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36th Cycle

Limit-Cycle Free Digitally Controlled Power Converters and Innovative Design of a Capacitive Wireless Power Transfer Circuit

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Research context and motivation

❖ **Limit-cycle Free, Digitally Controlled Boost Converter based on DDPWM**

- Digital controllers are more prevailing in switching-mode power converters
- flexibility, reliability, good performance, low cost and reduced susceptibility to aging.
- Boost converter used in photovoltaic systems, in battery powered and portable device applications

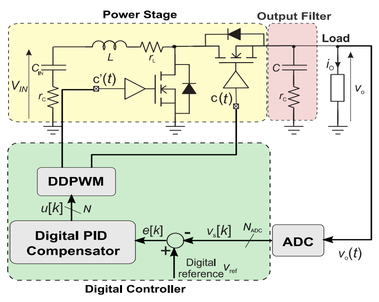
Spectral characteristics of DDPM

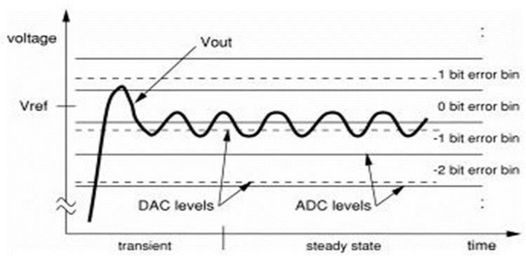
i. baseband digital-to-analog (D/A) conversion
ii. digital-based operational transconductance amplifiers
i. analog-to-digital (A/D) conversion
ii. digitally-controlled power converters
iii. DDPM is area and power-efficient all-digital hardware implementation

- Limit-cycle Oscillations (LCOs)

To remove LCOs, $N_{DDPM} > N_{ADC}$

a) Requires high clock frequency
b) Limited DC accuracy.





➢ Given $f_{clk} = 5$ MHz, $f_{sw} = 100$ kHz *limit to* $N_{ADC} \leq 5$ bits — *NOT ACCEPTABLE* DC accuracy for most cases

➢ Or, conversely $f_{sw} \approx 10$ MHz range *requires* $f_{clk} > 2$ GHz — *IMPRACTICALLY high* clock frequency
$N_{ADC} \geq 8$ bits DC accuracy

❖ **Design and efficiency analysis of an LCL capacitive power transfer system with load-independent ZPA**

- Capacitive based wireless Power Transfer CPT

References:
[1] M. Usmonov, P. S. Crovetti, F. Gregoretti and F. Musolino, "Suppression of Quantization-Induced Limit Cycles in Digitally Controlled DC-DC Converters by Dyadic Digital Pulse Width Modulation," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 2224-2231, doi: 10.1109/ECCE.2019.8913214.
[2] P. S. Crovetti, M. Usmonov, F. Musolino and F. Gregoretti, "Limit-Cycle-Free Digitally Controlled DC–DC Converters Based on Dyadic Digital PWM," in IEEE Transactions on Power Electronics, vol. 35, no. 10, pp. 11155-11166, Oct. 2020, doi: 10.1109/TPEL.2020.2978696.

Addressed research questions/problems

❖ **Limit-cycle Free, Digitally Controlled Boost Converter based on DDPWM**

- Sigma-Delta (Σ-Δ) modulation, multiphase PWM, digital thermometric dithering (DTD)
- Dyadic digital PWM (DDPWM)

a) DDPWM is implemented on FPGA
b) effective for LCO-free operation in a buck converter

➢ Buck converter $V_o = V_{in}.D$, while boost converter $V_o = V_{in}/(1-D)$

So, finer quantization steps at lower duty-cycle and coarser steps as duty-cycle increases.

❖ **Software-defined DDPM Modulators in General Purpose Microcontrollers**

- Significant attention to digital HW implementation
- SW implementation in a microcontroller HW has not been specifically addressed

❖ **LCL capacitive power transfer system with load-independent ZPA**

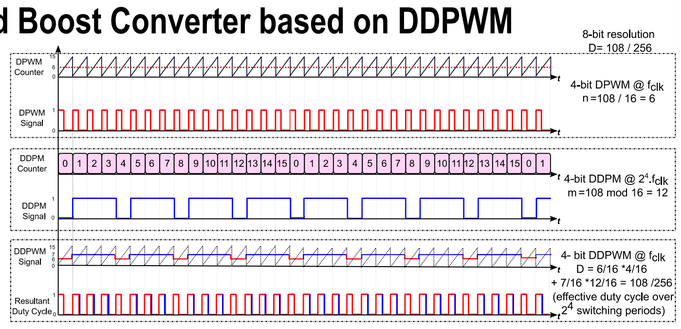
- desirable feature in battery charger is the zero-phase angle (ZPA)
- ZPA operation must be load independent

Novel contributions

❖ **Limit-cycle Free, Digitally Controlled Boost Converter based on DDPWM**

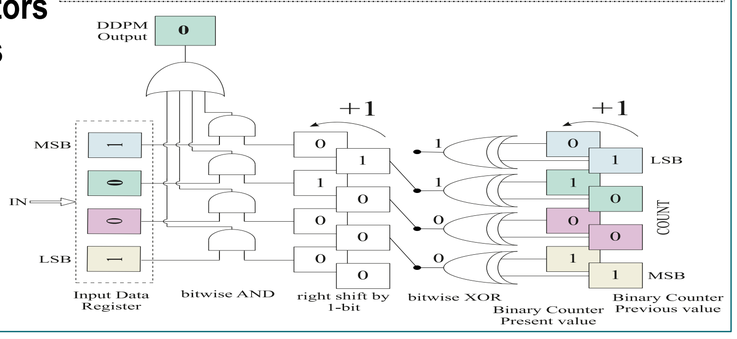
Dyadic Digital Pulse Width Modulation

- New and deterministic approach
- Effectively increase the DPWM resolution
- Spurious spectra pushed at high frequency



❖ **Software-defined DDPM Modulators in General Purpose Microcontrollers**

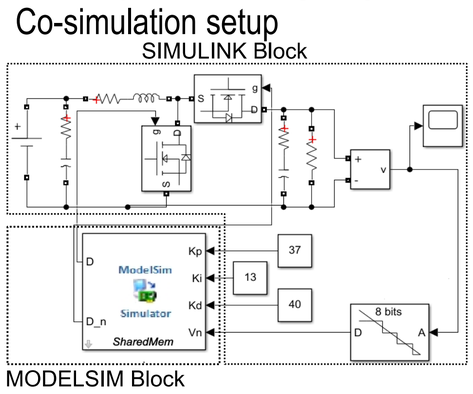
- New DDPM modulator architecture
- amenable to SW implementation on microcontroller.
- Compared to SW architecture resulting from straightforward translation of HW implementation.



Adopted methodologies & Results

❖ **Limit-cycle Free, Digitally Controlled Boost Converter based on DDPWM**

- Co-simulation setup

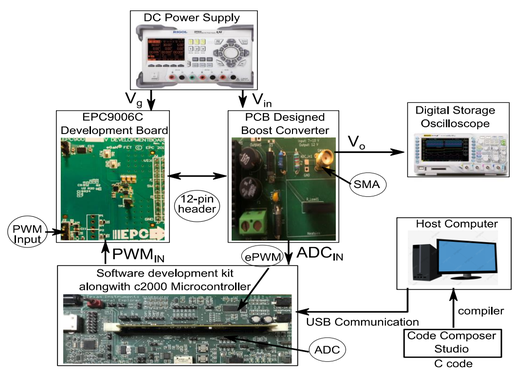


- Design Specifications

Param.	Val.	Unit	Param.	Val.	Unit
C_o	3	uF	V_{in}	7-10	V
R_L	25-30	Ω	V_O	13.8	V
L	900	nH	f_{sw}	1.17	MHz

- Experimental Test Setup

i. C2000 microcontroller board with onboard ADC and PWM modules
ii. Algorithm is programmed in C-language
iii. PCB designed boost converter
iv. EPC9006C board

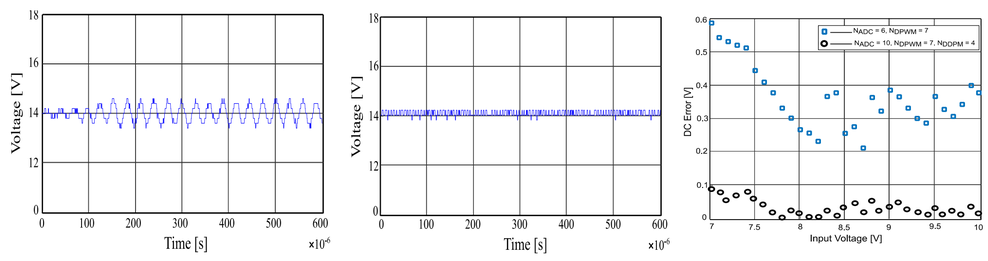


- Results

i. No LCOs

$N_{Adc} = 5, N_{DPWM} = 4$
$N_{Adc} = 5, N_{DDPWM} = 8$

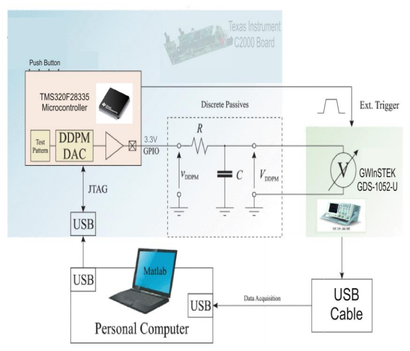
i. DC accuracy



❖ **Software-defined DDPM Modulators in General Purpose Microcontrollers**

- Experimental Test Setup

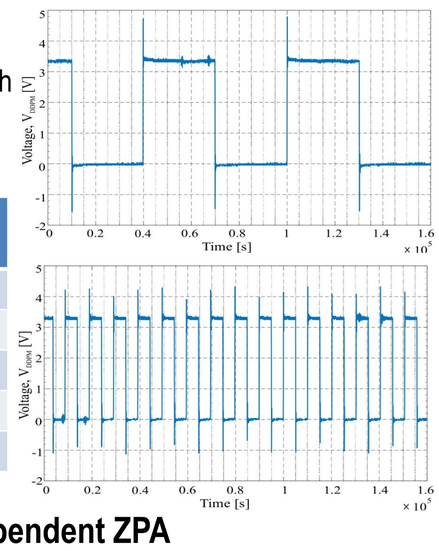
i. 8-bit DDPM DAC on c2000 microcontroller
i. low-pass RC filter



- Results

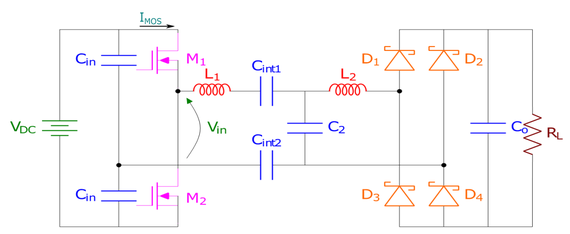
i. Maximum Pulse time graph
ii. Static characteristics
iii. Dynamic characteristics

Param.	Unit	Prop. DDPM	Iter. DDPM
INL	LSB	1.64	2.8
DNL	LSB	1.79	3.53
SNDR	dB	45.27	41.61
SFDR	dB	47.02	45.16
ENOB	Bit	7.23	6.62

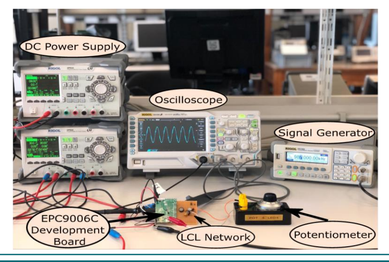


❖ **LCL capacitive power transfer system with load-independent ZPA**

- Schematic and Experimental test setup

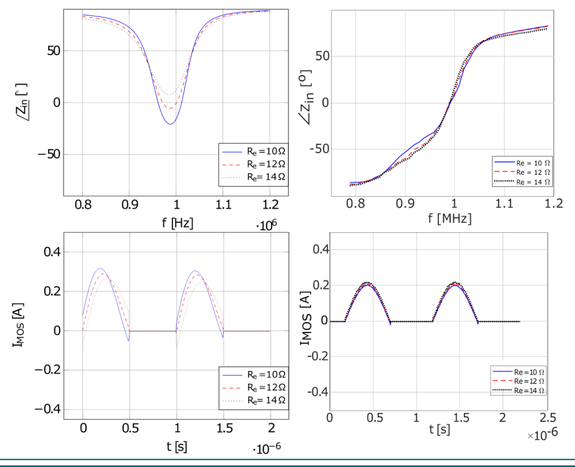


Comp.	Value
L_1	470 uH
L_2	10 uH
$C_{int1,2}$	100 pF
C_2	2.7 nF



- Results

Load-independent ZPA



Future work

❖ **Limit-cycle Free, Digitally Controlled Boost Converter based on DDPWM**

- In preparation to be submitted to IEEE Access
- Expand the research in the digitally controlled converter to limit the onset of LCOs

❖ Thesis writing and attend courses

❖ Collaborate with Prof. Francesco Musolino in conducting Power Electronics Lab

Submitted and published works

- A. Abdullah, F. Musolino and P. Crovetti, "Software-Defined DDPM Modulators for D/A Conversion by General-Purpose Microcontrollers," in IEEE Access, vol. 10, 2022, pp. 17515-17525
- P. Crovetti, R. Rubino, A. Abdullah and F. Musolino, "Emerging Relaxation and DDPM D/A Converters: Overview and Perspectives," 2022 IEEE 65th International Midwest Symposium on Circuits and Systems (MWSCAS), 2022, pp. 1-6
- Francesco Musolino, Ahmed Abdullah, Mario Pavone, Fabio Ferreyra, Paolo Crovetti, "Design and efficiency analysis of an LCL Capacitive Power Transfer system with Load-Independent ZPA," EPE'22 ECCE Europe, 2022
- A. Abdullah, F. Musolino and P. Crovetti, "Limit-Cycle Free, Digitally-Controlled Boost Converter based on DDPWM," in IEEE Access (to be submitted)

List of attended classes

- 01DNZRV – Emerging Ultra-low Voltage, Ultra-low Power Analog and Mixed-Signal Integrated Circuits for the IoT (06-22, 4)
- 01RGBRV – Optimization methods for engineering problems (07-06-22, 6)
- 01DMQRV – Power electronics for grid applications (06-22, 4)
- 08IXTRV – Project management (04-22, 1)
- 01QAAAA – Public speaking (04-22, 1)

Politecnico di Torino

PhD program in
Electrical, Electronics and Communications Engineering