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研究課題名（和文）Energy-efficient lightweight drives by multi-parametric machine-inverter co-design and split-mid-point modularization

研究課題名（英文）Energy-efficient lightweight drives by multi-parametric machine-inverter co-design and split-mid-point modularization

研究代表者
カステッラッズィ　アルベルト（Castellazzi, Alberto）

京都先端科学大学・工学部・教授

研究者番号：70866897

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研究成果の概要（和文）：この研究により、合計 10 件の論文が専門の国際会議や雑誌に投稿されました。 研究成果のハイライトとしては、高出力密度モーターのプロトタイピングが挙げられます。 電圧昇圧機能と優れた高調波特性を備えた高周波高効率インバーターのデモンストレーション。 損失を削減するための有効半導体面積の負荷依存変化を備えた分割ミッドポイントモジュラーインバーター設計のデモンストレーション。 パラメトリック マシンとインバーターの共同設計により、運転サイクル全体にわたるモーター ドライブのエネルギー効率を最適化します。

研究成果の学術的意義や社会的意義
Electric motor drives make up for over 90% of all power electronics applications. They are pivotal elements of society infrastructure. Integrated design enables new development paradigms, improved performance, power density and reliability, which open the path towards new deployment opportunities.

研究成果の概要（英文）：The research produced a total of 10 papers submitted to specialist international conferences and journals. Highlights of research achievements include: prototyping of a high power-density motor; demonstration of high-frequency high-efficiency inverter with voltage boost capability and excellent harmonic signature; demonstration of split-mid-

研究分野：Electrical Engineering - Power electronics

キーワード：Y-Inverter　WBG semiconductors　High power-density　Multi-level inverters

１．研究開始当初の背景

Many pivotal elements of societal infrastructure increasingly rely on electric motor drives. A key example is transportation, where, next to trains and automobiles, new strategic developments such as *drones* are also taking place. The input power source is DC (e.g., a battery) and an inverter is used to synthesize the AC supply required on the machine side; a filter is inserted between inverter and machine to extract a sinusoidal current and suitably operate the machine. To achieve low energy consumption and good operational range electric motor drives must be efficient and lightweight. However, joint achievement of these targets is non-trivial due to conflicting underlying technical requirements. Previous research has targeted the machine or the inverter independently, producing some punctual incremental progress, but leaving broader key scientific aspects still to be addressed and major progress to be achieved.

２．研究の目的

Given motor type and inverter topology, design optimization can exploit:

- number of levels (N_L): higher inverter N_L yields voltage waveforms closer to pure sinus, reducing filter size/weight and improving machine efficiency due to better harmonics; however, it typically implies lower inverter efficiency due to larger switch number;
- switching frequency (f_s): higher f_s reduces filter size/weight and losses in the machine, but adversely impacts inverter efficiency;
- heat-sink/iron temperature (T_{HS}):, depending on f_s, higher T_{HS} reduces heat-sink and machine size (natural convection is assumed), but inverter losses increase;
- DC voltage (V_{DC}): higher V_{DC} enables lower currents for given power, reducing ohmic losses and weight of harness; but depending on f_s, filter size increases. V_{DC} also affects battery size and weight;
- machine rotational speed (ω_R) and pole numbers (n_P): higher ω_R and n_P increase power density; both require higher f_s to keep good efficiency.

Wide-band-gap (WBG) transistors (silicon carbide, SiC MOSFETs; gallium nitride, GaN HEMTs) are replacing silicon (Si) ones in many applications, because they enable higher f_s, T_{HS} and power density without efficiency degradation at nominal load. But inverter switching losses dominate at low load and efficiency can drop significantly, even for modest f_s increase. Typical operation is at high load for short times, most of the time it is at low load. So, the most meaningful figure-of-merit is *energy efficiency*, as opposed to *power* efficiency (i.e., the losses time-integral); it emerges that the highest energy waste is due to the *prevalent load*, not the *highest* load. Low-load efficiency also requires innovative dedicated design solutions at machine level. The scenario described applies to all novel and upcoming motor drive applications, which draw benefits from WBG technology, including trains, aircraft, hybrid/electric cars, industrial drives, renewable energies, air conditioners. The overall cumulated waste from all these applications can be a very important fraction of the total energy usage in a given region or country; optimized design can yield important environmental benefits. However, presently, no comprehensive unified theory exists for optimum machine-inverter co-design and the methodology_focuses on peak load and power efficiency. So, the ambition of this research is to: develop an integrated parametric machine-inverter design framework, including validation by experiment; demonstrate a new modular inverter assembly approach, which enables for low-load efficiency boost, reduction of energy waste and better input source exploitation and operational range.

３．研究の方法

The project main aims are achieved by a series of intermediate objectives, mapped into interrelated Work-Packages and Tasks, outlined below.

WP1-Design delivers optimum machine-inverter co-design, simulation models, technical drawings.

WP2-Prototyping delivers functional prototypes of machine and inverter.

WP3-Control delivers fully functional validated control strategy, software and hardware platform, including sensor boards and interfaces.

WP4-System delivers validation of parametric design framework and modularization by quantitative efficiency-power density data.

WP5-Management delivers timely achievement of stated objectives and high-profile dissemination, in major scientific journals and conferences.

４．研究成果

1) For the machine, an *outer rotor Halbach* permanent magnet (PM) motor type (3 phases) was considered, with target power density higher than 5 kW/kg and rotational speed higher than 6000 rpm. In consideration of heat generation, a design relying on higher voltage and reduced current was challenged. Fig. 1 shows the first machine prototype, which features a reduction of 50% weight and volume as compared to a similarly rated induction machine designed for the same input voltage considered here.

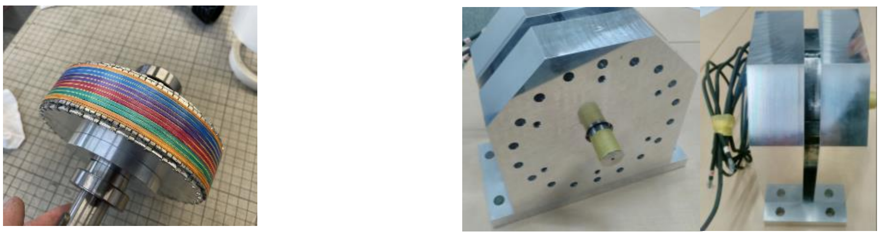


Fig. 1: outer rotor Halbach motor prototype

2) Correspondingly, the inverter was high-frequency high-voltage (WBG based, SiC MOSFETs and GaN HEMTs), featuring an innovative topology and modular assembly concept (Y-Inversion), capable also of output-to-input voltage amplitude boosting. Thus, a high voltage machine can be driven even from a relatively small input DC source. The key performance data are reported in Fig. 2 and correspond to important progress beyond state-of-the art.

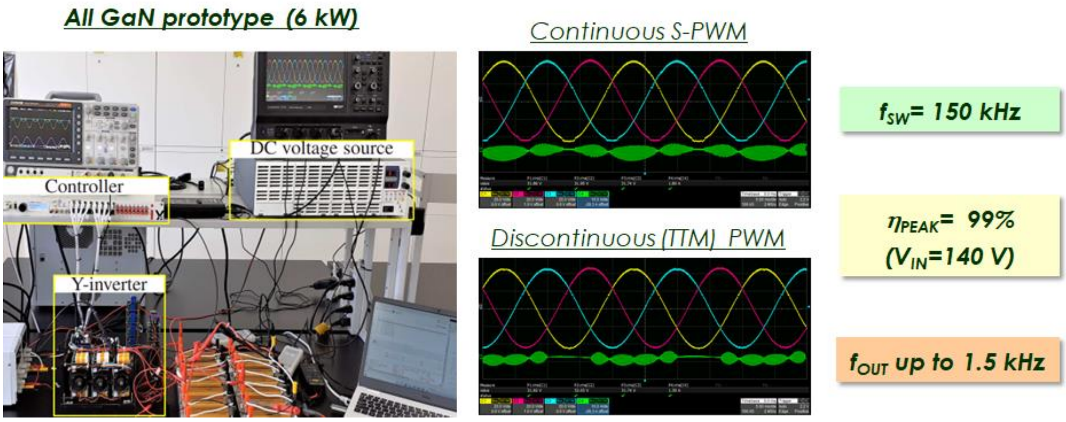
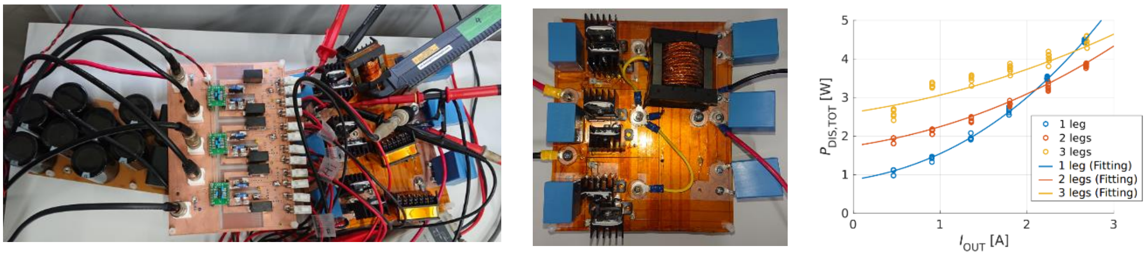
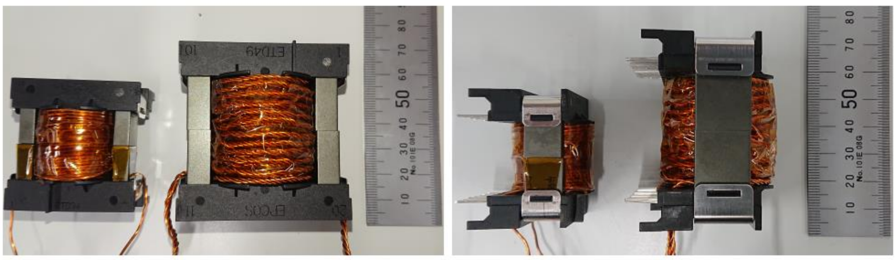


Fig. 2: GaN Y-Inverter test-bench setup, representative current and voltage experimental waveforms and key performance results.

3) Split-Mid-Point modular design of a conventional square-wave modulated inverter was also demonstrated to yield improved performance, without penalty on power density. A load dependent switching strategy to vary the equivalent semiconductor area during inverter operation was also demonstrated.



(a)



(b)

Fig. 3: (a) two level inverter phase implemented with 3 SMP connected legs, showing load-dependent change in performance in dependence of the number of legs used; (b) relative volume of split and lumped inductors.

4) Finally, important new knowledge and understanding in the parametric co-design of machine and inverter was generated by means of an integrated design framework, with an estimate to reduce energy consumption over a reference driving cycle of up to 20% in a 400V motor drive system and about 8% in an 800 V one, using a SiC MOSFET 3L ANPC inverter as the reference topology. Experimental demonstration focused on the inverter, tested under two different operational points in a driving cycle (low-speed high-torque and high-speed low-torque). The results indicated that overall performance can be optimized by implementing *hybrid* functional solutions (e.g., usage of multiple modulation strategies depending on the operational point).

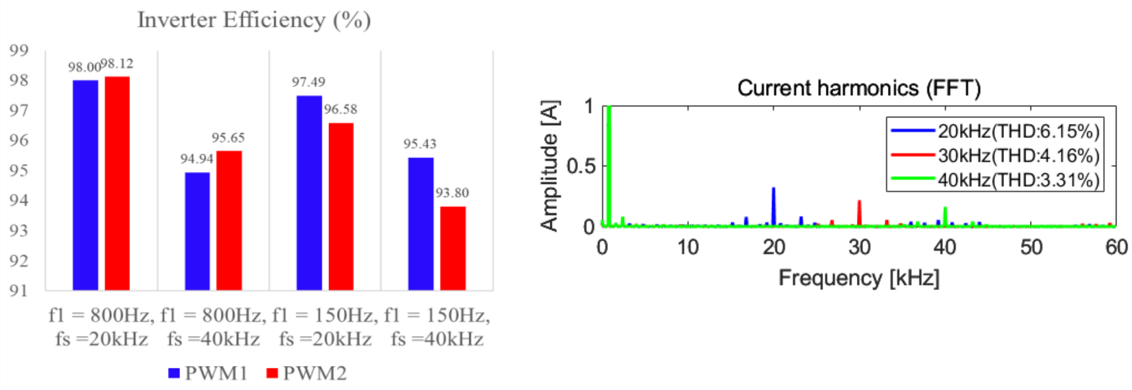


Fig. 4: Experimental results of 3L-ANPC SiC inverter modulated with two different PWM strategies under different operational conditions: left, efficiency; right, harmonic signature, indicative of potential motor losses.

The project resulted in a total of 10 papers in specialist international conferences and journals, presented by post-doctoral researchers, PhD students and UG students.

５．主な発表論文等

〔雑誌論文〕　計0件

〔学会発表〕　計8件（うち招待講演　0件／うち国際学会　8件）

１．発表者名 J. Kwak, A. Castellazzi
２．発表標題 Energy efficiency driven traction unit design
３．学会等名 EPE-ECCE Europe 2022, Hannover, Germany, Sep. 2022（国際学会）
４．発表年 2021年～2022年

１．発表者名 Y. Shiogai, A. Castellazzi, T. Hikihara
２．発表標題 Characterization and Switching Strategy Development for SMP SiC Power Modules
３．学会等名 IPEC-ECCE Japan 2022, Himeji, Japan, May 2022（国際学会）
４．発表年 2021年～2022年

１．発表者名 T. Dong, J. Kwak, L. Wei, A. Castellazzi, T. Nakamura
２．発表標題 High power-density high-efficiency electric drive design with Halbach-rotor PMSM and WBG-based high-frequency inverter
３．学会等名 ICEMS 2021, Gyeongju, South Korea, Nov. 2021（国際学会）
４．発表年 2021年

１．発表者名 Yu Shiogai, Alberto Castellazzi, Takashi Hikihara
２．発表標題 Split-Mid-Point Modular Design for Low-Load Efficiency Boost in WBG Power Converters
３．学会等名 ECCE Asia 2021（国際学会）
４．発表年 2020年～2021年

１．発表者名
Tran, H.N., Castellazzi, A., Domae, S., Dong, T. and Nakamura, T.

２．発表標題
Low-voltage-battery powered hybrid-GaN/SiC Y-Inverter dual-rotor Halbach motor drive for light electric vehicles.

３．学会等名
ICEMS 2021, Gyeongju, South Korea, Nov. 2021（国際学会）

４．発表年
2020年～2021年

１．発表者名
Jaber, H.J. and Castellazzi, A

２．発表標題
Frequency and Modulation Index Related Effects in Continuous and Discontinuous Modulated Y-Inverter for Motor-Drive Applications.

３．学会等名
EPE-ECCE Europe 2022, Hannover, Germany, Sep. 2022（国際学会）

４．発表年
2022年～2023年

１．発表者名
H. J. Jaber, K. Horie, S. Domae, A. Castellazzi

２．発表標題
Dual switching-frequency hybrid Si-SiC Y-Inverter

３．学会等名
ECCE Asia 2023, Jeju, South Korea（国際学会）

４．発表年
2022年～2023年

１．発表者名
Jaedon Kwak, Alberto Castellazzi

２．発表標題
Parametric Co-design of Machine-Inverter using Wide Band Gap and Three-level ANPC Inverter for 800V Traction System

３．学会等名
ECCE Asia 2023, Jeju, South Korea（国際学会）

４．発表年
2022年～2023年

〔図書〕　計2件

1．著者名	4．発行年
H. Trang, A. Castellazzi, S. Domae, T. Dong, T. Nakamura	2022年
2．出版社	**5．総ページ数**
Light electric vehicle motor-drive design based on hybrid Si/SiC Y-Inverter and dual-rotor Halbach machine	9
3．書名	
Journal of Electrical Engineering & Technology, 18(1)	

1．著者名	4．発行年
Jaedon Kwak, Alberto Castellazzi	2023年
2．出版社	**5．総ページ数**
Electro-thermal stress minimisation of motor-drive inverter switches by hybrid modulation strategy technique	7
3．書名	
Microelectronics Reliability	

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究分担者	中村　武恒 (Nakamura Taketsune) (30303861)	京都大学・工学研究科・特定教授 (14301)	

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関