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論文内容要旨

High performance applications of Switched Reluctance (SR) motor strictly depend on accurate modeling (or characterization), as well as appropriate torque control. As in the other closed - loop control, accuracy of torque feedback has significant effect on the instantaneous torque control, which also enables reducing torque ripples. Because of highly nonlinear relationship between electrical and mechanical terminals, the motor torque can not be analytically calculated by means of known quantities, as in the ac machines. Torque sensor is the most accurate way of obtaining torque but it is expensive and has to be properly mounted on the motor shaft. Therefore, the use of torque sensor is not preferable in SR motor applications. Instead of using torque sensor permanently, preparing a model from the known quantities is often preferred. Many researches have been done so far on accurate modeling and torque estimation of SR motors. Some of them need a priori use of torque sensor. The models and torque estimation can also be accurate as much as torque sensor, but it should be avoided such modeling because of the problem with use of torque sensor. The model of the SR motor is often prepared by using Finite Element Analysis (FEA) based software. However, motor modeling and calculation in FEA is time consuming and requires detailed information about dimensions and type of magnetic materials. Moreover, the results may not always meet the actual ones. Obviously, the most accurate and convenient way is to characterize SR motor from measured quantities. So far, it has been mostly done by applying static test to the SR motor to obtain current and flux linkage data at definite rotor positions. However, this method needs an extra assembly to lock the rotor, which is not available on a commercial SR motor.

This work introduces simple implemented - very accurate methods for characterization and static torque computation of an SR motor, which overcome problems mentioned above. These methods do not need either a priori use of torque sensor or an assembly for rotor locking. The motor characterization is done by using data collected from running mode. These methods also enable to estimate instant dynamic torque that is very important for high performance applications of SR motors.

Although the SR motor has simple structure, the control part is somewhat complicated. Moreover, some control strategies have to be applied to SR motors in order to avoid large torque ripples. So far, the significant part of the researches has concentrated on control of SR motors. The problems in the control have been still investigated for improvement so that the SR motor drives can really be competitive to other drives and take place in the variable speed drives. A control that uses the philosophy of direct torque control (DTC) of conventional ac machines has been proposed in previous research. DTC offers controlling torque and its ripple in simple way which is very important for realtime implementation. However, this control strategy requires position feedback to control speed and to estimate motor torque. Position is mostly obtained from position encoder, which makes the DTC drive more expensive and less reliable. Therefore, DTC should be achieved in position sensorless way.

This thesis also concerns position sensorless speed and torque estimation for DTC of the SR motor. A novel sensorless position and torque estimators have been introduced. Sensorless DTC of the SR motor have been experimentally realized and the performance has been verified for different running conditions. The experimental results have been also given in this chapter.

There are six chapters in this work, which can be summarized as follows:

The first chapter deals with the requirement of modeling and control strategies for the SR motor. Recent researches on modeling and torque control have been reviewed. The researches are first categorized, and then, the difficulties and drawbacks of these researches have been figured out and addressed in this chapter. The motivations of this research have been also clarified in this chapter.

The second chapter presents basic properties of SR motors. Analysis has been done by considering nonlinearity between electrical and mechanical terminals. Field energy and mechanical work done in one stroke have been explained in detail by investigating transistor conduction and diode freewheeling modes. In practice, discrete equations of coenergy and torque are mostly required because analytical expression of flux linkage is unknown. Discrete equations have also been derived in this chapter by assuming flux linkage data are known as a table form.

The third chapter mainly concerns modeling or characterization of an SR motor by using data collected from running operation. The experimental setup, control and measurement boards, and control algorithm during data collection has been introduced. Two novel characterization methods, which are based on Fourier series and Artificial Neural Network has been presented. Static torque computation has been done by both methods and the results have been compared by static measured values (Fig.1). Both modeling methods were found to be enough accurate so that they can be used instead of any modeling that needs rotor locking assembly or priori use of torque sensor. As compare to the static measured results, ANN based characterization has found to be more accurate than Fourier based characterization because noise in measurement has smaller effect on training. A torque estimator has been built from the static torque data computed by ANN. Dynamic response of the estimator has been investigated for different running conditions of a 6/4 SR motor.

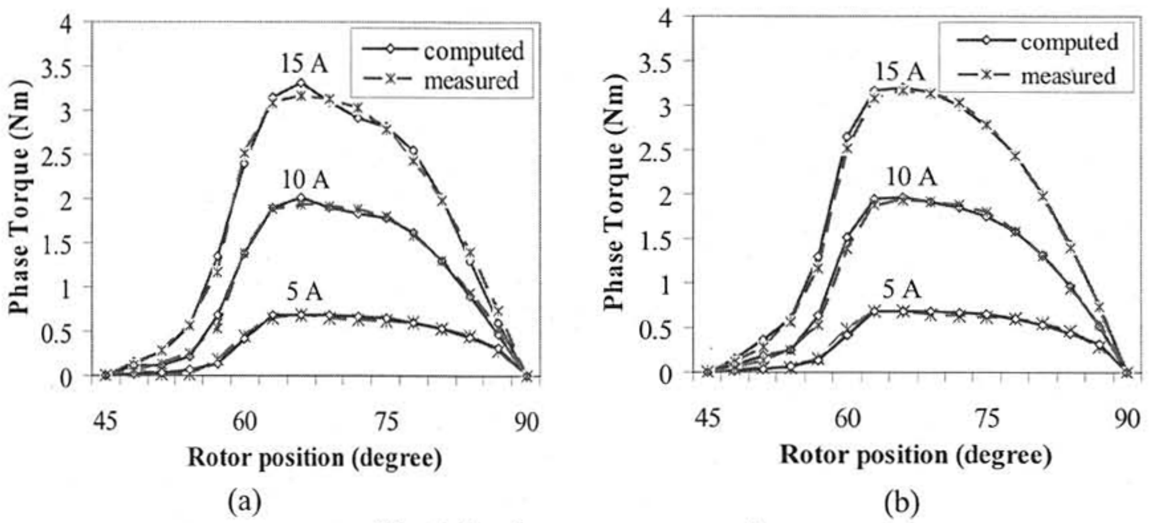

Fig. 1. Static torque computation
a) based on Fourier series, b) based on ANN

The fourth chapter deals with direct torque control (DTC) of SR motors. First, conventional DTC applied to the ac machines has been reviewed in order to make DTC for SR motor more comprehensive. Derivation of approximated toque equation which DTC strategy is constructed on has been shown. Then, the principle of DTC for SR motors has been explained in detail. The experimental results of DTC for the 6/4 SR motor with new torque estimation has been also given in this chapter.

The fifth chapter concerns position sensorless torque estimation and speed estimation Novel sensorless estimators for these purposes have been introduced so that position encoder has been removed from the system (Fig. 2). Both estimators are based on inductance vector angle, hence sensorless DTC can be easily implemented in realtime. The sensorless DTC of 6/4 SR motor have been experimentally verified for various operating conditions. The results have been also shown in this chapter.

The sixth chapter concludes the research and discusses some issues to increase performance of characterization and sensorless DTC of an SR motor. Some reasons of equivalent resistance change in the SR motor have been addressed. The effect of resistance change on flux linkage calculation, and hence, torque computation has been investigated. In addition, mutual effect occurred in DTC of SR motor have been also investigated and some solution have been recommended for increasing of control performance.

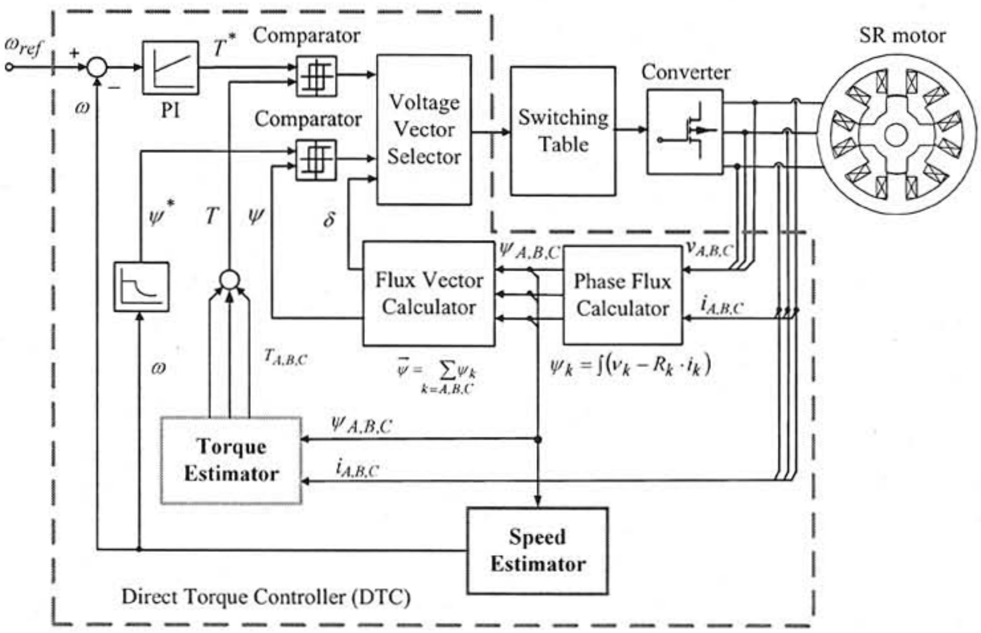

Fig. 2. Proposed position sensorless DTC for SR motors

論文審査結果の要旨

スイッチトリラクタンスモータ（以下SRモータ）は，構造が単純で堅牢，事故に対する耐性が強い，磁石を使用しないため安価などの特長を有するが，固定子と回転子がともに突極構造のためトルクリプルと騒音が大きく，広く実用されるには至っていない．また，SRモータの制御には回転子の位置検出が必要になるが，ロータリーエンコーダなどの位置センサは使用環境が制限され，設置スペースの増加や価格の上昇を招く．本論文は，これらの課題を解決することを目的として，ニューラルネットワークを利用したSRモータのトルク推定法を考案し，直接トルク制御（以下DTC）と組み合わせることによって，SRモータのトルクリプル低減とセンサレス駆動を同時に実現したもので全編6章からなる．

第1章は緒言であり，本論文の背景および目的を述べている．

第2章では，SRモータの原理や駆動回路，ならびにトルク式を説明し，SRモータの電流やトルク特性が鉄心の磁気飽和に起因する強い非線形性を示すことを述べている．

第3章では，SRモータの特性算定には励磁巻線の鎖交磁束と電流，および回転子位置角の関係が基本になることを明らかにし，これに基づいてSRモータのトルクを求める手法を提案している．まず，SRモータを回転させながら巻線電圧，電流，および回転子位置角を実測する．鎖交磁束は電圧と電流から計算する．これらの取得データがランダムでノイズも大きいことから，ここではニューラルネットワークを利用して取得データからモータモデルを作成する方法，ならびにトルク計算手法を提案した．提案手法に基づくトルクの計算値と実測値は良好に一致し，提案したモデルがSRモータの高精度なトルク算定に有用であることが明らかになった．

第4章では，トルクリプルの低減を目的として，SRモータのDTCについて検討を行っている．DTCは，誘導モータでは適用実績があるがSRモータに適用した例は殆どない．ここでは，SRモータの巻線電圧，電流，回転子位置角から推定されるトルクに基づいてSRモータの瞬時トルクを制御するDTCを提案し，これによりトルクリプルが通常駆動の約1/10に低減されることを実験により明らかにしている．これは実用上有用な成果である．

第5章では，SRモータのセンサレス制御について述べている．すなわち，4章で述べた制御においては回転子位置角の検出にロータリーエンコーダを使用したが，これを省略するために，磁束と電流および位置角に関するデータと，トルクと電流および位置角に関するデータから，ニューラルネットワークを利用して電流と磁束からトルクを求めるモータモデルを作成した．これを4章のDTCに組み込むことによって，センサレスでSRモータの速度制御を行うシステムを実現した．これは高く評価される．

第6章は結言であり，各章の成果をまとめている．

以上要するに本論文は，SRモータの特性改善を目的として，ニューラルネットワークとDTCを利用することによってSRモータのトルクリプルを抑制しつつセンサレスで速度を制御する手法を初めて提案したもので，パワーエレクトロニクスならびに制御工学の発展に寄与するところが少なくない．

よって，本論文は博士(工学)の学位論文として合格と認める．