



SENSORLESS AND INDEPENDENT SPEED CONTROL OF DUAL-PMSM DRIVES USING FIVE-LEG INVERTER (FLI)

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DOCTOR OF PHILOSOPHY

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Faculty of Electrical Engineering

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JURIFA BINTI MAT LAZI

**A thesis submitted
in fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical
Engineering**

Faculty of Electrical Engineering

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2016

DECLARATION

I declare that this thesis entitle “Sensorless and Independent Speed Control of Dual-PMSM Drives” 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 :

Date :

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 Doctor of Philosophy in Electrical Engineering.

Signature :

Supervisor Name :

Date :

DEDICATION

To my beloved family;
Samsudin Ahmad
Mat Lazi bin Ali
Julia binti Mohd Zain
Muhammad Imran Danial bin Samsudin
Nurul Iman Sofea binti Samsudin
Muhammad Irfan Daniah bin Samsudin
Mohd Lazim bin Mat Lazi
Siti Norazin binti Mat Lazi
Mohd Arif bin Mat Lazi

ABSTRACT

This research aims to develop and implement a combined sensorless and independent speed control for dual-PMSM (Permanent Magnet Synchronous Motor) drives fed by a single Five-Leg Inverter (FLI). Dual-motor drives are widely used in high traction power industry such as propulsion system, aircraft, locomotive, Hybrid Electric Vehicle (HEV) and others. In general, dual-motor drives are designed to reduce size and cost with respect to single motor drives. However, dual-motor drives using a single three-leg inverter has its limitation in the case of operation at different operating conditions and independent speed control requirement. Recent research has shown that, dual motor drives can be independently controlled by using Five-Leg inverter (FLI). By employing this FLI topology, the dual-motor drives can be used for four-quadrant control, variable speed operation and load disturbance rejection. In other words, it can be operated for different applications. In the case of conventional dual-PMSM drives, the drives system still requires current sensors and voltage transducers for speed and rotor position estimation. In PMSM drives, the information of the feedback speed and rotor angular position is compulsory. Therefore, this research is trying to implement a combined sensorless and independent speed control for dual PMSM drives system and at the same time eliminating the usage of voltage transducers. This thesis investigates the behavior of sensorless and independent speed control for Dual-Permanent Magnet Synchronous Motor (PMSM) drives. Initially, a single PMSM drives is designed and simulated, followed by the development of Dual-PMSM drives model. The speed and current controllers are implemented in $d-q$ rotor reference frame using Simulink/MATLAB and the switching signals are generated by the built-in function and dSPACE. Then, the sensorless drive system is developed based on adaptive speed and position estimator. The overall performance of the drives is investigated and evaluated in terms of speed responses overshoot under variation of speed reference and speed drop under load torque disturbances. The simulation results have proved that the performance characteristics of sensorless dual-PMSM are almost similar with system using sensor except during the start-up condition. The motor performance is degraded in terms of speed overshoot for small and medium speed reference or when the motor operates far from the designed operating condition (rated value). The proposed independent dual-PMSM drives fed by FLI have better load rejection capability compared with conventional dual-PMSM drives fed by single three-phase inverter. The experimental results of the drives under investigation have shown acceptable correlation between the theoretical and simulation.

ABSTRAK

Penyelidikan ini bertujuan untuk membangun dan melaksanakan gabungan sistem tanpa pengesan dan kawalan kelajuan berasingan bagi pemacuan dua-PMSM (Motor Segerak Magnet Kekal) yang menggunakan sebuah Penukar Lima-Kaki (FLI). Pemacuan dua-motor digunakan secara meluas dalam industri daya tarikan berkuasa tinggi seperti system penggerak, pesawat udara, keratapi lokomotif dan lain-lain. Pada dasarnya, pemacuan dua-motor adalah direka untuk mengurangkan saiz dan kos jika dibandingkan dengan pemacuan untuk satu mesin. Walaubagaimanapun, pemacuan dua-motor menggunakan sebuah penukar tiga-kaki mempunyai limitasi bagi kes yang berbeza keadaan operasinya dan pada keperluan untuk kawalan kelajuan berasingan. Penyelidikan pada akhir-akhir ini telah menunjukkan bahawa pemacuan dua-motor boleh dikawal secara berasingan dengan menggunakan penukar lima-kaki (FLI). Dengan menggunakan topologi penukar lima-kaki ini, dua-motor boleh digunakan bagi kawalan empat kuadran, kawalan variasi kelajuan dan gangguan penolakan beban. Dalam perkataan lain, ianya boleh beroperasi pada applikasi yang berbeza. Bagi kes pemacuan dua-PMSM tanpa pengesan yang lazim, sistem pemacuan masih memerlukan pengesan arus dan pemindaharuh voltan untuk anggaran kelajuan dan kedudukan rotor. Dalam pemacuan PMSM, maklumat bagi suap balik kelajuan dan kedudukan angular rotor adalah satu kemestian. Oleh itu, penyelidikan ini cuba untuk melaksanakan gabungan sebuah sistem pemacuan tanpa pengesan dan kawalan kelajuan berasingan bagi dua-PMSM dan pada masa yang sama menghilangkan penggunaan pemindaharuh voltan. Tesis ini menyiasat tingkah laku bagi pemacuan tanpa pengesan dan kawalan kelajuan berasingan bagi dua-PMSM (Motor Segerak Magnet Kekal). Pada peringkat awal, sistem pemacuan satu PMSM menggunakan sensor direka dan disimulasi, diikuti dengan pembangunan model pemacuan dua-PMSM. Pengawal-pengawal arus dan kelajuan adalah dilaksanakan dalam rangka dan rujukan d-q rotor menggunakan Simulink/Matlab dan arahan suis dijana menggunakan fungsi terbina-dalaman dan dSPACE. Kemudian, sistem tanpa pengesan pula dibangunkan berdasarkan penganggar penyesuaian kelajuan dan kedudukan. Pencapaian keseluruhan bagi pemacu ini adalah diteliti dan dinilai dalam terma lajukan sambutan kelajuan bagi variasi kelajuan rujukan dan kejatuhan kelajuan semasa gangguan daya kilas beban. Hasil simulasi telah membuktikan bahawa ciri-ciri pencapaian bagi sistem Dua-PMSM tanpa pengesan adalah hampir serupa dengan sistem menggunakan pengesan kecuali bagi keadaan permulaan. Pencapaian motor adalah menurun bagi terma lajukan kelajuan bagi rujukan kelajuan besar dan sederhana atau bila motor beroperasi jauh dari keadaan operasi rekaan (nilai kadaran). Pemacuan dua-motor berasingan yang disuap oleh penukar lima kaki (FLI) yang dicadangkan mempunyai keupayaan menolak beban yang lebih baik berbanding dengan pemacuan dua-motor lazim yang disuap oleh penukar tiga kaki. Hasil eksperimen menunjukkan keputusan korelasi yang boleh diterima di antara teori dan simulasi.

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CHAPTER 1

INTRODUCTION

1.1 Application of High Performance AC Motor Drives

Electrical machine is widely used in industrial processes which serve to drive the manufacturing facilities such as conveyor belts, robot arms, cranes, steel process lines, paper mills, waste water treatment and many more. Rapid development of industrial automation requires continuing improvement of different types of electrical drives. Manufacturing lines typically involve variable-speed motor drives to power conveyer belts, industrial robots and other types of processing operations. High reliability, good control characteristics, low maintenance requirements, low investment and low running costs are among the important features that are required from a modern drive.

Depending on the actual application, different types of electric machines can be used, such as induction motors (IM), permanent magnet synchronous motors (PMSM), switched reluctance motors (SRM), direct current (DC) motor, etc. Nowadays, the engineer in industry would like to utilize Alternating Current (AC) instead of DC motors in retrofitting and designing a new plant. This phenomenon happens because of the simpler structure of AC machines, better robustness, lower cost and virtually maintenance-free operation. .

The PMSM has numerous advantages over other motors that are conventionally used for AC servo drives. As compared to the induction motor, the use of permanent magnet in the rotor of the PMSM makes it unnecessary to supply magnetizing current through the stator for constant air-gap flux, whereas, the stator current need only torque command. Hence, for the same output, the PMSM will operate at a higher power factor

(because of the absence of the magnetizing current) and will be more efficient than the induction motor (IM),(Pillay and Krishnan, 1988).

As time flies, the power demand for AC drive is increasing. A lot of studies have been done to enhance the performance of machine drives by decreasing the cost and size of the drives. One of the solutions is using Multi-Machine System (MMS) application fed by a single inverter. Multi Machine Systems (MMS) are extensively used today especially in the case of dual motor drives (Jones et al., 2009, Perez-Pinal et al., 2009, Perez-Pinal et al., 2004, Ben Mabrouk et al., 2011). This system allows the field of high power applications to be extended and their flexibility, mechanical simplicity and safety operating system to be increased. However, this system requires a lot of power switches which are costly and bulky. Therefore, the need for dual motor drives fed by single inverter is preferable to reduce size and cost as compared to the single motor drives, either in industrial or in traction applications.

Previously, a few techniques have been developed to optimize the machine drives configuration. (He et al., 2010) was reported to use common DC bus voltage while each motor has its own three-phase voltage source inverter as the supply. Later, dual-motor drives fed by single inverter, especially in the case of PMSM was discussed clearly in (A.Del Pizzo, 2009, Acampa et al., 2008a, Acampa et al., 2008b, Del Pizzo et al., 2010, Jurifa Mat Lazi, 2010, Kelecy and Lorenz, 1995, Matsuse et al., 2004, Nishimura et al., 2007a, Zhao and Lipo, 1995). Dual-Motor drives in the case of Induction Motor is presented by (Bojoi et al., 2005, Kelecy and Lorenz, 1995, Li and Fengchun, 2009, Matsumoto et al., 2002a, Matsumoto et al., 2002b, Matsuse et al., 2004, Mohktari and Alizadeh, 2008, Nishimura et al., 2007a, Okabe et al., 1984, Report, 1997, Wang et al., 2006, Wei et al., 2006a, Wu et al., 2002, Zhao and Lipo, 1995).

Ledezma and colleagues have proposed a technique using 4-leg inverter (content 8 switches) to control dual motors (Ledezma et al., 2002). Then, the technique to use Five-Leg Inverter for supplying two-motor drives has been proposed (Delarue et al., 2003a, Francois and Bouscayrol, 1999, Francois et al., 2000, Kimura et al., Ohama et al., 2009, Vukosavi et al., 2008)

Throughout the research by the listed publications, it is proven that this topology is able to control independently two separate motors by using single inverter. The term independent refers to each motor that can be operated at different operating conditions such as different direction, speed, load torque and motors parameters.

1.2 Vector Control of PMSM

Almost 30 years ago, F. Blaschke presented the first paper on Field Oriented Control (FOC) for induction motor in year 1972 (Blaschke, 1972). Since then, the technique was completely developed and it is mature from the industrial point of view. Today, field oriented controlled drives also known as Vector Control (VC) drives are an industrial reality and are available on the market provided with different solutions and performance. Thirteen years later, a new technique for the torque control of AC motors was developed and presented by I. Takahashi as Direct Torque Control (DTC) (Takahashi and Noguchi, 1986) and by M. Depenbrock as Direct Self Control (DSC) (Depenbrock, 1988). This new technique was characterized by its simplicity, good performance and robustness.

A number of solutions have been proposed to implement vector control. In vector control drive, the quadrature axis stator current is used to control the torque, and thus indirectly control the speed and position of the motor up to the base speed. In order to operate above base speed, it is required to weaken the flux, which can be done using the stator *d*-axis current component (Boldea and Nasar, 1992). The efficiency of the drive

decreases because of the increases in copper loss that due to the increases in the stator current. In recent years, Vector (field-oriented) Control techniques have been employed in order to enable conversion of AC machine into an equivalent separately excited DC machine. Thus field oriented control enables decoupled (independent) control of flux and torque in an AC machine by means of two independently controlled stator currents, as in a separately excited DC machine. To obtain true vector control, stator current components must be placed into a pre-defined position with respect to one of the flux space-vectors. Basically, there are two common types of vector control used, which are rotor flux oriented control and stator flux oriented control. Rotor flux oriented control is the most common method applied in practical realizations (Vas, 1998a). The sole reason is due to the simplest system structure in its control orientation.

The ac machine is converted into its equivalent separately excited DC machine in the simplest way by selecting a reference frame fixed to the rotor flux. However, it is always a challenging task when the stator d - q axis current components that significantly needed for the decouple flux and torque control is absent in the actual machine. The problem is overcome by including co-ordinate transformation as an interface between the control system and the machine.

1.3 Methods of Sensorless Speed Control

In Permanent Magnet Synchronous Motor, it is necessary to know the information of speed and rotor position for the implementation of vector control or field-oriented control with fast dynamic response, accurate speed regulation and high efficiency. Various techniques in sensorless strategy have been discussed by different researchers. Most of the techniques are based on the voltage equations of the PMSM and the information of the terminal quantities, such as line voltages and phase currents. By using this information, the

rotor angle and speed are estimated directly or indirectly. Basically, estimation of the sensorless techniques can be based on different categories such as Back Electromagnetic Force, Excitation Monitoring, Motor Modification, Magnetic Saliency, Observer and Signal injection.

Elimination of the speed encoder is highly encouraged to increase the mechanical robustness of the system and to make the drive cheaper. This has made speed sensorless PMSM drive becomes popular. Therefore, vector-control methods in the absence of any position or speed sensor have been investigated by many researchers. In some methods (indirect methods)(Bolognani et al., 1999), the estimation of velocity is performed and followed by calculation of the trigonometric values. In some other methods(Peixe et al., 1995), the required trigonometric values are directly estimated from motor state equations. Estimation theory and especially Extended Kalman Filter (EKF) method is extensively used in indirect methods (Petrovic et al., 2003). Another method is using Model References Adaptive Control (MRAC)(Maiti et al., 2008).

MRAC computes a desired state (called as the functional candidate) using two different models (i.e. reference and adjustable models). The error between the two models is used to estimate an unknown parameter (here speed is the unknown parameter). Hence, there are many other speed estimation techniques reported in literature such as Back-EMF based method, Artificial Intelligent (AI), State observer based method and etc. Out of all the techniques discussed so far, MRAC is widely accepted for speed estimation due to its simplicity and good stability. Also the method does not require any extra hardware or signal injection or huge memory like EKF. The detailed discussion about sensorless drives will be presented in chapter 2.

1.4 Problem Experienced in Sensorless Speed Control of Dual-Motor Drives

In the case of Dual-motor drives, other than inverter block, the system still requires two sets of speed and current sensor. In PMSM drives, the information of the feedback speed and rotor angular position is compulsory. Therefore, this current study is trying to reduce the amount of the extra hardware and feedback devices to be used in this system. The best solution for this problem is by eliminating the usage of speed and position sensors. Based on previous literature in Five-Leg Inverter (FLI), none are using sensor-less technique for FLI supplying for Dual PMSMs. Classical method is explained through the functionality of speed sensor which is to get the rotor position information.

1.5 Aims of the Research

This research aims to develop sensorless technique using Adaptive Control for Dual-Motor Drives fed by Five-leg Inverter (FLI). The main contribution of sensorless technique in Dual-Motor Drives is to eliminate the use of speed sensor and this will reduce the system cost, size and complexity.

1.5.1 Thesis Objective

The objectives of this research are:

1. To examine the functionality of Independent Speed Control for Dual-PMSM drives.
2. To propose speed and position estimator of sensorless control for PMSM drives using adaptive model based on voltage and current differential.
3. To develop and implement a new combined Sensorless and Independent Speed control method for Dual-PMSM drives based on Five-Legs Voltage Source Inverter (VSI).

4. To validate the proposed control method in the speed response behavior and its characteristics of Sensorless and Independent Speed control for Dual-PMSM drives based on Five-Leg Inverter (FLI).
5. To develop PWM schemes for FLI using space vector approach, which enable to produce multi-frequency output and voltage applicable to control of Five-Leg Inverter connected to two-PMSM.

In order to achieve the research goals of this project, a comprehensive research approach will be developed based on simulation and experimental investigation. The approach includes of literature study, comparative study, mathematical modeling using Matlab Simulink, investigation of the proposed design, hardware in the loop of dSPACE experimental set-up and overall performance evaluation and verification. In order to investigate the behavior of the motor performance, the independent and dependent variables are captured and analyzed for further improvement. Finally, from the experimental results, it is expected that the speed and torque responses of the both motors performance will improve in term of stability, accuracy and robustness.

By achieving the objectives listed above, a significant of new knowledge has been produced. This is partially proven by the published research papers that have resulted from the thesis (refer to List of Publications).

1.5.2 Problem statement

The problem statements of this research are as follows;

1. A conventional Dual-Motor drive, fed by a three-leg voltage inverter design is attractive for industrial applications because of its simple structure. However, this

topology has its limitation which can only be operated under the same conditions of which having the same motor model, speed command profile and DC-link supply.

Therefore, Dual-Motor drives using Five-Leg Inverter (FLI) is designed to provide independent speed control for dual-motor drives under variation of operating conditions. The proposed topology of FLI consists of ten switches, which one of the leg is commonly shared by Dual PMSMs as depicted in Fig. 2.1.

In the case of conventional FLI (Five-Leg Inverter) drives, a lot of external wires, sensors and other supporting components are needed because it deals with the two sets of current sensors, two sets of encoders or resolvers in order to capture the information of rotor position. The appearance of all the transducers increases the total size and cost of the drive.

In order to reduce the capital cost and optimize the area of the drives, the proposed sensorless technique is able to lower overall drive cost by eliminating the use of mechanical position sensor and at the same time maintaining the system performance for the same price.

2. The Requirement of Multi-Motor System (MMS) in industry is growing faster nowadays. Especially with the application of high traction power such as propulsion system, aircraft, locomotive, Hybrid Electric Vehicles (HEV) and others. Among these industries, multi motor drives are usually used in different speed control application such as one motor is connected to the compressor and the other one to the

blower. Other than that, multi motor is also used in conveyer belt which operates using two motors in different direction, forward and reverse.

The conventional multi-motor arrangement is usually done by cascading the individual drives, causing the number of the drives to increase and consequently making the total cost of the control system to increase. Therefore, in order to reduce the individual number of drives as well as the total number of inverter legs, the independent speed control of the PMSM drives using Five-Leg Inverter is proposed as an alternative to the conventional multi-motors drives in the industry.

3. In Permanent Magnet Synchronous Motor (PMSM) drives, the information about the rotor position is compulsory, makes the speed sensor need to be attached to the motors. The implementation of multi-motor drives will increase the number of feedback devices such as speed encoder, voltage transducer, current sensors and others. The increasing number of those devices will indirectly reduce the reliability of the system performance in terms of complexity and difficulty to install and control the tuning parameters of the drives.

To improve the reliability of the drives and to simplify the system design, sensorless control is suggested by eliminating the usage of speed sensor, encoder and voltage transducer for Dual-PMSM drives.

4. A few industries such as oil and gas industry, application of long cable is required to drive their motors which need to be controlled at different location from the controller room. The usage of long cable may increase the number of transducers and

also the need for additional cable for all devices. These will indirectly increase the cost and complexity of the drive.

Therefore, sensorless and independent PMSM drives is introduced to eliminate those additional cables and devices, hence can reduce the cost and improve the system performance.

5. There is no detailed study has been done on both sensorless and independent drives particularly for PMSM drives under wide range of speed operation. Therefore, this current research comes out with the detailed investigation for sensorless and independent dual-PMSM drives in order to analyze the system behavior and characteristics of the speed, voltage and current of the motors.

1.5.3 Research Contributions

The contributions of this research are listed as follows;

1. For this research, the sensorless control method based on differential of d-q current and voltage is successfully developed to estimate the speed and rotor position for Independent Speed Control of Dual PMSMs drives. To our best knowledge, this is the first try in the literature. Also, the novelties of the proposed estimation algorithm are the position algorithm equation and the final mathematical form of the estimation.

The contribution of the proposed estimation algorithm is the position estimation equation and the process of compensation of the Five-Leg Inverter, which also

suggest the final mathematical form of the estimation. The mathematical structure of the estimation guarantees a high degree of robustness against parameter variation as presented in this thesis.

2. Another contribution of this current study is the absent of three-phase voltage transducers. The proposed speed and position estimator does not utilize any voltage transducers which makes it more reliable, reduces the system complexity and creates additional cost saving for PMSM drives. With two PMSM involved, the absent of the voltage transducers really reduce the total number of feedback devices used in this Dual- PMSM drives.
3. It is observed that based on the literature review, there is no other research being done on implementation of Independent speed control for dual-PMSM drives fed by Five-Leg Inverter. However based on the available literature, existing research only emphasized on implementation on Induction Motor drives for limited operating condition.
4. Additionally, there is no other research being done on hardware implementation of combined Independent speed and sensorless control for dual-motor drives fed by FLI (Five-Leg Inverter). The conclusion based on the experimental study can also be applied to Induction Motor (IM) drives as long as vector control principle is applied in the control algorithm.

1.6 Research Methodology

The methodology of this research is done based on the flowchart shown in Figure 1-1. It starts with literature review of Multi-Motor drives, Dual-motor with either non-independent or independent drives and sensorless drives. Then, the PMSM drives for single motor using speed sensor is modelled and simulated. The modelling of PMSM drive is utilizing the PI controller for speed and current control.

After a single PMSM drives is successfully simulated, the Dual-PMSM drives is then developed by using Three-leg and Five-Leg Inverter (FLI). The independent control for each motor is achieved by using Five-Leg Inverter; meanwhile the three-leg inverter is referring to non-independent Dual-PMSM performance. The simulation results for these two types of Dual-PMSM drives are then being compared.

The next step is to develop the position and speed estimator specifically for sensorless PMSM drives of a single motor. After the modelling process of sensorless drive for a single motor is completed, then, the modelling of the sensorless for Dual-PMSM drives is established. All simulation investigation are done using MATLAB/Simulink development tools environment.

After done with simulation investigation for a single and Dual-PMSM drives, either by using speed sensor or “sensorless” drives, the experimental investigation for entire drives system is carried-out. Firstly, the experimental investigation is done for a single PMSM drives using sensor, followed by Dual-PMSM drives using speed sensor. Then, the sensorless PMSM drive is investigated experimentally for both cases, single and for Dual-PMSM drives.

Finally, the experimental results for all cases are compared and analyzed. The overall evaluation and verification for experimental investigation are carried-out using