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Zhixun Ma

**FPGA-Based High Performance
Sensorless Control for PMSM Drives**

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TECHNISCHE UNIVERSITÄT MÜNCHEN

Lehrstuhl für Elektrische Antriebssysteme und Leistungselektronik

FPGA-Based High Performance Sensorless Control for PMSM ~~Drives~~

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Abstract

This work focuses on the development of high performance sensorless controllers for PMSM drives. Main contributions are as follows: a linearly compensated sensorless flux observer based on back EMF is proposed; using Delta-Sigma modulator, based on FPGA current oversampling and signal processing techniques, a lower HF current response is sufficient to implement HF voltage injection sensorless control methods; for the EKF based sensorless observer, it demonstrates that different frame models have notably various influences on the FPGA based implementation; a continuous set nonlinear model predictive control (CS-NMPC) for PMSM drives is proposed; a model based design (MBD) method for fully FPGA based drive system controller is presented.

Kurzzusammenfassung

Die vorliegende Arbeit befasst sich mit der Entwicklung von leistungsfähigen geberlosen Regelkonzepten für PMSM-Antriebe in folgenden Aspekten: (1) ein linear kompensierter, geberloser Flussbeobachter wird vorgeschlagen, der auf Gegen-EMK beruht; (2) auf Grundlage von Strom-Überabtastung und Techniken der Signalverarbeitung wird mittels eines Delta-Sigma-Modulators eine hohe Auflösung der digitalen Strom-Signale erreicht; (3) die Wahl des Koordinatensystems hat unterschiedlich starke Einflüsse auf die Implementierung in FPGAs; (4) eine nichtlineare Modellprädiktive Regelung mit kontinuierlicher Stellgröße (CS-NMPC) für PMSM-Antriebe wird vorgeschlagen; (5) eine modellbasierte Entwurfsmethodik (MBD) für FPGA-basierte Antriebsregelsysteme wird vorgestellt.

Extended Abstract

This thesis focuses on the development of high performance sensorless controllers for PMSM drives. To realize this goal, two aspects are investigated. One is the improvement of control algorithms. The other is the exploitation of capabilities of FPGAs which are the most promising candidates for the future drive control platform, to advance implementation performance.

The main contributions of this work are as follows:

A linearly compensated sensorless flux observer based on back EMF is proposed. This flux observer exhibits excellent dynamic and steady-state performance, which is robust to parameter variation. It is effective with $0 \sim 3$ times stator inductance variation at the speed above 0.03 pu (per unit). At the speed of 0.03 pu, the flux observer works well with $0 \sim 2$ times resistance variation with and without load. As the speed increasing, the sensitivity of the flux observer to stator resistance variation decreases.

Using Delta-Sigma modulator, based on FPGA current oversampling and signal processing techniques, high resolution of digital current signals is obtained. Therefore, a lower HF current response is sufficient to implement HF voltage injection sensorless control methods. This can also result in lower acoustic noises, less losses and disturbances of the system. Using the designed FPGA controller, the injection could be reduced to one third in the standard drive system.

For the EKF based sensorless observer, an interesting result has been found. It demonstrates that different frame models have notably various influences on the implementation, especially for the implementation of FPGA. For instance, the well-known simplified rotating frame EKF observer cannot work properly. This problem can be found immediately in the implementation of FPGA based fixed-point data type. Thus, an approach using the hybrid rotating frame model is presented in this work to solve the problem.

A continuous set nonlinear model predictive control (CS-NMPC) for PMSM drives is proposed. It is easy to include nonlinearities and constraints of the control system. Therefore, the control system has not only high dynamic performance in the transient state, but also excellent performance in the steady state. Moreover,

it is very easy for the control system to combine the sensorless control methods in realizing sensorless control for PMSMs.

A model based design (MBD) method for fully FPGA based drive system controller is presented. Using Matlab/Simulink and HDL Coder, machine control and sensorless control methods are designed and implemented in a single FPGA chip. Based on fast parallel processing of FPGAs, sensorless control algorithms are implemented without disturbance of the execution of main control algorithms. High performance sensorless control is obtained due to high sampling frequency and low excitation time. It is reasonable to believe that FPGAs will become the core of drive control platforms in the near future, and the MBD method for FPGA based controller design presented in this work will receive more attention.

Zusammenfassung

Die vorliegende Arbeit befasst sich mit der Entwicklung von leistungsfähigen geberlosen Regelkonzepten für PMSM-Antriebe. Um dieses Ziel umzusetzen, werden zwei Aspekte untersucht. Einer ist die Verbesserung der Regelalgorithmen. Der andere ist die Ausnutzung des Potenzials von FPGAs, den meistversprechenden Kandidaten für eine zukünftige Antriebsregelungs-Plattform, um die Leistung in der Umsetzung zu verbessern.

Diese Arbeit leistet Beiträge zur derzeitigen Implementation in folgenden Aspekten:

Es wird ein linear kompensierter, geberloser Flussbeobachter vorgeschlagen, der auf Gegen-EMK beruht. Dieser Flussbeobachter zeigt eine ausgezeichnete Dynamik und stationäre Eigenschaften, die robust gegenüber Parametervariation sind. Bei Geschwindigkeiten über 0,03 pu (per unit) ist er läuffähig mit 0- bis 3-facher Variation der Statorinduktivität und arbeitet gut mit 0- bis 2-facher Variation des Statorwiderstands - mit und ohne Last. Für höhere Geschwindigkeiten sinkt die Empfindlichkeit des Flussbeobachters gegenüber Abweichungen des Statorwiderstands.

Auf Grundlage von Strom-Überabtastung und Techniken der Signalverarbeitung wird mittels eines Delta-Sigma-Modulators eine hohe Auflösung der digitalen Strom-Signale erreicht. Daher ist eine geringere HF Strom-Antwort bereits hinreichend, um Methoden der injektionsbasierten geberlosen Regelung zu implementieren. Dies kann sich ebenfalls in einem abgeschwächten akustischen Geräuschpegel, verringerten Verlusten und kleineren Störungen auf das System auswirken. Mit dem entworfenen FPGA-Controller konnte die Injektion im Vergleich zu einem Standardsystem auf ein Drittel reduziert werden.

Für den EKF-basierten geberlosen Beobachter wurde ein interessantes Ergebnis gefunden. Es zeigt sich, dass die Wahl des Koordinatensystems verschiedene starke Einflüsse auf die Implementierung hat, vor allem auf die Implementierung in FPGAs. Beispielsweise kann der der weit verbreitete, vereinfachte rotorfeste EKF-Beobachter nicht richtig funktionieren. Dieses Problem kann unmittelbar bei der Implementation mit der FPGA-basierten Festkomma-Arithmetik gefunden werden. Deshalb wird in der vorliegenden Arbeit ein Ansatz mit einem hybriden rotorfesten

Modell beschrieben, um dieses Problem zu lösen.

Eine nichtlineare Modellprädiktive Regelung mit kontinuierlicher Stellgröße (CS-NMPC) für PMSM-Antriebe wird vorgeschlagen. Die Berücksichtigung von Nichtlinearitäten und Beschränkungen ist leicht. Daher hat die Regelung nicht nur eine hohe transiente Dynamik, sondern auch hervorragende Eigenschaften im stationären Zustand. Darüber hinaus ist die Kombination geberloser Verfahren sehr einfach.

Eine modellbasierte Entwurfsmethodik (MBD) für FPGA-basierte Antriebsregelsysteme wird vorgestellt. Mittels Matlab / Simulink und HDL Coder werden die Motorregelung und geberlose Regelverfahren konzipiert und in einem einzigen FPGA-Chip implementiert. Basierend auf der schnellen und parallelen Verarbeitung von FPGAs werden geberlose Regelalgorithmen ohne Auswirkungen auf die Ausführung der übrigen Regelalgorithmen implementiert. Die Leistungsfähigkeit der geberlosen Regelung wird aufgrund der hohen Abtastfrequenz und niedrige Anregungszeit erreicht. Es ist anzunehmen, dass in naher Zukunft FPGAs der Kern von Antriebregler-Plattformen werden und dass die in dieser Arbeit vorgestellte MBD für FPGA-basierten Reglerentwurf mehr Aufmerksamkeit gewinnen wird.

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