanwhile, the superscript c indicates the layer number. Followings will present the mathematical views of the signal propagation, basic functions, and its learning concept in each layer of the FNN's structure.

1)Layer1-input layer: For the ith node at this layer, the net input and the net output O_i^1 can be represented as:

$$g_i^1(x_i^1;W_i^1) = W_i^1 \cdot x_i^1 = x_i$$

$$O_i^1 = f_i^1(g_i^1) = g_i^1(x_i^1;W_i^1) \tag{2-9}$$

2)Layer2-membership layer: In layer 2, each node performs a membership function. The Gaussian function is used as the membership function. For the jth node, say:

$$g_{ij}^2\left(x_i^2;W_{ij}^2\right) = g_{ij}^2\left(x_i^2;m_{ij};\sigma_{ij}\right) = -\frac{\left(x_i^2 - m_{ij}\right)^2}{\sigma_{ij}^2} \,.$$

$$O_{ij}^2 = f_{ij}^2\left(g_{ij}^2\right) = \exp(g_{ij}^2)^2 \tag{2-10}$$

where x_i^2 means the ith input vector to the nodes of layer 2. m_{ij} and σ_{ij} denote, respectively, the mean (or center) and variance (or width) of the Gaussian function in the jth node.

3) Layer3-rule layer: The related links are implemented in this layer by the product operation, represented in the form of

$$g_j^3\left(x_{ij}^3;W_{ij}^3\right) = \prod_{i=1}^{n} W_{ij}^3 \cdot x_{ij}^3$$

$$O_j^3 = f_j^3\left(g_j^3\right) = g_j^3\left(x_{ij}^3;W_{ij}^3\right) \tag{2-11}$$

The connection weight between the jth node of the membership layer and the ith input of the rule layer is not adjusted, that is, $W_{ij}^3 = 1; \forall i, j$.

4) Layer4-output layer: Layer 4 performs the defuzzification to obtain numerical outputs. The weight W_{ij}^4 between the ith rule node and the jth output node represents the consequence fuzzy singletons. Besides, the applied FNN is modified to be non-normalized type operation for advantages of less training time and simpler relation of input-output sensitivity [7], expressed as:

$$O_j^4 = g_i^4\left(x_i^4; W_{ij}^4\right) = \sum_{i=1}^{m} W_{ij}^4 \cdot x_i^4 \qquad (2\text{-}12)$$

5) Learning concept: A error back-propagation (BP) algorithm, based on a gradient descent computation approach, is employed to adjust the weights of this FNN. The main goal of learning is to minimize the energy (or cost) function, chosen as

$$E = \left(d(t) - O(t)\right)^2 / 2 \qquad (2\text{-}13)$$

where *O(t)* is the output of the FNN ,and *d(t)* means the desired output for the input pattern. If W_{ij} is the adjusted parameter, then the learning rule that used is

$$W_{ij}(t+1) = W_{ij}(t) - \eta \cdot \frac{\partial E}{\partial W_{ij}} + \alpha \cdot \Delta W_{ij}(t)$$

$$\Delta W_{ij}(t) = W_{ij}(t) - W_{ij}(t-1) \qquad (2\text{-}14)$$

where η represents the learning rate, and α, between 0 and 1, is the momentum parameter.

Then, the learning algorithm based on error BP method is described and introduced as below (see Table 2-1).

Table 2-1:Learning algorithms for the applied FNN.

Description	Algorithms	Related definitions
Layer 4	$-\frac{\partial E}{\partial W_{ij}^4} = -\frac{\partial E}{\partial O_j^4} \cdot \frac{\partial O_j^4}{\partial W_{ij}^4}$ $= (d_j^4 - O_j^4) \cdot x_i^4 = \delta_j^4 \cdot x_i^4$ The consequence weights are updated by $W_{ij}^4(t+1) = W_{ij}^4(t) + \eta_W \cdot \delta_j^4(t) \cdot x_i^4(t) + \alpha_W \cdot \Delta W_{ij}^4(t)$	$\delta_j^4 = (d_j^4 - O_j^4)$, denotes the error signals with respect to the jth output node. Where η_w, and α_w are the parameters for adjusting.
Layer 3	$\delta_i^3 = -\frac{\partial E}{\partial g_i^3}$ $= -\sum_{j=1}^{p} \frac{\partial E}{\partial O_j^4} \cdot \frac{\partial O_j^4}{\partial O_i^3} \cdot \frac{\partial O_i^3}{\partial g_i^3} = \sum_{j=1}^{p} \delta_j^4 \cdot W_{ij}^4$	P is the number of the output nodes. No weights adjusted in this layer. Only the error signal δ_i^3 needs to be computed.
Layer 2	$-\frac{\partial E}{\partial m_{ij}} = -\frac{\partial E}{\partial g_j^3} \cdot \frac{\partial g_j^3}{\partial O_{ij}^2} \cdot \frac{\partial O_{ij}^2}{\partial m_{ij}}$ $= \delta_j^3 \cdot (\prod_{i=1}^{n} O_{ij}^2) \cdot \frac{2(x_{ij}^2 - m_{ij})}{\sigma_{ij}^2}$ $= \delta_{ij}^2 \cdot \frac{2(x_{ij}^2 - m_{ij})}{\sigma_{ij}^2}$ and $-\frac{\partial E}{\partial \sigma_{ij}} = -\frac{\partial E}{\partial g_j^3} \cdot \frac{\partial g_j^3}{\partial O_{ij}^2} \cdot \frac{\partial O_{ij}^2}{\partial \sigma_{ij}}$ $= \delta_j^3 \cdot (\prod_{i=1}^{n} O_{ij}^2) \cdot \frac{2(x_{ij}^2 - m_{ij})^2}{\sigma_{ij}^3}$ $= \delta_{ij}^2 \cdot \frac{2(x_{ij}^2 - m_{ij})^2}{\sigma_{ij}^3}$ The update rules are expressed as $m_{ij}(t+1) = m_{ij}(t) + \eta_m \cdot \delta_{ij}^2 \cdot \frac{2\left(x_{ij}^2 - m_{ij}\right)}{\sigma_{ij}^2} + \alpha_m \cdot \Delta m_{ij}(t)$ $\sigma_{ij}(t+1) = \sigma_{ij}(t) + \eta_\sigma \cdot \delta_{ij}^2 \cdot \frac{2\left(x_{ij}^2 - m_{ij}\right)^2}{\sigma_{ij}^3} + \alpha_\sigma \cdot \Delta \sigma_{ij}(t)$	$\delta_{ij}^2 = \delta_j^3 \cdot \prod_{i=1}^{n} O_{ij}^2$, means the error signal with respect to the jth term set of the ith input. m_{ij}, and σ_{ij} are two parameters related to update rules, respectively. In the meanwhile η_m, η_σ, α_m, and α_σ are parameters of learning rate and momentum, respectively, related to the update rules.
Layer 1	Not needed.	Not needed.

A training scheme of FNN that conforms to the procedure depicted in Fig.2-6 is used to construct the inductance L mapping relationship for SRM. The inductance is a highly related parameter to the flux linkage λ, which is the function of current i, and rotor position θ[32,47]. Hence, L is chosen to be the output of FNN. Then, the related data is collected by pre-measurement procedure and to be taken as the input of this FNN. Therefore, the mapping relationship is achieved by the preliminary knowledge described above.

2.3.2 Partial Derivative Computation Scheme

From Eqs.(2-1) to (2-4), it can be realized that the partial derivatives computation is the critical requirement for accurate analysis of the SRM drives for the output performance evaluation. The FNN applied in this dissertation is also featured as a computational scheme that can deployed for partial derivatives computing. The primary concept for explaining is based on the membership functions of the FNN, all Gaussian functions, are differentiable for any order.

For simplicity, just the kth output of the layer 4, $O_k^{(4)}$, is shown since the other outputs have the same structure but different connection weights. The representation of $f_{ij}(.)$ is used to denote the membership function of the jth term set of the ith input and other labels are the same as the precedent. The outputs of each layers of the FNN are respectively expressed as:

$$O_1^{(1)} = X_i \tag{2-15}$$

$$O_{ij}^{(2)} = f_{ij}(X_i). \tag{2-16}$$

$$O_j^{(3)} = \prod_{i=1}^{n} O_{ij}^{(2)}. \tag{2-17}$$

$$O_k^{(4)} = \sum_{j=1}^{m} W_{jk} O_j^{(3)} \tag{2-18}$$

Clearly, from Eq.(2-18), the partial derivative can be obtained in the form of

$$\frac{\partial O_k^{(4)}}{\partial x_i} = \sum_{j=1}^{m} W_{jk} \frac{\partial O_j^{(3)}}{\partial x_i} \tag{2-19}$$

By Eq.(2-17), it can be realized that $O_{ij}^{(2)}$ is a function of only x_i. Then, from Eq.(2-13), the following results can be derived as

$$\frac{\partial O_j^{(3)}}{\partial x_i} = \prod_{p=1, p\neq i}^{n} O_{pj}^{(2)} \cdot \frac{dO_{ij}^{(2)}}{dx_i}$$

$$= \prod_{p=1, p\neq i}^{n} O_{pj}^{(2)} \cdot f_{ij}^{'}(x_i) \tag{2-20}$$

$$= \frac{O_{pj}^{(3)}}{O_{ij}^{(3)}} \cdot f_{ij}^{'}(x_i) \tag{2-21}$$

Substituting Eq.(2-20) into Eq.(2-19), the partial derivatives computation can be done in this FNN by

$$\frac{\partial O_k^{(4)}}{\partial x_i} = \sum_{j=1}^{m} W_{jk} \cdot \frac{O_j^{(3)}}{O_{ij}^{(2)}} \cdot f_{ij}^{'}(x_i) \tag{2-22}$$

The partial derivatives can be obtained by replacing the membership functions with their derivative functions with the ith input since $O_k^{(4)}$ is the linear combination of the product of the functions of single variable.

2.4 Simulations and Analysis

The FNN-based model is the main computation structure to develop a estimation scheme for the SRM drives in this dissertation. The FNN introduced in the former section is taken to construct the FNN-based estimation model of torque and to estimate speed. Its overall computation flow has shown in Fig. 2-8[22]. There are three major networks of the FNN-based model for obtaining the torque and speed values. Here, the FNNs, labeled as FNN 1, FNN 2, and FNN 3, will be explained as followings.

1) FNN 1: It is to make use of the mapping capability of the network to construct the relation between inductance L and data pair of current i and rotor position θ, defined as "inductance model".

2) FNN 2: Based on Eq.(3), the computation requirement for field energy W_{fld}, flux linkage λ, and current i is satisfied by the partial derivative computing capability of the FNN. The field energy is taken as the comparison parameter with flux linkage to substitute into Eq.(2-2) to obtain the co-energy W'_{fld} for the succeeding FNN3 operating. The error BP algorithm is actuated by the difference between the computing $\tilde{i}$ and data i by FNN2, which also needs to set up a computing switch to transmit the FNN2 output while the difference is small enough. Here, the FNN2 function block is defined as "energy value mapping" for the field energy being the consideration parameter.

3) FNN3: As Fig. 2-9 shown, the FNN3 will complete the final computation to obtain the SRM output torque. To provide the accurate estimate torque, the partial derivative computing is needed. The information from FNN1 and FNN2 is taken to operate FNN3, respectively. The FNN3 is named as "torque estimation" on the basis of Eq.(2-4), and the BP algorithm is operated by the difference between FNN3 mediate estimate co-energy $\tilde{W}'_{fld}$ and co-energy W'_{fld} of the computing results of FNN2.

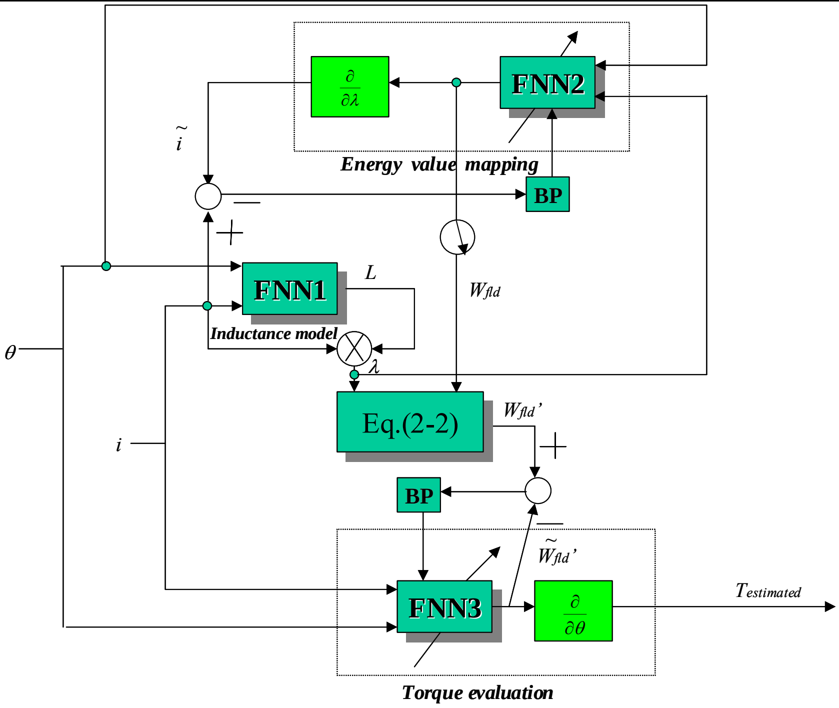


Figure 2-9: The overall schematic representation of the FNN analysis model for torque computation.

As shown of Fig.2-9, the estimated torque from FNN3 can be utilized to compute the speed by Eq.(2-6) to Eq.(2-8). Figure 2-10, then, illustrates the modified scheme that the applied FNN to compute the motor speed, that is intended to be utilized if needed and a high-performance computing unit is embedded.

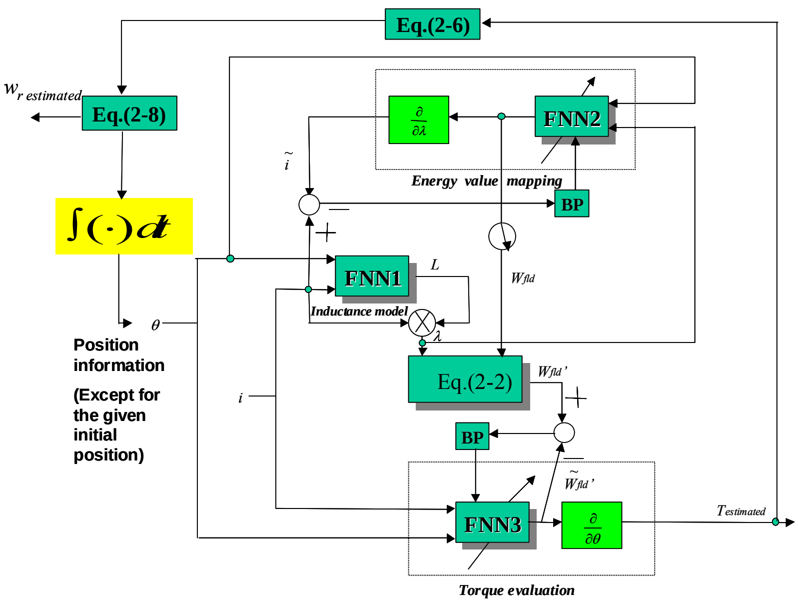


Figure 2-10: The applicable scheme of the FNN analysis model for speed computation.

The verification scheme for demonstrating the proposed FNN-based model is shown as Fig. 2-11[23]. The controller scheme is based on the proportional-integration (PI) control for speed-loop and the current-loop controller is to utilize the hysteresis control to regulate the current value by the appropriate error limit for tracing the desired current value.

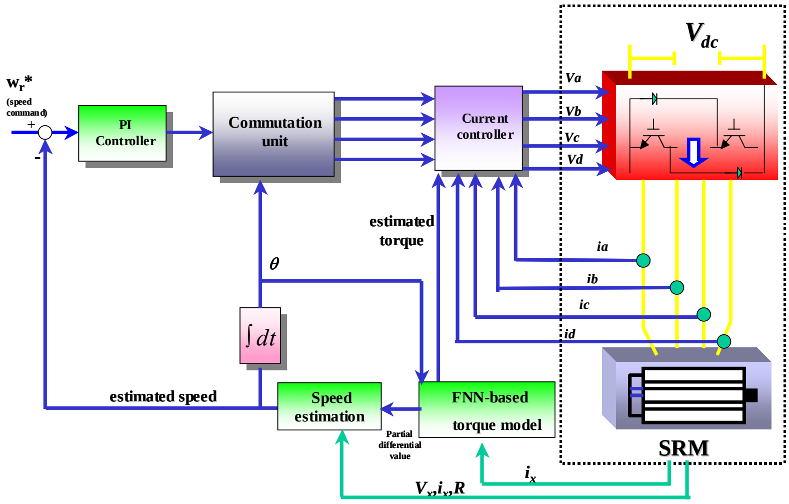


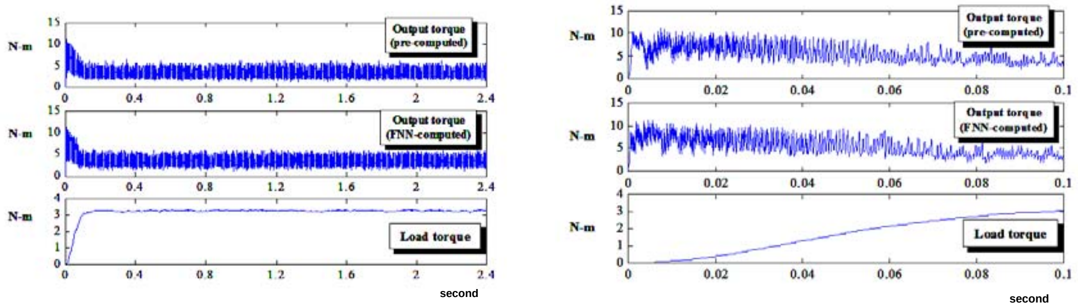
Figure 2-11: The overall SRM drives scheme for verification.

The parameters of SRM, say SRM 1, taken for verifying and evaluating of the proposed FNN are listed in Appendix A and Appendix B. In addition, the data sampling time is set to be 1/10000 second.

Based on the scheme of Fig. 2-9, the speed commands set for simulation are rated speed and 1/40 rated speed, respectively, for showing the competence of the FNN-based model while operating at high and relative low speed range. The loading torque is set to be related to the speed as the relationship:

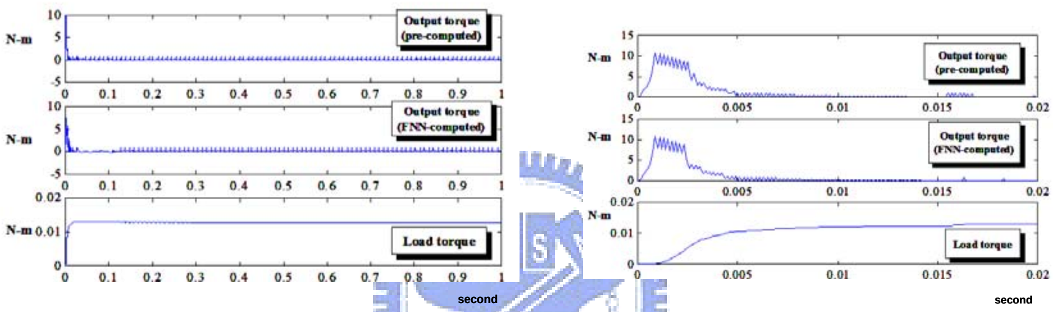
Loading torque=0.00002 × angular velocity

By the pre-computed torque information, the verification results for operating at rated speed command, both in complete testifying period (0~2.4 second) and transient state (0~0.1 second), are figured in Fig. 2-12. Figure 2-13 shows the FNN model operation results under the 1/40 rated speed command for time interval being 0~1 second and 0~0.02 second as well.



(a) (b)

Figure 2-12: The torque estimation results of rated speed command:(a)Full-time period results ;(b)Transient results.



(a) (b)

Figure 2-13: The torque estimation results of 1/40 rated speed command:(a)Full-time period results;(b)Transient results.

The arrangement information for the MSE (mean square error) computing results for the difference between the pre-computed torque and the value acquired from the proposed FNN-based torque model is shown as Table 2-2.

Table 2-2: The comparison results for two operation conditions.

Speed command / Response status	**Rated speed**	**1/40 rated speed**
Transient results (MSE)	0.0897	0.0066
Steady-state results(MSE)	0.0142	0.0014

By the torque value obtained from the FNN-based model, the speed of the SRM drives can be estimated based on Eq.(2-6) and Eq.(2-8). Under the same conditions of the operation, the comparison of response of speed using pre-computed speed from primary SRM-characteristics function and the proposed computing algorithm can be observed by Fig. 2-14 and Fig. 2-15. Both at commands of rated speed and 1/40 rated speed, the speed estimation values are very close to those pre-computed theory values at any time and being acceptable for application.

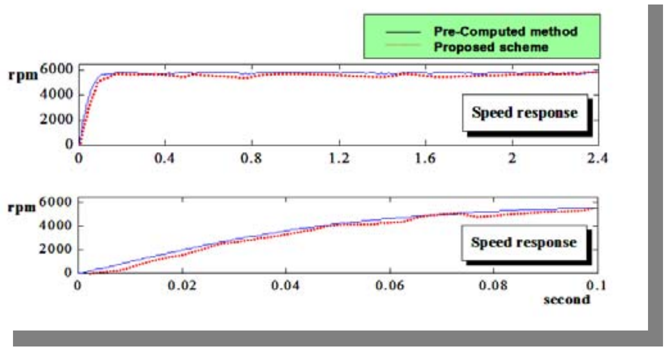


Figure 2-14: The speed estimation results at rated speed command.

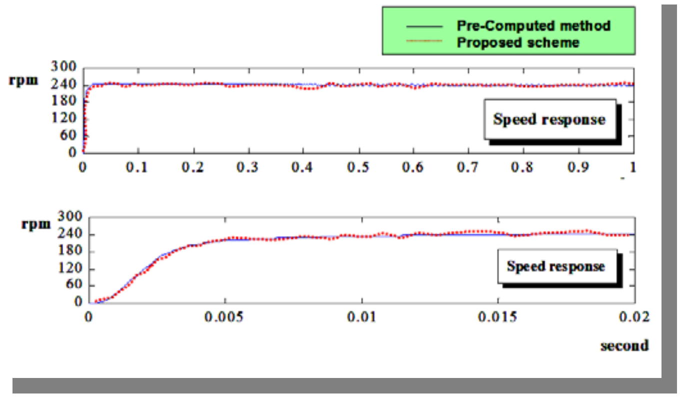


Figure 2-15: The speed estimation results of 1/40 rated speed command.

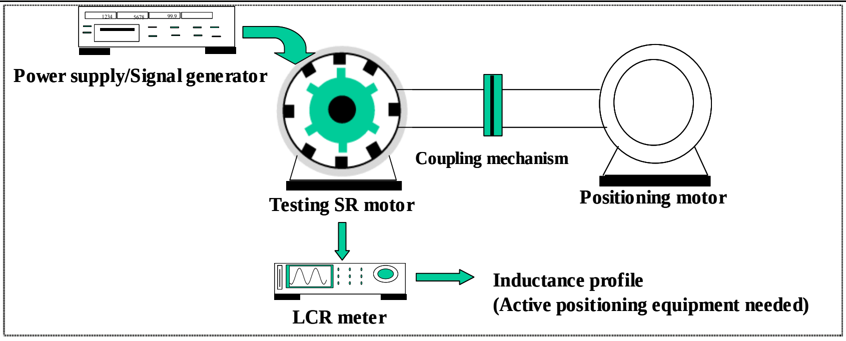
The analysis technique of the proposed FNN-based torque model applying for speed sensorless SRM drives is explained and given as well as the verification details. The overall FNN model demonstrates that the new scheme can successfully estimate the instantaneous torque of the SRM under possible operating conditions. With the information acquired and computed from the torque model, both an applicable sensorless drives scheme and speed estimator can be constructed, which is useful for the proposed optimizing efficiency control strategy.

Chapter 3 Parameters Identification Approaches

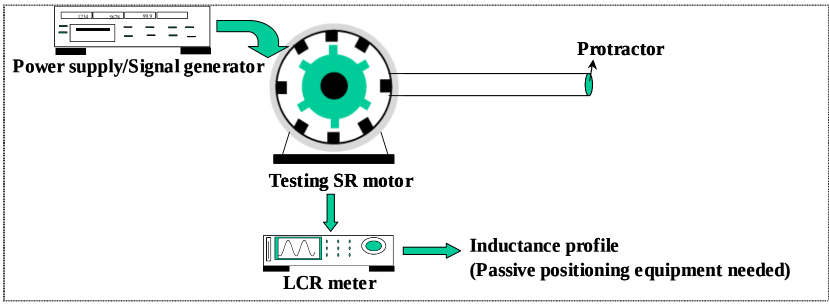
As description of the research motivation of this study for a SRM drive, more effort should be devoted within the construction of more function-like algorithms or schemes that can help to provide the needed information for system driving. Parameters of the SRM, certainly the crucial requirements to the understanding and modeling of the SRM, may be needed to give either by measuring or by estimation for established a practical drive with acceptable specifications to the users. A practical drive system containing a parameter identification scheme has been a trend in drive technology as long as it is functioned with the parameters obtaining scheme that can provide parameters helpful to the control of system[24,25,29,75,76]. Therefore, the approaches that contribute to the identification of parameters for the SRM drives, proposed and arranged in Chapter 3, is presented to support the construction of the optimizing efficiency control for the operation of present usage and the consideration with future potentials for the SRM drive system.

3.1 Inductance Estimation

For understanding of characteristics of an SRM, it is no doubt that the parameter highly related to magnetic flux, said inductance, shall be taken as the basis for construction of the SRM's model and analysis of drives' performance. To describe it in details, knowledge of inductance profile is critical in design verification, performance evaluation, and rotor position sensing. Generally speaking, various methods are available to use the specific power supply or signal generator for obtaining the needed response caused by the inductance of the SRM winding utilizes LCR meter. The two mainly basic measurement schemes can be illustrated as Fig. 3-1. However, the methods depicted by Fig. 3-1 require the positioning equipments: for instance, the servo control positioning motor, protractor, and other components of that kind for the inductance is highly related to the rotor position.



(a)



(b)

Figure 3-1: Conventional inductance measurement methods for the SR motors: (a) The scheme that servo control motor is required for positioning; (b) The scheme that an angle measurement ruler and fix mechanism are needed for positioning.

For improving the performance of SRM drives, several approaches had been proposed and focused on the inductance measurement related issues. The frequency of inducing signal would be useful to enhance the measurement precision, addressed in [6,7]. The position estimation using the information of inductance profile to excite the stator winding at appropriate instant is applied referred to [8]. Besides of that, the inductance information is also taken in SR motor sensorless drives applying resonant method, linked control strategy design, and flux estimation respectively in [9,10,11].

To provide useful and applicable inductance profile information and level down the requirement of positioning equipments in laboratories, the proposed measurement and estimation method of inductance is carried out during dynamic status operated by a speed control counterpart motor. This mainly new concept presented is to utilize LC circuit analysis techniques for inductance measurement after reviewing the past-existing measurement methods addressed in [3-11].

Afterwards, the validity of the experimental results, using the two types of SRMs and different signal generation sources, are evaluated by the comparison of the inductance profile measured by the proposed approach and that obtained by a static measurement method. It is demonstrated that the developed method can meet the primary requirement for measuring the inductance from unaligned to aligned position of the rotation angle and own the prospective potential to operate in dynamic status and the related control applications.

3.1.1 Off-Line Scheme

As description in former section, the LCR meter is one of the measurement instrument that can obtain the inductance information. The relation can be illustrated in phase equivalent circuit of SRM model as Fig.3-2.

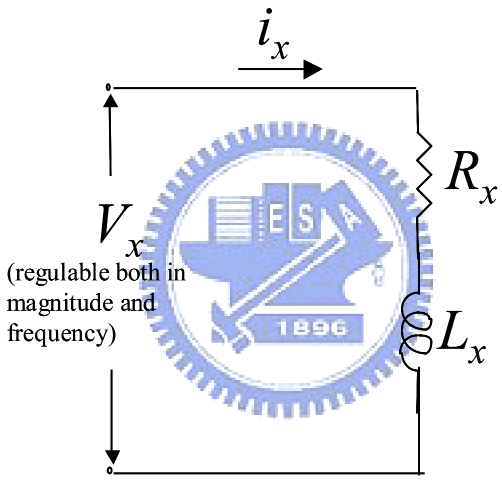


Figure 3-2: The relation for measurement.

In Fig.3-2, where V, i ,R, and L denote the supplying alternative voltage, current, phase resistance, and inductance, all within the suffix x for denoting the operation phase By changing of the voltage signal inputted to the SRM, the inductance can be computed based on Eq.(3-1) and Eq.(3-2) as:

$$|V| = |i| \cdot |z| \tag{3-1}$$

$$|z| = \sqrt{R^2 + X^2} \tag{3-2}$$

where X=wL. w is the frequency of electric signals. Then, by the value that phase resistance being given, the inductance can be obtained in the form of

$$L = \sqrt{\frac{V^2/i^2 - R^2}{w^2}} \tag{3-3}$$

Based on the SRM analysis model related to the phase inductance shown as Fig.3-2, it can be described as that this model basically consists of a resistance and a nonlinear variation inductance. This model provides the basic concept for the SRM research of the inductance measurement and estimation. And, the further discussion is introduced in the subsequent sections.

By the transformation and modification of the equivalent circuit model of the SRM, the analysis model can be obtained to be either a series or parallel LC circuit topology while the capacitor is added. The series type LC circuit originated from the SRM model is shown as Fig.3-3.

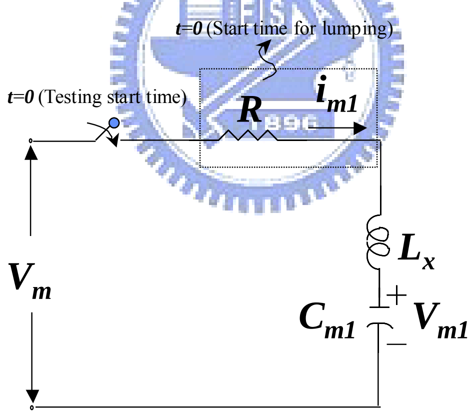


Figure 3-3.: The series type LC circuit related to the SRM.

Then, to arrange the operation status of electric signals while the testing starts (time $t \geq 0$, and to lump the product of resistance and current as voltage drop function that processed separately) as following Eq.(3-4) and Eq.(3-5):

$$i_{m1} = i_{st0}\cos w_{0s}(t-t_0) + \frac{V_m - V_{st0}}{Z_{0s}}\sin w_{0s}(t-t_0) \tag{3-4}$$

$$V_{m1} - V_m = -(V_m - V_{st0})\cos w_{0s}(t-t_0) + Z_{0s} i_{st0}\sin w_{0s}(t-t_0) \tag{3-5}$$

where

$$w_{0s} = \frac{1}{\sqrt{L_x C_{m1}}} \tag{3-6}$$

$$Z_{0s} = \sqrt{\frac{L_x}{C_{m1}}} \tag{3-7}$$

i_{m1}: the current flows through L_x

V_m: the supply voltage

t_0: initial analysis time for series type circuit

i_{st0}: the current value flows through L_x at t_0

C_{m1}: the adding capacitor

V_{m1}: the voltage of C_{m1} for series type circuit

V_{st0}: the voltage of C_{m1} at t_0

For the parallel type LC circuit, analysis and derivation can be given as followings, by the same lumping method as series type analysis, based on the scheme of Fig.3-4.

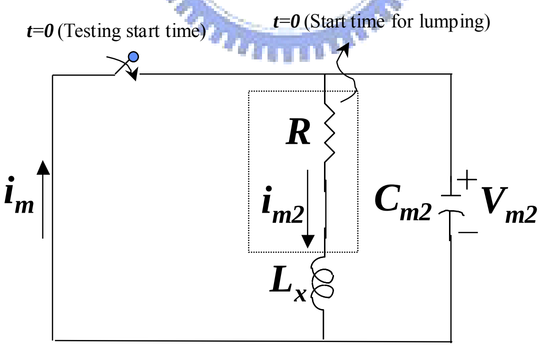


Figure 3-4: The parallel type LC circuit related to the SR motor.

$$i_{m2} - i_m = (i_{pt0} - i_m)\cos w_{0p}(t - t_{01}) + \frac{V_{pt0}}{Z_{0p}}\sin w_{0p}(t - t_{01}) \tag{3-8}$$

$$V_{m2} = Z_{0p}(i_m - i_{pt0})\sin w_{0p}(t - t_{01}) + V_{pt0}\cos w_{0p}(t - t_{01}) \tag{3-9}$$

where

$$w_{0p} = \frac{1}{\sqrt{L_x C_{m2}}} \tag{3-10}$$

$$Z_{0p} = \sqrt{\frac{L_x}{C_{m2}}} \tag{3-11}$$

i_{m2}: the current flows to the branch leg with L_x

i_m: the supply current

t_{01}: initial analysis time for parallel type circuit

i_{pt0}: the current value flows through L_x at t_{01}

C_{m2}: the adding capacitor for parallel type circuit

V_{m2}: the voltage of C_{m2}

V_{pt0}: the voltage of C_{m2} at t_{01}

The described two types LC circuit both can construct the analysis model for measuring the inductance profile by various computing or estimation methods. Besides, the related specifications of capacitors should be determined for resonant oscillation avoidance, referred to resonant frequency depicted as Eq.(3-7) and Eq.(3-8), which is related to the settings for output signal of power supply as well.

The main advantage of the proposed method is that measurement can proceed under dynamic operation status for obtaining the inductance information without servo level or manual adjusting positioning equipments. As followings, the core concept of computing will be derived further for ease of solving and to illustrate the relation and operation procedure for the proposed measurement method.

As the description above, the inductance is the desired measurement parameter needs to be obtained. The inductance can be computed making use of the trigonometric formula and thereby to solve the following combined equations for acquiring the value of inductance.

-The series LC circuit type:

Based on Eq.(3-5), to let:

$$A_{s1} = \frac{V_m - V_{st0}}{Z_{0s}} \tag{3-12}$$

$$B_{s1} = i_{st0} \tag{3-13}$$

Then Eq. (3-15) can be deduced to be Eq. (3-14):

$$i_{m1} = \sqrt{A_{s1}{}^2 + B_{s1}{}^2}\sin(w_{0s}(t-t_0)+\varphi_{s1}) \tag{3-14}$$

where

$$\varphi_{s1} = \tan^{-1}\frac{A_{s1}}{B_{s1}} \tag{3-15}$$

In the similar way, to define:

$$A_{S2} = Z_{0s} i_{st0} \tag{3-16}$$

$$B_{s2} = -V_m + V_{st0} \tag{3-17}$$

To derive Eq. (3-6) further and the results can be obtained as Eq. (3-18):

$$V_{m1} - V_m = \sqrt{A_{s2}{}^2 + B_{S2}{}^2}\sin(w_{0s}(t-t_0)+\varphi_{s2}) \tag{3-18}$$

where

$$\varphi_{s2} = \tan^{-1}\frac{A_{s2}}{B_{s2}} \tag{3-19}$$

In practical measurement, the inductance can be estimated either by combination computation or approximate fitting techniques by Eq. (3-14) and Eq. (3-18).

-The parallel LC circuit type:

The derivation procedure is similar to the above procedure merely with different symbol definitions and introduced as followings.

The expression of Eq.(3-20) can be obtained from Eq. (3-9):

$$i_{m2} - i_m = \sqrt{A_{p1}{}^2 + B_{p1}{}^2}\,\sin(w_{0p}(t - t_{01}) + \varphi_{p1}) \tag{3-20}$$

where

$$\varphi_{p1} = \tan^{-1}\frac{A_{p1}}{B_{p1}} \tag{3-21}$$

From Eq.(3-10), it can be derived as Eq.(3-22):

$$V_{m2} = \sqrt{A_{p2}{}^2 + B_{p2}{}^2}\,\sin(w_{0p}(t - t_{01}) + \varphi_{p2}) \tag{3-22}$$

where

$$\varphi_{p2} = \tan^{-1}\frac{A_{p2}}{B_{p2}} \tag{3-23}$$

The related symbols are respectively defined as Eq.(3-24) to Eq.(3-27):

$$A_{p1} = \frac{V_{pt0}}{Z_{0p}} \tag{3-24}$$

$$B_{p1} = i_{pt0} - i_m \tag{3-25}$$

$$A_{p2} = Z_{0p}(i_m - i_{pt0}) \tag{3-26}$$

$$B_{p2} = V_{pt0} \tag{3-27}$$

Then, the inductance can be solved, based on Eq.(3-30) and Eq.(3-22).

The objective of the proposed measurement method is to observe the phenomenon of the inductance profile of the SRMs. The measurement for the inductance can be generally concluded to be the mapping relationship among the inductance, rotor angle, and current. By the preliminary understanding, the concept can be depicted as Fig. 3-5.

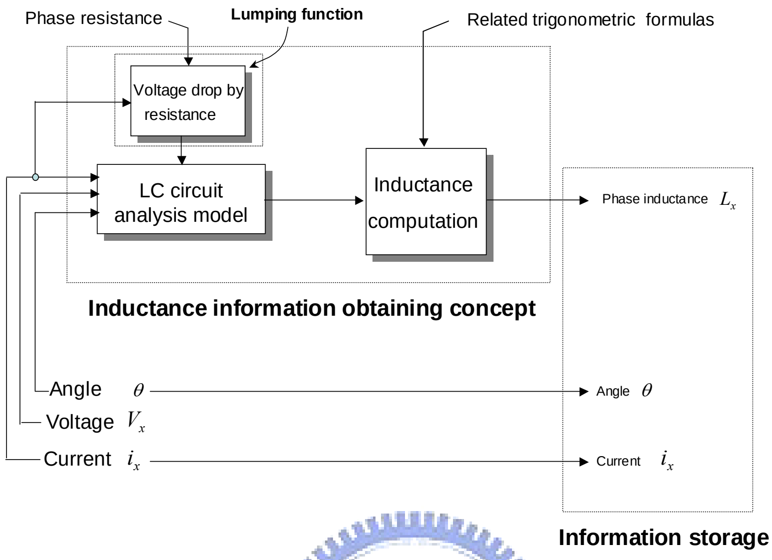


Figure 3-5: The linking relation of the proposed measurement method.

The linking relation for analysis is aimed for the rotor position, relevant phase current, and inductance value; hence the operation procedure can be arranged and illustrated as Fig. 3-6.

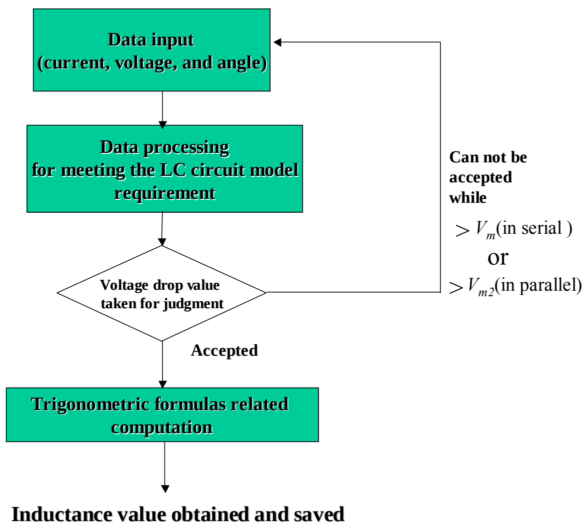


Figure 3-6: The operation procedure for the inductance measurement.

3.1.2 On-Line Scheme

The energizing of phase windings must be synchronized with the rotor position. The angular position sensor is required for this reason, which leads to degrading of robustness and cost rising problems. Therefore, many research for eliminating the position sensor is going on. The understanding of the incremental inductance ($d\lambda/di$) related data provides useful information for development of the SR motor drives and design of the machines. The partial/differential value of the inductance with respect to the rotor angle ($\partial L/\partial\theta$ or $dL/d\theta$) is the critical index, as being mentioned above, to do the evaluation of current applying design and outputted torque performance, introduced in [8]. In this proposed measurement method, the computation is easy to be extended either by different computing techniques or derivation results of Eqs.(3-14), (3-18), (3-20), and (3-22). And by differentiation computation of the storage/computed inductance value with respect to time, the speed of the SR motor can be estimated from Eq.(3-28):

$$\frac{dL_x}{d\theta} = \frac{dL_x}{dt} \cdot \frac{1}{w_r} \tag{3-28}$$

where w_r means angular velocity of the SRM.

The proposed measurement method can provide the critical information to motion drives designers and specifications of driver capabilities. The resolution angle for analysis of this measurement system under dynamic operation can be given in Eq.(3-29):

$$\frac{2\pi \cdot w_{SET}/60}{1/T_S} \qquad (radian) \tag{3-29}$$

where w_{SET} (*r/min*) and T_s (*second*) denote the motor speed and sampling time, respectively.

3.2 Resistance Estimation

An estimation approach of phase resistance for the switched reluctance motor drives is introduced in this part [29]. A strategy for current command compensation based on energy loss caused by resistance, which leads to influence of output performance, is also presented herein to improve the robustness of drives to variation of SRM's parameters. The effectiveness of the proposed approach is validated and can provide reference information for speed sensorless drives that need to put phase resistance into account.

The resistance can be observed in our daily life by the formulation of Eq.(3-30):

$$R_x(T) = R_x(T_0) + \alpha(T - T_0) \tag{3-30}$$

where T and T_0 denote measured temperature and primary temperature. α is temperature coefficient. R_x (T) and R_x (T_0) mean the resistance under temperature of T and T_0.

Equation (3-30) constructs the relation to find the relation between resistance and flux. It can be depicted further as Eqs.(3-31) and (3-32) as:

$$[V_x] = [i_x][R_x + \Delta R_x] + [\frac{d\lambda_x}{dt}] + [\Delta\frac{d\lambda_x}{dt}] \tag{3-31}$$

$$[i_x][\Delta R_x] = -[\Delta\frac{d\lambda_x}{dt}] \tag{3-32}$$

where [$\Delta d\lambda_x/dt$] means the change of flux caused by resistance variation.

According to Eq.(3-31) and Eq.(3-32), the resistance estimation can be constructed in Fig. 3-7 and Fig. 3-8.

Let $[i_x] = Q$, $X = [\Delta R_x]$, and $U = -[\Delta\frac{d\lambda_x}{dt}]$, respectively. It is clear that Eq.(3-32) can also be taken as solving $QX=U$ problem, and related methods to obtain the answer can be utilized and applied, hereafter described as optimum searching .

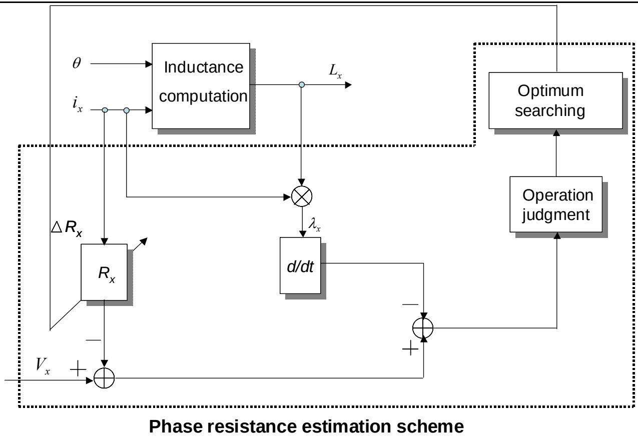


Figure 3-7: Resistance computation scheme-derivative type.

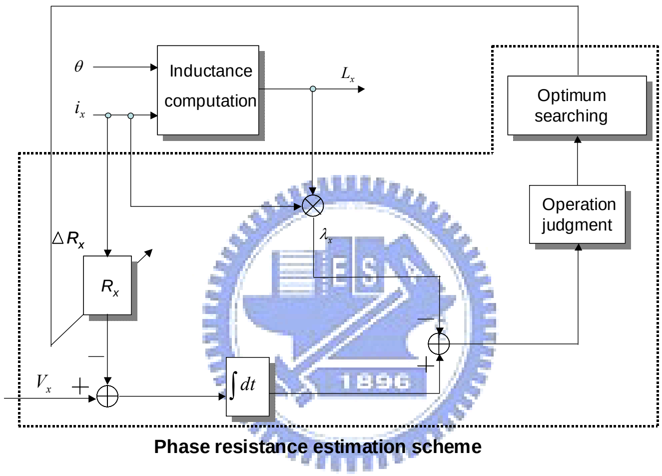


Figure 3-8: Resistance computation scheme-Integral type.

3.3 Mutual Inductance Estimation

In many switched reluctance motors industrial applications described above, the overlapping of phase currents (mainly related to adjacent phases) for the time scale portion is significant in each conduction cycle [9,62,65]. The mutual inductance leads to the mutual flux linkages between windings can reach 10% or more of the self-flux linkages of a phase.

To find an expression for more accurate SRM parameters linked to the practical case, taking a four-phase SRM for example, Eq.(3-33) can be discussed as follows:

$$\begin{bmatrix} \lambda_A \\ \lambda_B \\ \lambda_C \\ \lambda_D \end{bmatrix} = \begin{bmatrix} L_A & M_{BA} & 0 & M_{DA} \\ M_{AB} & L_B & M_{CB} & 0 \\ 0 & M_{BC} & L_C & M_{DC} \\ M_{DA} & 0 & M_{CD} & L_D \end{bmatrix} \cdot \begin{bmatrix} i_A \\ i_B \\ i_C \\ i_D \end{bmatrix} \tag{3-33}$$

where M is the mutual inductance between phases indicated by the subscript.

To make a brief remark that for simplicity of expressions, the assumptions without losing the generality of single-phase or multi-phase excitation are given as followings [16,17]:

1. The mutual inductance exists between the two adjacent phases.
2. The value of mutual inductance for the two considered phases, as the former definition, is equal, such as $M_{AB}=M_{BA}$.

The focus of the tasks of the dynamic mutual inductance model is to find the method for providing the current command compensation value for improving the performance of SRM while the previously neglected effect being involved. According to the development experience of high performance SRM drives, the pre-measured/on-line flux linkage λ related information, such as the relation between the inductance and electric properties, is needed. It is based on this opinion then the development evaluation method and operation flow is arranged and depicted as Fig. 3-9.

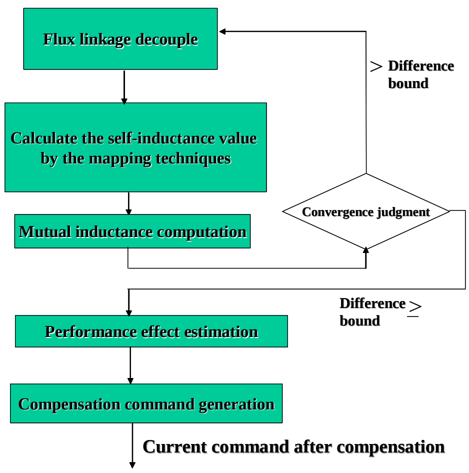


Figure 3-9: The operation flow for the dynamic model..

The method is set for the control performance improvement by the model computation capability. For SRM speed response caused by the outputted torque, which includes mutual flux linkages effect, can be taken as the reference for current controller design and performance regulation.

By the former section discussion, the mutual inductance related expression could be rearranged for further derivation. Based on Eq.(3-33), to transpose the matrix as Eq.(3-4):

$$\begin{bmatrix} i_A \\ i_B \\ i_C \\ i_D \end{bmatrix}^T \cdot \begin{bmatrix} L_A & M_{BA} & 0 & M_{DA} \\ M_{AB} & L_B & M_{CB} & 0 \\ 0 & M_{BC} & L_C & M_{DC} \\ M_{DA} & 0 & M_{CD} & L_D \end{bmatrix}^T = \begin{bmatrix} \lambda_A \\ \lambda_B \\ \lambda_C \\ \lambda_D \end{bmatrix}^T \tag{3-34}$$

Let $Q=\begin{bmatrix} i_A \\ i_B \\ i_C \\ i_D \end{bmatrix}^T$, $X=\begin{bmatrix} L_A & M_{BA} & 0 & M_{DA} \\ M_{AB} & L_B & M_{CB} & 0 \\ 0 & M_{BC} & L_C & M_{DC} \\ M_{DA} & 0 & M_{CD} & L_D \end{bmatrix}^T$, and $U=\begin{bmatrix} \lambda_A \\ \lambda_B \\ \lambda_C \\ \lambda_D \end{bmatrix}^T$, respectively.

It is clear that Eq.(3-34) can also be taken as solving $QX=U$ problem, and related methods to obtain the answer can be utilized and applied.

3.4 Speed and Torque Estimations

Research to find the methods related to speed and torque estimation for SRM drives is an important topic that not limited to SRM drives, but for drives of most of electric machines. The product of speed and toque represents the outputted power of the drive system, thus, it is discussed in this section for supporting the function of the proposed optimizing efficiency approach which is highly linked to the performance judgment of the overall operation scheme as well.

3.4.1 Artificial Neural Network-Based Scheme

An estimation method capable of computing two critical values regarding the speed, and torque for sensorless control of switched reluctance machines based on power relations is presented in this part. The proposed model utilizes the artificial neural networks (ANN) with simple error back-propagation (BP) method to obtain related parameters including equivalent inductance and its partial differential values in accordance with rotor position, mechanical output, and resistance of the SRM for constructing a high effective driving scheme for applications. Input power with succeeding content of both core and cooper loss is taken into account in this model strategy. Flux linkage per phase, being important for exploiting motor parameters, is monitored from integration formula as well as its primary definition for updated resistance value of this ANN during on-line operation. All the described parameters can be estimated under cross-quadrant operation by this ANN-based model, and both simulation and experimental results verify the applicability and performance improvement of this control structure utilized in sensorless control of a 3hp SRM applied for prototype motion driving system.

The ANN is useful computational scheme with learning capabilities. With long-term research efforts devoted to the ANN study, the related theories and types of networks have evolved into sophisticated and mature status. With the rapid growth and development of micro-controllers and related electronic technology, the time-consuming problems can be solved, enabling the ANN to be better employed in commercial applications. That is the previous complicated ANN's structures and time taken due to computing accuracy are now acceptable and applicable. However, the related complex algorithms result in difficulty in software coding and operating consideration is one of the main reasons for relatively few mature industrial applications so far. At present, the feed-forward type ANN which is not necessary for bi-directional information flows during operating and actuating of network, has been accepted by more product designers. Generally speaking, the feed-forward ANN is usually employed with the BP method constructed by the supervised schemes to establish the mapping relation among the network's input signals, output signals, and the ANN's weights, and introduced in [1,2].

In view of above, parameters estimation has become one of the main research topics recently which is arranged in [5] and [6]. Though the accuracy of the SRM parameters is crucial for the performance of sensorless drives, it, however, attracts less concern. Obviously, more efforts are needed on parameters estimation, especially in terms of operational convenience of parameters measurement and estimation, and the analysis of parameter variation in different control methods and load conditions, which result in practical limitation of SRM in high precision required applications. Thus, there is need of more research on parameters identification and analysis between SRM motor parameters and operation conditions to improve control performance.

Related researches on the parameters identification and estimation for SRM have moved toward on-line estimation from off-line operation and computation described in [7] and [8]. Furthermore, there are more researches focusing on the combination of parameters estimation applied in sensorless drives discussed in [9] and [10]. Therefore, this paper presents a feasible method of parameters identification, accompanying simulation observation and experimental verification. With the information acquired and computed from the proposed ANN, both the sensorless drives scheme and torque estimator can be constructed. The proposed method applied to parameters estimation has advantage of simplicity and accuracy, improving the applicability of drives.

3.4.1.1 Speed

Fig. 3-10 shows the parameters relation when constructing the proposed ANN scheme [26,30], representing the main concept of this section.

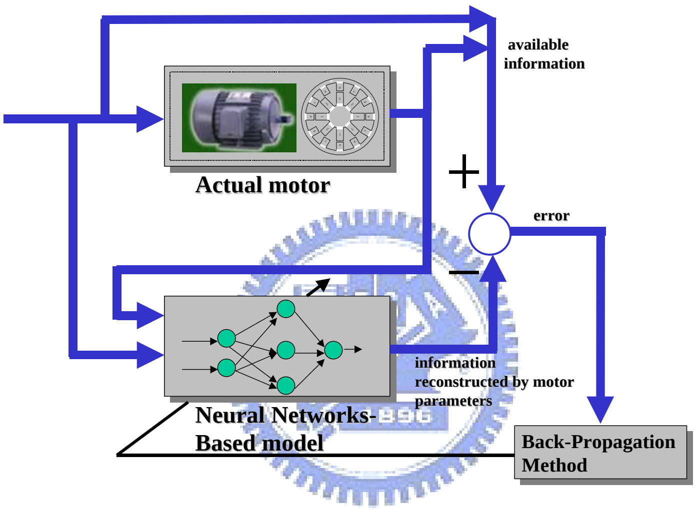


Figure 3-10: The ANN-based estimation scheme.

A reference model applying the parameters of SRM is described in Chapter 2. With the consideration for easy signal measurement and the link between input and output, the instantaneous power is selected as the output of this model, which clearly takes advantages on the point of parameters and value correction. Eq. (3-35), shows the input instantaneous power, $\overline{P}$, per phase for SRM:

$$\overline{P_x} = i_x \cdot V_x \tag{3-35}$$

From Eq.(2-2), another input power equation related to inductance and speed can be derived as Eq.(3-36):

$$P_x = i_x^{\ 2} \cdot R + L_x \cdot i_x \cdot \frac{di_x}{dt} + i_x^{\ 2} \cdot w \cdot \frac{dL_x}{d\theta} \tag{3-36}$$

where P also represents the input instantaneous power per phase.

Allowing network output being the input instantaneous power in Eq.(3-36), an ANN as shown as Fig. 3-11 is constructed. The proposed ANN is a two-layer network and its input and output relation can be described as Eq.(3-37):

$$P(k) = W1 \cdot X1 + W2 \cdot X2 + W3 \cdot X3 \tag{3-37}$$

where, $X1 \overset{\Delta}{=} i_x(k) \cdot \frac{i_x(k) - i_x(k-1)}{DT}$;

$X2 \overset{\Delta}{=} i_x^{\ 2}(k) = X3$;

$W1 \overset{\Delta}{=} L_x(k)$;

$W2 \overset{\Delta}{=} R$;

$W3(k) \overset{\Delta}{=} w(k) \cdot \frac{L_x(k) - L_x(k-1)}{\theta(k) - \theta(k-1)}$;

k and DT denote step number and sampling time, respectively.

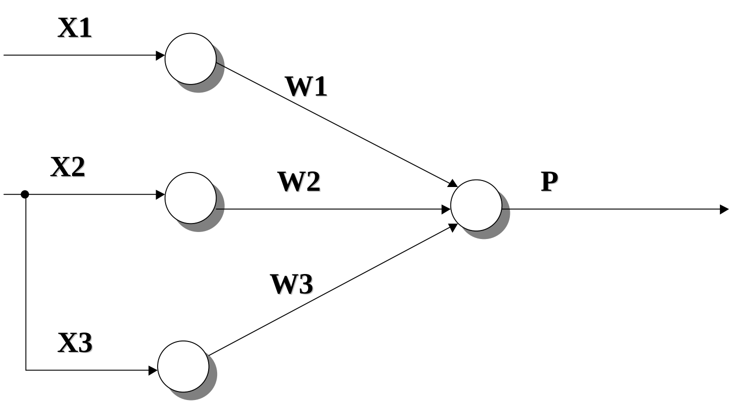


Figure 3-11: The two-layer ANN for parameters estimation.

The ANN shown in Fig. 3-10 can then establish the parameters estimation capability, which is illustrated in Fig. 3-12.

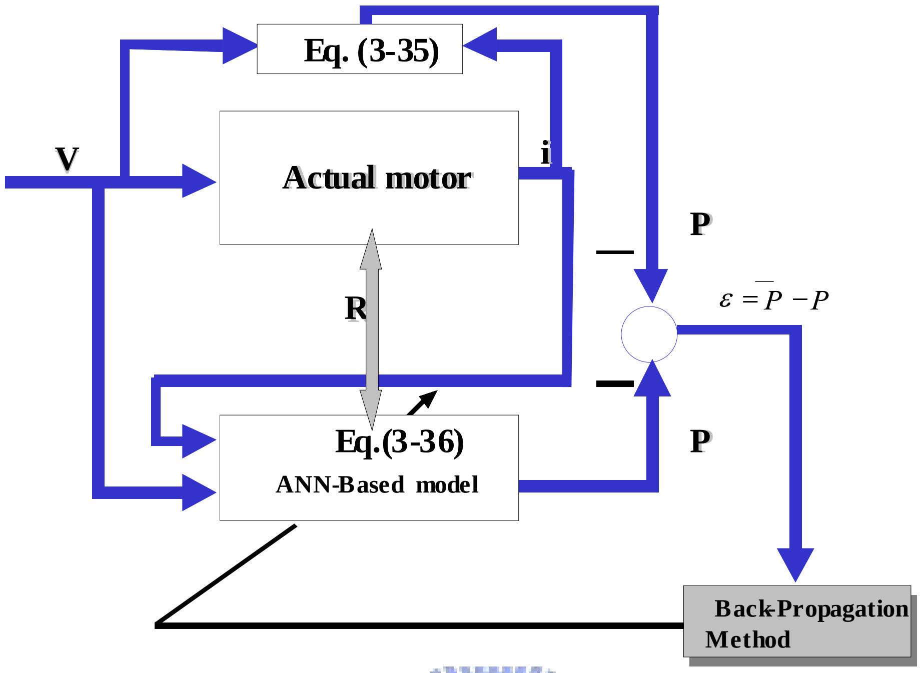


Figure 3-12: The schematic representation for speed estimation.

Equation (3-38) shows the relation between phase inductance makes, and the phase current and the applied voltage.

$$L_x(k) = \frac{\lambda_x(k)}{i_x(k)} = \frac{(V_x(k) - i_x(k) \cdot R) \cdot DT}{i_x(k)} \tag{3-38}$$

The ANN utilizes the BP method to regulate and obtain speed information and inductance related parameters. The difference between the two instantaneous powers computed in Eq. (3-35) and Eq. (3-37) can be the comparison basis for ANN weight adjustment. Hence the cost function is chosen as the difference of input power, which is defined as Eq.(3-39):

$$E = \frac{1}{2}(\varepsilon)^2 = \frac{1}{2}(\bar{P} - P)^2 \tag{3-39}$$

The objective of the ANN is to minimize *E*. The weight *W3* related to speed and partial differentials of inductance can be derived as Eq.(3-40):

$$\Delta W3(k)\alpha\frac{\partial E}{-\partial W3} \tag{3-40}$$

Applying the chain rule, eq. (3-41) is thus obtained:

$$\Delta W3(k)=\frac{\partial E}{-\partial P(k)}\cdot\frac{\partial P(k)}{\partial W3} \tag{3-41}$$

Equation(3-41) can be rearrange as following Eq.(3-42):

$$\Delta W3(k)=(P(k)-\overline{P}(k))\cdot X3(k) \tag{3-42}$$

To decrease the time taken for the convergence of value computation and improve performance of the ANN, some adjust terms is added to Eq.(3-42) and represented as Eq.(3-43):

$$W3(k)=W3(k-1)+\eta\cdot\gamma(k)\cdot W3(k-1)+\alpha\cdot\Delta W3(k-1) \tag{3-43}$$

where, $\gamma(k)\overset{\Delta}{=\!=}(P(k)-\overline{P}(k))$. η denotes the learning rate, and α is the momentum related to the adjusting quantity of last weight updating. Adding the coefficients above, the convergent time and alleviate oscillation situations can thus be regulated.

The estimation of speed and partial differentials of inductance with respect to the rotor mechanical angle, can be obtained by the weights *W1* and *W3* as Eq.(3-44):

$$w(k)=\frac{W3(k)\cdot w(k-1)\cdot DT}{W1(k)-W1(k-1)} \tag{3-44}$$

3.4.1.2 Torque

The ANN parameter estimation scheme shown as Fig.3-12 can be modified as Fig.3-13 by setting the judgment value ε_t and defining the computation flow as Fig. 3-14, for beginning the torque estimation procedure. The torque is estimated by following Eq.(3-45) and Eq.(3-46).

By D'Lamber's principle and magnetic co-energy concept, the output torque of SRM can also be derived based on the energy balance in the form of

$$T_e = \sum \frac{1}{2} i_x^{\ 2} \frac{\partial L_x}{\partial \theta} \tag{3-45}$$

where T_e is output torque also.

$$T_e = \frac{W3(k)}{2 \cdot w(k)} \cdot X2(k) \tag{3-46}$$

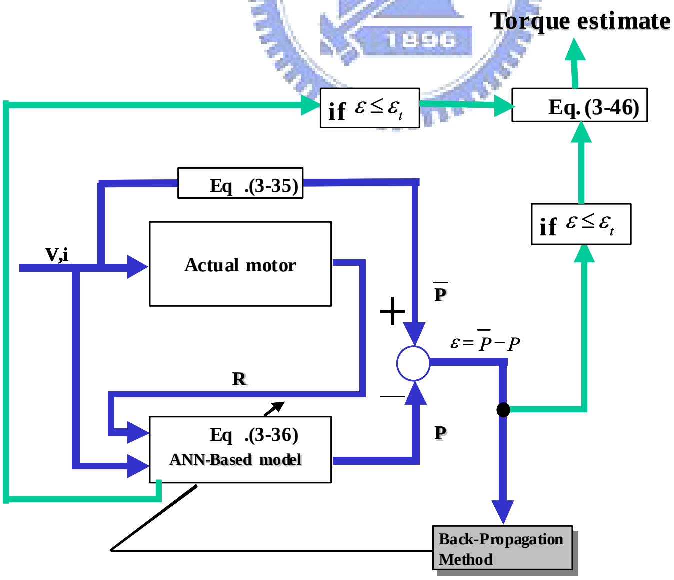


Figure 3-13: The schematic representation for torque estimation.

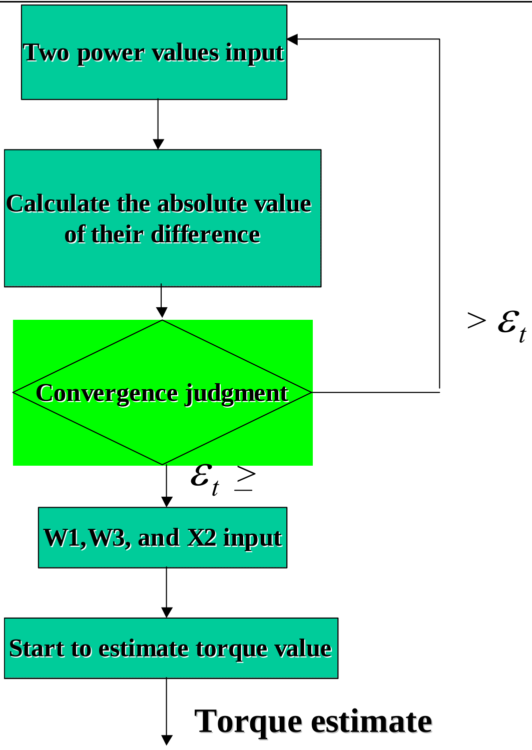


Figure 3-14: The torque estimation computation procedure.

3.4.2 Fuzzy Neural Networks-Based Scheme

The FNN-based scheme has been partly described in Chapter 2, and the follow figure illustrates the main computation scheme for torque computation. Though as description in previous section, the speed estimation can be achieved also merely modified this scheme, it is added while the drives system with high-performance processing unit.

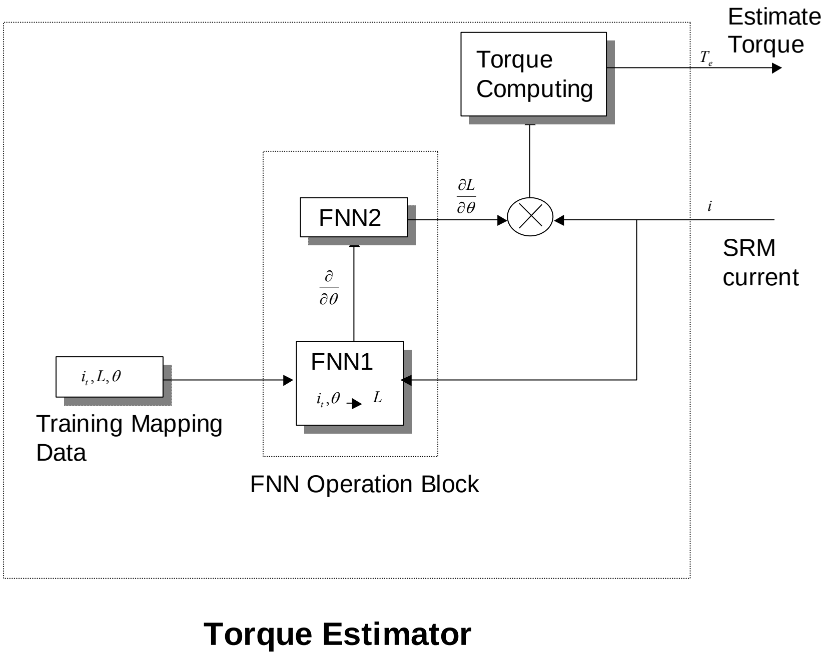


Figure 3-15: The torque estimator scheme based on FNN.

Chapter 4 Efficiency Control for Switched Reluctance Motor Drives

Efficiency is a crucial index that shows the state of energy usage for the intended applications. For SRM drives, the research focus should be formed on that to conform to the increasingly demand on energy conservation issue today. The main reason and achievements of the proposed approach in this part can be concluded as three items:

1)A novel efficiency improvement approach is presented with simple concept while only few have considered the efficiency improvement among the SRM drives studies for ease of practical applications.

2)The expectation of efficiency considerations originated from a motor model research is achieved.

3)A method that improve the efficiency without losing the conventional performance requirement in a simpler way is contented.

The main concept of efficiency is to apply the linking relation of equivalent magnetic inductance and reluctance for SRM to construct the simple efficiency control scheme. Efficiency optimizing is realized for compensating the conventional current command to operate at the desired or higher efficiency. Two SRM drives systems are also taken as examples to testify the feasibility of this efficiency control method.

The requirement for an easy and simple utilization for efficiency control motivates us to propose the core concept of the optimizing efficiency control strategy. From Eq. (2-2), it can be derived one step further by the chain rule with respect to specific time set to be Eq.(4-1):

$$T_e = \sum \frac{1}{2} i_x^{\,2} \frac{dL_x}{dt} \cdot \frac{1}{W_r} \tag{4-1}$$

The symbol definitions are the same as the description in previous part.

Equation (4-1) can be rearranged by the SRM's output power view, which is defined as the definition related to the product of torque and speed, expressed as Eq.(4-2):

$$i_x^* = \sqrt{\frac{2P_{out}}{K\cdot\left({dL_x}/{dt}\right)}} \tag{4-2}$$

where the superscript * is the expression for the command value. K is 1.027 or 0.1047 while the applied output power unit is (*kgf.m.rpm*) or (*N.m.rpm*), respectively.

By the definition of the input power for the SRM drives, which is the product of applied phase voltage and current, Eq.(4-2) can be further derived as Eq.(4-3) by a normalizing factor $\sqrt{V_x}$ for smoothing the value:

$$P_{in(i_x^*)} = \sqrt{2}\cdot\sqrt{P_{out}}\cdot\sqrt{\frac{1}{K\cdot\left({dL_x}/{dt}\right)}\cdot V_x} \tag{4-3}$$

Equation (4-3) is the input power (P_{in}) and output power (P_{out}) related expression, being a transformation to provide the basis for efficiency control. Thus, Eq.(4-3) can be derived further applying the important concept and expressed in the form of

$$\frac{i_x^*}{V_x} = 2\cdot Eff^{*(i_x^*)}\cdot\frac{1}{K\cdot\left({dL_x}/{dt}\right)} \tag{4-4}$$

where $Eff^{*(i_x^*)}$ means the desired efficiency that can be achieved under command current for the SRM drives.

In Chapter 4, Eq.(4-4) has been derived from the motor model, being highly related to the equivalent magnetic inductance, with the capability to regulate the efficiency by appropriate programming of the ratio of the phase command current to the applied voltage. Based on the estimation information obtained from the FNN-based model described in Chapter 3, the SRM drives can estimate the outputted torque and the inductance information. Then, by the reluctance model relevant derivation procedures and observation, the efficiency control scheme with simple regulation method can be understood and, hence, constructed.

4.1 Conventional Dealing Opinions

The need for energy conservation and efficiency is global. It affects both products and processes. It spans industrial, commercial and consumer applications. It is being driven both by government mandate and by the need for greater productivity in order to be competitive in increasingly global markets. Energy conservation and efficiency manifests itself in the drives market by increasing the demand for usage in fans, pumps and compressors used in HVAC (heating, ventilating and air-conditioning) systems, building water delivery systems, chemical processing, utility equipment, material-handling equipment, household appliances, commercial refrigeration, etc. [77,79]. Figure 4-1 and Fig. 4-2 illustrate the conventional analysis opinion for the efficiency consideration with matching of loading power.

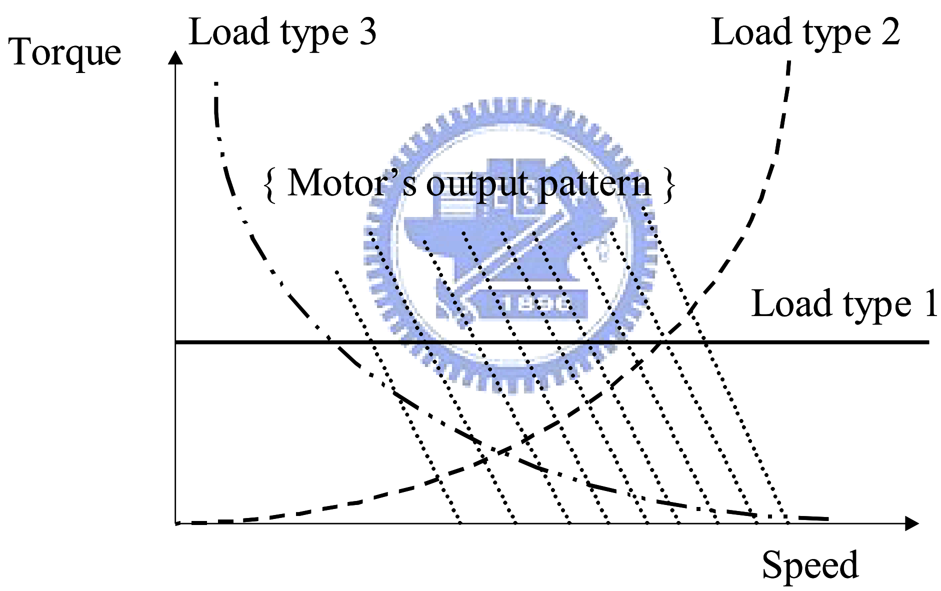


Figure 4-1: The loading types.

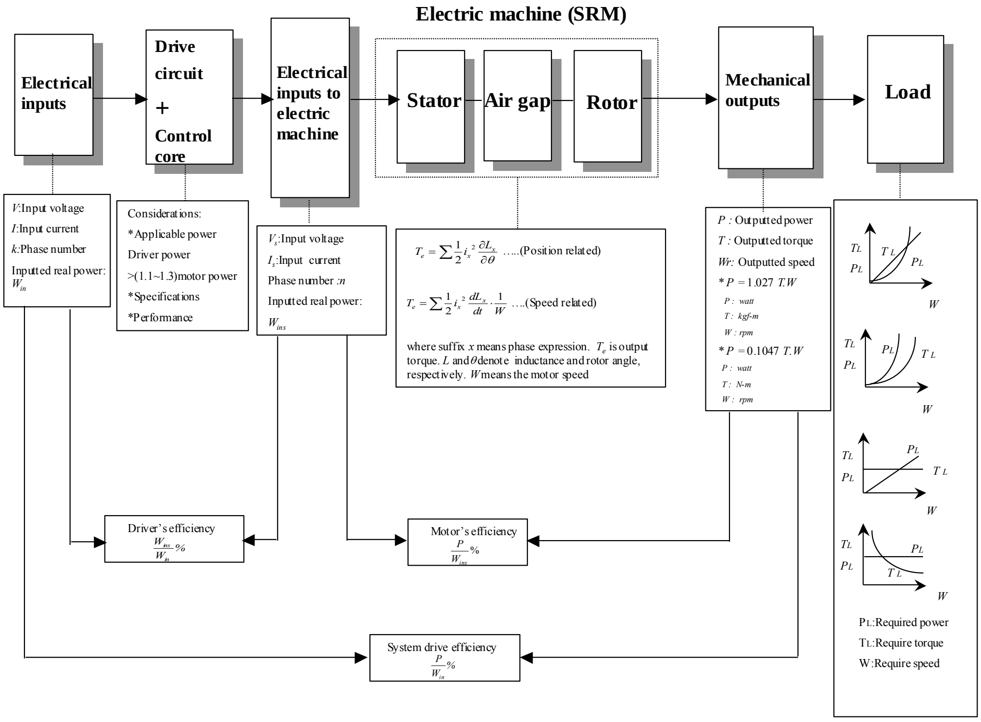


Figure 4-2: The analysis scheme for SRM drives.

The dealing strategy has focused on the energy relation that may exist between forms of electronics and mechanics. Adjustable speed drives (ASD) or solid-state adjustable speed drives (SSASD) are the primary drives schemes and the function requirements should be specified by those systems. However, for advanced function development and enhancement of product acceptance to users, more novel design ideas with consideration of ease of implementation are still needed and expected [25,26,27,30,54,75].

4.2 Reluctance-Based Analysis Concept

The definition of reluctance can be described as" magnetic resistance, being equal to the ratio of magneto-motive force to magnetic flux" . For the characteristics of SRM, it is no doubt that the magnetic flux highly related parameter, we say equivalent magnetic inductance, can be taken as the basis of reluctance-based analysis. According to the topological and electromagnetic effect, it is known that the equivalent magnetic inductance will change with rotor position and phase current, which affects the SRM's output directly.

L and θ, as the former definition, denote equivalent magnetic inductance and rotor angle, respectively. It is apparently that the torque is the function of reluctance force for the motive effect, which also means that the equivalent magnetic inductance is strongly involved. In addition, the inductance, in general, is the function of the current also. To obtain the inductance information, the torque, current, and the extended concept of magnetic resistance, magneto-motive force, and magnetic flux, the relation can be inspired by those mentioned properties with input power as well as output power.

By Fig. 4-3, three energy regulation patterns are shown. Through the opinion of input power, the overlapping area of the inputted current and voltage of the SRM drive can be found as the proposed regulation approach shown in Fig.4-3(c), which links to the current value from the reluctance concept that constructed by the relation of inductance and current.

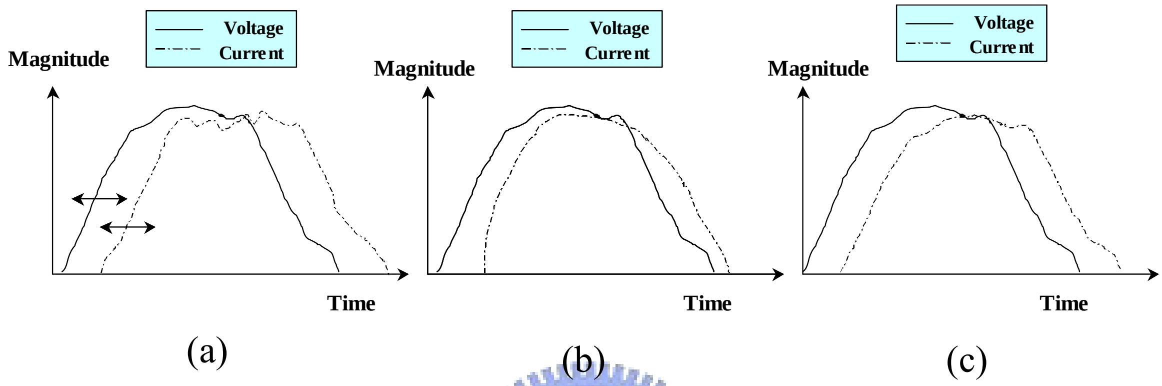


Figure 4-3: The illustration for input power regulation:(a) By switching angle regulation;(b) By profiling the current;(c) By regulating the ratio of current to voltage.

4.2.1 Scheme with Inductance Information

The derivatives or partial differential computation for both equivalent magnetic inductance related information and output torque for SRM can be obtained by the mentioned four-layer FNN in Chapter 2, comprised of input layer, linguistic term layer, rule layer, and output layer, which has established a dual computation networks, with the learning rates and momentum parameters being 0.71 and 0.92 for succeeding estimation.

The mapping capability is carried out by the comparison of the FNN computing inductance and the pre-measured inductance. One comparison result is shown as the screen display in Fig. 4-4, written in VB (Visual Basic) language. The inductance variation interval is at the start-up period for the speed command is set to be 6000 r/min under load 1.5 N-m for SRM 1.

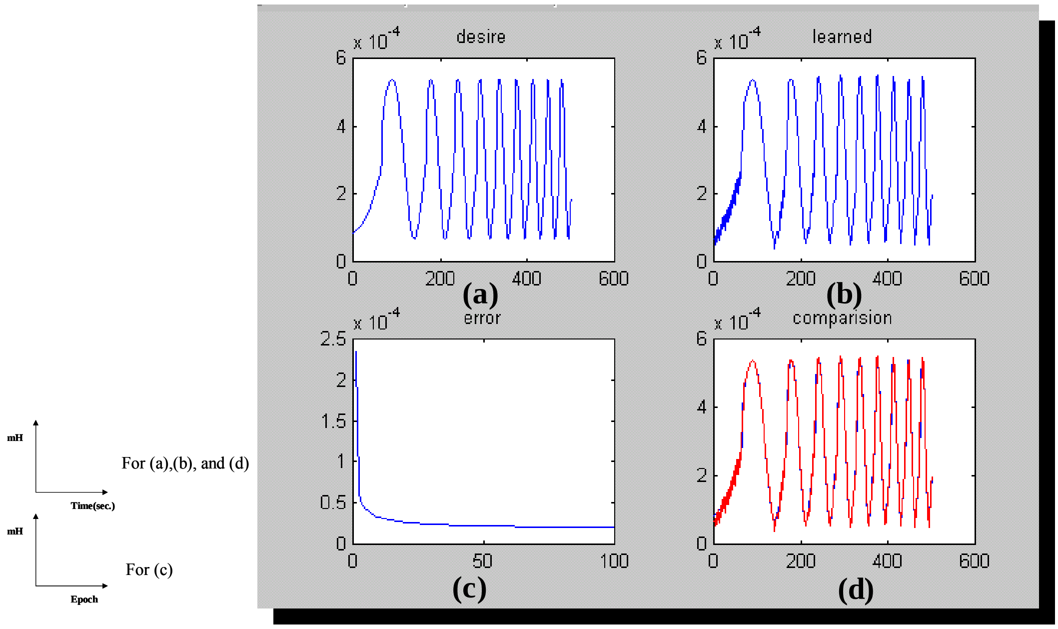


Figure 4-4: The verification of the inductance mapping: (a) pre-measured inductance value; (b) the FNN learned inductance value; (c) the error between the two inductance value; (d) the overlaping plot.

The mapping capability is acceptable for the difference of inductance L is less than one order (<10%), and the related computing information, which is different as the applied values for the drives for showing the choosing range, is as followings:

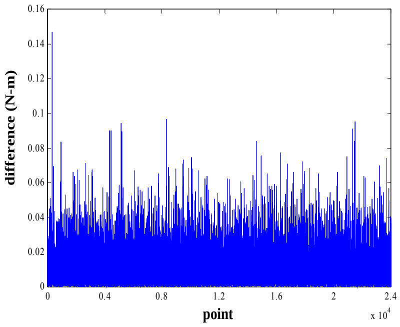
Data Point form 35 to 534 (0.0035~0.0534 second);

epoch: 4;

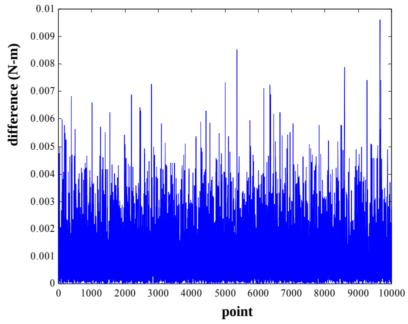
learning rate: 0.78;

momentum: 0.88.

Figure 4-5 depicts the difference, apparently less than one order, between the measured torque value and the proposed FNN-based model estimated torque value.



(a)



(b)

Figure 4-5: The difference plot of the torque computation:(a) under rated speed command; (b) under 1/40 rated speed command.

4.2.2 Scheme without Speed Sensor Information

While many current 'sensorless' SRM drives' designs, arranged in Table 4-1 from the information of [5,29,36,38,45,49,73], have eliminated the encoder, they still require current, voltage or temperature sensors. Most sensorless methods monitor the current and voltage in each winding of the motor in order to estimate the inductance from which position can be inferred by the use of look-up tables or function-like steps. Therefore, the speed information can be modeled by the electric signals for the features of electric machine with practice feasibility. The operation scheme can be applied based on Fig.2-10 within the previous computational operation flow .

Table 4-1: Arrangement of some common concepts for speed sensorless conrtrol techniques of SRM drives

Approach	Features
Designed estimator	By the phase voltage of the excited phase and phase current to estimate flux, to estimate the counterpart current and voltage to obtain the speed, but the needed computation is frequently complicated and high-performance microprocessor is required.
Voltage impressing	Impress impulse voltage to un-excited phase to measure the response of phase current. By the variation of phase current, the simultaneous inductance can be computed. Then the speed can be computed, however, the negative torque may be generated.
Measurement of rise time and falling time of the excited-chopping current	By the time measurement to compute the self-inductance then the speed can be obtained. However, it merely applicable to low-speed range and it will cause the negative torque under

	operation of falling status within a larger average exciting current.
Self-inductance measurement by linear -frequency regulation converter.	By the self-inductance measurement of un-excited phase to find the position of rotor. But it is difficult to properly select the desired phase and also hard to connect the wire to the needed converter.
Measurement of induced voltage at un-excited voltage	By the induced voltage between adjacent phases or phases in opposition to obtain the speed. Nevertheless, to sample the signals simultaneous is difficult and the accuracy can not be guaranteed as well. 。

4.3 Power Relation for Optimizing Efficiency Planning

From the former description of this dissertation, it can be realized that the equivalent magnetic inductance can be chosen as the desiring variable for further analysis of SRM drives. By Eq. (2-2), it can be figured out that the inductance and rotor angle both being the important computation needing parameters, especially taking current command regulation into account. From the derivation of Eq.(4-1) to Eq.(4-4), it can be observed that the efficiency index is formed using the power relation between inputs and outputs, even the simple relation is originated from the state within the assumption of relative-low portion of magnetic saturation. Though the relation may not be perfectly utilized under all operation range, the basic items of the relations can provide the important reference to the planning of the efficiency optimizing for SRM drives. It is reasonable to inference that by the regulation of phase current command to voltage with the inductance change rate under specific time period, the efficiency based on the ratio of output power to input power can be predicted.

The another explanation for the concept of the presented efficiency control is to apply the linking relation related to equivalent magnetic inductance, rough description can be given as that there exists an inverse ratio between it and reluctance, for SRM drives to construct the optimizing efficiency control scheme. From the relations established in Eq.(4-2) and Eq.(4-3), the efficiency-based ratio is derived by the power relation between inputs and outputs. As depiction of Eq.(4-4), the efficiency can be planed by the ratio value of the phase current to voltage. An illustration of Fig. 4-6 that shows the possible relations among real power, reactive power, and complex power, can depict that the power relation may be variant under the change of inductance, which is highly relevant to complex power, and it constructs the applicable mechanism by the planning of relation of input power and output one.

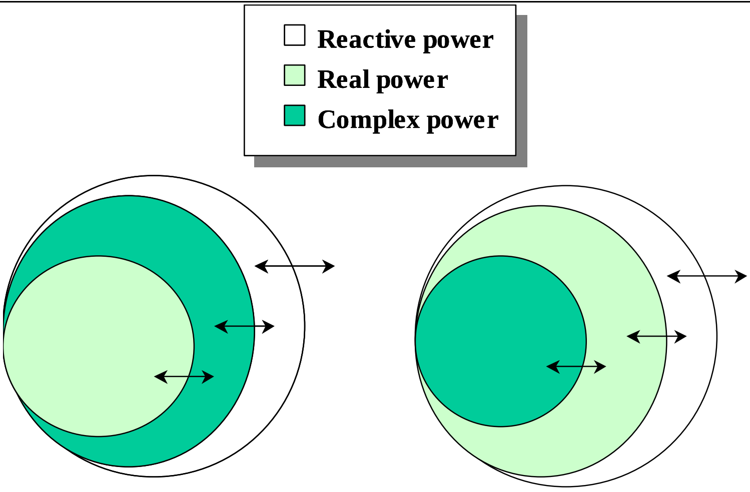


Figure 4-6: Illustration for relation among powers.

4.3.1 Optimizing Concept

Efficiency control is realized for compensating the conventional current command to operate at the desired efficiency or higher one. The optimizing steps can be illustrated that, based on the former deriving relations in 4.1, shown in Fig.4-7 and Fig.4-8, respectively.

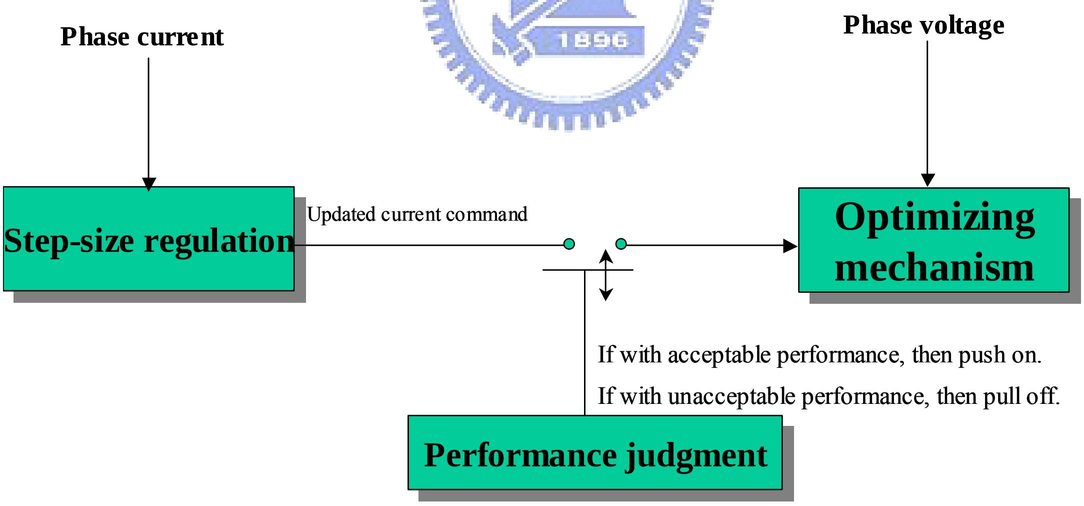


Figure 4-7: The operation scheme that without directly voltage-controlled capability.

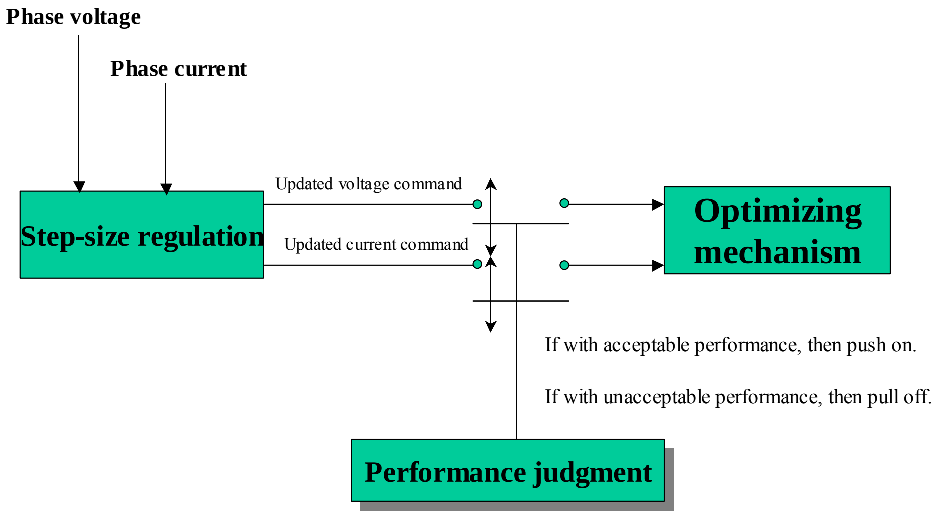


Figure 4-8: The operation scheme that with directly voltage-controlled capability.

The step-size regulation is merely a set of pre-assigned values applied to regulate the commands in a step-like fashion, such as 3 % or curve like mapping value of the command current. The optimizing mechanism will terminate the change of command values while the outputted performance can not be conformed to the requirements that specified in the function of performance judgment. The concept of the optimizing step can be illustrated as Fig. 4-9.

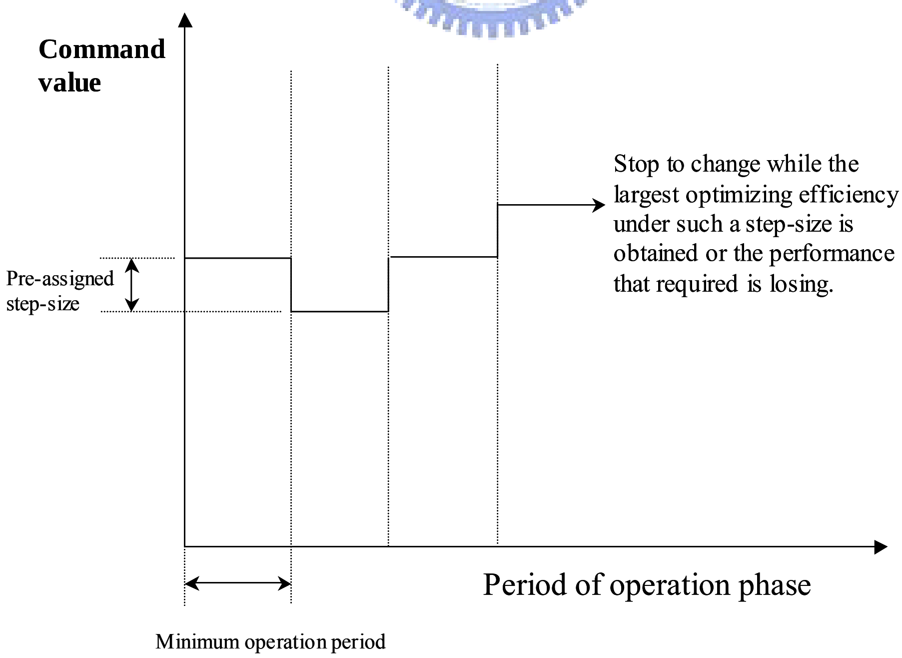


Figure 4-9: The illustration of optimizing concept.

The stop or termination conditions for efficiency optimizing shown in Fig.4-9 can be realized by two if-then rules while the SRM drives operated in steady-state by:

(1)

If

Efficiency(z+1)>*Efficiency*(z), where z denote operation step number, belong to 0 and positive integer.

Then

Back to the former value

end

(2)

If

Performance(z+1)> Performance(z), where performance can be employed by outputted power, speed, and/or torque.

Then

Back to the conventional operation

end

Figure 4-10 shows the operation block for the action of the optimizing efficiency function. While stop by either of the two stop conditions, the regulation may terminate or return to the previous command value.

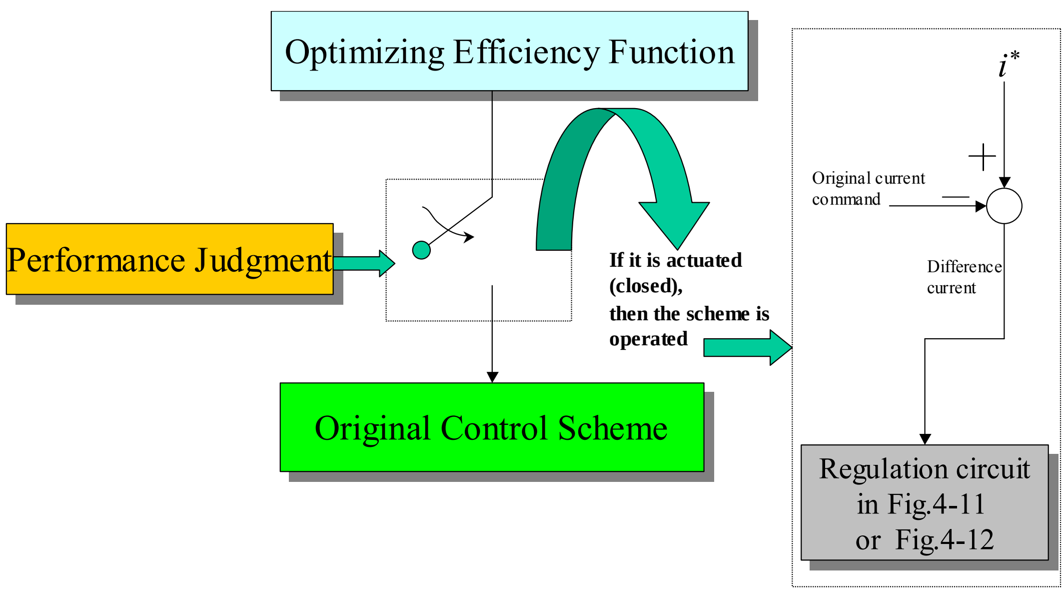


Figure 4-10: The function block for efficiency optimizing operation.

Two applicable control schemes are illustrated in Fig. 4-11 and Fig. 4-12, which can be constructed by part of software function.

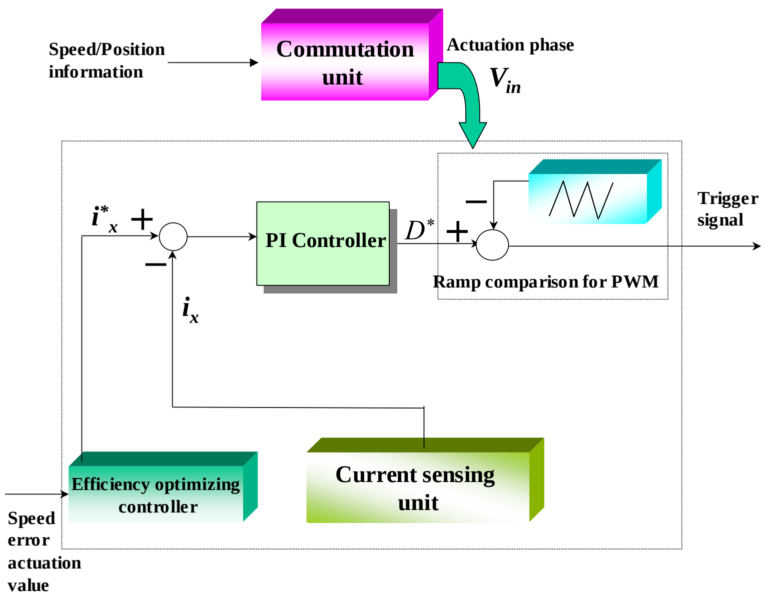


Figure 4-11: Duty-cycle controlled scheme with adding of current control loop.

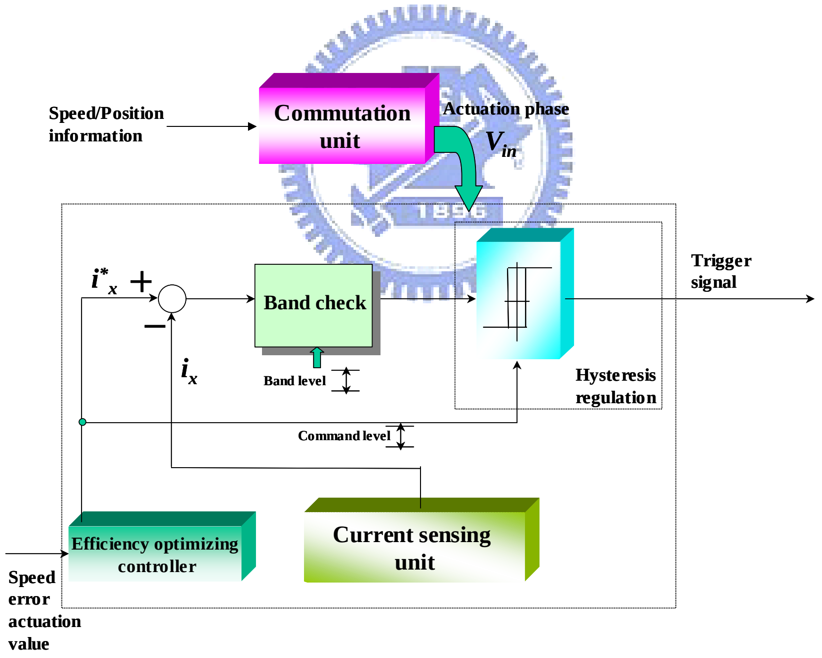


Figure 4-12: Current hysteresis control scheme

4.3.2 Electrical Signals Planning

As shown from Figs.4-6 to 4-8, it is clearly that the planning of electric signals, for voltage and current, can generate the resulting efficiency. Many software can be applied to simulate the operation of the status of SRM drives, for instance, ANSOFT, SpeedLAB, Rmexp, PC-SRM, VECTOR FIELDS, OPERA-3D, Magnet, JMAG, and Matlab, etc. To consider and evaluate the control approach, working formula, and usage setting, a drive's model established in simulink environment of Matlab utilized within S-Funciton for parameter computation based on FNN, and the ANN model for performance judgment, shown in Fig. 4-13.

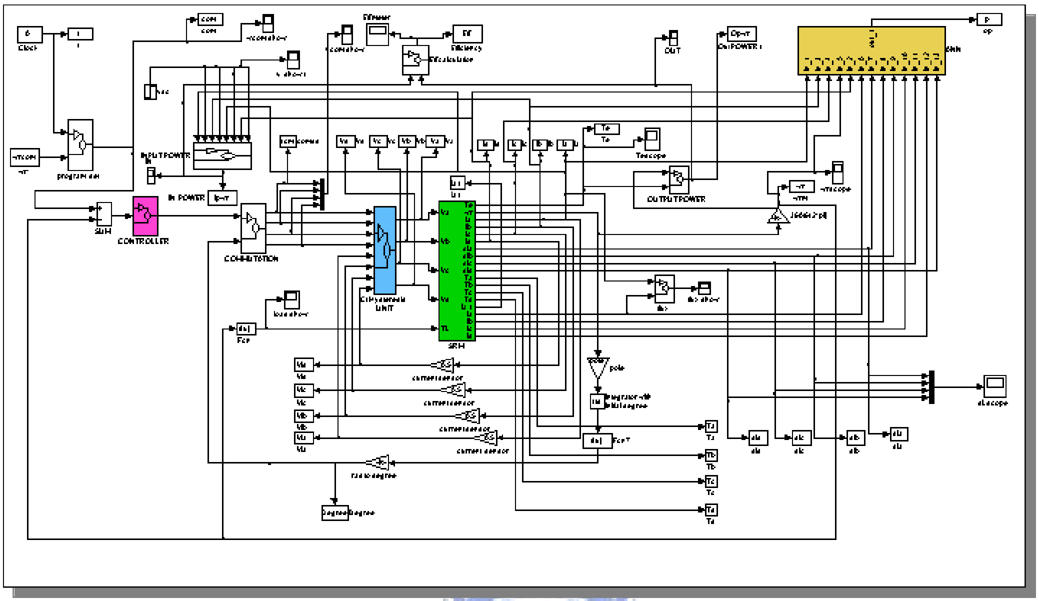


Figure 4-13: The established simulation model for the SRM drives.

Figure 4-14 shows the simulation results, which with the settings of sampling time and speed command being 1/10000 second and 1000 r/min, for the comparison of current profile for the conventional hysteresis control and the proposed optimizing efficiency control. The area and profile of the current utilizing the proposed approach, based on sinusoidal ratio of command current to voltage, is less and smoother than that by the conventional controller.

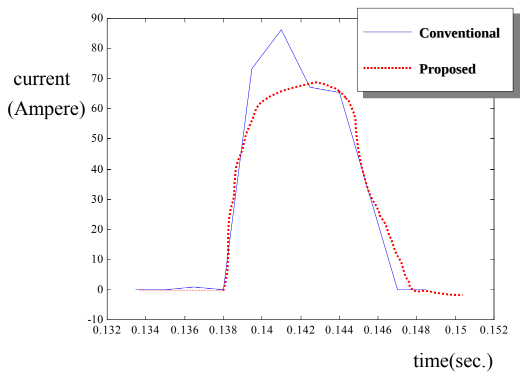


Figure 4-14: The comparison of current profile of efficiency and conventional current control.

4.4 Efficiency Regulation Capability

As the approach is featured by an optimizing concept, not the optimum solution, the efficiency regulation is operated with different capability. It is affected by the related settings such as step-size of the variation, operation period, performance requirement, and so forth. Based on Eq.(4-4), it is obviously that, the resulting efficiency depends on the ratio of electric signals and the change of inductance with respect to time. Thus, the efficiency regulation capability can be realized by the inductance related value except for the concept of the optimizing approach. To use the information, the motor operation speed can be considered as well, and Fig. 4-15 shows an example for comparison of computed values and measured values while taking SRM 1 as the driving target.

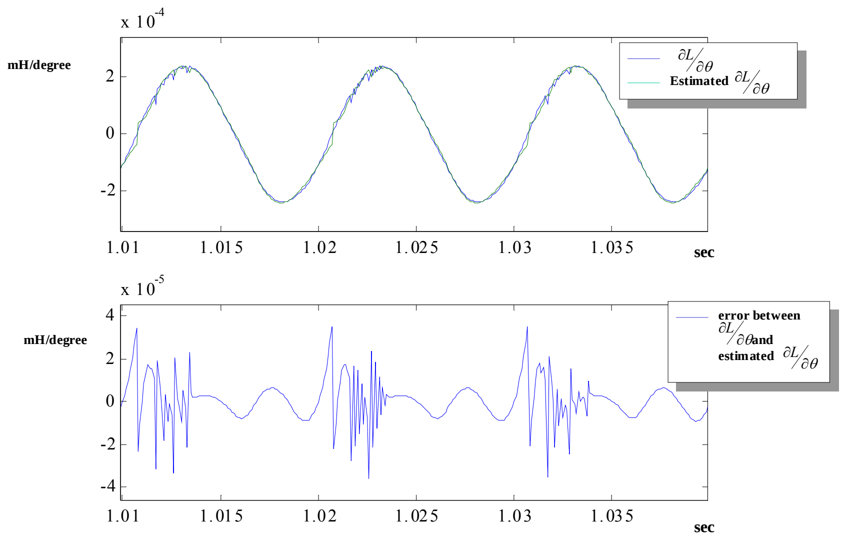
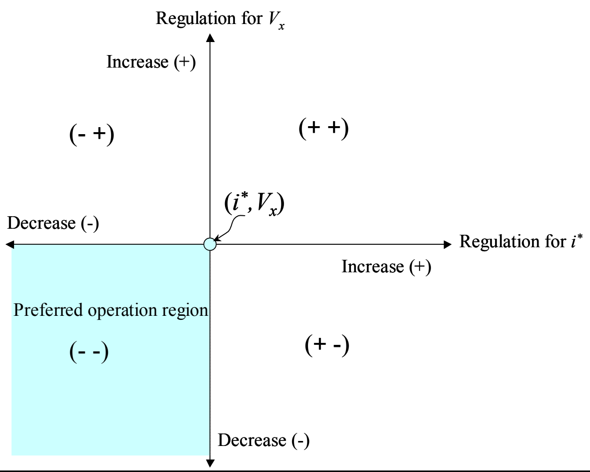


Figure 4-15: The comparison of estimated and pre-measured equivalent magnetic inductance that can be referred to efficiency capability.

As the expression of Table 4-2, the efficiency regulation capability is specified again by the criterion that using less input power, which arranges the operation states by filling dark color.

Table 4-2: The operational planning for efficiency regulation

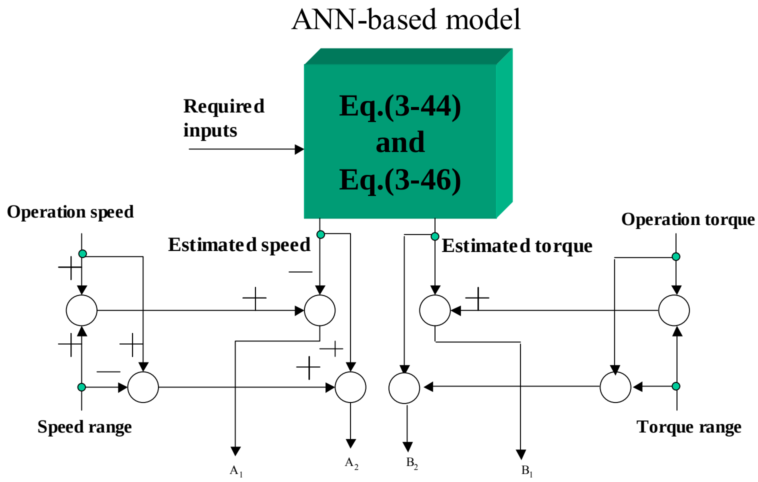
V_x / i^*	**Increase (+)**	**Fixed as the same value (=)**	**Decrease (-)**
Increase (+)	Increase (+ +)	Increase (= +)	Contingent (- +)
Fixed as the same value (=)	Increase (+ =)	The same (= =)	Decrease (- =)
Decrease (-)	Contingent (+ -)	Decrease (= -)	Decrease (- -)



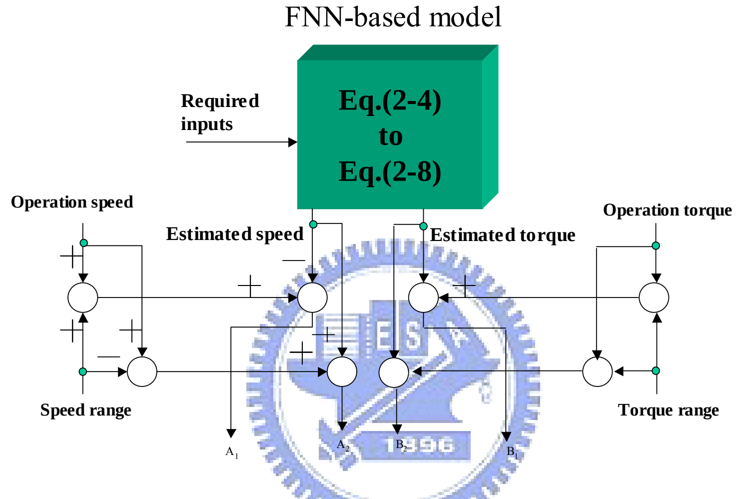
4.5 Constant Efficiency Application

The operation merely to set the efficiency command, and to force the ratio of current to voltage keeping in a fix value, then constant efficiency control may succeed while the power requirement of the SRM drives can be conformed to the requirements. For the application of the constant efficiency control, the ranges of applied speed and torque, which are the computing variables for output power, should be discussed. Three schemes with performance judgment are arranged in Fig. 4-16. The output patterns of [A_1, B_1, A_2, B_2] will decide whether the optimizing operates or not related to the speed range as well as the torque range both based on the accuracy of applied parameters and the power requirement.

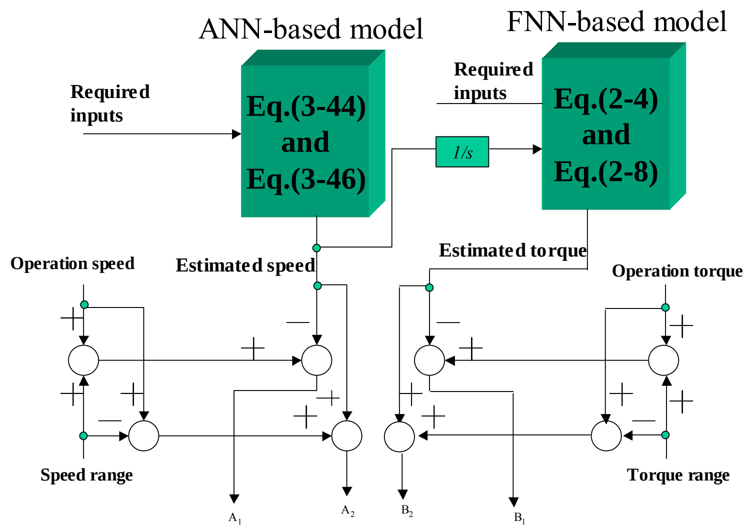
,



(a)



(b)



(c)

Figure 4-16: The operation schemes with performance judgment:(a)FNN-based scheme ;(b)ANN-based scheme;(c) Hybrid scheme.

4.5.1 Applied Speed Range

The applied speed range can be testified by the comparison of Fig. 4-16.

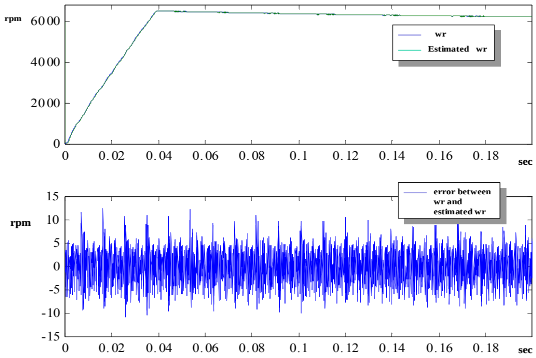


Figure 4-17: The information of applied speed range.

4.5.2 Applied Torque Range

In the similar way, the applied torque range can be testified by the comparison example of Fig. 4-18.

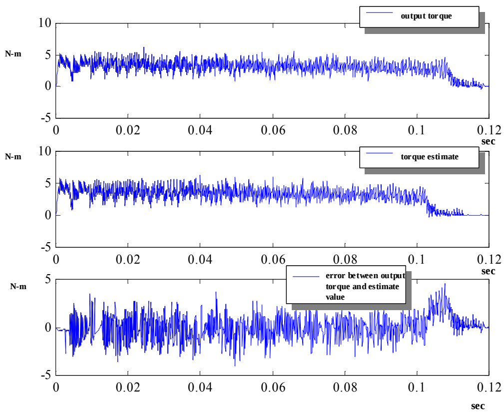


Figure 4-18: The information applied torque range.

4.6 Efficiency Observer Application

Energy monitoring has been an important issue in advanced system. The early detection and control processing strategies of energy in rotating machines can significantly enhance the effectiveness, applicability, and related performance-keeping capability of the operation systems.

By the inverse relation, the equations and the related formulations can be derived easily to observe the efficiency of SRM drives, as expressed of Eq.(4-5):

$$Eff^{*(i^*)} = \frac{i_x^* \cdot k\left({dL_x}/{dt}\right)}{2 \cdot V_x} \cdot \qquad (4\text{-}5)$$

A simple illustration for this efficiency observer is shown in Fig.4-19.

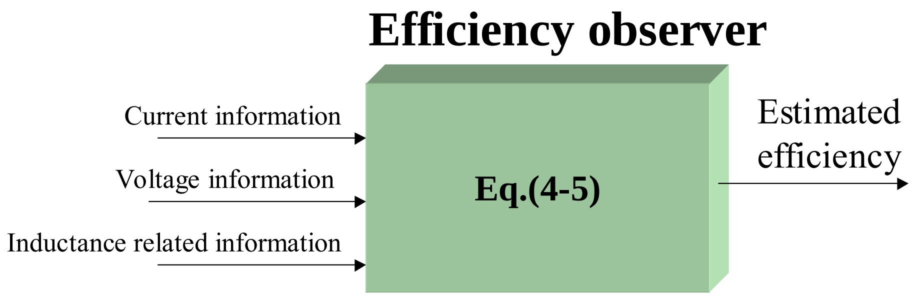


Figure 4-19: The observer opinion to the proposed strategy.

Chapter 5 Performance Enhancement Study

System modeling is a fundamental problem in system theory and is the kernel of many engineering problems. A model that can show the behavior of the controlled plant and to support and enhance the control developments is no doubt requested. Recently, research achievements for the switched reluctance motor (SRM), including control strategies, converters topologies, motor design and related systems applied to industries for traction application and so on, mature reliability has been accepted in this fields[27,29,33,62,75]. The parameters estimation and controller analysis methodology for improving effectiveness to development of SRM drives is still important focus in research works [27,29,44,47].

5.1 Compensation Rule for Resistance Variation

Based on the introduction of the resistance estimaiton approach in Chapter 3, the derivation can proceed fruther linking to the SRM model and gaining the current compensator required information from Eqs.(5-1) to Eq.(5-3) as:

$$i_{x(c)}^{*} = i_x^{*} + \Delta i_x^{*} \tag{5-1}$$

$$\frac{1}{2}(i_x^{*} + \Delta i_x^{*})^2 \frac{\partial L_x}{\partial \theta} - \frac{1}{2} i_x^{*2} \frac{\partial L_x}{\partial \theta} = (k \cdot i_x^{*2} \cdot \Delta R_x) / w_r \tag{5-2}$$

$$\frac{1}{2}\Delta i_x^{*2} + i_x^{*} \cdot \Delta i_x^{*} - (k \cdot i_x^{*2} \cdot \Delta R_x)/(w_r \cdot \frac{\partial L_x}{\partial \theta}) = 0 \tag{5-3}$$

$$\Delta i_x^{*} = -i_x^{*} + \sqrt{i_x^{*2} + \frac{2 \cdot (k \cdot i_x^{*2} \cdot \Delta R_x)}{(w_r \cdot {}^{\partial L_x}\!/\!_{\partial \theta})}} \tag{5-4}$$

where the notation $i_{x(c)}{}^{*}$ means the current command after compensated operation. Figure 5-1 shows the operation scheme of this compensation concept.

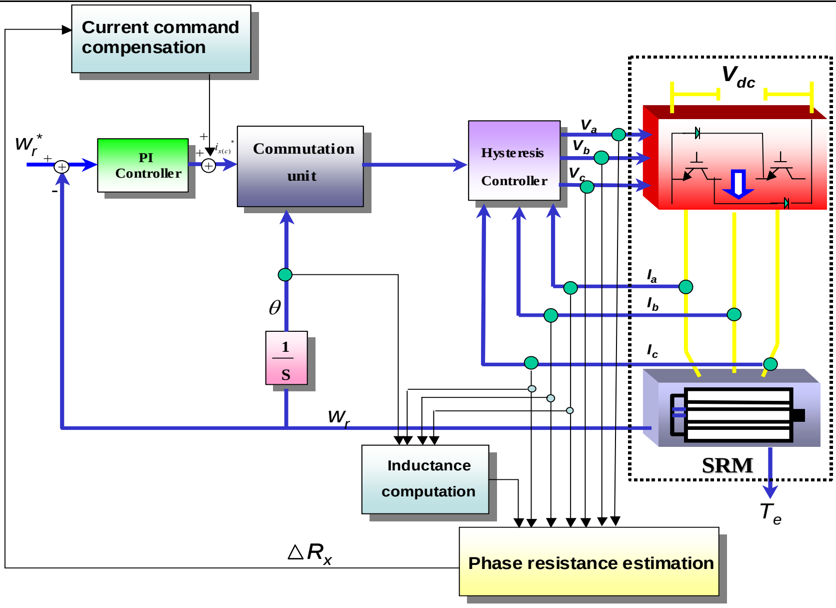


Figure 5-1: The current command compensation scheme based on change of resistance.

5.2 Compensation Rule for Mutual Inductance Effect

The dynamic mutual inductance model is set for improving the SRM drives performance. The previous controller can achieve the goal by adding the model output information to compensate the controller command or to be a new integration model type controller. Followings will arrange the derivation procedure:

For ease-of–introduction, the usually neglected torque production definition can be expressed and generalized as Eq.(5-5) :

$$\Delta T_{ed} = \frac{1}{2} i_{x1}^{\ 2} \frac{dL_{x1}}{d\theta} + i_{x1} \cdot i_{x2} \frac{dM_{x1x2}}{d\theta} \tag{5-5}$$

Then the modified current command can be expressed as the term $i_{x2} + \Delta i_{x2}$, where i_{x2} and Δi_{x2} mean the previous current command and compensated current for output the desired torque while the mutual flux linkages related torque exist. The relation after the compensated current being added can be stated as:

$$T_e = \frac{1}{2}(i_{x2} + \Delta i_{x2})^2 \cdot \frac{dL_{x2}}{d\theta} + \Delta T_{ed} \tag{5-6}$$

Hence, the compensation current can be computed as:

$$\Delta i_{x2} = -i_{x2} + sign(\Delta T_{ed})\sqrt{\left| i_{x2}^{\ 2} - 2 \cdot \frac{d\theta}{dL_{x2}} \cdot \Delta T_{ed} \right|} \tag{5-7}$$

To use the derivation results of current compensation value and to add it to the convection current command from Eq.(5-7), the torque produced by the mutual flux linkages and non-ideal current phase switching can be eliminated and keep the SRM drives to output the desired performance under the previous control scheme, being not fully taking mutual inductance related effect into account.

For the development of SRM drives, the output performance is the most important concern topic. The objective of this developed model is to find a current compensation command to circumvent the problem that the original current command is usually not completely considering mutual inductance and non-ideal switching. The optimum searching method based on the least-squares analysis is the main computation structure to develop a tool type environment. The overall dynamic model for compensation current control command is depicted as Fig. 5-2. The procedure for designing a current control compensation command by the algorithm description in former sections are three major function parts and involves the following steps:

1) To develop the self-inductance table by the pre-measured data of the mapping relation between rotor angle, current, and the self-inductance.

2) To compute the mutual inductance by the known self-inductance and current using the least-squares optimum searching method.

3) To obtain the non-ideal effect of current overlapping for toque production and its compensation current command from Eq.(5-6) and Eq.(5-7).

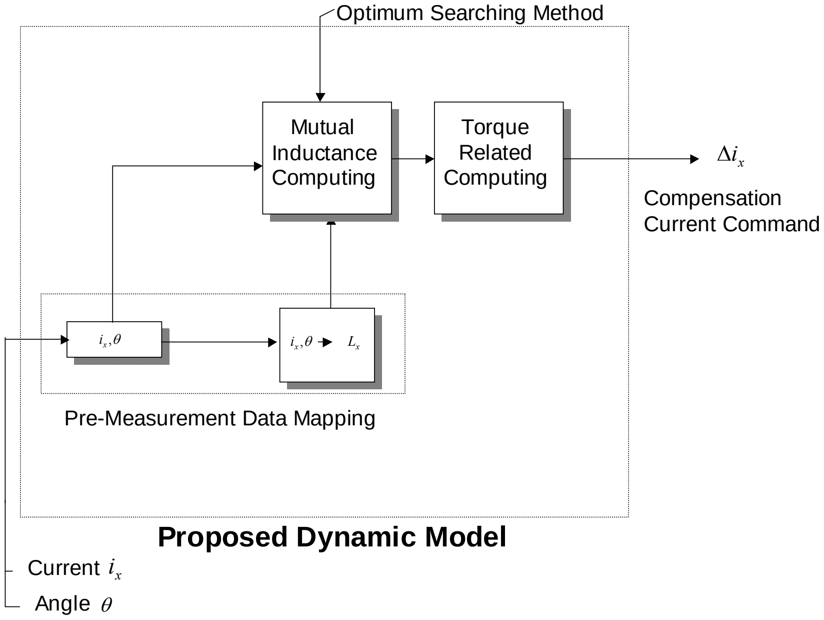


Figure 5-2 : The overall schematic representation of the proposed model .

5.3 Verifications

In practice, for the non-ideal measurement values may occur, such as waveforms of low-frequency roll off, ringing, propagation delay, etc., hence, a dynamic smoothing techniques are deployed by the average computing opinion to reduced the sharp variant of the measurement values. As description in 3.2 and 3.3, the computation problem is viewed as a over-determined system here, and the matrix with the entries of the required parameters is solved using the least square opinion by $X^* = (Q^T Q)^{-1} Q^T U$[72], where X^* is the optimum vector that with least square error for $\|QX - U\|^2$ to the desired X.

The method that makes use of the optimum searching for shorten the computation time, which is applicable for on-line application, can be applied. Least-squares opinion can be taken, and the answer can be transferred to find a vector that minimizes the objectives value and described as:

The unique minimizer of $\|QX - U\|^2$ is computed by $X^* = (Q^T Q)^{-1} Q^T U$, where X^* is the desired vector.

Thus, both of the mutual inductance and phase resistance can be obtained by the least-square analysis using the mapping and measured information by the preliminary knowledge described above.

Figures 5-3 to 5-5 show the verification result based on the compensation scheme of resistance variation.

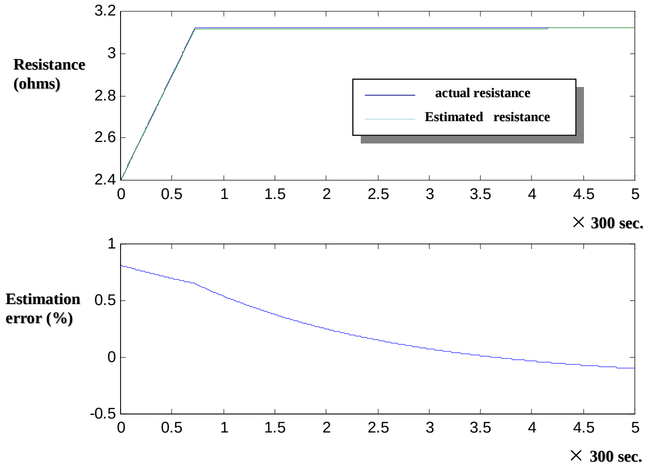


Figure 5-3: Resistance computation result. (1000 r/min, by derivative type)

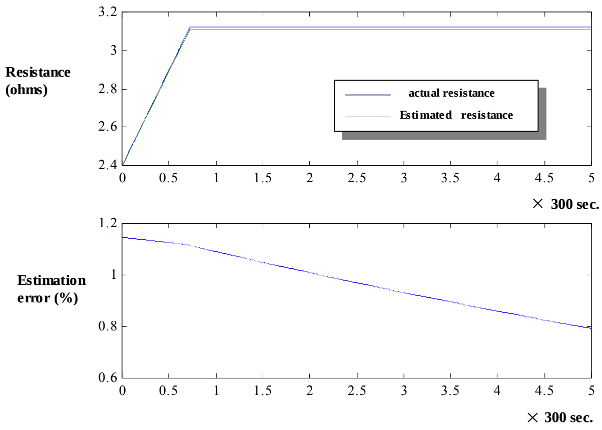


Figure 5-4: Resistance computation result. (1000 r/min, by integral type)

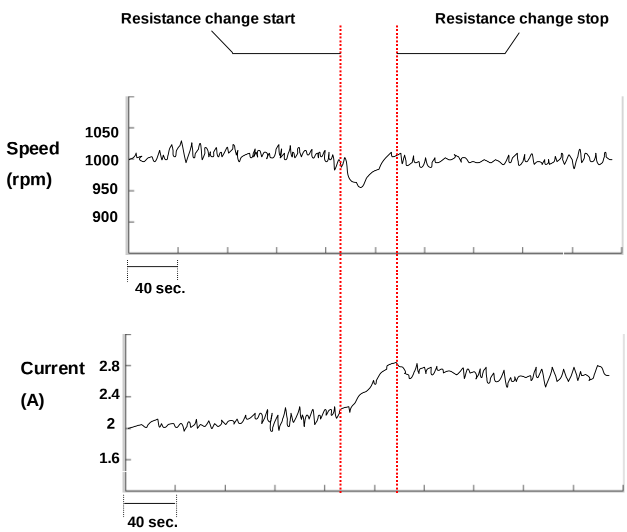


Figure 5-5: Operation record for compensation.

Figure 5-6 presents the experimental result of the phase current (including the adjacent phase) and the speed response during steady state as the speed command based on the scheme of Fig.5-6 is set to be 925 rpm. The current overlapping can be shown apparently and the speed difference between command and actual response having relatively large portion during that region.

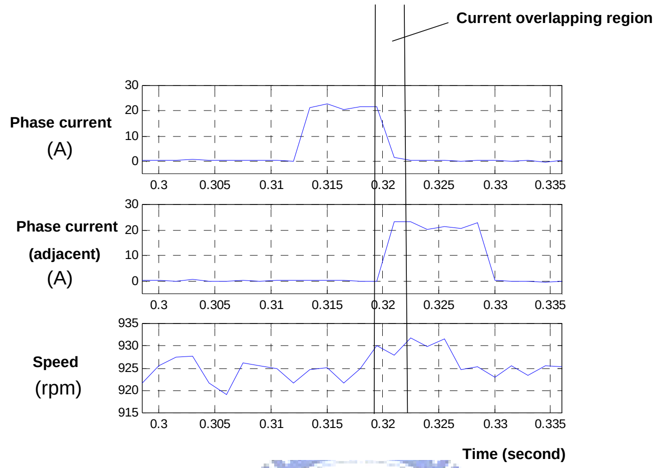


Figure 5-6: The related results of speed command 925rpm without current compensation.

The whole motion and operation re-processes utilizes the dynamic model to obtain the compensation command for current and the related waveforms being shown as Fig.5-7. The speed difference with the command is smaller than the results of the previous design.

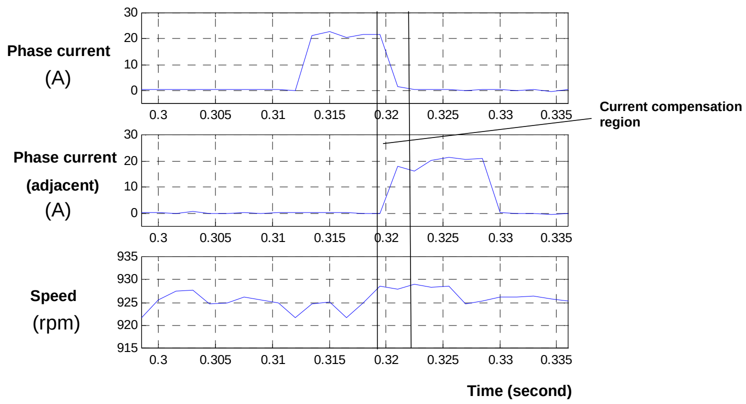


Figure 5-7: The related results of speed command 925rpm with current compensation.

The current compensation command is added to the adjacent phase current command and depicted as Fig.5-8.

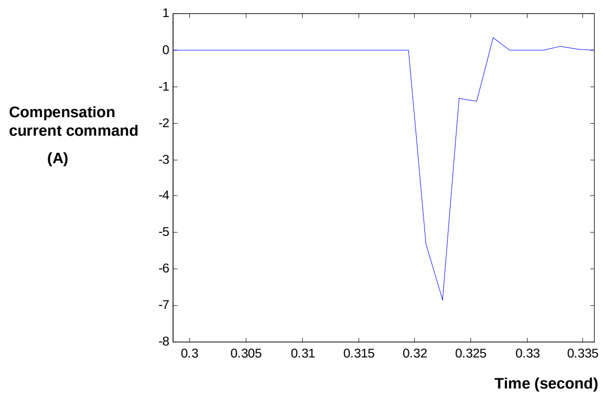


Figure 5-8: The current compensation command.

Followings is the arrangement for the MSE(mean square error) computing results for the speed difference between the actual speed and speed command under the time interval (0.2985~0.3360 sec.) (see Table 5-1). The verification results show the feasibility of the proposed model and the potentials to provide the needing information for control design for improving the SRM drives performance.

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Table 5-1: The performance comparison results.

Current compensation / Speed difference	N/A	Applied
error index (MSE)	3.91	2.17

Chapter 6 System Implementation

In this part, the system implementation illustrations will be given to provide the reference and introduction for demonstration in the subsequent parts and future development of SRM drives. By the implementation of the proposed technique in a laboratory prototype, it shows the feasibility and performance of the respective schemes. Three sections are edited to introduce the applied schemes for estimation and control, function-block illustrations for hardware, and signals processing concept based on the structure of a personal computer(PC), respectively.

6.1 Introduction to Schemes and Functions

A system that can show the behavior of the controlled plant is requested to support and enhance the control developments. The function blocks that basically depict the drive scheme for the SRM, included but with specific modified functions, are arranged and connected in Fig. 6-1.

The verification scheme for demonstrating the proposed dynamic analysis model is planned based on the system of Fig. 6-1. The proportional-integration (PI) speed control design is utilized . Meanwhile, the current-loop controller, being actuated with band-band control based on hysteresis concept if not specified, regulates the current value by the appropriate error limit to trace the desired current value.

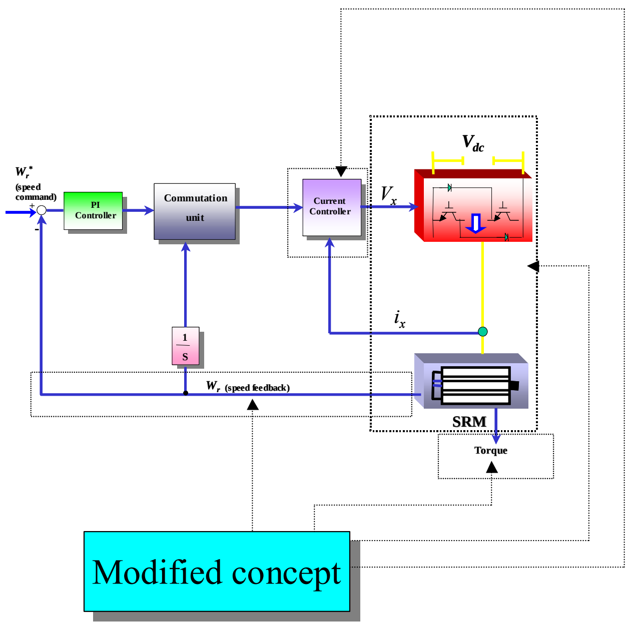

Figure 6-1: The modified base of SRM drives for verification.

The primary parameters of SRM taken into verifying and evaluating the performance and feasibility of the proposed model are listed in Appendix A and Appendix B. Figure 6-2 shows the related photos for the two applied SRMs with rated power of 3 hp and 1/2 hp, respectively.

Frame Rotor Stator

(a)

Frame Rotor Stator

(b)

Figure 6-2:Photos of outward appearance and the taking apart states for the applied SRMs:(a) SRM 1;(b) SRM 2.

6.2 Hardware Description

The hardware is constituted and organized as the function block described in the previous section. The information for electric properties is obtained through the applying scheme shown in Fig. 6-3. The hardware with main components of AD532 and TL084 (the main page of the datasheets are shown in Appendix C) is set up for measurement of input power and the relative electronic values, including current and voltage.

In addition, the energizing of phase windings must be synchronized with the rotor position. The angular position sensor is required for this reason, which leads to degrading of robustness and cost rising problems. Therefore, many research for eliminating the position sensor is going on, and the alternative way to reduce the hardware usage is also the objective for this verification arrangement.

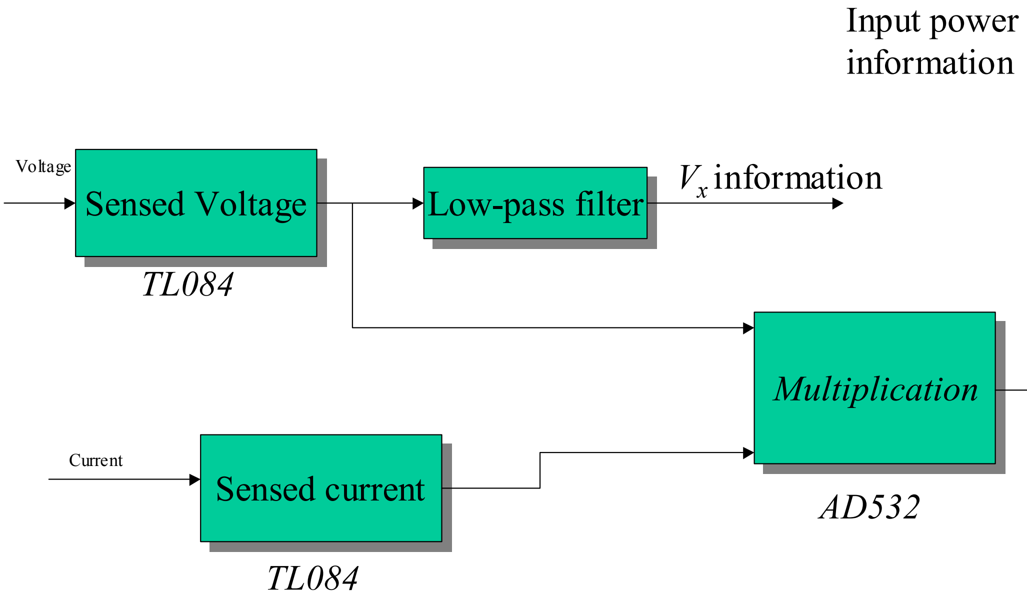

Figure 6-3: The electric properties information acquiring scheme.

6.2.1 Block Diagrams for Functionalities

To construct the signal flow for the verification based on the experimental setup, a interface circuit featured by the block diagrams is shown in Fig. 6-4 for expressing the functionalities of this design.

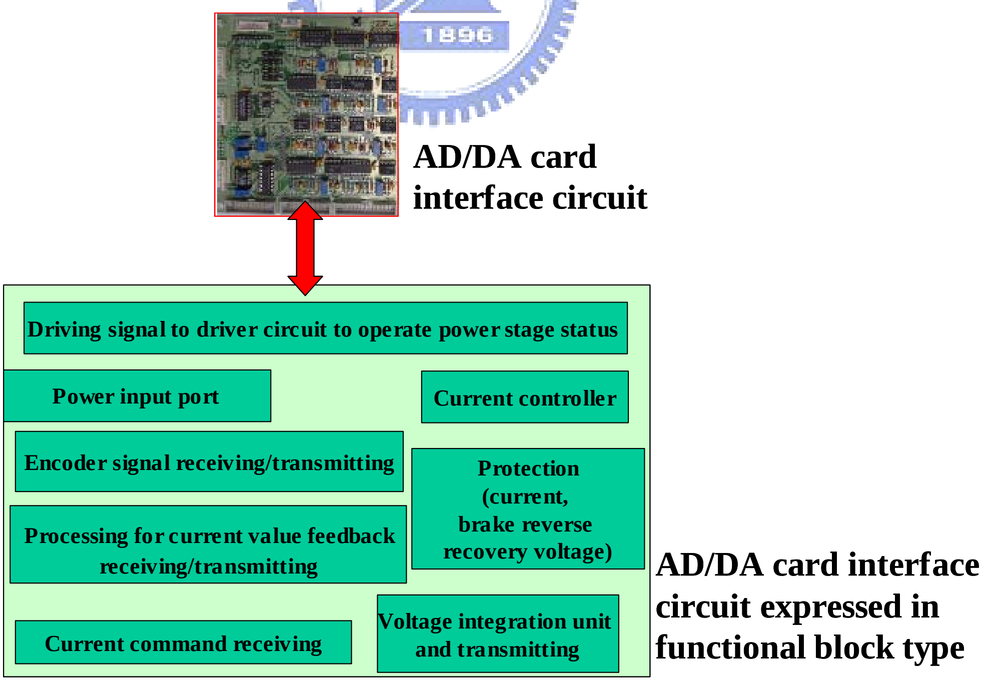

Figure 6-4: The block diagram for functionality evaluation.

6.2.2 Efficiency Computation

The efficiency is computed using the scheme of efficiency observer introduced in 4.6. The main computation scheme that is actuated under performance conforming to the requirement, and start to compute by the logic scheme shown as Fig. 6-5.

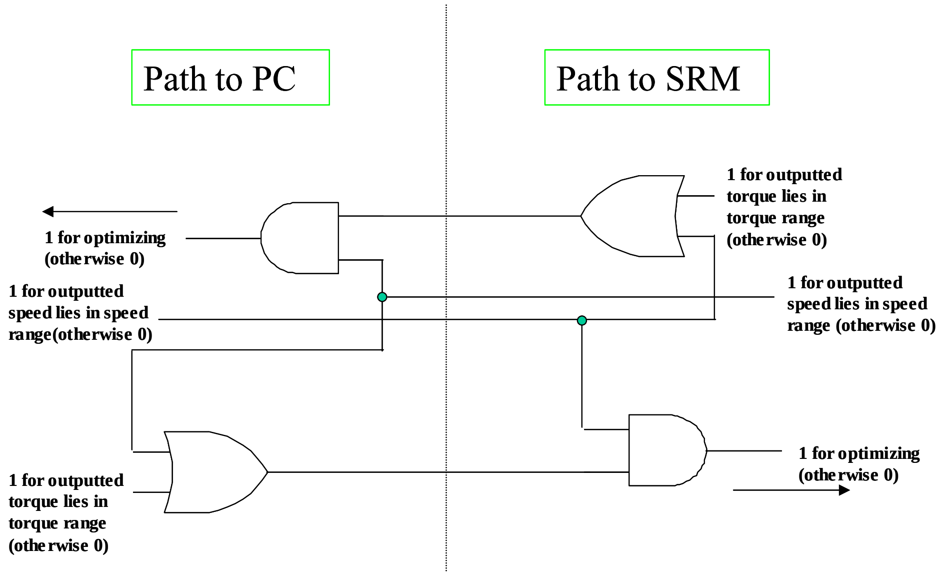

Figure 6-5: The operation for efficiency computation scheme based on the logic relation.

6.3 Computer-Based Processing Structure

The computer with interface circuit is functioned with command output, feedback signal processing and computations. It works by three steps as: gaining the SRM drives operation message, processing utilizing the proposed algorithms, and output the driving force to the drives. A data acquisition card (CH1020 AD/DA) constitutes the main signal flow way utilizes the ISA bus to connect the PC, provides eight A/D converters, four D/A converters, and an encoder counter, respectively, shown in Fig. 6-6.

The experimental platform, a PC-based SRM drives development system with analog/digital card and interface circuit, are set up for different evaluation as Fig. 6-6, Fig. 6-7, and Fig. 6-8, respectively, for verifying the feasibility and applicability of the proposed schemes. The loading torque is added by a circular metal material coupled with the output axle of SRM, hysteresis brake machines, or AC electric machines, respectively. .

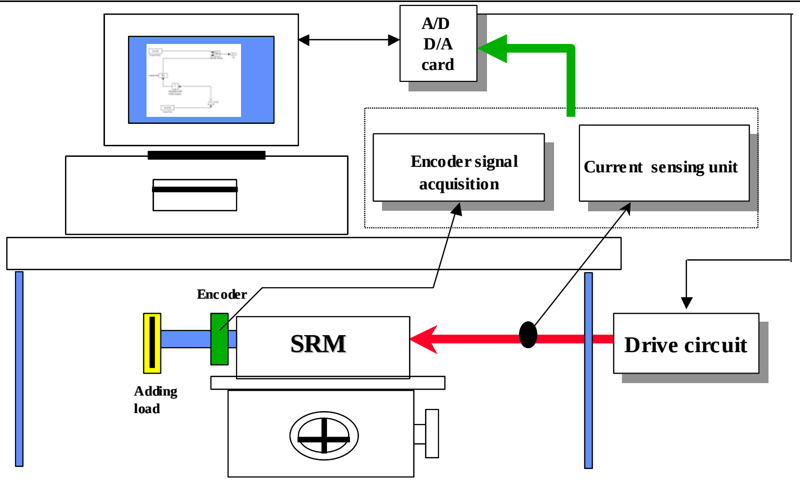

Figure 6-6: The experimental platform for torque/speed estimation.

The hysteresis brake, chosen to be the load torque, and a developed PC-based SRM drives circuit with analog/digital card and interface circuit for information acquisition are applied for setting up the experimental platform, illustrated as Fig. 6-7.

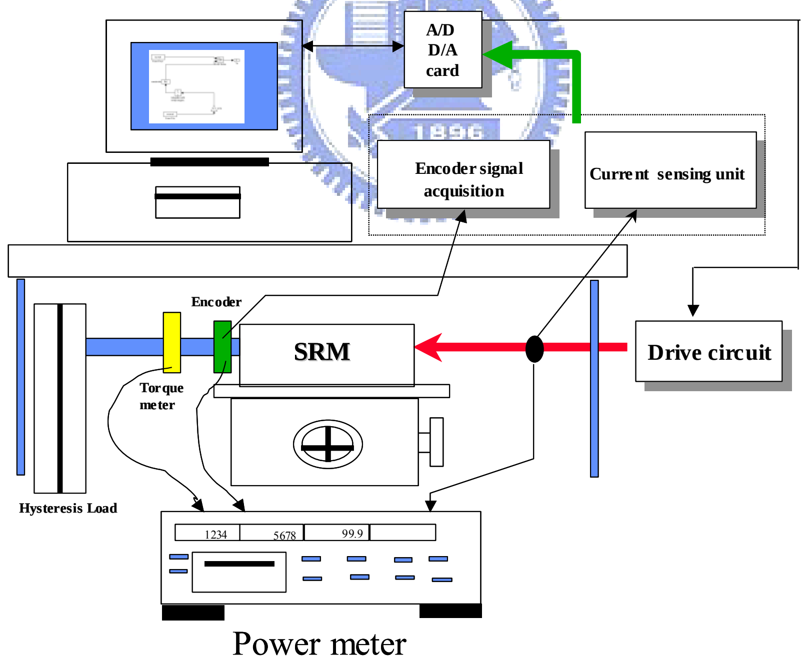

Figure 6-7: The set-up experimental scheme for efficiency index verification.

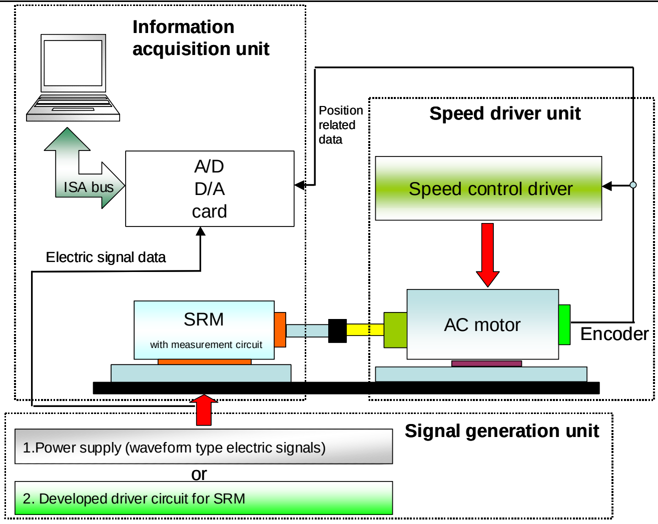

Figure 6-8: The representative scheme of experimental setup for inductance measurement.

The overall computer-based system can be depicted by the illustration of Fig. 6-9.

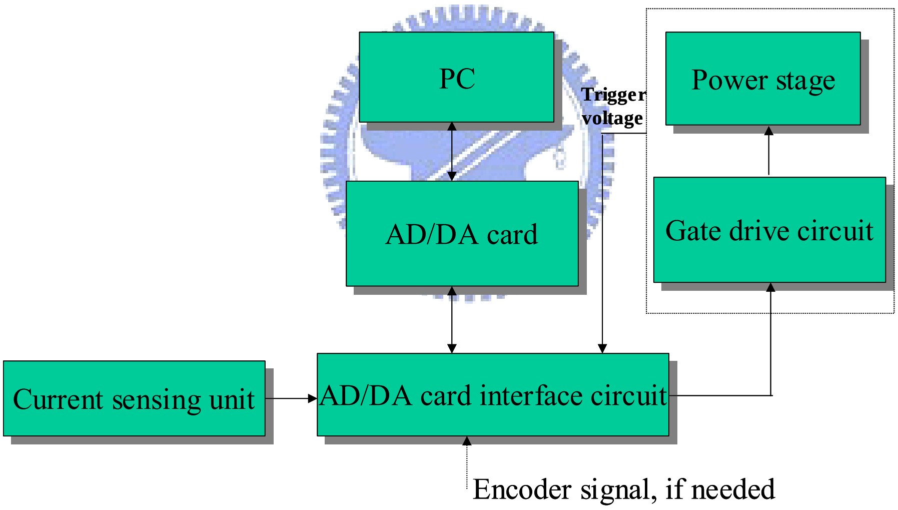

Figure 6-9: The processing scheme for the computer-based system.

Chapter 7 Experimental Test and Analysis

In the former part, the algorithms of the proposed optimizing efficiency control and some parameters' estimation approaches are developed and derived. Some verifications have been made through computer simulation and preliminarily specific practice under various assumptions. In Chapter 7, experiments are carried out to verify the efficiency regulation capability and operation status. The proposing inductance measurement results is shown as well. Then, some experimental results related to efficiency improvement, inputted current reduction, and responses of speed and torque are presented, respectively, to demonstrate the performance of the proposed control strategy for the SRM drive. The verification result is arranged follows the content of Chapter 6, and to make the comparison of performance for the SRM drive. The details follow.

7.1 Experimental Setup

The experimental scheme for verifying the proposed optimizing efficiency control strategy is based on Fig. 7-1. The elementary controllers scheme that designed is the PI controller for speed control loop, which is the preferred controller to the most industrial application due to its simplicity in concept and implementation, and the hysteresis controller for current control loop as well, say, conventional controller, to regulate the current value by the appropriate error limit to trace the desired current value. The optimizing efficiency control strategy is constructed as efficiency controller for SRM drives that utilizes both torque and inductance related parameters estimated by the FNN. Then, the reference current value is updated simultaneously by specific size step toward the higher efficiency that the SRM drive may be in optimizing way based on Eq.(4-4) that using the equivalent inductance value obtained from the trained FNN.

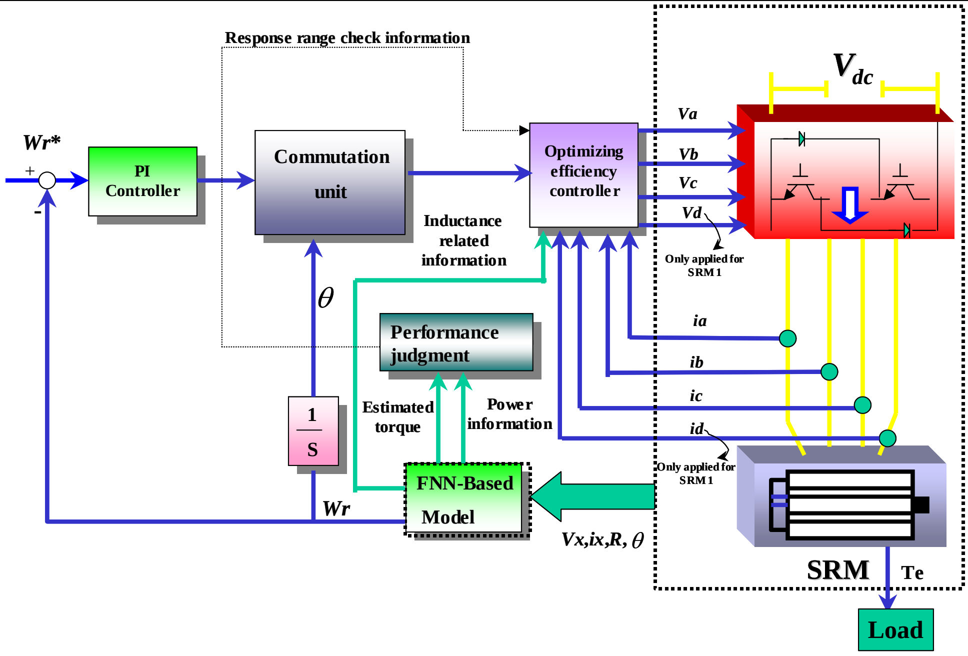

Figure 7-1: The optimizing efficiency control scheme for the SRM drive.

The driving circuit for SRM 1, intended to applied in electric bike, is shown as Fig. 7-2 with power modules and current sensors with code number of FUJI-2MBI150N-060 and LEM-NANA-FC-100P, respectively.

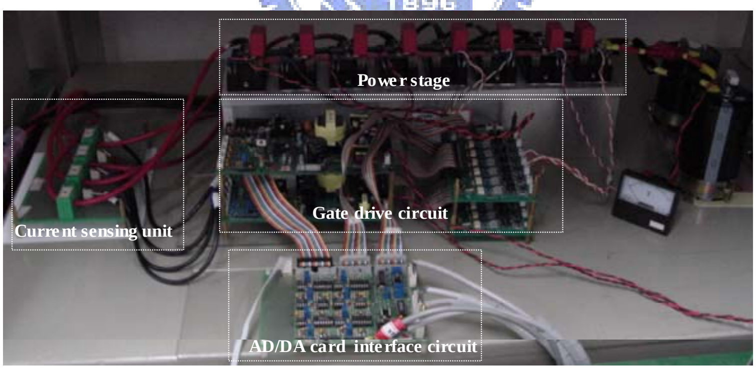

Figure 7-2: The developed driving circuit that is applied to SRM 1 related measurement and estimation.

Besides, the driving circuit for SRM 2, utilized for washing machines, photos as Fig. 7-3, with power modules of IR-GPC40U as well as current sensors of LEM-NANA HY-5P.

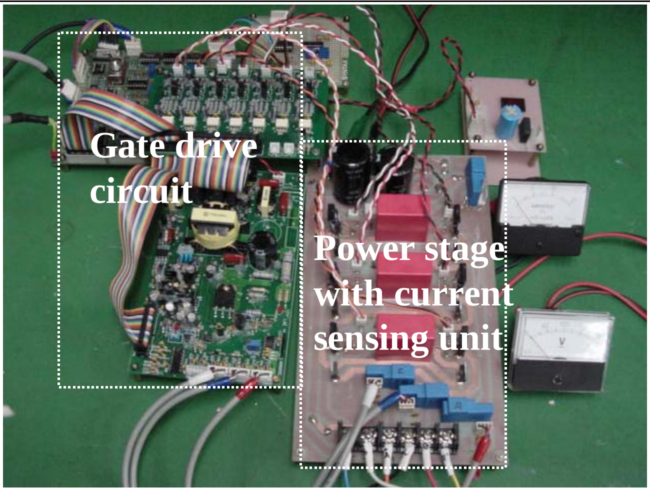

Figure 7-3: The developed driving circuit that is applied to SRM 2 related measurement and estimation.

The measurement scheme for on-line operation of the optimizing efficiency control with the synchronous acquiring of electric properties and states is shown in Fig. 7-4.

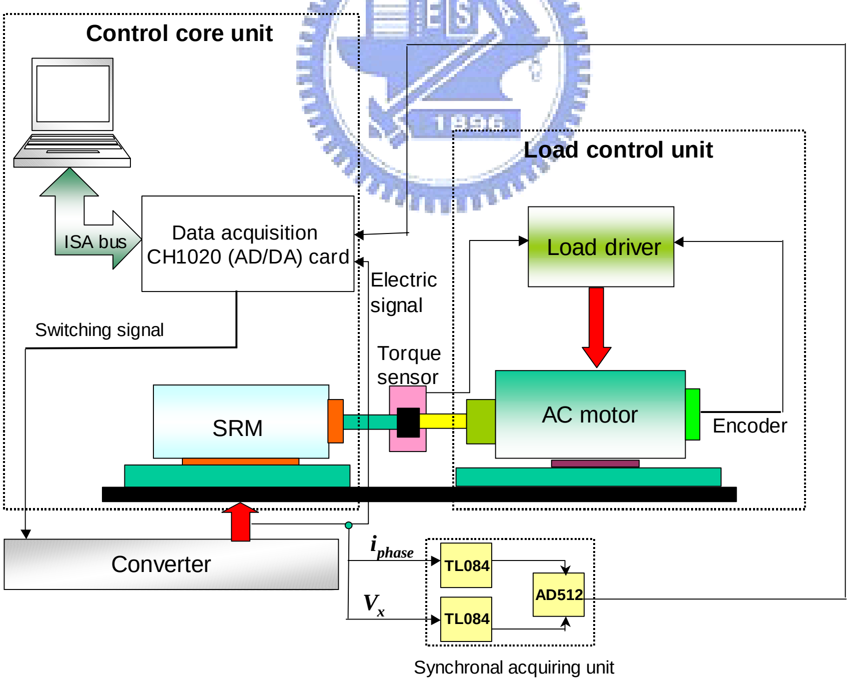

Figure 7-4: The measurement scheme for the optimizing efficiency operation.

In addition, the hysteresis brake is also chosen to be the load torque, not shown in Fig. 7-4, and the two developed PC-based SRM drives circuit with analog/digital card and interface circuit for information acquisition are applied for setting up the experimental platform as well, as illustration of

Fig.6-7. An example of operational monitor screen of the PC is shown in Fig.7-5

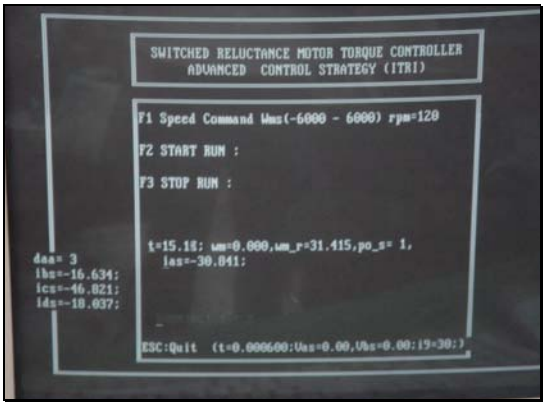

Figure 7-5: An example of the PC monitoring screen under operation.

7.2 Experimental Results

The performance of drives can be taken to estimate for further evaluation. To take the increment of inductance for example, it can be considered to aid the torque estimation while the precise and expensive sensors are not affordable for research laboratories. The presented experimental results applying the two SRMs have verified the proposed measurement method and the information is needed for the proposed optimizing efficiency control scheme. This method also enables the inductance measurement to be done under movement status, rotating or shifting, and may be greatly useful while no accurate positioning promising capabilities for the counterpart motor.

The condition for motor speed command is set to be 6000 r/min for the SRM 1, Fig. 7-6 shows the estimation result under dynamic operation status comparing to the values from inductance information of look-up table.

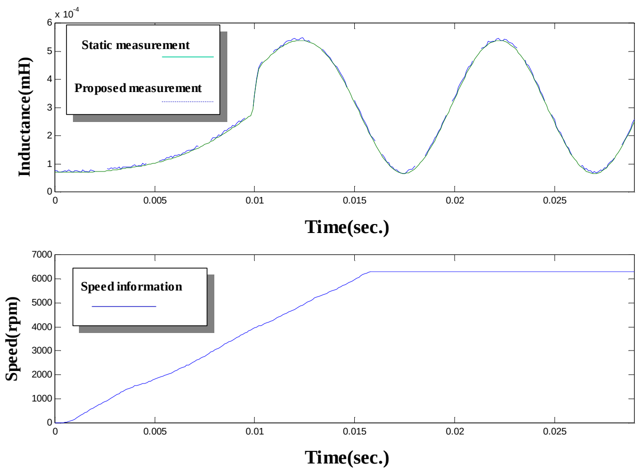

Figure 7-6: The comparison of the inductance profile at 6000r/min for the SRM 1.

Under the same motor speed, the computation result of the inductance differentials with respect to rotor position for showing the applicability of the extended estimation capability is illustrated as Fig.7-7. The difference between the value of estimation by the proposed method and the computing results based on look-up table is clearly less than one value order and demonstrates the feasibility of this method.

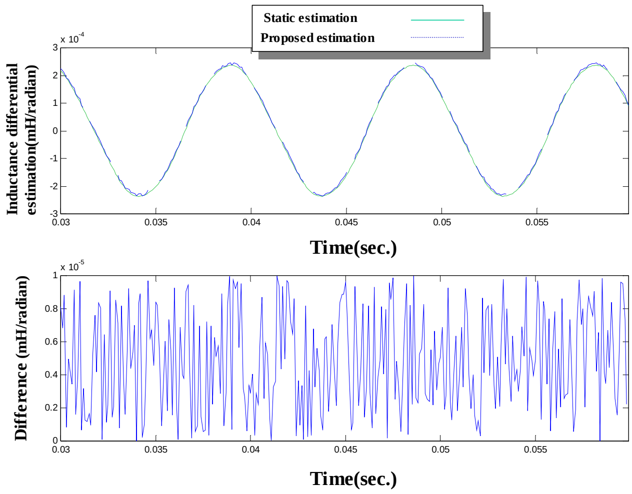

Figure 7-7: The comparison of the inductance differential value with respect to rotor angle of SRM 1 by the proposed estimation method and post-computed method.

The experimental results of the inductance profile in conditions of high current and low current for comparison of the proposed measurement method and the conventionally static measurement approach for the SRM 2 are respectively shown in Fig. 7-8 and Fig. 7-9. Though the maximum differences are existing in the aligned position for approximate 41.6% rated current and the unaligned position for saturation case, the total difference is less than 4.92% and acceptable.

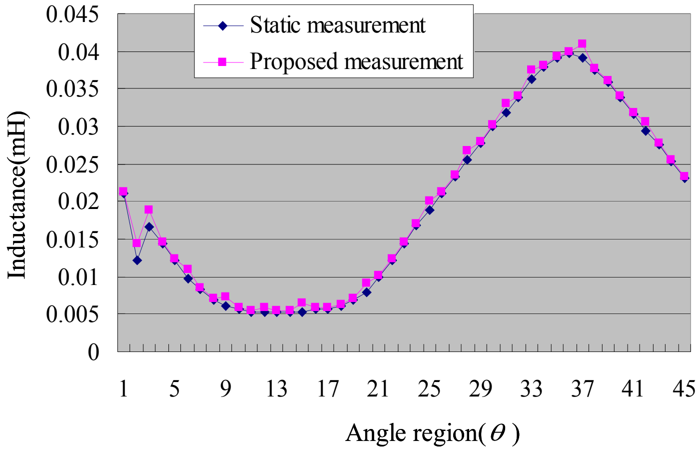

Figure 7-8: The comparison of the inductance profile for the SRM 2 - 1 Ampere (under-saturation condition).

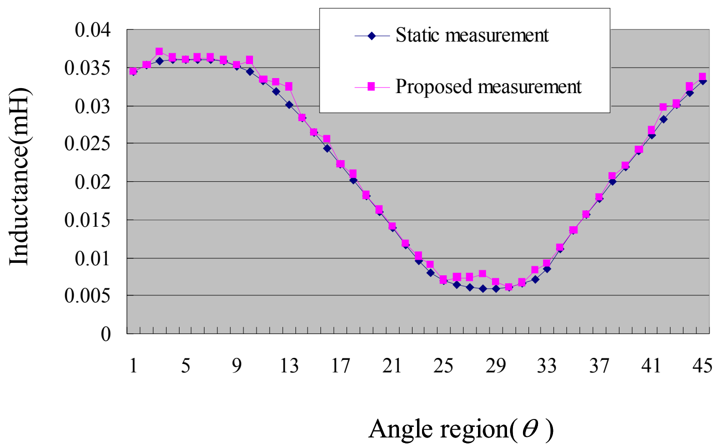

Figure 7-9: The comparison of the inductance profile for the SRM 2 - 6 Ampere (saturation condition).

Under the states of the optimizing efficiency actuation, the current response and the corresponding efficiency change for SRM 2 is shown in Fig. 7-10.

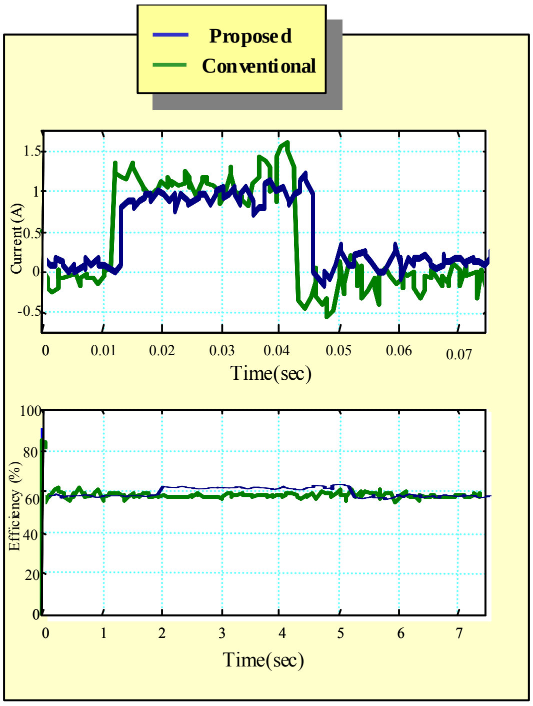

Figure 7-10: The response record for the optimizing efficiency operation(240r/min).

7.3 Performance Comparison

The inductance can be computed by three approaches, including FNN's mapping, ANN-based weight updating, and the on-line measurement scheme, that all proposed in this dissertation. Figure 7-11 and 7-12 show the comparison for the obtained inductance in aligned and unaligned positions in ten operation cycles for SRM 1, which within maximum of 9.2% and 8.1% deviation percentage.

Meanwhile, the obtained inductance value comparison for SRM 2 under aligned as well as unaligned positions in ten operation cycles, shown as Fig. 7-13 and Fig. 7-14, which show the maximum differences are 7.8% and 7%, respectively.

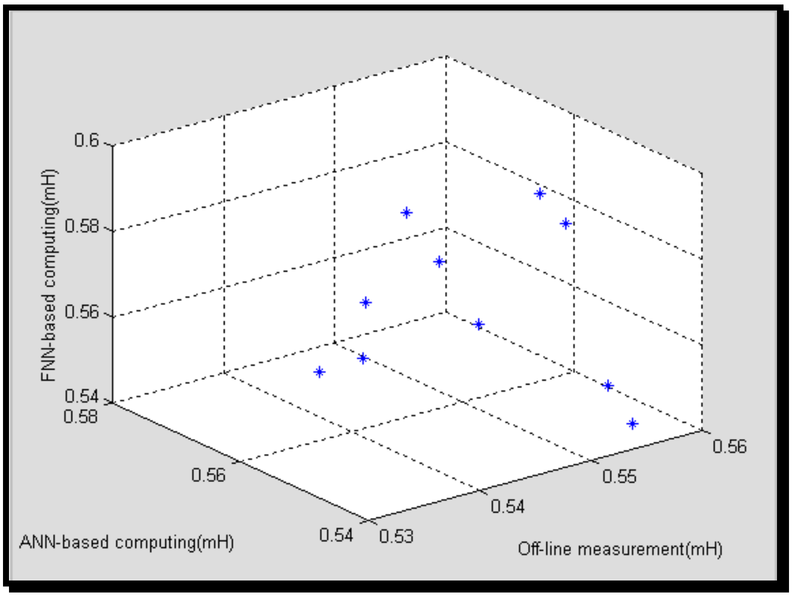

Figure 7-11: The comparison of the inductance values at aligned position for SRM 1.

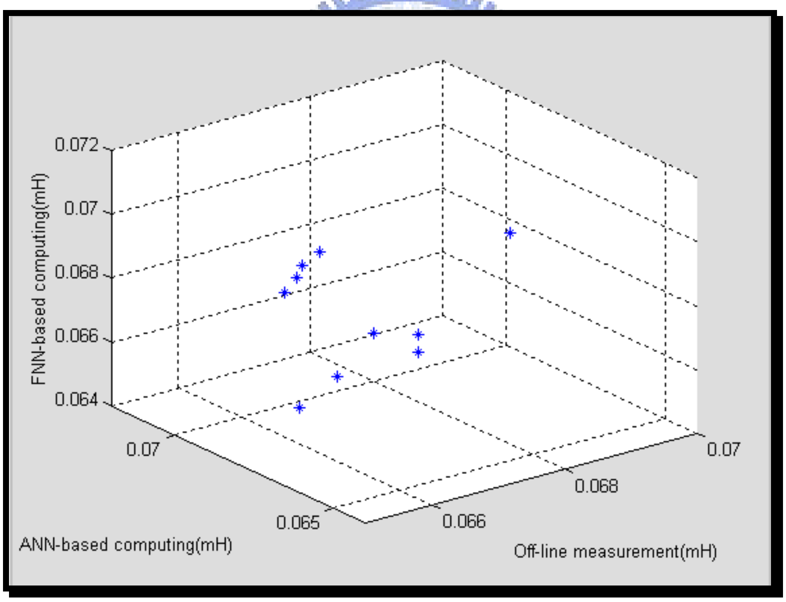

Figure 7-12: The comparison of the inductance values at unaligned position for SRM 1.

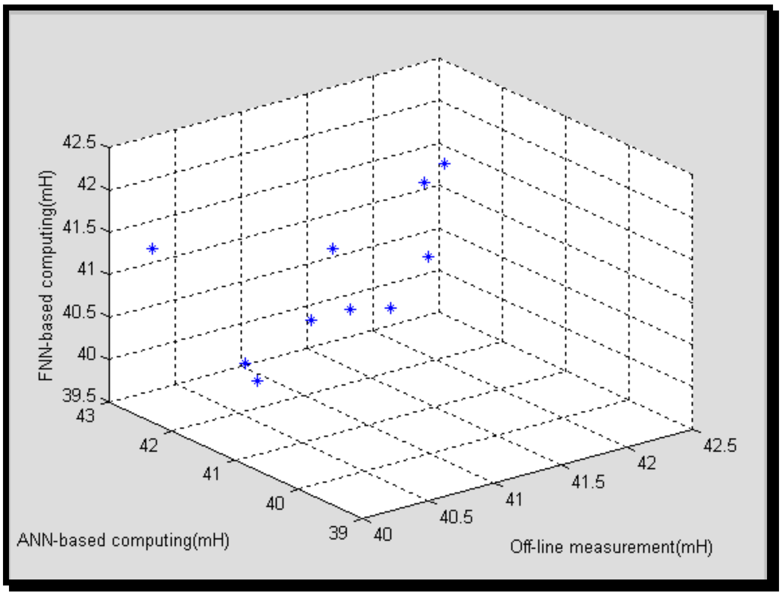

Figure 7-13: The comparison of the inductance values at aligned position for SRM 2.

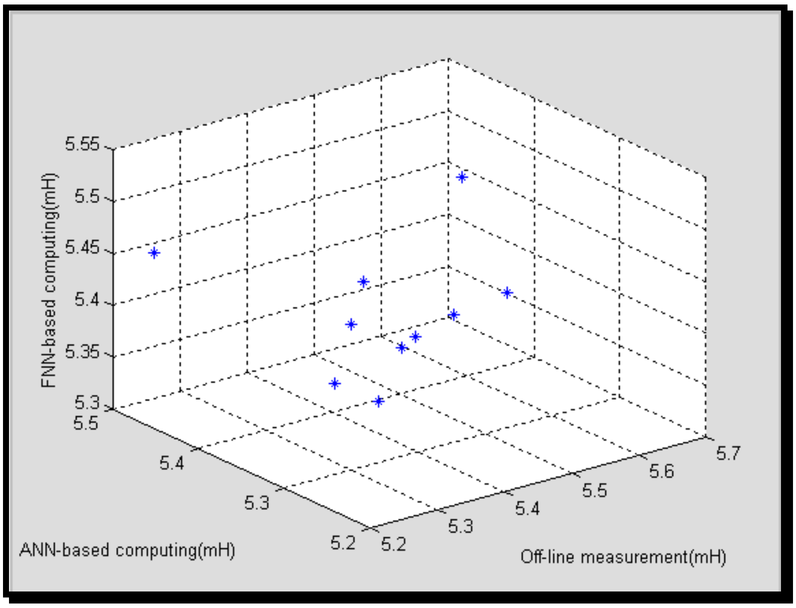

Figure 7-14: The comparison of the inductance values at unaligned position for SRM 2.

Based on the inductance information from the presented approaches in the previous section, the experimental results demonstrated the validity of the capability for the proposed strategies with maximum efficiency improvement of 3.5 %, 5 %, and 7.1 % for SRM 1, and with 3 %, 2.2 %, and 5.1 % to SRM 2 as well, both under the testing of ratio of 0.2, 0.5, and 1, rated power of the applied SRM drives, shown in Fig. 7-15 and Fig. 7-16 , respectively.

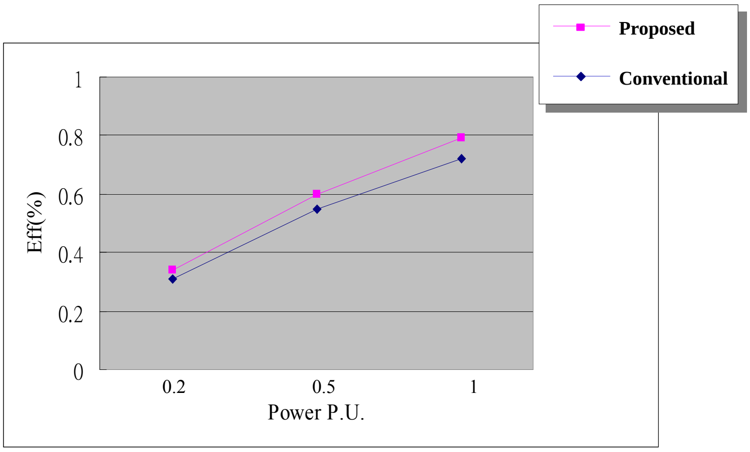

Figure 7-15: The efficiency comparison for SRM 1 (with ordinate of 100 times transformation).

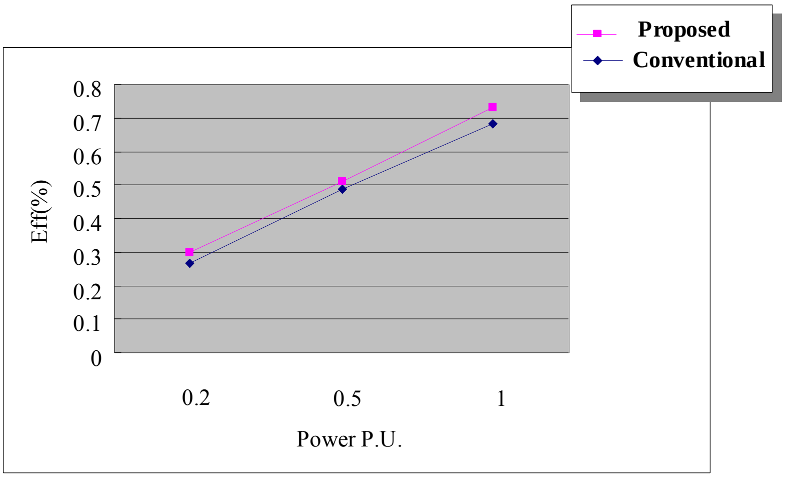

Figure 7-16: The efficiency comparison for SRM 1 (with ordinate of 100 times transformation).

To sum up, by the brief description of experimental results, it has demonstrated the validity for equivalent magnetic inductance estimation at operational conditions and showed the applicability and effectiveness of the proposed strategy by efficiency improvement.

Chapter 8 Conclusions

From the introduction, related derivations, applied schemes, and performance verification by either simulation or actual state measurement, or both of the two, the proposed optimizing efficiency control strategy for switched reluctance motor drives in this dissertation has demonstrated its applicability within crucial parameters' estimation schemes as well as two mechanisms of current-command compensator subjected to the compensation to the variation of phase resistance and existence of mutual inductance owning prospective potential. The arranged and concluded information for providing reference concept for SRM drives is also described in this part.

8.1 Outlined Achievements

Following will give the final remarks and opinions of the achievements of this research having been done so far:

1)An arrangement that focused on development for SRM drives from academic research and industrial information, including statistic of published papers and issued patents that can provide reference trends and concept of developing techniques for those involved in the related fields. That helps in understanding the opportunities and states of the SRM drives.

2)The main concept of optimizing efficiency control is to apply the linking relation of parameters and operate by assigned step size to regulate the current command for optimizing the efficiency of the applied SRM drives, which has constructed a simple efficiency control scheme. In another explanation opinion, the optimizing efficiency control is realized for compensating the conventional current command to operate at the desired or the higher efficiency. There are two SRM drives having taken as examples to evaluate the feasibility of the optimizing efficiency control method. Simulation and experimental results have demonstrated the validity for estimation of inductance related information at operational conditions and showed the applicability and effectiveness of the proposed strategy by efficiency improvement.

3)An FNN-based analysis technique is explained and the verification details are given, which provide an alternative way of performance evaluation and parameters' estimation for SRM drives. The simulation results testified the mapping capabilities for the nonlinear variation of the inductance by only a few epochs. The overall FNN computation scheme demonstrates that the new structure can successfully and effectively predict the instantaneous torque of the SRM under possible operating conditions, which means the inductance-related information being obtained with acceptable accuracy also.

4)A developed ANN-based model to reconstruction the required information of parameters, meanwhile to act as an estimator, which will enhance or keep the acceptable performance while adding to a conventional control scheme to form a speed sensorless drive. In addition, it shows the competence and acceptable results to obtain the speed and torque by proposed estimation strategy while comparing to those computed by pre-measured parameter values both in steady state and transient response analysis through the simulation. The experimental SRM drives prototype and platform are also set up to verify the applicability of the proposed ANN and show that it owns potential for applications for both of sensorless drives and integration to the optimizing efficiency scheme.

5)It has suggested the method using the least-square-error computation strategy to construct a dynamic mutual inductance model, which can generate current compensation command to strengthen the outputted performance for the SRM drive. The torque produced by mutual inductance, as well as self-inductance, are both taken into account for generating a current command that can keep the performance of SRM drives while generally neglecting the effect of mutual inductance. Besides, the analysis technique for the dynamic model is explained and the verification results are given, which provide an alternative way of performance improvement and parameters estimation for SRM drives. By verification, it has demonstrated that the new scheme can successfully improve SRM speed response performance by current compensation under possible operating conditions, which also provide the useful information for the controller design and development of SRM drives.

6)An estimation approach of phase resistance for the current command compensation based on energy loss caused by resistance, which leads to the influence of outputted performance, is presented herein to improve the robustness of drives for variation in such a way. The effectiveness of the proposed approach is validated and show that it can provide reference information for speed sensorless drives which needs to put resistance into account, especially in low speed operation.

7)The method for the inductance measurement applying LC circuit concept, which means circuit with inductance and capacitor effect, for analysis of SRM in operation status, is proposed. The inductance profile is an important parameter bearing on the performance of an SRM. The main strategy of the presented methodology is to combine the standard circuit topology analysis results and the machine's equivalent model to find a dynamic measurement method for the inductance related characteristics. The capacitors in series or parallel connection to the phase inductance of the SRM are the key components to construct the applicable LC circuit analysis model. Besides, this method owns the capability that being easy to be extended to estimate the incremental inductance for further performance prediction. The measurement results based on the two SRMs taken into verification both demonstrate the effectiveness of this method under dynamic operation condition while comparing to the conventionally off-line static measurement.

8)Some opinions for the future research, which is described in 8.2, provide the more concrete steps relevant to the research topics after this study

To conclude, a novel method, the optimizing efficiency control for the switched reluctance motor drives, is proposed in this dissertation. This concept is realized by a simple mechanism that to regulate the ratio of phase current command to voltage based on motoring operation state, utilizing the time-dependent derivatives of the equivalent magnetic inductance obtained from reluctance related opinion. In addition, some useful approaches that can integrate into the optimizing efficiency control are also presented to make it possible owning combination or integration schemes for future application and operation based on the trend information that given in this dissertation. The algorithms and the related computational procedures are derived and completed taking the crucial parameters into consideration. Simulation and experimental results demonstrated the effectiveness of the capability for efficiency regulation for efficiency optimizing.

8.2 Future Works

By the trend of function-type scheme requirement in product development and energy saving issue all over the world, more efforts should be involved in the electronic motor drives, which may affect more than close 50% or more energy usage in our daily life and industrial applications, is deemed to be a important job. Control strategy research is a driving force to do that job. However, the approach owns merely one focus point for enhancing the energy using is difficult to obtain acceptance under commercial considerations. No doubt, some auxiliary functions and structures that can make the SRM drive under development phase within more operation and design capabilities for the overall drive scheme are expected and needed. Hence, in this section, the final part of this dissertation, some opinions for the future research will be brought up not simply limit to the single efficiency topic but include some issues of drives' development for SRM in this status.

Based on author's knowledge and experience during this research, all future work is summarized schematically in the following ideas for providing reference to the engineers working in the related fields and researchers within this interesting area:

1)To design the scheme, not only for efficiency improvement, but also for reducing EMI from the main fundamental voltage driving profile which may be helpful to pass the important verification and testing to SRM drives under product phase.

2)Integrated-chip (IC) realization for optimizing efficiency control is the most important work in the near future to enhance the applicability both for industrial practice and home appliance products. The concept of this proposed methodology that can be integrated into the development of the SRM drive is another discussion issue and should be investigated and developed further.

3)Overall four-quadrant operation mechanism for the optimizing efficiency control that can extend the usage of this approach from motoring to generating, and both of them in bi-direction operation is required for most applications.

4)Performance index that may help the operational performance judgment is needed such as the applied torque range, specified in 4.5.2, should just be one deployed opinion to affect the operation of the efficiency optimizing. For instance, a current-based analysis index that related to the torque is given as follows [30]:

Torque evaluation index obtained by the current difference between the command value and actual value, implying the deviation degree of outputted torque to the desired value, while the torque-current relation has been well established for the developed SRM drive and can be expressed in the form of

$$T_{evaluation} = \sum (I^{x}_{command} - i_x)^2 \tag{8-1}$$

where $T_{evaluation}$, $I^{x}_{command}$, and i_x denote torque evaluation index based on the current difference, current command for phase symbol x, and actual current for phase symbol x, respectively.

5)A product-type platform that being setup for the verification under its counterpart having been adjoined, which is greatly useful to consider the selection of components and the related settings of the drives such as circuit elements, data sampling assignment, life-cycle verification, and so forth, should be designed and integrated.

6)Performance enhancement based on parameter computation mechanism that focuses on realization of module-like functions is needed.

7)Efficiency regulation capability for multiphase excitation SRM drives and the relevant parameter estimation approaches is expected.

8)Well-chosen optimizing step size for efficiency improvement is needed to analyze further from specific application concept to general-purpose usage both based on energy balancing of the operation system.

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Appendix A-Applied Switched Reluctance Motor Information

Table A-1: The parameters' information of the two SRMs.

Specifications	SRM 1	SRM 2
Rated power[hp]	3	1/2
Pole pair number	8/6	12/8
Rated voltage[V_{rms}]	48	120
Phase number	4	3
Aligned inductance[mH]	0.5382	39.8
Unaligned inductance[mH]	0.0652	5.2
Phase resistance [Ω]	0.0095	2.4
Rated speed [r/min]	6000	950

Appendix B-Mechanical Parameters

The related parameters is measured by the dynamometer platform based on the Eq.(B-1), express as:

$$\frac{dW_r}{dt} = \frac{1}{J_m}(T_e - T_l - B_m W_r) \tag{B-1}$$

where T_e, T_l, B_m, W_r, J_m, and t mean the outputted torque of the drive, loading torque, viscous coefficient, motor speed, rotor moment of inertia, and time, respectively.

Those are given as Table B-1:

Table B-1: The mechanical parameters of the applied SRMs.

SRM 1	SRM 2
0.1023 N.m^2 (J_m)	0.0152 N.m^2 (J_m)
0.00009 N.m.sec/rad (B_m)	0.000017 N.m.sec/rad (B_m)

Appendix C- Patent Information of Japan

Table C-1: Patent collection that related to SRM concept (till May 2003)

No.	Publication No.	Title
1.	2003 - 299383	Method and device of controlling switched reluctance motor
2.	2003 - 244873	Stator core for motor of superior noise characteristics
3.	2003 - 243214	Non-grain oriented electrical steel sheet for motor iron core and its manufacturing method
4.	2003 - 204660	Switched reluctance motor
5.	2003 - 189669	Rotor position detection for switched reluctance drive apparatus
6.	2003 - 111488	Method and apparatus of controlling switched reluctance motor and compressor
7.	2003 - 088157	Motor controller
8.	2003 - 061381	Driving method of switched reluctance motor
9.	2003 - 032979	Switched reluctance motor
10.	2003 - 018890	Control method for switch reluctance driving system
11.	2002 - 369580	Drive circuit of switched reluctance motor
12.	2002 - 369568	Excitation of switched reluctance motor
13.	2002 - 354881	Operation control method of switched reluctance motor
14.	2002 - 354867	Control method for switched reluctance motor
15.	2002 - 300755	Switched reluctance motor
16.	2002 - 291212	Switching reluctance motor
17.	2002 - 272176	Switched reluctance motor, its control method and apparatus, and program thereof
18.	2002 - 272071	Switched reluctance motor
19.	2002 - 253896	Washing machine equipped with switched reluctance motor
20.	2002 - 247888	Torque ripple reduction method for motor
21.	2002 - 242872	Rotary compressor
22.	2002 - 238276	Switched reluctance motor, method for controlling the same and its positional angle deciding mechanism as well as inverter and program
23.	2002 - 226952	Nonoriented silicon steel sheet for iron core of motor and production method therefor
24.	2002 - 218791	Method and system for deciding rotor position in changeover-type reluctance machine
25.	2002 - 199784	Current chopping in switched reluctance drive system
26.	2002 - 199783	Operation method for switched reluctance drive operated from dual-voltage source
27.	2002 - 199769	Drive method for switched reluctance motor
28.	2002 - 186283	Switched reluctance motor and its drive circuit without sensor
29.	2002 - 168166	Magnet switch for starter
30.	2002 - 136073	Switched reluctance motor
31.	2002 - 124716	Magnetoresistance element and memory element using the element
32.	2002 - 119086	Device and method for controlling electric machine
33.	2002 - 058287	Holding circuit of reluctance apparatus and operating circuit of electric hoist using that holding circuit
34.	2002 - 058272	Method and apparatus for controlling switched reluctance motor
35.	2002 - 034300	Control circuit of SR generator
36.	2002 - 010661	Method for aligning rotor of switched-reluctance motor and driving circuit for the motor
37.	2002 - 010595	Switched reluctance motor

38.	2002 - 010593	Switched reluctance motor
39.	2001 - 309691	Switched reluctance motor and its sensorless drive circuit
40.	2001 - 309622	Switched-reluctance motor
41.	2001 - 298983	Detection of position of switching reluctance machine
42.	2001 - 292560	Eddy current reducer
43.	2001 - 286172	Single phase SRM (switched reluctance motor) drive unit and its method
44.	2001 - 268961	Method and apparatus for controlling switched reluctance motor
45.	2001 - 268868	Switched reluctance motor
46.	2001 - 258283	Inverter system for driving electric vehicle
47.	2001 - 197777	Brushless machine control
48.	2001 - 197776	Brushless machine control
49.	2001 - 197775	Monitoring of rotor position of reluctance driving device
50.	2001 - 190049	Self-excited reluctance motor
51.	2001 - 186797	Drive circuit for switched reluctance motor and compressor
52.	2001 - 186693	Switched reluctance motor
53.	2001 - 157387	Switched reluctance motor
54.	2001 - 128490	Switched reluctance motor and rotation-control device
55.	2001 - 128477	Control method for switched reluctance motor, driving method for compressor, and apparatus thereof
56.	2001 - 103787	Switched reluctance motor and rotation controller therefor
57.	2001 - 090670	Hydraulic device
58.	2001 - 090668	Hydraulic device
59.	2001 - 086729	Switched reluctance linear motor
60.	2001 - 080375	Automobile driving system
61.	2001 - 078490	Control method for sr motor, and the sr motor
62.	2001 - 065420	Forcibly feeding unit for fuel
63.	2001 - 057791	Control method and control device of switched reluctance motor
64.	2001 - 045689	Coil for switching reluctance machine
65.	2001 - 025286	Sr motor
66.	2001 - 025280	Active reduction of torque mismatching for rotary machine
67.	2001 - 014622	Alternating magnetic field generating circuit and evaluation device of magnetoresistance head
68.	2001 - 008435	Switched reluctance motor and load transfer device
69.	2001 - 008434	Switched reluctance motor and load transfer device
70.	2000 - 358395	Control of line harmonic
71.	2000 - 350390	Switched reluctance motor
72.	2000 - 341901	Method for improving bearing strength of switched reluctance motor
73.	2000 - 324887	Reluctance polyphase motor
74.	2000 - 324886	Reluctance motor
75.	2000 - 324869	Reluctance type multiphase motor
76.	2000 - 320466	Servo motor driven type hydraulic pump
77.	2000 - 315305	Magnetic reproducing head, magnetic head assembly, magnetic disk driving device and manufacture of magnetic head assembly
78.	2000 - 312500	Method and device for controlling switched reluctance motor
79.	2000 - 312494	Operation of switched reluctance machine by dual supply voltage
80.	2000 - 299996	Reluctance motor drive controller
81.	2000 - 299517	Magnetoresistance element and magnetic memory element
82.	2000 - 295891	Inverter device for switched reluctance motor and its control method
83.	2000 - 294855	Magnetoresistive element
84.	2000 - 287480	Control method of brushless motor
85.	2000 - 262037	Switched reluctance linear motor

86.	2000 - 245186	Switching control for reluctance machine
87.	2000 - 237492	Washing machine
88.	2000 - 224888	Rotor position detection in changeover reluctance machine
89.	2000 - 224877	Speed controlling method of switched reluctance motor
90.	2000 - 217394	Stepping motor
91.	2000 - 209894	Stator winding structure of switched reluctance motor
92.	2000 - 197383	Control of reluctance machine to be switched
93.	2000 - 197338	SR motor, SR linear motor, and cargo transfer device
94.	2000 - 189376	Dish washing and drying machine
95.	2000 - 175383	Stator for switched reluctance motor
96.	2000 - 166292	Switched reluctance motor and its driving circuit
97.	2000 - 125585	Reluctance type motor
98.	2000 - 116183	Drive for switched reluctance motor
99.	2000 - 116180	Controller for chopping power application to electric motor
100.	2000 - 102276	Rotor position detector and detecting method therefor, and rotor position detector, and detecting method for sensorless switched reluctance motor
101.	2000 - 078884	Changeover type reluctance driving device having high power factor
102.	2000 - 078883	Current conduction controller for electric motor
103.	2000 - 069780	Multiphase reluctance motor
104.	2000 - 069779	Matching method for rotating angle sensor of switched reluctance motor
105.	2000 - 060089	Switched reluctance motor
106.	2000 - 050587	Switched reluctance motor
107.	2000 - 033061	Cleaner with soft starting function and its method
108.	11 - 356085(1999)	Short circuit detector for coil of electric motor
109.	11 - 356080(1999)	Sr motor
110.	11 - 356079(1999)	Sr motor, and electric power steering device using the same
111.	11 - 356018(1999)	Switched reluctance motor
112.	11 - 346494(1999)	Conduction controller for electric motor
113.	11 - 346464(1999)	Operation of changeover reluctance machine
114.	11 - 346463(1999)	Laminate for switching reluctance machine
115.	11 - 341875(1999)	Drive circuit of switched reluctance motor
116.	11 - 332189(1999)	Switched reluctance motor
117.	11 - 308828(1999)	Switched reluctance motor and its control method
118.	11 - 307353(1999)	High efficiency reluctance motor
119.	11 - 275891(1999)	Control method for switched reluctance motor and its device
120.	11 - 275890(1999)	Drive circuit for sensorless switched reluctance motor
121.	11 - 262290(1999)	Rotor position detecting equipment of sensorless switched reluctance motor and its method
122.	11 - 262225(1999)	Reduction of noise in reluctance machine
123.	11 - 252971(1999)	Rectification control device
124.	11 - 235083(1999)	Rotor position detection device of sensorless switched-reluctance motor and method thereof
125.	11 - 206181(1999)	Device and method for detecting rotor position of sensorless switched reluctance motor
126.	11 - 196597(1999)	Motor controlling method and its circuit
127.	11 - 191987(1999)	Switched reluctance motor
128.	11 - 146685(1999)	Controller of dc brushless motor
129.	11 - 146677(1999)	Equipment and method for driving sensorless switched reluctance motor
130.	11 - 136984(1999)	Conduction controller for switched reluctance motor

131.	11 - 134616(1999)	Magnetic reluctance type reading sensor, magnetic storage device and manufacture of magnetic reluctance type sensor
132.	11 - 113229(1999)	Switched reluctance motor and its driving circuit
133.	11 - 104266(1999)	Exercise device
134.	11 - 103595(1999)	Drive circuit of SR motor
135.	11 - 103594(1999)	Drive circuit of switched reluctance motor
136.	11 - 069857(1999)	Digital control of drive circuit for switched reluctance motor
137.	11 - 041976(1999)	Position controller for switched reluctance motor
138.	11 - 041975(1999)	Drive circuit for switched reluctance motor
139.	11 - 032493(1999)	Positioning control device of switch-type reluctance motor
140.	11 - 008993(1999)	Torque controller of reluctance motor
141.	10 - 337081(1998)	Circuit for driving switched reluctance motor
142.	10 - 337073(1998)	Starting method for three-phase SR motor
143.	10 - 336979(1998)	Switched reluctance motor
144.	10 - 323080(1998)	Controller for switched reluctance motor
145.	10 - 322992(1998)	Switched reluctance motor
146.	10 - 309095(1998)	Drive circuit of switched reluctance motor
147.	10 - 304690(1998)	Operation control circuit of switched reluctance motor with variable dc power supply voltage
148.	10 - 304632(1998)	Switched reluctance motor
149.	10 - 295990(1998)	Spin tub braking method of washing machine
150.	10 - 288191(1998)	Pump
151.	10 - 285987(1998)	Position detector for switch reluctance motor
152.	10 - 285986(1998)	Controller for switched reluctance motor
153.	10 - 271886(1998)	Current controller for switched-reluctance motor
154.	10 - 271885(1998)	Abnormal-operation inhibiting method of switched-reluctance motor
155.	10 - 271869(1998)	Method and device for controlling electric current of switch reluctance motor
156.	10 - 271868(1998)	Movable stage device
157.	10 - 210782(1998)	Drive control method for switched reluctance motor
158.	10 - 210708(1998)	Brake mechanism of switched reluctance motor
159.	10 - 201196(1998)	Cooling mechanism of switched reluctance motor
160.	10 - 201195(1998)	Switched reluctance motor
161.	10 - 201187(1998)	Coil assembling method of switched reluctance motor
162.	10 - 180583(1998)	Main spindle driving device for machine tool
163.	10 - 174475(1998)	Start control method for switched reluctance motor
164.	10 - 164801(1998)	Position detector of switched reluctance motor rotor
165.	10 - 164707(1998)	Hybrid prime mover and its controlling device
166.	10 - 146093(1998)	Switched reluctance motor controller
167.	10 - 146092(1998)	Motor driver
168.	10 - 146083(1998)	Controller of switched reluctance motor
169.	10 - 146082(1998)	Velocity controller of switched reluctance motor
170.	10 - 112964(1998)	Switched reluctance motor
171.	10 - 108437(1998)	Switched reluctance motor
172.	10 - 098861(1998)	Low noise switched reluctance motor
173.	10 - 080182(1998)	Drive control apparatus for motor
174.	10 - 070875(1998)	Switched reluctance motor
175.	10 - 066378(1998)	Driver for SR(switched reluctance) type motor
176.	10 - 047910(1998)	Non-contact type measuring device for measuring magnetic head worn amount
177.	10 - 028396(1998)	Current control method for SR(switched reluctance)-type motor
178.	10 - 023778(1998)	Converter circuit for SRM motor

179.	10 - 014186(1998)	Switched reluctance motor
180.	09 - 331663(1997)	Switched reluctance motor
181.	09 - 322581(1997)	Current detection method of switched reluctance type motor
182.	09 - 294394(1997)	Driving circuit for reluctance motor
183.	09 - 294359(1997)	Switched reluctance motor
184.	09 - 285181(1997)	Driving circuit for switched reluctance motor and control thereof
185.	09 - 285180(1997)	Driving system for switched reluctance motor
186.	09 - 285086(1997)	Switched reluctance motor
187.	09 - 275698(1997)	Drive circuit and control method for switched reluctance motor
188.	09 - 275697(1997)	Drive circuit and control method for switched reluctance motor
189.	09 - 266654(1997)	Switched reluctance motor
190.	09 - 247913(1997)	Switched reluctance motor
191.	09 - 247911(1997)	Switched reluctance motor
192.	09 - 238453(1997)	Switched reluctance motor
193.	09 - 182490(1997)	Controller for switched reluctance motor
194.	09 - 163792(1997)	Electronic control of resonance power for switching type reluctance motor
195.	09 - 135593(1997)	Method for driving switched reluctance motor
196.	09 - 121590(1997)	Rotary compressor with reverse rotation braking mechanism
197.	09 - 103056(1997)	Switched reluctance motor
198.	09 - 103055(1997)	Switched reluctance motor
199.	09 - 098595(1997)	Input voltage compensation for electric motor drive
200.	09 - 093887(1997)	Method and apparatus for reducing defective winding in switched reluctance machine
201.	09 - 089590(1997)	Position encoder having failure display
202.	09 - 089589(1997)	Position encoder of improved type
203.	09 - 084375(1997)	Angle controller for switched reluctance drive using high frequency clock
204.	08 - 340693(1996)	Switched reluctance driving system, method of controlling two-phase switched reluctance machine, and position transducer for two-phase switched reluctance machine
205.	08 - 340665(1996)	Switched reluctance motor
206.	08 - 336266(1996)	Single phase variable reluctance motor system and its starting method
207.	08 - 331815(1996)	Duplex salient pole reluctance machine and its assembly method
208.	08 - 317689(1996)	Control circuit and drive system for switched reluctance machine, and method of controlling the system
209.	08 - 317680(1996)	Control system and method for switched reluctance machine
210.	08 - 317617(1996)	Single-phase variable reluctance motor
211.	08 - 313367(1996)	Temperature monitor circuit and temperature monitoring method for object
212.	08 - 293691(1996)	Circuit board
213.	08 - 237982(1996)	Switch type reluctance motor and its starting method
214.	08 - 235548(1996)	Information reading and writing device
215.	08 - 232542(1996)	Automatic door opening-closing device
216.	08 - 214519(1996)	Both-saliency motor-generator using permanent magnet
217.	08 - 205581(1996)	Switched reluctance motor
218.	08 - 191599(1996)	Switched reluctance generator
219.	08 - 191551(1996)	Stator for electric machine and lamination thereof
220.	08 - 182383(1996)	Polyphase reluctance machine
221.	08 - 182277(1996)	Switched reluctance motor
222.	08 - 182276(1996)	Switched reluctance motor
223.	08 - 172795(1996)	Controller for electric machine

224.	08 - 168290(1996)	Reluctance flat three-phase motor
225.	08 - 154368(1996)	Switched reluctance motor
226.	08 - 103097(1996)	Torque control method of switching-form reluctance motor
227.	08 - 051790(1996)	Control circuit for inductive load
228.	08 - 047224(1996)	Single-phase switched type reluctance motor and starting method therefor
229.	08 - 035130(1996)	Individual motor drive device for use in rotor type open-end spinning apparatus
230.	07 - 337084(1995)	Controller and control method for switched reluctance motor
231.	07 - 337062(1995)	Counter electromotive force compensation system for switch type reluctance motor
232.	07 - 337061(1995)	Control system for switched reluctance motor
233.	07 - 337060(1995)	Toque ripple suppression system for switched reluctance motor
234.	07 - 303348(1995)	Switched reluctance motor
235.	07 - 298669(1995)	Control equipment for switched reluctance motor
236.	07 - 274586(1995)	Drive circuit of switched reluctance motor
237.	07 - 274570(1995)	Controller for switched reluctance motor
238.	07 - 211365(1995)	Method and device for connecting superconducting wire and superconducting coil device
239.	07 - 194178(1995)	Circuit for controlling energization of reluctance motor
240.	07 - 163105(1995)	Switched reluctance motor
241.	07 - 143790(1995)	Method and system for driving two-phase dc brushless motor
242.	06 - 296393(1994)	High-speed motor
243.	06 - 296392(1994)	High-speed motor
244.	06 - 121588(1994)	Drive system for variable reluctance motor
245.	06 - 054600(1994)	Switching reluctance generator device
246.	06 - 046589(1994)	Rotor position detector of switching reluctance motor
247.	06 - 038487(1994)	Polyphase switch type reluctance motor assembly and constitution method thereof
248.	06 - 022589(1994)	Reluctance motor to be regeneratively braked
249.	05 - 322575(1993)	Electronic azimuth meter
250.	05 - 308795(1993)	Reluctance type three-phase motor
251.	05 - 292722(1993)	Brushless dc reluctance motor
252.	05 - 292716(1993)	Reluctance motor
253.	05 - 260791(1993)	Driver circuit and drive control system for reluctance motor
254.	05 - 219787(1993)	Driving device for three-phase variable reluctance motor
255.	05 - 207784(1993)	Reluctance type three-phase high speed motor
256.	05 - 207783(1993)	Driver for variable reluctance motor
257.	05 - 207721(1993)	Dc brushless motor
258.	05 - 199794(1993)	Device and method for presuming rotor position of switching reluctance motor
259.	05 - 176504(1993)	Switching-type reluctance motor and its constituting method
260.	05 - 115197(1993)	Rotary encoder for reluctance motor and driver therefor
261.	04 - 229093(1992)	Control circuit for switching reluctance motor
262.	04 - 228809(1992)	Method for damping track motion
263.	04 - 183294(1992)	Reluctance type motor
264.	04 - 101698(1992)	Driving method of induction motor
265.	04 - 069089(1992)	Brushless motor
266.	04 - 030286(1992)	Counting circuit
267.	04 - 026392(1992)	Driving circuit for brushless motor
268.	03 - 293993(1991)	Driving system for variable reluctance motor
269.	03 - 273891(1991)	Drive circuit of variable reluctance motor

270.	03 - 169288(1991)	Control of variable reluctance type motor
271.	03 - 159531(1991)	Reluctance rotary machine
272.	03 - 098489(1991)	Reluctance-type motor capable of regenerative braking
273.	03 - 089897(1991)	Drive for variable-reluctance motor
274.	03 - 070488(1991)	Method for operating polyphase switching reluctance motor in regeneration mode
275.	03 - 052589(1991)	Drive for variable reluctance motor
276.	03 - 052588(1991)	Drive for variable reluctance motor
277.	03 - 040744(1991)	Universal motor and rotor unit used for same motor
278.	03 - 036979(1991)	Variable reluctance type ac servomotor control system
279.	03 - 032387(1991)	Plural phase reluctance type motor
280.	03 - 015290(1991)	Control method for switching reluctance motor
281.	03 - 015289(1991)	Method and system for controlling low speed switching reluctance motor
282.	02 - 269813(1990)	Ring spinning frame and winding of yarn
283.	02 - 261085(1990)	Driver of variable reluctance motor
284.	02 - 254993(1990)	Drive of variable reluctance motor
285.	02 - 237493(1990)	Switching reluctance motor and its operating method
286.	02 - 231986(1990)	High speed 3-phase dc motor
287.	02 - 216323(1990)	Retarder
288.	02 - 145016(1990)	Magnetic switch
289.	02 - 123998(1990)	Driving gear for variable reluctance motor
290.	02 - 123997(1990)	Driving gear for variable reluctance motor
291.	02 - 101988(1990)	Three-phase reluctance motor
292.	02 - 065690(1990)	High speed reluctance type motor
293.	02 - 023098(1990)	Driver for variable reluctance motor
294.	02 - 017898(1990)	Driving gear of variable reluctance motor
295.	01 - 164288(1989)	Method and device for indirectly estimating instantaneous position of rotor
296.	63 - 296320(1988)	Electromagnetic actuator
297.	63 - 249068(1988)	Preventive maintenance of switching apparatus
298.	63 - 186410(1988)	Power transformer
299.	63 - 129891(1988)	Control device of switch type reluctance motor
300.	63 - 129850(1988)	Switch-type reluctance motor
301.	62 - 036501(1987)	Position detector using magnetic reluctance element
302.	61 - 124297(1986)	Automatic field pole positioning system of variable reluctance pulse motor
303.	61 - 073597(1986)	Reluctance generator controller
304.	61 - 015554(1986)	1-phase reluctance type semiconductor motor
305.	59 - 103763(1984)	Magnetic switch printer
306.	59 - 025204(1984)	Variable reactance type shunt reactor
307.	59 - 013315(1984)	Shunt reactor of variable capacitance type
308.	58 - 185008(1983)	Recorder of magnetic information
309.	58 - 086856(1983)	Polyphase type variable reluctance stepping motor
310.	58 - 068912(1983)	Switching type electromagnetic plunger
311.	57 - 197816(1982)	Shunt reactor
312.	57 - 169679(1982)	Detecting circuit for revolution
313.	57 - 151824(1982)	Electronic water meter
314.	57 - 141042(1982)	Magnetic video recording and reproducing device
315.	57 - 092815(1982)	Choke coil
316.	57 - 088865(1982)	Linear stepping motor
317.	56 - 110055(1981)	High-voltage current sensor for switch

318.	55 - 088562(1980)	Linear step motor
319.	55 - 058402(1980)	Position detector
320.	55 - 029278(1980)	Device for starting squirrel-cage induction motor
321.	52 - 067583(1977)	Magnetic reluctance device

Appendix D- Main Pages of the Datasheets of Applying Chips for Power Computation

AD532 for signals' multiplying:

ANALOG DEVICES

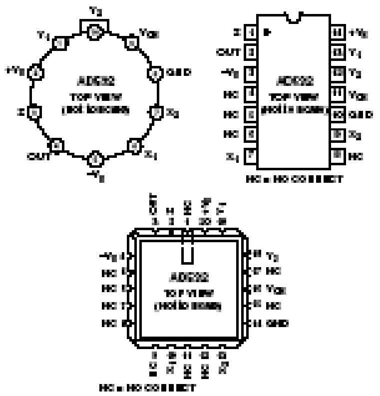
Internally Trimmed Integrated Circuit Multiplier

AD532

FEATURES
- Pretrimmed to ±1.0% (AD532K)
- No External Components Required
- Guaranteed ±1.0% max 4-Quadrant Error (AD532K)
- Diff Inputs for $(X_1 - X_2)(Y_1 - Y_2)/10$ V Transfer Function
- Monolithic Construction, Low Cost

APPLICATIONS
- Multiplication, Division, Squaring, Square Rooting
- Algebraic Computation
- Power Measurements
- Instrumentation Applications
- Available in Chip Form

PIN CONFIGURATIONS



PRODUCT DESCRIPTION

The AD532 is the first pretrimmed single chip monolithic multiplier/divider. It guarantees a maximum multiplying error of ±1.0% and a ±10 V output voltage without the need for any external trimming resistors or output op amp. Because the AD532 is internally trimmed, its simplicity of use provides design engineers with an attractive alternative to modular multipliers, and its monolithic construction provides significant advantages in size, reliability and economy. Further, the AD532 can be used as a direct replacement for other IC multipliers that require external trim networks.

FLEXIBILITY OF OPERATION

The AD532 multiplies in four quadrants with a transfer function of $(X_1 - X_2)(Y_1 - Y_2)/10$ V, divides in two quadrants with a $10\text{ V } Z/(X_1 - X_2)$ transfer function, and square roots in one quadrant with a transfer function of $\pm\sqrt{10\text{ V } Z}$. In addition to these basic functions, the differential X and Y inputs provide significant operating flexibility both for algebraic computation and transducer instrumentation applications. Transfer functions, such as $XY/10$ V, $(X^2 - Y^2)/10$ V, $\pm X^2/10$ V, and $10\text{ V } Z/(X_1 - X_2)$, are easily attained and are extremely useful in many modulation and function generation applications, as well as in trigonometric calculations for airborne navigation and guidance applications, where the monolithic construction and small size of the AD532 offer considerable system advantages. In addition, the high CMRR (75 dB) of the differential inputs makes the AD532 especially well qualified for instrumentation applications, as it can provide an output signal that is the product of two transducer-generated input signals.

GUARANTEED PERFORMANCE OVER TEMPERATURE

The AD532J and AD532K are specified for maximum multiplying errors of ±2% and ±1% of full scale, respectively at 25°C, and are rated for operation from 0°C to 70°C. The AD532S has a maximum multiplying error of ±1% of full scale at 25°C; it is also 100% tested to guarantee a maximum error of ±4% at the extended operating temperature limits of –55°C and +125°C. All devices are available in either the hermetically-sealed TO-100 metal can, TO-116 ceramic DIP or LCC packages. J, K, and S grade chips are also available.

ADVANTAGES OF ON-THE-CHIP TRIMMING OF THE MONOLITHIC AD532

1. True ratiometric trim for improved power supply rejection.
2. Reduced power requirements since no networks across supplies are required.
3. More reliable since standard monolithic assembly techniques can be used rather than more complex hybrid approaches.
4. High impedance X and Y inputs with negligible circuit loading.
5. Differential X and Y inputs for noise rejection and additional computational flexibility.

REV. C

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781/329-4700 World Wide Web Site: http://www.analog.com
Fax: 781/326-8703

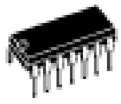
TL084 for signal sensing:

SGS-THOMSON MICROELECTRONICS

TL084
TL084A - TL084B

GENERAL PURPOSE
QUAD J-FET OPERATIONAL AMPLIFIERS

- LOW POWER CONSUMPTION
- WIDE COMMON-MODE (UP TO V_{CC}^{+}) AND DIFFERENTIAL VOLTAGE RANGE
- LOW INPUT BIAS AND OFFSET CURRENT
- OUTPUT SHORT-CIRCUIT PROTECTION
- HIGH INPUT IMPEDANCE J–FET INPUT STAGE
- INTERNAL FREQUENCY COMPENSATION
- LATCH UP FREE OPERATION
- HIGH SLEW RATE : 16V/µs (typ)



N
DIP14
(Plastic Package)

D
SO14
(Plastic Micropackage)

DESCRIPTION

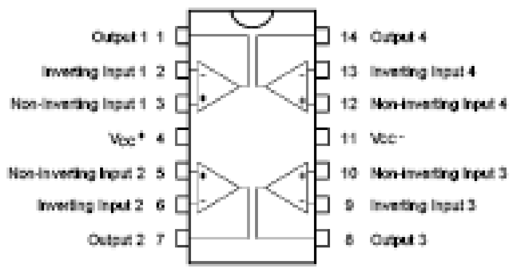
The TL084, TL084A and TL084B are high speed J–FET input quad operational amplifiers incorporating well matched, high voltage J–FET and bipolar transistors in a monolithic integrated circuit.

The devices feature high slew rates, low input bias and offset currents, and low offset voltage temperature coefficient.

ORDER CODES

Part Number	Temperature Range	Package	
		N	D
TL084M/AM/BM	–55°C, +125°C	•	•
TL084I/AI/BI	–40°C, +105°C	•	•
TL084C/AC/BC	0°C, +70°C	•	•
Examples : TL084CN, TL084CD			

PIN CONNECTIONS (top view)



February 1996 1/10

Vita

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性別：男

出生日：民國 61 年 11 月 22 日

論文題目:

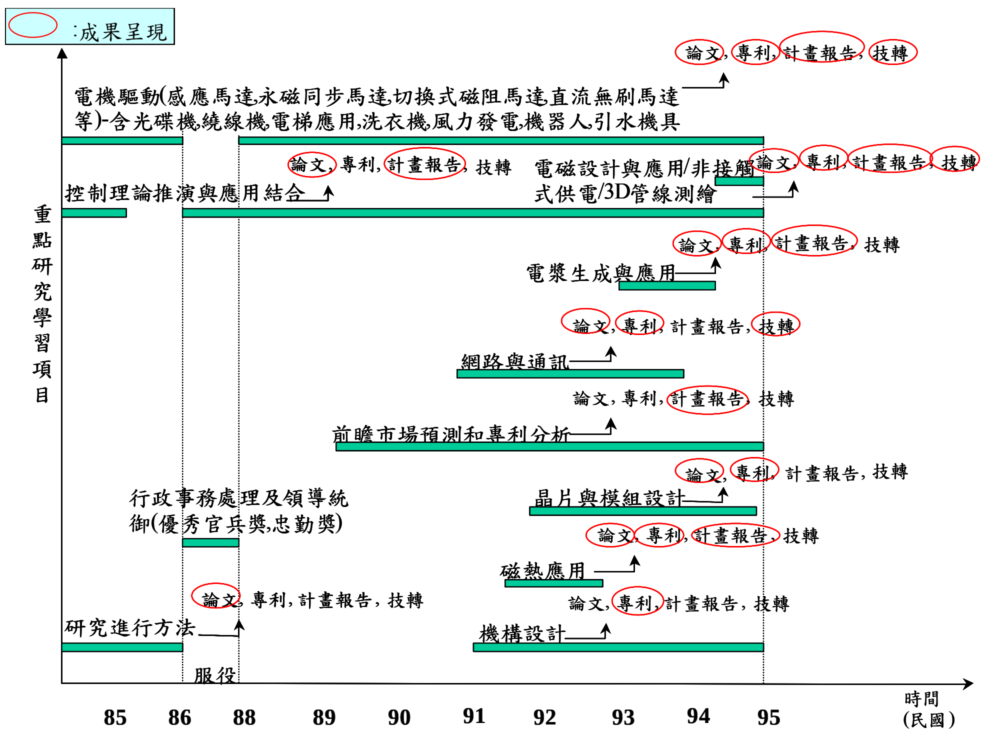
1.中文:切換式磁阻電動機驅動系統之效率優化控制策略

2.英文: An Efficiency Improvement Strategy
for Switched Reluctance Motor Drives

學歷/經歷：

1.80 年 9 月～84 年 6 月 華梵大學 機械工程學系
2.84 年 9 月～86 年 6 月 華梵大學 機電工程研究所
3.88 年 9 月迄今 交通大學 電機與控制工程研究所 博士班
4.89 年 8 月～94 年 12 月 工業技術研究院 能源與資源研究所 研究實習（含部分全時研究）
5.90 年 9 月～91 年 2 月 明新科技大學 電機工程學系 兼任講師
6.95 年 2 月迄今 東南技術學院 電機工程學系 兼任講師
6.95 年 4 月迄今 工業技術研究院 能源與環境研究所 研究實習

研究學習成長過程暨主要成果：



Publication List

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（A）Journal Papers

Published/Accepted:

[1] **Wen-Nan Huang** and Ching-Cheng Teng, "A Simple Magnetic Refrigerator Evaluation Model," Journal of Magnetism and Magnetic Materials, vol. 282, pp.311- 316, October 2004.

[2] **Wen-Nan Huang** and Ching-Cheng Teng, "A Simple Reluctance-Based Efficiency Control Strategy Taking Equivalent Magnetic Inductance into Account for the Switched Reluctance Motors," Journal of Magnetism and Magnetic Materials, vol. 282, pp. 364-368, October 2004.

[3] **Wen-Nan Huang**, Po-Shen Chen, Mu-Ping Chen, and Ching-Cheng Teng,"A Novel Design of the High-Precision Magnetic Locator with Three-Dimension Measurement Capability Applying Dynamically Sensing Mechanism," (Accepted for publication to Journal of Magnetism and Magnetic Materials).

[4] **Wen-Nan Huang**, Wan-Pei Chen, Ching-Cheng Teng, and Mu-Ping Chen,"A Novel Design and Driving Strategy for a Hybrid Electric Machine with Torque Performance Enhancement Both Taking Reluctance and Electromagnetic Attraction Effects into Account," (Accepted for publication to Journal of Magnetism and Magnetic Materials).

[5] Wan-Pei Chen, **Wen-Nan Huang**, Po-Shen Chen, Tsun-Yao Fan, Mu-Ping Chen, and Ching-Cheng Teng, "Design and Control Strategy Applying the Novel Highly Effective Magnetic Flux Coupling (HEMFC) Scheme for a Non-Contact Power Transfer System," (Accepted for publication to Journal of Magnetism and Magnetic Materials).

[6] Morgan Yang, **Wen-Nan Huang**, Po-Yen Chen, and Mu-Ping Chen," Design and Implementation for a Low-Cost Wiring Machine Applying Adaptive Control Approach for Load Planning," Power Electronics, vol.3, no.3, pp.10-20, May 2005.(in Chinese)

[7] Wan-Pei Chen, Po-Shen Chen, Tsun-Yao Fan, **Wen-Nan Huang**, Wei-Zhu Wang, Po-Yen Chen, Mu-Ping Chen, and Ching-Piao Chen," Introduction to Non-Contact Power Supply Technology," Power Electronics, vol.3, no.3, pp.53-65, May 2005.(in Chinese)

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[11] **Wen-Nan Huang** and Mu-Ping Chen, "A Novel Power Electronics Design

Concept-IPEM," Power Electronics Technology Bimonthly, vol 63, pp.1-7, June 2001.(in Chinese)

[12] **Wen-Nan Huang**, James Yi-Chin Wu, and Shih-Chieh Chiu, "Conceptual Integration on Induction Motor Control Strategies, "Power Electronics Technology Bimonthly, vol 38, pp.86-104, April 1997. (in Chinese)

[13] **Wen-Nan Huang**, James Yi-Chin Wu, and Shih-Chieh Chiu, "Concept Design of a FTS-Based Motor Testing System," Power Electronics Technology Bimonthly, vol 36, pp.27-38, December 1996.(in Chinese)

[14] Shih-Chieh Chiu, James Yi-Chin Wu, and **Wen-Nan Huang**, "CAT-based Signal Conditioning and Circuit Implementation, " Power Electronics Technology Bimonthly, vol 36,pp.39-50, December 1996.(in Chinese)

[15] James Yi-Chin Wu, **Wen-Nan Huang**, and Shih-Chieh Chiu, "The Matching Study of SSASD Systems, " Power Electronics Technology Bimonthly, vol. 35, pp.1-13, October 1996.(in Chinese)

[16] James Yin-Chin Wu, Tian-Fure Shine, and **Wen-Nan Huang**, "The Estimation of the Power Loss of IGBTs and the Selection of Heat Sinks for the Inverter Application, " Power Electronics Technology Bimonthly, vol.33, pp.11-20, June 1996.(in Chinese)

Submitted:

[1] **Wen-Nan Huang** and Ching-Cheng Teng, "Intelligent Tuning for Control of Switched Reluctance Motor Drives Applied for Electric Vehicle Applications under Fault Conditions," submitted to IEEE Trans. Industrial Applications.

[2] Chih-Hsing Fang, **Wen-Nan Huang**, and Ching-Cheng Teng, "Adaptive Type Fuzzy Neural-Network (FNN) Backstepping Position Control Strategy Based on Sliding-Mode Scheme for Induction Motor Drives," submitted to IFAC Control Engineering Practice.

[3] **Wen-Nan Huang** and Ching-Cheng Teng, "A New FNN-Based Control Strategy For Improving Track-Following Performance for Optical Disk Drives Utilizing the Gram-Schmidt Algorithm," submitted to ASME Journal of Dynamic Systems, Measurement, and Control.

[4] **Wen-Nan Huang**, Bao-Tung Lin, and Ching-Cheng Teng, "Self-Tuning Strategy Based on Combined QFT/H_∞ Design Techniques Applying for Improvement of Robustness of Switched Reluctance Motor Drives with Uncertain Variation Intervals of Mechanical Parameters," submitted to IEEE Trans. Power Electronics.

[5] **Wen-Nan Huang**, Bao-Tung Lin, and Ching-Cheng Teng, " Parameters Estimation Using Artificial Neural Networks Approach for Switched Reluctance Motor Drives," submitted to WSEAS Trans. Systems.

[6] **Wen-Nan Huang**, Ching-Cheng Teng, and Bao-Tung Lin ", A Low-Order Robust Controller Design Approach Utilizing Ordinal Optimization," submitted to IEEE Trans. Control and Systems Technology.

[7] **Wen-Nan Huang**, Wan-Pei Chen, and Mu-Ping Chen," Design and Modeling of Flux Operation Applying for Contactless Power Supply System," submitted to IEEE Trans. Magnetism.

Note: Journal IF value comparison based on JCR(4/6/2006): Journal (IF)

J. Magn. Magn. Mater. (1.031). IEEE Trans. Magn. (0.837).

IEEE Trans. Power Electr.(1.202). IEEE Trans. Ind. Appl.(0.987).

IEEE Trans. Control Syst. Technol.(0.923). IEEE Trans. Ind. Electron.(0.976).

J. Dyn. Syst. Meas. Control-Trans. ASME(0.325). Control Eng. Pract.(0.527).

（B）Conference Papers

Published:

[1] **Wen-Nan Huang**, Bao-Tung Lin, and Ching-Cheng Teng, "Self-Tuning Approach of Interval Specification Determination Applying Combined QFT/H_∞ Design Technique," Proc. of 2005 R.O.C. Automatic Control Conf., November 2005.

[2] **Wen-Nan Huang** and Ching-Cheng Teng, "Torque Estimation Model Based on Fuzzy Neural Networks Applying for Speed Sensorless Switched Reluctance Motor Drives," 2005 National Conf. Fuzzy Theory and its Applications,October 2005.

[3] **Wen-Nan Huang**, Wan-Pei Chen, Ching-Cheng Teng, and Mu-Ping Chen, "A Novel Design and Driving Strategy for a Hybrid Electric Machine with Torque Performance Enhancement Both Taking Reluctance and Electromagnetic Attraction Effects into Account," International Symposium on Advanced Magnetic Technologies and International Symposium on Magnetic Materials and Applications (ISAMT/SOMMA), pp.54-55, August 2005.

[4] **Wen-Nan Huang**, Ching-Cheng Teng, and Chin-Hsing Fang, "A Simple Analysis Model of Active Magnetic Regenerator (AMR) Operation Applying for Magnetic Refrigeration Evaluation," International Symposium on Advanced Magnetic Technologies and International Symposium on Magnetic Materials and Applications (ISAMT/SOMMA), pp.135-136, August 2005.

[5] **Wen-Nan Huang**, Po-Shen Chen, Mu-Ping Chen, and Ching-Cheng Teng,"A Novel Design of the High-Precision Magnetic Locator with Three-Dimension Measurement Capability Applying Dynamically Sensing Mechanism," International Symposium on Advanced Magnetic Technologies and International Symposium on Magnetic Materials and Applications (ISAMT/SOMMA), pp.56-57, August 2005.

[6] Wan-Pei Chen, **Wen-Nan Huang**, Po-Shen Chen, Tsun-Yao Fan, and Mu-Ping Chen,"Design and Control Strategy Applying the Novel High-Effective Magnetic Flux Coupling (HEMFC) Scheme for a Non-Contact Power Transfer System," International Symposium on Advanced Magnetic Technologies and International Symposium on Magnetic Materials and Applications (ISAMT/SOMMA), p.165, August 2005.

[7] Chih-Hsing Fang, **Wen-Nan Huang**, and Ching-Cheng Teng, "Adaptive Type Fuzzy Neural-Network (FNN) Backstepping Motion Control Strategy Based on Sliding-Mode Scheme for Induction Motor Drives with Robust Position Tracking Capability," IEEE International Conf. Industrial Technologies (ICIT), Hong-Kong, pp.1030-1036, December 2005.(**Best Paper Selected for Consideration**)

[8] **Wen-Nan Huang**, Wan-Pei Chen, Tsun-Yao Fan, Ching-Cheng Teng, and Mu-Ping Chen,"Study of Detachable Transformer Design Strategies for Contactless Power Supply System," 2005 Taiwan Power Electronics Conf., pp.489-493, September 2005.(in Chinese)

[9] Po-Sen Chen and **Wen-Nan Huang**,"Analysis of Buried Pipeline Location Measured by Locator," 2005 Taiwan Power Electronics Conf., pp.1262-1265, September 2005.(in Chinese)

[10] Po-Sen Chen and **Wen-Nan Huang**, "Analysis of Patent of Locator Technology," 2005 Taiwan Power Electronics Conf., pp.1266-1270, September 2005.(in Chinese)

[11] **Wen-Nan Huang**, Ching-Piao Chen, Mu-Ping Chen, Ching-Cheng Teng, Hwei-Shoung Chun, and Tsun-Yao Fan, "Implementation of Demonstration Platform Based on Equivalent Air Impedance of Resistive Barrier Discharge Plasma Generation Applied for Design Reference of Power Converter," 2005 Taiwan Power Electronics Conf., pp.489-495 September 2005.(in Chinese)(**Oustanding Papar Awarded**)

[12] Po-Yen Chen, **Wen-Nan Huang**, Morgan Yang, and Mu-Ping Chen,"Design and Implementation Applying Mechatronics System Concept for a Low-Cost High Performance Wiring Machine Based on Brushless DC Motor Drives," IEEE

International Conf. Mechatronics (ICM), pp.173-178, July 2005.

[13] Chih-Hsing Fang, Tsun-Yao Fan, Shir-Kuan Lin, **Wen-Nan Huang**, and Chih-Hsin Chen, "Design and Control for an Intensity Controllable Uni-Polar Magnetic Field Supplying Unit for Magnetic Refrigeration," IEEE International Conf. Mechatronics (ICM), pp.733-738, July 2005.

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