Center for Embedded Systems (CES)
Request for Proposals Template – YEAR 6

DUE: Monday, March 31, 2014, by 5 p.m.

TITLE:	Optimized Switching Pattern Generator Embedded into an SoC				
PI:	Constantine J. Hatziadoniu	**EMAIL:**	hatz@siu.edu	**TEL:**	(618) 453-7036
DEPT:	ECE	**SCHOOL:**	SIUC		

ABSTRACT: (250 OR FEWER WORDS)

The project will be the continuation of a previous project funded by the I/UCRCES under the title: 'Ground Work for Embedding a Field Oriented Motor Controller (FOC) into a Single System on a Chip', 2012-13. The previous project developed and integrated FOC into a SoC applicable to motor drives of the PM type. The new project proposes to embed an optimized switching pattern generator (SPG) for the inverter gates. The SPG will generate the gating signals for the inverter valves in order to minimize the harmonic output of the inverter, especially at operations with a high modulation index. The project will investigate the design and implementation of such generator using the system-on-chip (SoC) approach. The proposed SPG will be integrated into the SoC along with the already developed elements of the FOC thereby providing a complete integrated system for the control of the PM motor. The project will benefit the industry because it will significantly reduce the size of filter components, which are otherwise needed to deal with increased harmonic and EMI at the output of the inverter.

PROBLEM:

The project proposes to embed an optimized switching pattern generator (SPG) into the field-orienting controller (FOC) of permanent magnet (PM) motors. The SPG will generate the gating signals for the (3-phase) inverter valves in order to minimize the harmonic output of the inverter, especially at operations with a high modulation index. The project will investigate the design and implementation of such generator using the system-on-chip (SoC) technology. The proposed SPG will be integrated into the SoC along with the already developed elements of the FOC thereby providing a complete integrated system for the control of the PM motor.

RATIONALE:

This project will be the continuation of a previous project funded by the I/UCRCES under the title: 'Ground Work for Embedding a Field Oriented Motor Controller into a Single System on a Chip', 2012-13. This project developed and integrated a FOC including a resolver-to-digital converter (RDC) into a SoC. The sensor/controller system is applicable to motor drives of the PM type. The output of the SoC provides the gating logic to an inverter that drives the PM motor. The switching algorithm is based on the conventional sinusoidal PWM method.

Sinusoidal PWM generates an inverter output of multiple switching transitions. In the linear modulation region, the harmonic output of the inverter contains (in addition to the fundamental) high order harmonics at frequencies near the carrier and its multiples. The lower region of the spectrum is empty. In operation during over-modulation (non-linear modulation), the number of pulses in the output waveform decreases. As a result, harmonics of significant magnitude begin to occupy the lower frequency of the inverter output spectrum [1]. Lower order harmonics are much more difficult to filter and they require inductive filters to be added in series with the inverter ac terminals. Inductive filters increase the size of the drive. Therefore, in applications where compactness is important, reducing the harmonic content of the inverter output, especially in the over-modulation operation, can significantly impact the overall size as well as the quality of the drive.

APPROACH:

There are a number of approaches in the literature that deal with optimizing the inverter output under a low switching frequency [1], [2], [3], [4], [5]. The most prominent of these methods is the sigma/delta modulation expanded in [1], [2], [3].

The principle of the sigma/delta modulation is shown in fig. 1. A sinusoidal signal is compared to a triangular carrier with constant up and down slopes. The comparison is done within a fixed window. The comparison generates the gate signals of the inverter [1]. An analogue circuit for the implementation of the scheme is shown in fig. 2 [1].

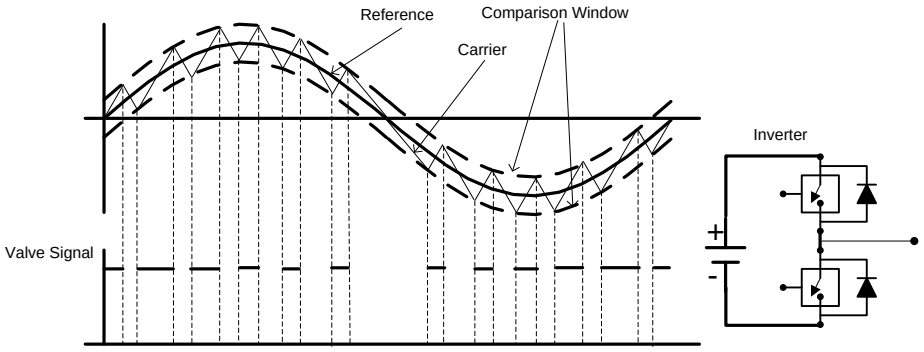

Fig. 1: Synthesizing a Delta modulated inverter output [1], [2]

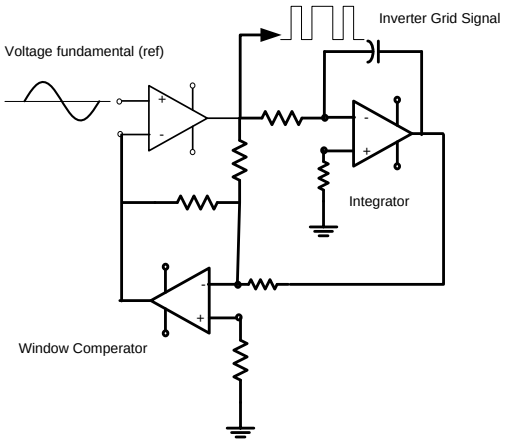

Fig. 2. Analogue implementation of the sigma/delta modulator, after [1].

The scheme is suitable for drives operating in the constant V/Hz mode (i.e. constant flux). The switching frequency of the scheme is constant as long as the frequency of the reference signal is below an upper limit. The output harmonics concentrate on bands around the switching frequency and its multiples. The advantage of the sigma/delta modulation over the conventional sinusoidal PWM method is that it provides a smoother transition of the lower order harmonics as the drive frequency increases and the inverter operation moves into the single-pulse operation (e.g. over-modulation). Therefore it extends the harmonic quality achieved in the linear modulation region to a portion of the over-modulation region. In addition, it provides a constant V/Hz ratio necessary for the variable speed drive [1].

Variations of the sigma/delta method include a reference model (e.g. an inductive circuit or its equivalent to represent the PM motor stator) [3]. The reference model is driven by the gating signals (from each of the three phases). The model output is compared to a sinusoidal reference representing the motor current. Subsequently, the error generates a constant frequency PWM gating signal of high order harmonics. This method, in addition to

optimizing the harmonic output of the inverter, it also provides indirect constant current operation enhancing the motor protection.

The above methods use deterministic switching resulting in periodic waveforms. Therefore the inverter output spectrum contains discrete lines: that is, high power density concentrates in a narrow BW. Even with a significant elimination of low harmonic orders, therefore, a significant EMI problem may exist at the high frequency orders, requiring additional filtering [6]. Randomized switching has been proposed to mitigate some of these problems [4], [5]. Randomized switching produces a quasi-periodic inverter output. In turn, the harmonic power spreads over a wider BW.

The proposed project will design an optimized SPG based on a combination of the above techniques. Modeling of the entire drive system under the proposed SPG will be done in MATLAB in order to simulate the harmonic response of the inverter and fine-tune the design. The optimized SPG will be integrated into the SoC previously design to complete the drive control. The final result will be a standalone compact controller suitable for PM motor drives.

NOVELTY:

The proposed project will result in a complete motor drive controller integrated into a SoC. The novelty of the proposed project is in the investigation of suitable switching patterns within the constraints imposed by the present SoC technology and the all-digital implementation of the algorithms.

POTENTIAL BENEFITS TO INDUSTRY MEMBERS:

The proposed project will result in significant reduction of hardware, which is needed to filter current harmonics from the motor. In addition, this project will complete the previous effort to produce a complete integrated drive controller into the SoC, which further reduces the hardware requirements compared to similar schemes using discrete and analogue components.

DELIVERABLES:

The project deliverables are:
1. An optimized SPG based on combining delta modulation with randomized modulation techniques;
2. Integration of the SPG into the previously developed SoC including the complete controller of a PM motor.

TIMELINE/MILESTONES: (PER QUARTER)

Term	Deliverable
August-December	Research and design of the SPG
December-January	Integration of SPG into the SoC

TECHNOLOGY TRANSFER:

The previous project developed a FOC integrated into the SoC. The results of this proposed project will be transferred directly to the existing SoC at the SIUC site.

BUDGET:

The project requests $25k for the entire duration. The funds will support a graduate student and half of a month salary for the PI.

BIBLIOGRAPHY: (ATTACH IN IEEE CONFERENCE OR JOURNAL FORMAT)

[1] P. D. Ziogas, “The Delta Modulation Technique in Static PWM Inverters,” *Ind. Appl. IEEE Trans. On*,

vol. IA-17, no. 2, pp. 199–204, Mar. 1981.
[2] G. Joos and P. D. Ziogas, "On maximizing gain and minimizing switching frequency of delta modulated inverters," *Ind. Electron. IEEE Trans. On*, vol. 40, no. 4, pp. 436–444, Aug. 1993.
[3] G. Joos, P. D. Ziogas, and D. Vincenti, "A three phase model reference adaptive PWM technique with improved features," in *Industry Applications Society Annual Meeting, 1990., Conference Record of the 1990 IEEE*, 1990, pp. 997–1004 vol.2.
[4] A. M. Stankovic, G. C. Verghese, and D. J. Perreault, "Analysis and synthesis of randomized modulation schemes for power converters," *Power Electron. IEEE Trans. On*, vol. 10, no. 6, pp. 680–693, Nov. 1995.
[5] B. Jacob and M. R. Baiju, "Spread spectrum modulation scheme for multilevel inverters using vector quantized sigma delta modulation," in *Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE*, 2012, pp. 2428–2435.
[6] K. Mainali and R. Oruganti, "Conducted EMI Mitigation Techniques for Switch-Mode Power Converters: A Survey," *Power Electron. IEEE Trans. On*, vol. 25, no. 9, pp. 2344–2356, Sep. 2010.

PI INFORMATION: (ATTACH 2-PAGE CV)

CONSTANTINE J. HATZIADONIU, Professor, hatz@siu.edu
Electrical and Computer Engineering at Southern Illinois University
1230 Lincoln Dr.
Carbondale, IL 62901-6603

Education

Diploma in Electrical Eng., University of Patras, Greece, 1983
Ph.D. in Electrical Eng., West Virginia University, Morgantown, 1987

Professional Experience

- Professor of Electrical and Computer Engineering, Southern Illinois University Carbondale. Sept 1987-present.
- Teaching and Research Assistant. Department of Electrical Engineering, West Virginia University, Morgantown. August 1984-1987.
- Consulting engineer, Greece. August 1983-1984.

Research Interests

Power electronics, Energy harvesting devices, wind and photovoltaic energy systems, power system modeling and simulation; power system control and protection.

Recent Publications.

Hany A. Abdelsalam and **C.J. Hatziadoniu**, "A Robust Wide Area Controller of Multiple FACTS for Damping Oscillations in Multi-Area Power System Using the H∞ Method", Power System Conference 2011 PSC11, March 15-18, 2011 at Clemson University, Clemson, SC, USA.

A. Albanna and **C.J. Hatziadoniu**, 'Harmonic Modeling of Hysteresis Inverters in the Frequency Domain', IEEE Trans. on Power Electronics, Vol. 25, No 5, May 2010, pp.1110-4.

Ahmad Albanna, **C.J. Hatziadoniu**, "Harmonic Modeling and Analysis of Multiple Residential Photo-Voltaic Generators", Power and Energy Conference, University of Illinois Urbana-Champaign, February 2010.

Ahmed Albanna, **C.J. Hatziadoniu**, "Harmonic Modeling of Three-Phase Neutral-Point Inverters", Proceedings of the 2009 North American Power Symposium, Mississippi State University, Starkville, MS, Oct 4-6, 2009.

Ahmed Albanna, **C.J. Hatziadoniu**, "Harmonic Modeling of Single-phase Three-level Hysteresis Inverters", Proceedings of the 2009 North American Power Symposium, Mississippi State University, Starkville, MS, Oct 4-6, 2009.

C.J. Hatziadoniu, N.B. Harp, and A.J. Sugg, "Finite-Element Models for Open-Air Power Lines in Broadband PLC", IEEE Trans. On Power Delivery, Vol. 21, No. 4, Oct. 2006, pp. 1898-1904.

F. Pourboghrat, F. Farid, C.J. **Hatziadoniu**, M. Daneshdoost, F. Mehdian, M. Lotfalien, "Local Sliding Control for Damping Inter-Area Power Oscillations", IEEE Trans. On Power Systems, PES 19-2, May 2004, pp. 1123-34.

G. Chang, **C.J. Hatziadoniu**, W. Xu, P. Ribeiro, R. Burch, W.M. Grady, M. Halpin, Y. Liu, S. Ranade, D. Ruthman, N. Watson, T. Ortmeyer, J. Wikston, A, Medina, A. Testa, R. Gardinier, V. Dinavahi, F. Acram, P. Lehn, "Modeling Devices with nonlinear Voltage-current Characteristics for harmonic studies", IEEE Trans. On Power Delivery, Vol. 19, No. 4, Oct. 2004, pp. 1802-11.

Synergetic Activities.

- "Pilot Study of Energy Harvesting Devices towards the Development of a Prototype", (PI C.J. Hatziadoniu, Co-PI Tsuchin Chu and Fran Harackiewicz), NSF, I/UCRC for Embedded Systems August 2012-August 2013.
- "Resolver Sensor Conditioning Size Reduction", (PI C.J. Hatziadoniu, Co-PI W. Haibo), NSF, I/UCRC for Embedded Systems, August 2012-August 2013.
- "Distribution System Modeling for Power Line Communication", Research grant, AMEREN-UE, 2001-2002.
- "Software for the optimum operation and planning of high-data rate PLC Systems", Research grant, AMEREN-UE 2003-04.
- "Workstation Computer Program for Insulation Coordination of ac and dc Substations"
- Research grant (EPRI 1989-1992), RP 2323, with G.D. Galanos and M. Daneshdoost.
- "Advanced Voltage Systems", Research grant (EPRI 1990-1992), RP 4000-22, with G.D. Galanos and F. Pourboghrat.
- "Faraday's Law Electric Machine Laboratory", Equipment grant (NSF 1991), with G.D. Galanos, V. Feiste and M Daneshdoost.

Collaborators and Other Affiliations.

Collaborators: D. Takach, Ameren UE, Saint Louis, Missouri.
Graduate Advisor: Dissertation Advisor: G.D. Galanos, Department of Electrical and Computer Engineering, SIUC.
Thesis and Dissertation Advisor (recent): A. Albana (PhD), H. Ahmed (PhD), Dler Dler (MS), H. El-Hadji (MS), D. Schleeper (MS).

I/UCRC Executive Summary - Project Synopsis		Date: March 31, 2014
Project Title: Optimized Switching Pattern Generator Embedded into an SoC		
Center/Site:SIUC		
Principle Investigator: Constantine J. Hatziadoniu		**Type: (Continuing)**
Tracking No.: (CES office to input)	**Phone (618) 453-7036**	**E-mail: hatz@siu.edu**
		Proposed Budget: $25,000

Abstract: The project will be the continuation of a previous project funded by the I/UCRCES under the title: 'Ground Work for Embedding a Field Oriented Motor Controller (FOC) into a Single System on a Chip', 2012-13. The previous project developed and integrated FOC into a SoC applicable to motor drives of the PM type. The new project proposes to embed an optimized switching pattern generator (SPG) for the inverter gates. The SPG will generate the gating signals for the inverter valves in order to minimize the harmonic output of the inverter, especially at operations with a high modulation index. The project will investigate the design and implementation of such generator using the system-on-chip (SoC) approach. The proposed SPG will be integrated into the SoC along with the already developed elements of the FOC thereby providing a complete integrated system for the control of the PM motor. The project will benefit the industry because it will significantly reduce the size of filter components, which are otherwise needed to deal with increased harmonic and EMI at the output of the inverter.

Problem: The project proposes to embed an optimized switching pattern generator (SPG) into the field-orienting controller (FOC) of permanent magnet (PM) motors. The SPG will generate the gating signals for the (3-phase) inverter valves in order to minimize the harmonic output of the inverter, especially at operations with a high modulation index. The project will investigate the design and implementation of such generator using the system-on-chip (SoC) technology. The proposed SPG will be integrated into the SoC along with the already developed elements of the FOC thereby providing a complete integrated system for the control of the PM motor.

Rationale / Approach: The rational of the project is minimize the harmonics of the motor drive by designing a optimum switching pattern for the inverter. The proposed optimized SPG will be based on a combination of the techniques including sigma/delta modulation and spread spectrum modulation. Modeling of the entire drive system under the proposed SPG will be done in MATLAB in order to simulate the harmonic response of the inverter and fine-tune the design. The optimized SPG will be integrated into the SoC previously design to complete the drive control.

Novelty: The proposed project will result in a complete motor drive controller integrated into a SoC. The novelty of the proposed project is in the investigation of suitable switching patterns within the constraints imposed by the present SoC technology and the all-digital implementation of the algorithms.

Potential Member Company Benefits: The proposed project will result in significant reduction of hardware, which is needed to filter current harmonics from the motor. In addition, this project will complete the previous effort to produce a complete integrated drive controller into the SoC, which further reduces the hardware requirements compared to similar schemes using discrete and analogue components.

Deliverables for the proposed year: The project deliverables are:

1. An optimized SPG based on combining delta modulation with randomized modulation techniques;
2. Integration of the SPG into the previously developed SoC including the complete controller of a PM motor.

Milestones for the proposed year: The proposed project will produce a standalone controller integrated into an SoC for the permanent magnet motor.

Progress to Date: **THIS SECTION TO BE UPDATED IN JANUARY**

Estimated Start Date: August 18, 2014	**Estimated Knowledge Transfer Date**: May, 2015