Faculty of Electrical Engineering

IMPROVED POSITIONING CONTROL OF A ROTARY SWITCHED RELUCTANCE ACTUATOR USING MODIFIED PID CONTROLLER

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DECLARATION

I declare that this thesis entitled “Improved Positioning Control of a Rotary Switched Reluctance Actuator using Modified PID Controller” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:
Name	: Tee Siau Ping
Date	: 18 / 9 / 2019

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechatronic Engineering.

Signature :

Supervisor Name : Assoc. Prof. Dr. Mariam Md Ghazaly

Date : 18 / 9 / 2019

DEDICATION

To my parents

ABSTRACT

Over the past decade, the rotary switched reluctance actuator (SRA) has been gaining attention not only in the areas of industrial applications as well in promising research areas such as robotics and automotive engineering. The popularity can be much associated with the attractive advantages SRA has to offer such as inherent fault tolerance, simple and robust structure in addition to the ability for high frequency operations. Despite the attractive advantages it has to offer, SRA exhibits significant nonlinear characteristics due to its unpredictable magnetic flux flow and operation in saturation region. Subsequently, these dynamic behaviors often make modelling and real time motion control a challenging effort. Although various control methods have been developed, these controller design procedures frequently require exact model of mechanism and deep understanding in modern control theory which leads to their impracticability. Henceforth, in this research, a practical control strategy namely the modified proportional-integral-derivative (PID) control scheme is proposed for point-to-point motion control of the rotary SRA mechanism. The practical control scheme presented heavily emphasizes on simple structure and straightforward design framework. Hence, the proposed modified PID controller includes control elements that are derived from the measured open loop responses. Complex system modelling or high computational learning algorithms are not required in the controller design process. The performance evaluation is examined and compared to a conventional PID controller through experimental works. At fully aligned and almost aligned positions, experimental results showed that the proposed controller successfully reduced steady-state error in step positioning by an average improvement of 94%. The maximum overshoot and settling time are improved by an average 62.5% and 47%. At intermediate positions, although zero steady-state error can be enjoyed on both controllers, modified PID controller performed better by showing a reduced overshoot and settling time response of 60% and 37% improvement. Overall, the proposed controller displayed superiority compared to conventional PID controller with a smoother displacement response with reduced steady-state error, overshoot and settling time in all positioning tasks.

ABSTRAK

Menelusuri dekad yang lalu, penggerak berputar Bertukar Keengganan (SRA) semakin mendapat perhatian bukan sahaja dalam industri malahan dalam bidang-bidang penyelidikan yang prominen seperti robotik dan kereta elektrik hybrid. Populariti ini boleh dikaitkan dengan kelebihan yang ditawarkan oleh penggerak berputar SRA seperti ciri-ciri keselamatan, struktur bina yang mudah dan kebolehan beroperasi menggunakan putaran frekuensi tinggi. Walau bagaimanapun, penggerak berputar SRA mempamerkan ciri-ciri tidak linear yang ketara yang disebabkan pengaliran fluks magnet yang sukar dijangka dan operasinya dalam kawasan ketepuan. Justeru itu, kelemahan dinamik ini sering kali menyebabkan pencirian sistem dan kawalan gerakan satu usaha yang mencabar. Walau terdapat beberapa jenis sistem kawalan yang telah dicadangkan, rangka kerja sistem kawalan yang dicadangkan memerlukan model yang tepat dan juga pengetahuan yang mendalam berkaitan teori sistem kawalan moden di mana sistem kawalan sering kali menjadi tidak praktikal. Oleh itu, dalam penyelidikan ini, satu strategi kawalan praktikal yang dinamakan sebagai skema pengawal modifikasi PID dicadangkan untuk kawalan gerakan titik ke titik untuk mekanisme penggerak berputar SRA. Skema kawalan praktikal ini mempertimbangkan struktur yang mudah dan rangka kerja yang ringkas. Pengawal modifikasi PID yang dicadangkan mempunyai elemen pengawal yang dibina melalui hubungan antara input dan keluaran yang boleh didapati melalui pencirian gelung terbuka. Pemodelan yang kompleks dan algoritma pembelajaran berkiraan tinggi tidak diperlukan dalam proses rekabentuk pengawal modifikasi PID. Seterusnya, prestasi pengawal modifikasi PID dinilai dan dibandingkan dengan pengawal PID lazim melalui eksperimen. Hasil ujikaji menunjukkan bahawa sistem pengawal yang dicadangkan berjaya mengurangkan ralat keadaan mantap dalam penempatan langkah dengan pembaikan purata sebanyak 94% di posisi berjajar dan hampir berjajar. Terlajak maksimum dan masa penepatan diperbaiki sebanyak 62.5% dan 47% secara purata. Di posisi perantaraan, walaupun kedua-dua pengawal mempamerkan ralat keadaan mantap sifar, pengawal modifikasi PID mencapai terlajak maksimum terturun dan masa penepatan terturun dengan pembaikan sebanyak 60% dan 37%. Keseluruhannya, pengawal modifikasi PID menunjukkan keunggulan berbanding dengan pengawal PID lazim dengan pencapaian sambutan sesaran yang licin, ralat keadaan mantap terturun, terlajak maksimum terturun dan masa penepatan terturun dalam semua kes penempatan.

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LIST OF SYMBOLS AND ABBREVIATIONS

ANFIS	-	Adaptive neural fuzzy inference system
DITC	-	Direct instantaneous torque control
DSP	-	Digital signal processor
DTC	-	Direct torque control
e_x	-	Error
FLC	-	Fuzzy Logic Control
FOPI	-	Fractional order Proportional-Integral element
HEV	-	Hybrid electrical vehicle
ISE	-	Integral Squared Error
K_p	-	Proportional gain
K_i	-	Integral gain
K_d	-	Derivative gain
K_u	-	Ultimate gain for Ziegler-Nichols tuning
MEMS	-	Microelectromechanical systems
MOEMS	-	Optical electromechanical systems
NGSA-II	-	Non-dominated sorting genetic algorithm-II
P	-	Proportional element
PC	-	Personal computer
PD	-	Proportional-Derivative element
PI	-	Proportional-Integral Element
PID	-	Proportional-Integral-Derivative element
PM	-	Permanent magnet
P_u	-	Ultimate period for Ziegler-Nichols tuning
rpm	-	Revolution per minute
SRA	-	Switched reluctance actuator
SRM	-	Switched reluctance motor

TSF	-	Torque sharing function
u_D	-	Derivative control signal
u_i	-	Integral control signal
Δu_i	-	Change rate of u_i
u_P	-	Proportional control signal
u_{PID}	-	Maximum value of PID signal at 2A

LIST OF PUBLICATIONS

Journal:

1. Tee, S. P., Ghazaly, M. M., Chong, S. H. and Jamaludin, I. W., 2017. Rotary Switched Reluctance Actuator: A Review on Design Optimization and Its Control Methods, *International Journal of Power Electronics and Drive System*, Vol. 8, No. 3, pp. 1087-1100.
2. Tee, S. P., Ghazaly, M. M., Tan, P. K., Chong, S. H., Amran, A. C., Jamaluddin, M. H. and Aras, M. S. M., 2016. Tracking Control Performances a Dual-Limb Robotic Arm System, *International Journal of Mechanical & Mechatronics Engineering*, Vol. 16, No. 05, pp. 48-53.

Conference:

1. Tee, S. P., Ghazaly, M. M., Chong, S. H. and Jamaludin, I. W., 2017. Optimization of Hollow Rotor for Switched Reluctance Motor. In: *2017 International Symposium on Research in Innovation and Sustainability (ISoRIS).*

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter highlights the background of the study, problem statement, objectives and the scope of the research. The background study includes a brief exposition on the structure, working principle and advantages of the actuator in this project. The problem statement dictates the core issues to be addressed through this research. Meanwhile, the objectives serve as benchmark and the scope defines the boundaries and limit in overseeing the completion of the project.

1.2 Background

Switched reluctance actuator (SRA) is a subdivision of electromagnetic machines which fundamentally, operate by converting electrical energy to magnetic field, then through magnetic field interactions, produces electromagnetic force that drives a mechanical part (rotational or linear motion). Electromagnetic actuation can be applied in optical electromechanical systems (MOEMS) to provide large and long-range forces for industrial applications such as magnetic matrix array of micro-switches for optical network (Helin et al., 2000) and magnetostrictive scanner for automobile obstacle detection (Bourouina et al., 2001). Electromagnetic actuators carry the ability to operate via remote control, which allows actuation of microsystems with a silicon-based structure by just reacting to an external magnetic field (Reyne, 2002). Apart from that, electromagnetic actuators can easily achieve bi-stability due to the presence of permanent magnet in its structure. Actuation positions are retained from one position to another steadily by a pulse of excitation current through the forces of magnetic field interactions. Electromagnetic actuators are also implemented in microelectromechanical systems (MEMS) for applications such as and positioning stage with nanometer precision (Ahn et al., 2015; Lv et al., 2015) and medical laser scanners (Shevchenko et al., 2018). The general characteristics of several types of actuators (Ulbrich, 1994; Yang and Xu, 2017) can be summarized as in Table 1.1.

Table 1.1: Comparison of general characteristics for 4 types of actuators

	Characteristics			
Actuator types	Working Range	Transfer characteristics	Actuation force	Precision
Hydraulic	Large	Complex (fluid dynamics)	Large	Low
Electrostatic	Large	Simple	Small	High
Piezoelectric	Small	Simple	Large	High
Electromagnetic	Large	Simple	Large	High

Electromagnetic actuators carry the advantage of high actuation force, a wide working range with high precision, simple electrical transfer characteristics and operations in high speed mode. However, the most significant drawback of electromagnetic actuators is their complex design structure which require permanent magnets (PM). The constant excitation of PM in high speed modes brings high power dissipation and lowers the actuator efficiency (Bostanci et al., 2017). Hence, the SRA steps in as a solution to this flaw. In this thesis context, the actuator used would be known as the rotary switched reluctance actuator or rotary SRA.

The rotary SRA is classified as a member of the electromagnetic actuators, but it boasts a simple and robust structure with no implementation of highly expensive permanent magnets, which allow it to operate at higher temperature (Zabihi and Gouws, 2016). The rotary SRA operates based on the principle of magnetic reluctance and inductance. The rotor will rotate and align with the excited stator poles to form a path with least reluctance and highest inductance, which allows the flow of magnetic flux. Sequential excitation of stator poles will hence allow the continuous rotation of the actuator. The fabrication material for this whole actuator does not involve any rare-earth elements. Along the years, advanced design structures for rotary SRAs are introduced such as the double stator SRA (Abassian et al., 2010), multilayer SRA (Siadatan et al., 2011) and the segmental rotor SRA (Xu and Ahn, 2013) mainly to produce enhanced torque and eliminate torque ripple. However, reverting to the fundamental design structure of rotary SRA, the actuator consists of three main components, which are the rotor, stator and coil windings as shown in Figure 1.1.

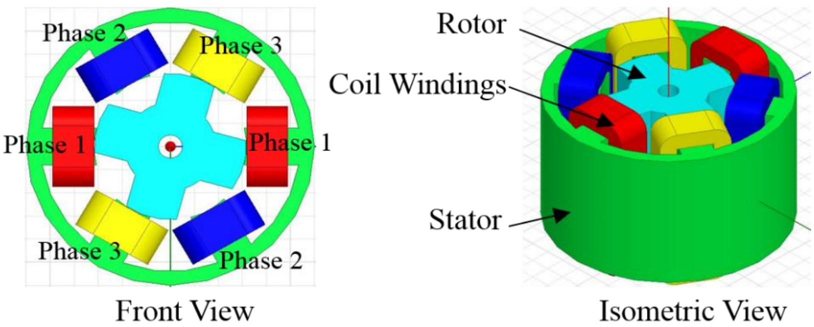

Figure 1.1: Design of a conventional rotary SRA

The typical rotary SRA is equipped with six stator poles and four rotor poles (6/4) as shown in Figure 1.1. The number of poles differ in various rotary SRA configurations because it affects the acoustic behaviour (Hofmann et al., 2014). A greater number of stator and rotor poles delivers the advantage of noise and vibration reduction, besides minimizing radial force (Li et al., 2008). The actuation torque can also be improved with higher ratios of stator and rotor poles (Yusri et al. 2016a; Yusri et al. 2016b). SRA operates based on the principle of magnetic reluctance. When a sequential excitation scheme is initiated, the rotor will rotate accordingly to align with the excited stator poles to form a path with least reluctance for the flow of magnetic flux. An air gap exists between the rotor and stator of rotary SRA. Ideally, air gap is made to be as small as possible because air has high resistance against the flow of magnetic flux which lowers the output torque (Balaji et al., 2004). However, the gap must be sufficient to allow smooth rotational motion without contact between the rotor and stator. The example 6/4 rotary SRA in Figure 1.1 is driven by 3-phase excitation current. Opposite stator poles are wounded with winding coils which forms one phase of the excitation current. SRA does not have any windings on its rotor, the only stator windings can be formed externally and inserted into the stator which provides a simple construction process (Fairall et al., 2015). Rotary SRA is typically powered by 3-phase current but there are development projects involving up to 6-phase (Han et al., 2016). The multi-phase characteristic of SRA provides inherent fault tolerance (Parsa, 2005). The electrical configurations of each phase are independent of each other. In case one phase fails, the machine maintains continuous operation. This allows SRA to be applied in aerospace applications (Fronista and Bradbury, 1997; Schramm and Gerling, 2006) and mining equipment (Hao and Guilin, 1998). When operating under high speed modes, SRA displays a high power factor as well as enhanced efficiency. This allows SRA to be well-suited for hybrid electrical vehicle (HEV) applications (Rahman et al., 2000; Ding et al., 2017) which could be a breakthrough for the industry. HEV are environmental friendlier and provide a lower maintenance cost compared to gas-powered vehicles. Apart from that, the simple, robust, low cost structure of SRA and absence of speed multiplication system makes rotary SRA suitable for wind power systems (Ogawa et al., 2011). There are also other useful applications for rotary SRA such as robotic joints and manipulator (Hernandez-Guzmann et al., 2013; Li et al., 2017) to replace the existing PM stepper motor.

Despite the advantages, there are a few significant weaknesses of rotary SRA where its usage is concerned. Rotary SRA intricately exhibits non-linear characteristics which is attributed to the unpredictable flow of magnetic flux linkage and magnetic saturation. The non-linear nature of the rotary SRA makes analytical modelling extremely challenging. Measurements or finite element predictions for magnetization curves are necessary to formulate control schemes which complicates controller design processes. Henceforth, these factors limit the real-time motion control of rotary SRA in which often deemed as a challenging effort with low accuracy.

At present, there are numerous control methods proposed and established for motion control of linear SRA. However, for rotary SRA it is fairly limited. Most of these early works involved model-based control which yields ameliorated performance but is highly dependent on the accuracy and quality of the system's modelling. Hence, through classical control, the proportional-derivative-integral is widely used as alternative because it has simple design procedures and high applicability well suited for industrial operations. However, this method deteriorates in performance when non-linear mechanisms are involved due to the controllers' linear structure. Various model-free controllers such as intelligent and hybrid are also employed. The complexity of control architecture is reduced compared to model-based controllers and their performance are enhanced because system uncertainties and variations can be accommodated through decision making skills of the controller. However, these controllers require sufficient knowledge in control theory and a tedious, time-consuming design procedure. Therefore, in this research, a control strategy that has a simple and practical framework is presented. The proposed control method will then be validated through a 3-phase 6/4 rotary SRA.