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BOOK OF ABSTRACTS

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   9th Symposium on Power Electronics
10. 1999 - X Simpozijum Energetska Elektronika - Novi Sad
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FOREWORD

The Power Electronics Conference is celebrating 48 years from its first gathering in Belgrade way back in 1973. This long tradition shows that the power electronics society in Serbia is active and has significant results, valuable worldwide. The first conference was held in the Serbian language as a national one, and 47 papers from all over ex–Yugoslavia had been presented. It introduced the popular title abbreviation ***Ee*** (abbreviated from Serbian name *Energetska elektronika*). The next conferences were held in Belgrade in 1975 with 50 papers, Zagreb in 1978 with 94 papers, Sarajevo in 1981 with 95 papers, Ljubljana in 1984 with 104 papers, Subotica in 1986 with 126 papers, and Belgrade in 1988, with 109 papers.

After a long break, due to unfortunate events in ex-Yugoslavia, Power Electronics revives and continues in 1995 in Novi Sad, with 79 papers. It started as a scientific symposium and with an idea to organize it with an exhibition, so for the venue, the International Fair on Electronics and Informatics had been chosen. The next symposiums were held in Novi Sad – in 1997, with 98 papers, and in 1999, with 82 papers. Significant participation of foreign authors resulted in an upgrade of the symposium into an international one, which in 2001 gathered 107 papers, in 2003 101 papers, in 2005 94 papers, in 2007 101 papers, and 2009 105 papers. From 2011 the symposium is included in the new wider-scope event „Energy Days“ in Master Conference Center of Novi Sad Fair and attracted 102 papers in 2011 and 69 in 2013. The conference changed the venue in 2015 and 71 papers have been presented in the Central Building of the University of Novi Sad. The average number of participants was between 150 and 200 of which a significant portion was students and industry experts.

The 19th International Symposium on Power Electronics Ee 2017 established itself and future symposiums as the top Worlds scientific conferences. It was the first one technically co-sponsored by IEEE Power Electronics Society (PELS) and IEEE Industrial Electronics Society (IES), European Power Electronics (EPE) Association, and the European Centre for Power Electronics (ECPE), as well as by IEEE Serbia and Montenegro Section and IEEE Joint Chapter PELS/IES/IAS of Serbia and Montenegro Section. This strong involvement of IEEE brought changes in the paper review and acceptance process, which were performed according to IEEE standards, so 75 papers and lectures by 248 authors from 29 countries were presented. All presented papers were included in the IEEE Xplore database and cited in Web of Science, Scopus, and Google Scholar. The 20th jubilee symposium continued with IEEE technical sponsorship and gathered in 2019 in Novi Sad 73 papers and lectures, which were written by 235 authors & co-authors from 23 countries.

The 21st International Symposium on Power Electronics *Ee 2021* is the first to be held in virtual form (online) due to the effects of the Covid-19 pandemic. Still, 247 authors from 27 countries (Algiers, Australia, Austria, Bulgaria, Canada, Chile, China, Croatia, Denmark, France, Germany, India, Italy, Montenegro, Nederland, North Macedonia, Paraguay, Poland, Romania, Russia, Serbia, Slovakia, Spain, Switzerland, Turkey, United Kingdom, and the USA) prepared in total 81 papers and lectures (3 invited and 58 top-quality regular papers, 7 Key-notes, 3 invited lectures, 3 industry presentations, 2 tutorials, and 5 papers at national conference). All papers have passed through a double-blind reviewing process by the International Program Committee and technical adjustment by the Secretariat. From 87 submitted, 71 (81%) have been accepted and will be presented in Key-Note, Invited, and Regular sessions. Additionally, two industrial sessions, three distinguished professor lectures, and two tutorials will be organized. I would like to acknowledge the great work of Prof. Petar Grbović, the Technical Chair, who gathered a large team of power electronics experts as topic chairs and reviewers, invited famous key-note speakers and high expert presenters and organized the tutorials, which resulted in high quality of the symposium program. Also, the Publication Chair Prof. Miroslav Vasić managed to go through *a* complex procedure of preparing fundamentals for post-conference inclusion of all presented papers in the *IEEE Xplore* digital library and Web of Science, Scopus, and Google Scholar citation bases. His work is highly appreciated.

The presented contributions show the latest research results and new trends, as well as achievements of the industry. It is to the Symposium to evaluate the significance of these contributions. The authors themselves are responsible for the accuracy of the results, statements, and conclusions

As parallel events, the XXI National conference "Energetska elektronika" (in the Serbian language) and the annual assembly of the Serbian Power Electronics Society will be held.

Prof. Dr. Vladimir Katić

Ee 2021 Chairman &
President of the Serbian Power Electronics Society

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XXI Savetovanje Energetska elektronika – Ee 2021

PREDGOVOR

Konferencija Energetska elektronika obeležava 48 godinu od svog prvog susreta u Beogradu davne 1973. godine. Ova duga tradicija pokazuje da su istraživači iz oblasti energetske elektronika u Srbiji aktivni i da imaju značajne, svetski priznate rezultate.

Prvo nacionalno savetovanje iz Energetske elektronike, popularno Ee, održano je u Beogradu davne 1973. godine sa 47 prikazanih radova iz svih krajeva eks-Jugoslavije. Naredna savetovanja održana su u Beogradu 1975. godine sa 50 radova, u Zagrebu 1978. godine sa 94 rada, u Sarajevu 1981. godine sa 95 radova, u Ljubljani 1984. godine sa 104 rada, u Subotici 1986. godine sa 126 radova i u Beogradu 1988. godine sa 109 radova. Posle duge pauze, zbog nemilih događaja na prostoru bivše SFRJ, Energetska elektronika oživljava i nastavlja svoj rad u Novom Sadu 1995. godine sa 79 radova, ali sada u formatu naučnog simpozijuma i u novom okruženju - Međunarodnom sajmu elektronike i informatike. Sledeći simpozijumi su održani u Novom Sadu – 1997. godine, sa 98 radova i 1999. godine sa 82 rada. Značajno učešće stranih autora rezultiralo je podizanjem nivoa simpozijuma na međunarodni nivo i rad na engleskom jeziku. 2001. godine predstavljeno je 107 radova, 2003. godine 101 rad, u 2005. godini 94 radova, 101 rad u 2007. godini, odnosno 105 radova u 2009. godini. Od 2011. godine simpozijum se održava u sklopu „Dana energetike“ u Master centru Novosadskog sajma, kada je prezentovano 102 rada u 2011. godini i 69 radova u 2013. godini. 18-ti simpozijum održan je na novoj lokaciji, u Centralnoj zgradi Univerziteta u Novom Sadu, kada je prezentovano ukupno 75 radova. 19-ti simpozijum je predstavio radove 246 autora i koautora i okupio učesnike, koji dolaze iz 29 zemalja. U sklopu XX jubilarnog simpozijuma predstavljeno je 73 radova od strane 235 autora/ko-autora iz 23 zemlje sveta.

Vreme održavanja XXI simpozijuma/savetovanja karakteriše pandemija Covid-19 virusa i to je razlog što će on biti po prvi put održan u virtuelnoj formi (online) sa izlaganjima na daljinu. Učesnici, njih 247, dolaze iz 27 zemalja sveta (Alžira, Australije, Austrije, Bugarske, Crne Gore, Čilea, Danske, Francuske, Holandije, Hrvatske, Indije, Italije, Kanade, Kine, Nemačke, Rumunije, Rusije, Paragvaja, Poljske, SAD, Severne Makedonije, Slovačke, Srbije, Španije, Švajcerske, Turske i Velike Britanije), a predstaviće 81 rad i prezentacija (uključujući i one na nacionalnom savetovanju). Svi radovi su prošli kroz proces recenziranja od strane Međunarodnog programskog odbora i tehničkog prilagođavanja od strane Sekretarijata. Želeo bih da istaknem veliki trud prof. dr Petra Grbovića kao predsedavajućeg Programskog odbora, koji je okupio veliki tim stručnjaka energetske elektronike kao i rukovodioca tema i recenzenata, pozvao poznate ključne govornike i visoke stručne izlagače i organizovao tutorijale, što je doprinelo visokom kvalitetu programa simpozijuma. Takođe, želeo bih da se zahvalim i na velikom radu prof. Miroslavu Vasiću, koji je uspeo da savlada kompleksne procedura i omogući da se radovi, nakon izlaganja na simpozijumu uključe u IEEE Xplore bazu podataka i citiraju preko Web of Science, Scopus and Google Scholar-a.

Rezultati ovih radova pokazuju da autori prate najsavremenije trendove u energetskoj elektronici. Na učesnicima simpozijuma je da procene značaj ovih doprinosa, a sami autori su odgovorni za tačnost rezultata, izjava i zaključaka iznetih u svojim radovima.

XXI Savetovanje Energetska elektronika (na srpskom jeziku), koje se održava kao paralelnih događaji u sklopu međunarodnog simpozijuma, predstaviće 5 domaćih radova. Pored toga održaće se i redovna godišnja skupština Društva za Energetsku elektroniku Srbije.

Prof. dr Vladimir Katić
Predsednik Organizacionog odbora Ee 2021 i Predsednik
Društva za Energetsku elektroniku Srbije

Ee 2021

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21st International Symposium on Power Electronics - Ee2021

KN

KEYNOTE LECTURES

KN1.1

Leo Lorenz, Germany

POWER SEMICONDUCTOR DEVICES - DEVELOPMENT TREND AND APPLICATION CHALLENGES WILL SILICON BE REPLACED BY WB-TECHNOLOGIES?

Abstract – Having a look at the ITRS (International Technology Roadmap for Semiconductors) it can be seen that since the middle of the 90ties power semiconductors are not any more pure technology driven devices such as memory products. The feature size is having a minor influence on the performance improvement. The major improvement in electrical performance is coming from the overall Silicon utilization (vertical- & horizontal optimization). Based on this idea the technology Roadmap follows a chip horizontal optimization e.g. smaller feature size is translated into higher cell densities and a vertical optimization to minimize the drift layer and reduce the bulk substrate material significantly. This power device main stream technology development is applied to all device types such as the IGBT, Fast Recovery Diode, Super Junction Transistor low voltage MOSFET and WBG Devices.
However it has to be considered that the new generation of power dies having a smaller chip volume. A smaller chip volume translates into higher switching speed, extremely high knowledge for chip design is required as well as application engineering to operate the devices in short-circuit, avalanche and how to optimize the thermal management. To improve the cooling performance and reliability of the device new chip interfacing technologies have been developed.
The megatrends of our modern society such as energy efficiency, E-Mobility and Renewable Energy Technologies are asking for green power Electronic solutions. Power semiconductor devices are an enabling technology to meet these requirements. The major electrical improvement of the new generation of power devices is coming from SMART chip design based on more than 40 years dedicated experience. The reliability and ruggedness of these new power semiconductors is driven by an advanced chip silicon design and new interfacing and packaging technology. For ultra high efficiency and ultra high power density system solutions WB-devices are being developed. However it has to be considered that the application engineer is faced with new challenges of how to manage all the parasitic , the thermal management and the circuit design.
In the presentation the development trend of Power Devices will be shown and the challenges in packaging technologies and system application will be discussed. Advanced devices structures will be highlighted and their impact on the electrical and thermal performance outlined.

Academician Prof. Dr. Leo Lorenz
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LEO LORENZ received the M.Eng. degree from Univ. of Berlin Germany in 1976 and the PhD. degree (first class Hons.) from University of Munich in 1984 (Germany).
He is currently Technology Advisor for several Research Institutions , Board Member of key Power Electronics Conferences and President of ECPE. From 1988 to 1998 he was Senior Director at Siemens responsible for Power Semiconductor Devices in Automotive & Industrial Application. From 1998 to 2012 he served as Senior Principle in Application and Concept Engineering for all power semiconductor Technologies in Munich/Singapore/Shanghai. In this field he has published more than 400 Journal/conference papers with a high citation rate and is the owner of many basic patents. He gave more than 90 key note presentations at high level Summits and Conferences. Beside his work in Industry he is a Honorable/Adjunct Professor at several Universities in Germany and Worldwide . In this function he provides courses on power semiconductor technologies and supervised more than 20 PhD Students.

Dr. Lorenz is one of the Key Founder of ECPE (European Center of Power Electronics) and since the foundation in 2003 President of this organization. He is Founder/Co-founder of several conferences such as CIPS (Conference on Integrated Power Systems), PCIM Asia, ISPSD, etc. He served as General Chair of several Conferences e.g. CIPS since 2005, EPE 2005, ISPSD 1997, PCIM since 2001 and is in the Advisory Board of all of these Conferences. Dr. Lorenz received several times the best paper Award at IEEE Conferences. In 1996, 98 and 99 he received the Siemens Innovation Award and from the German Industry Society the Innovation Award in 2002.
Beside these he received several high level IEEE Awards e.g. IEEE-ISPSD Outstanding Contributory Award in 2010 (Japan), the IEEE- Gerald Kliman Innovator Award in 2011 (USA) and the IEEE- William E. Newell Power Electronics Award in 2012 (USA), Ernst Blickle Award in 2015 (Germany), Sun Yun-Suan Honorary Professorship from Nat. Tsing Hua University TW in 2016 and a Dr. Honoris Causa nomination in 2017, Honorary Prof . Xi-An Jiaotong Univ.2018, IEEE Hall of Fame 2018 He is a distinguished lecturer at several Universities since 2003. He owns an IEEE- Fellowship since 2006 and is a Member of German Academy of Science since 2005. Dr. Lorenz is in the Advisory Board of several Research Institutions e.g. Fraunhofer Institute, Robert Bosch Center, etc. and a Technology Advisor/Reviewer of Governmental Organizations and Funding Programs.

KN1.2

Jelena Popović, Netherlands

ENERGY ACCESS – CHALLENGES AND OPPORTUNITIES FOR THE POWER ELECTRONICS COMMUNITY

Abstract – Achieving universal, affordable and sustainable energy access to almost 1 billion people without electricity access is one of the biggest societal challenges of our time. Decentralised, bottom-up approaches, such as solar home systems and microgrids, are being deployed as an alternative to the centralised grid approach, however affordability, reaching scale and long-term sustainability remain challenging. The lecture will discuss the role and opportunity for the power electronics community in addressing these challenges. Furthermore, it will throw a spotlight on the second round of the IEEE PELS challenge Empower a Billion Lives.

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Assoc. Prof. Jelena Popovic received the Dipl. Ing. degree from the Faculty of Electrical Engineering, University of Belgrade, Belgrade, Serbia, in 2001, and the Ph.D. degree from the Delft University of Technology, Delft, The Netherlands, in 2005. From 2005 to 2011, she was with the European Center for Power Electronics (ECPE) as a Technology Transfer Coordinator. From 2008 to 2017 she was with the Delft University of Technology as an Assistant Professor. In 2018 she co-founded a start-up in energy access, Klimop Energy. From October 2019, she joined University of Twente as an Associate Professor to develop a multidisciplinary research and education Energy Access programme.

She has published over 90 publications in scientific journals, magazines and conferences. She has co-authored strategic research agendas, technology roadmaps and white papers in the field of power electronics, energy efficiency, solid state lighting. Her recent interests are bottom-up solutions for energy access, appropriate technology and socio-technical integration. She is the vice-chair of the PELS Technical Committee TC-12 Energy Access.

KN1.3

Slobodan Vukosavić, Serbia

INTEGRATION OF RENEWABLE SOURCES IN AC GRIDS

Abstract – Stability and reliability of power systems with increased share of renewable sources depends on dynamic properties of grid-side converters, power electronics devices that interface the ac grod with renewable sources, storage facilities, direct-current transmission lines, as well as with active loads, prosumers and micrograids. While the basic dynamic properties of synchronous generators depend on electromagnetic and mechanical properties of the machine, dynamics of grid-side converters prevalently depend on DSC-implemented control algorithms which depend on the converter topology, the switching frequency and which require exact information on grid parameters. This lecture will discuss converter topologies, improvements of semiconductor power switches and the algorithms for control and for evaluation of network parameters. In addition to theoretical considerations, the lecture will consider experimental results obtained with industrial samples of grid-side converters.

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Slobodan N. Vukosavic graduated with honours at the Electrical Engineering Department, University of Belgrade. He got his diploma in Power engineering in 1985, and his diploma in Electronics in 1986. He defended the magisterial thesis entitled "Control algorithms for the voltage source inverters" in 1987.The doctoral dissertation "Adaptive digital control of induction motors" is defended 1989. with the same University.

Since 1985, he worked as an R/D engineer with "Nikola Tesla" Institute in Belgrade, engaged with research, development and design of static power converters, electrical drives and digital control systems for industrial and military applications. Relevant projects were closely related with his magisterial thesis, PhD thesis, and his first papers. In 1988, he joined Electronic Speed Control Division of Emerson-Electric in St. Louis, where he developed and patented sensorless controller for brushless permanent magnet motors in HVAC applications. He also developed asymmetrical switched reluctance machines and original power converter topology for SRM supply. Invited by Vickers-Electric, manufacturer of hydraulic actuators, he joined their new R/D team, developing electric actuators for industrial robots. Leading the R/D with Vickers Electric, and later on with MOOG-Electric, he developed motion control products for the car manufacturers and automotive industry in Europe.
He started teaching at the Electrical Engineering Department, University of Belgrade part-time in 1993. and full time from 1995. He was elected associate professor in 1998. and full professor in 2003. In 2003, he was elected adjunct professor at the North Eastern University, Boston. In cooperation with Imperial College, London, he developed a new curriculum in Mechatronics. He established two R/D laboratories: Laboratory for digital control of electrical drives and Laboratory for electrical vehicles. In cooperation with other universities and companies, the laboratories completed 13 international and 20 national R/D projects. He mentored 74 diploma thesis, 17 magisterial thesis, 12 master thesis and 12 PhD thesis. He conducted research and design of motion control algorithms, servo-amplifiers and servo motors for production automation and industrial robots. As the team leader in R/D departments of Vickers-Electric and Moog, he conducted design and deployment of motion control solutions and several original methods and devices. Developments include one of the first multi-axis servo-amplifiers with proprietary algorithms for the suppression of the mechanical resonance and torsional oscillations, the algorithms for trajectory optimization and the control laws that reduce the losses and increase the energy efficiency. His motion control products and devices are mainly used at European car manufacturers, accounting for more than 80.000 servo axis. Large power, high reliability servo-amplifiers developed in cooperation with Moog are widely used for running the flight simulators and high-pressure injection molding machines.

S. N. Vukosavic published over 250 papers, 50 of them in journals on JCRlist. He wrote 10 books, including DigitalControlofElectricalDrives, "电机" (Electrical motors), ElectricalMachines and Grid-Side Converters Design and Control published by Springer. According to Scopus, his papers were cited 2127 times(excluding self citations)with h = 27.
S. N. Vukosavic is an associate member of the Serbian Academy ofSciences and Arts. He is also a member of Academy of Engineering Sciences of Serbia and Senior member of the IEEE and member of Atiner institute for education and research.
He is associate editor of IET Electric Power Applications, of IEEE Transactions on Energy Conversion, member of editorial board and guest editor of international journal Electronics, member of editorial board of international journal Facta Universitatis: Electronics and Energetics.
S. N. Vukosavic is member of program boards of InternationalSymposiumonIndustrialElectronics(INDEL) and International Symposium on Power Electronics. He is also member of the Advisory Editorial Board of International Journal of Electrical Power & Energy Systems.

KN2.1

Branislav Kisačanin, USA

"TRANSFORMERS" FOR ARTIFICIAL INTELLIGENCE

Abstract – In this keynote we start on the funny side of AI, examining AI naming schemes that often magnificently collide with other engineering and scientific disciplines – "transformers" being only one of them. We continue into a no less entertaining discipline of predicting where AI is going. But history is a good teacher, so we methodically review where AI has been and what it has achieved, to conclude that it is currently where chemistry was when it was called alchemy, or perhaps a more appropriate analogy for this meeting, where electrical engineering was when Oersted discovered there was something going on between electricity and magnetism. In other words, there is a lot of work and many discoveries ahead of us!

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Branislav Kisačanin is the Chief Scientist of the recently founded br.ai.ns Institute (officially: The Institute for Artificial Intelligence Research and Development of Serbia), a part-time professor at the Faculty of Technical Sciences at the University of Novi Sad, and a scientist at Nvidia, working on visual perception algorithms and related processor architectures in the context of autonomous driving. He is also a passionate teacher of mathematically gifted kids, preparing them for math and physics olympiads through the AwesomeMath Academy and Summer Programs. Branislav has published five books on control theory and computer vision, four books for math and physics competitors, and was a guest editor for six special issues of leading computer vision journals.

KN2.2

Huai Wang, Denmark

AI APPLICATIONS FOR POWER ELECTRONICS – CHALLENGES AND OPPORTUNITIES

Abstract – The applications of Artificial Intelligence (AI) for power electronics have been increasingly reported since the 1990s. This first part of this talk will revisit the research and development in the last three decades with selected application examples in the design, control, and condition monitoring of power electronic converters. The AI-based or AI-assisted solutions rely on in-depth understandings of the defined engineering problems, deterministic physical models, uncertainty analyses, data collection methods, and affordable AI algorithms and hardware platforms. The second part of this talk will share perspectives on the specific challenges and opportunities in AI for power electronics compared to other known application areas.

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Huai Wang is currently Professor at the Center of Reliable Power Electronics (CORPE) at Aalborg University, Denmark. His research addresses the fundamental challenges in modelling and validation of power electronic component failure mechanisms, and application issues in system-level predictability, condition monitoring, circuit architecture, and robustness design. He also leads a project on light-AI for cognitive power electronics. His team collaborates with various industry companies across the value chain, from power electronic materials, components to systems.

Prof. Wang lectures three short-term Industrial/PhD courses on Reliability of Power Electronic Systems, Design FMEA in Power Electronics, and Capacitors in Power Electronics Applications at Aalborg University. He has contributed more than 120 journal papers and co-edited a book on the Reliability of Power Electronic Converter Systems in 2015. He has given 25 tutorials at leading power electronics conferences (e.g., PCIM Europe, APEC, ECCE, etc.) and more than 80 invited talks.
Prof. Wang received his PhD degree from the City University of Hong Kong, Hong Kong, China, and B. E. degree from the Huazhong University of Science and Technology, Wuhan, China. He was a short-term visiting scientist with the Massachusetts Institute of Technology (MIT), USA, and ETH Zurich, Switzerland. He was with the ABB Corporate Research Center, Baden, Switzerland, in 2009. Dr. Wang received the Richard M. Bass Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society in 2016 for the contribution to reliability of power electronic converter systems. He serves as General Chair of IEEE IFEC 2020 and Associate Editor of IEEE Transactions on Power Electronics.

KN3.1

Minjie Chen, USA

MANAGING POWER COMPLEXITY FOR EXTREME PERFORMANCE: CIRCUIT, ARCHITECTURE, AND MAGNETICS

Abstract – Power electronics have been traditionally designed with topologies that have low component count and simple architecture. These designs typically require substantial energy storage and bulky passive components, and are reaching their fundamental limits with decreasing performance gains. Moreover, they do not leverage the dramatic advances that have been made in semiconductor materials and integrated circuits. With the advent of wide-bandgap semiconductor materials, high-frequency magnetics, and the opportunities offered by emerging high-impact applications, sophisticated and modularized power conversion architectures are becoming extremely attractive.
This talk will present three on-going efforts about high complexity power electronics, ranging from point-of-load power converter design, differential power processing architecture, to magnetics core loss modeling based on machine learning. These three examples extend the fundamental performance boundary of power electronics from three different perspectives, and enlighten the path to much more sophisticated and modularized power electronics that will benefit a wide range of applications.

Assist. Prof. Minjie Chen Andlinger Center for Energy and the Environment
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Assist. Prof. Minjie Chen is an Assistant Professor of Electrical Engineering and Andlinger Center for Energy and the Environment at Princeton University. He leads the Princeton Power Electronics Research Lab. He received the B.S degree from Tsinghua University in 2009, and the Ph.D degree from MIT in 2015. His research interests include high frequency power electronics, advanced power electronics architectures, power magnetics, and the design of high-performance power electronics for emerging and important applications.

He is a recipient of the NSF CAREER Award, two IEEE Transactions Prize Paper Awards, a COMPEL best paper award, the outstanding Ph.D. thesis award from MIT, and many other awards from the IEEE Power Electronics Society. He has published over 40 papers in journals and conferences and holds 4 issued patents.
He is the Vice Chair of PELS-TC10-Design Methodologies, an Associate Editor of the IEEE Transactions on Power Electronics and IEEE Journal of Emerging and Selected Topics in Power Electronics, the Associate Technical Program Committee Chair of ECCE 2019, and the Technical Program Committee Chair of ICDCM 2021.

KN3.2
Kevin Hermanns, Germany

COMPONENT DATA - THE KEY TO UNLEASH THE POTENTIAL OF DESIGN AUTOMATION FOR POWER ELECTRONICS

Abstract – A variety of decisions must be taken during the design process of power electronics. Increasing system complexity due to new semiconductor technologies (SiC, GaN), innovative manufacturing methods and various fields of application make it impossible.
For system designers to grasp all variation of possible solutions. The designed system normally fits the requirements but is never the optimal solution. To overcome this, design automation in power electronics is currently evolving from academical examples to industrial applications, solutions and products. The basis of design automation is the generation, processing and the provision of data, which describes components and systems.
The obvious way is to collect component data from each vendor and build up one centralized data base for each software tool, that helps to solve one certain issue during the design process. This way seems not to be the optimal way, because data must be provided for each tool by each component vendor. Additionally, each software tool vendor is responsible to keep the data up to date and will have different requirements on the applied data.
A better way is to use standardization to define a basic data set and to empower component vendors to make their product data available in machine-readable formats.
The realization of a standard data format as well as several application examples, improving the design process of power electronics significantly, are presented in this keynote.

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Kevin Hermanns is founder and managing director of PE-Systems GmbH. PE-Systems offers solutions in the field of design automation for power electronics including automated characterization and device modelling. Before becoming an entrepreneur, Kevin started his professional career at Siemens in the project office of large-scale railway automation projects. Afterwards, he worked as a research associate at the Technical University of Darmstadt in the Power Electronics Department. During this time, his research interests focused mainly on the distortions of high-power converters.

He actively contributed to Cigre working group B4.67, which resulted in the technical brochure “AC side harmonics and appropriate limits for VSC HVDC”. He is also an active participant in national and international standardization committees (e.g. IEC and CENELEC). As of this year Kevin is chair of the newly formed IEEE Power Electronics Society Technical Committee on Design Methodologies. As such, he sees his role as promoting the use of novel design methodologies. In particular, he focuses on the interaction between design tools and test and measurement techniques.
Kevin was born 1984 in Germany. He received his bachelor’s degree in electrical engineering from the Technical University of Braunschweig, Germany and graduated from the same university with a Master of Science in electrical power engineering.

IP

INVITED PAPERS

Blockchain-based Smart Decentralized Energy Trading for Grids with Renewable Energy Systems

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***Abstract*—The rise of renewable energy sources and smart grids and the almost simultaneous appearance of blockchain technology has, through their synergy, opened a path to a fundamental shift in the very nature of energy systems as we know them. Traditionally, production, distribution, and trading of electrical energy has been a centralized process based on a limited number of regional, vertically integrated monopolies. Today, the share of energy produced using renewable energy systems by former consumers, now termed 'prosumers,' is constantly increasing, leading to a decentralized environment in which the line between producers and consumers is getting ever blurrier. In this paper, we first discuss the current state-of-the-art in applications of distributed ledgers and blockchain in the energy sector. For addressing novel challenges which appear in such a decentralized setting, we propose a system based on a lean distributed ledger with aggregator nodes and intelligent-agent trading founded on the notion of a shared supraordinal grid and a common carrier/producer that serves as the medium of exchange and supplier of last resort. We also show how such a pragmatic solution may be extended to allow for a futuristic fully decentralized grid while still respecting the here-and-now.**

***Keywords*—energy trading, distributed ledger technology, blockchain, renewable energy, smart grid, distributed systems**

I. Introduction

In the past decade, we have witnessed a tremendous rise of renewable energy sources, including new electrical energy plants and distributed generators, the inclusion of storage and electrical vehicles, and the appearance of a new type of grid entity - prosumers[1], contributing to the realization of the concept of the smart grid in the field of power engineering [1]. Almost simultaneously, the revolutionary appearance of the blockchain technology has created a fundamentally new way to record data and perform transactions [2]. Through their synergy, these technologies open a path to a fundamental shift in the very nature of energy systems as we know them [3, 4]. For more than a century, the process of production, distribution, and trading of electrical energy was centralized and based on a limited number of regional, vertically integrated monopolies. Today, the share of energy produced using renewable energy systems by former consumers, which are now prosumers, is constantly increasing [3]. This leads to a decentralized energy system in which the line between producers and consumers is getting ever blurrier. The driving force in this transformation was power electronics converters, but they introduce much faster control, so the power system is transforming to the low inertia one. Further, companies in the energy sector are increasingly reporting higher energy costs and lower revenues [5]. At the same time, utilities face demands for increasing transparency by the regulatory authorities [5]. As a result, any possibility of cost savings and efficiency improvement in the operation of energy systems and markets can prove significant and is worth investigating.

We feel that all of the above makes clear a necessity for a trustworthy, transparent, traceable, and auditable data exchange system in trading of electrical energy produced in such decentralized renewable energy systems. All of the energy companies and prosumers involved in systems of this nature need to be able to independently verify that energy transactions, which are automatically executed in their thousands every second, are being performed in accordance with the rules and pricing schemas agreed upon in advance. Therefore, we discuss a system for energy trading in decentralized systems with a large number of prosumers. The system is a lean private permissioned distributed ledger with aggregator nodes and intelligent-agent trading based on the notion of a shared supraordinal grid and a common carrier/producer that serves as the medium of exchange and supplier of last resort. The system we propose offers low operational costs and high scalability due to its use of private permissioned distributed ledger in similar fashion to the work presented in [6, 7]. Further, it offers a transparent view on the operations of the system to all of the stakeholders and assures direct oversight of transactions to regulatory authorities. Therefore, such a smart, transparent, traceable, and auditable lean distributed ledger can serve as an "information backbone" of both contemporary and future electrical energy systems. We also discuss how such a pragmatic solution may be extended to allow for a futuristic fully decentralized grid while still respecting the here-and-now.

The remainder of the paper is organized as follows. In Section 2, we give an overview of distributed ledger technology (DLT) and blockchain, as a subset of DLT, and their current and potential applications in the energy sector. Section 3 presents the proposed blockchain-based smart decentralized energy trading system, first in terms of it's differences from existing solutions, and then in it's general architecture, technology stack, and use cases. The final section

[1]The concept of prosumer is a portmanteau of words producer and consumer. It was coined by Alfin Toffler in his influential futurology book "The Third Wave" (1980) where he noticed that the technological breakthrough and rise in user participation blurs the line between production and consumption activities, with the consumer now becoming a prosumer.

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offers a closing discussion containing most important conclusions drawn from our research and directions for future work.

II. Distributed Ledger Technology in the Energy Sector

This section is composed of two subsections. In the first one, we give a brief overview of the DLT and blockchain terminology. The second one explores the current state-of-the-art in applications of distributed ledgers in the energy sector, with special emphasis on the existing DLT applications for energy trading.

A. Distributed Ledger Technology and Blockchain

A common misconception puts an equality relation between cryptocurrencies and DLTs and blockchain. Therefore, before we proceed to the discussion of the current state-of-the-art in applications of DLT in the energy sector, we will briefly address the terminology.

A distributed ledger or distributed ledger technology is a special type of distributed database which assumes the existence of malicious users within the distributed system [2]. DLT can also be defined as a consensus of replicated, shared, and synchronized digital data geographically spread across multiple locations [8]. A blockchain is a data structure first proposed in [2] which implements a distributed ledger in a specific way. It is composed of a chain of cryptographically linked blocks containing sets of transactions [2]. These blocks are then typically broadcasted to all the participants in the blockchain's peer-to-peer (P2P) network. In addition to the distributed ledger and the peer-to-peer network, blockchains have two other key components - smart contracts and the consensus algorithm. Smart contracts are self-executing computer programs which automatically perform actions such as reading from or writing to the distributed ledger when certain conditions are met. The role of the consensus algorithm is to ensure that data on the ledger are the same for all participants in the blockchain network and, in doing so, prevent malicious actors from manipulations.

There are two classes of DLTs most often found in real-world applications. The first one is composed of public permissionless DLTs, such as Bitcoin [2] and Ethereum [9], which are typically used as a basis for cryptocurrencies and offer pseudo anonymity to their users. The second class contains private permissioned DLTs which are often much better suited for enterprise applications [8, 10, 11]. In comparison to their public counterparts, they offer more granular data access control, higher transaction throughput, better scalability, more privacy, and improved modularity, all at the price of required user authentication and authorization. Most popular representatives of private permissioned DLTs include systems such as R3 Corda [10] and Hyperledger Fabric [11]. It should be noted that R3 Corda performs read and write operations to the distributed ledger on the level of each transaction, instead of creating blocks of transactions, and thus is a DLT, but not a blockchain [10].

B. Application of DLTs in the Energy Sector

In the last several years we have witnessed a tremendous rise of interest in the application of DLTs in order to improve various processes in the energy sector. This development has been analysed and summarized in detail in a broad study performed by Andoni et al. [3]. This study first explains the key principles of DLTs and then offers a systematic review of its use in the energy sector. As shown on Fig. 1 taken from [3], one third of all energy sector use cases for DLT goes to energy trading, which is also the main topic of this paper. Use of cryptocurrencies and tokens are in the second place, followed by applications of blockchain in smart devices, automation, and asset management. Significant number of projects are further found addressing topics such as metering, billing, and security, as well as carbon certificates and carbon trading.

As presented in Fig. 2, research from [3] also includes a classification of DLT energy sector use cases by DLT platform used. They found that one half of the considered projects were using the public Ethereum blockchain, with another tenth of the market taken by Energy Web, which is also Ethereum-based. The Hyperledger private family of blockchains were also found in a significant number of projects, while all the other DLTs combined commanded one-quarter of the considered use cases. Since the study by Andoni et al. was published in 2019, the interest in applying private DLTs in the enterprise domain has significantly risen, mainly due to improved maturity of these technologies [8, 10, 11] which appeared much later than public blockchains.

We also performed a detailed analysis of research, projects, and companies which present use cases of peer-to-peer (P2P) energy trading. We found that a rising number of projects, such as [12] and [13], have already successfully tested blockchain based energy trading in practice. This proves the feasibility and value of the approach based on the DLT and attracts further interest from researchers and investors alike.

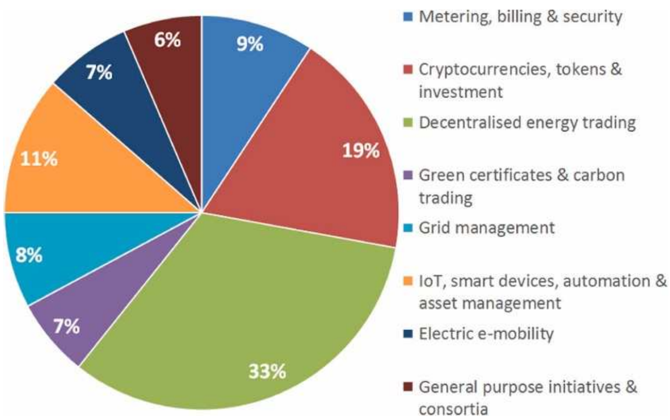

Fig. 1. DLT energy sector use case classification according to their activity field (taken from [3]).

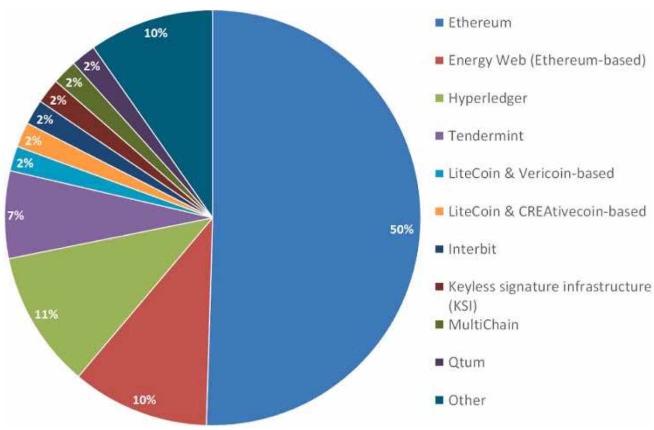

Fig. 2. DLT energy sector use case classification according to DLT platform used (taken from [3]).

A case study which completed a successful three-month trial run of P2P energy trading in a small Brooklyn, New York, community in the United States is described in detail in [12]. Prosumers were allowed to sell energy surplus directly to their neighbors using the implemented infrastructure. The Brooklyn Microgrid platform used the public Ethereum based smart contracts and a PBFT [14] consensus implemented by Tendermint to achieve the goals of the project. Another similar project is Power Ledger [13]. It offers a widely tested and mature power trading solution. At the time of writing of this paper, Power Ledger is used in eight countries, which signals that blockchain-based decentralized power trading platforms are a viable solution and have the possibility to truly transform the way we produce and trade energy. The Power Ledger platform uses a hybrid public and consortium blockchain solution to minimize energy consumption that comes with the public Ethereum ledger and the proof-of-work (POW) algorithm that it uses. Power Ledger offers tokens (named POWR and Sparkz) which can be publicly traded to make profit or consumed to provide electricity.

The existing academic research on the topic of DLT-based energy trading which we focus on in this paper includes references such as [6, 7, 15, 16, 17]. The research reported in [17] presents the state-of-the-art in applications of blockchain for energy trading in power electrical systems in 2019. This study first identifies and summarizes challenges in blockchain-based energy trading. Afterwards, they discuss the existing energy trading schemes and classify them into three categories based on their main focuses: energy transaction, consensus mechanism, and system optimization. Further, in [6] a Hyperledger Fabric-based model for localized P2P energy trading is proposed. The model consists of three entities which are energy nodes, energy aggregators, and smart energy meters. Energy nodes are used for selling or buying of energy and their role depends on the energy state of the owner. Energy aggregators perform the role of brokers which regulate trade between energy nodes. Smart meters are in charge of recording energy trade in real time. A system for energy trading based on a blockchain network which uses tokens to allow P2P trading is also proposed in [16]. Tokens are created or consumed by nodes which transfer energy through the Energy Storage System. The research reported in [15] proposes a custom blockchain network which uses the proof-of-work (POW) consensus algorithm [2] to store all energy trading transactions. The use of the POW algorithm introduces delays in transaction validation, which is addressed by designing a credit-based payment schema. Nodes apply for loans according to their credit strategy. They also propose an optimal loan pricing strategy for credit-based payment schema to maximize utility of credit banks. Research reported in [7] proposes a solution with a provided case study and a prototype for P2P energy trading based on the Hyperledger Fabric private permissioned blockchain. This implementation allows users to seamlessly trade energy with use of a two-phase algorithm. The first phase focuses on scheduling energy generation day-ahead, while the second phase is used for real time network management (hour-ahead scheduling).

As reported in [3], in addition to energy trading, a significant number of other use cases of DLT in the energy sector exist. Ponton has developed a pilot blockchain-based solution called Gridchain that simulates processes used for real-time grid management [18]. They focus on in-advance balancing of power loads. This allows smart control over power generators before they are ramped up and keeps grid load and frequency stable. Wipro and SAP have developed a green energy tracking and distribution platform based on the SAP's blockchain cloud platform [19]. This system leads to reduction in cost of green energy transactions, and enables new business models between retailers, prosumers, and commercial consumers. It provides a cheaper alternative for demand side management when compared to large CAPEX-driven green energy power plants [19]. It also increases adherence to regulatory demands considering green energy sourcing [19]. General Electric is investigating potential blockchain use in their digital power plants (DPS) [20]. As trend moves away from large central power plants towards distributed small or middle generators, General Electric DPS considers the use of Hyperledger Fabric as a blockchain solution, along with other software innovations, in order to satisfy diverse needs of power assets with high-speed and intelligent infrastructure [20]. In addition to these industry-led projects, the academic research on the use of blockchain technology for addressing different challenges in the smart grids and renewable energy system is also very extensive. A comprehensive survey of these topics is presented in [21], as well as in the book [22] and papers such as [23].

III. The Proposed Blockchain-based Smart Decentralized Energy Trading System

This section consists of four subsections. First, we discuss a different path to developing a solution which applies DLTs and blockchain in energy trading. Then, we describe the overall structure of the proposed system and what it is meant to do as well as a desired use-case. Afterwards, we present details of the architecture of the discussed system to a greater extent. Finally, we discuss the classes of participants we identified for the peer-to-peer network of the proposed system.

A. A Different Path to Applying Blockchain in Energy Trading

The solutions enumerated in Subsection 2.2 have several virtues and represent a commendable degree of technical sophistication. The Brooklyn Microgrid [12], for instance, represents an incredibly detailed practically functional vision of the future. Power Ledger [13] and Energy Web [24] present concerted efforts to make a software infrastructure that makes such a future possible. Our approach in this paper will be somewhat different.

The difference of approach is not focused on purely technical issues but a fundamental one of adoption and the possibility of engineering undirected growth into a system. All the solutions surveyed have one of the two fundamental blockchain risks: either they are expensive at scale as all processing time must be bought from a public blockchain at non-negligible cost [16] or they are expensive both at scale and at the start due to the substantial costs of running blockchain node instances for every participant when private distributed ledgers are used [6, 7].

We would like to propose an alternative approach to earlier works on the topic of blockchain-based energy trading such as [6, 7, 15, 16]. Our approach is focused on its ability to make a maximum of sense for both the producers, the prosumers, and the electrical distribution companies at any scale. A system that might be worth joining and using even if you are one of the first users, and something which can grow and expand on its own merits without requiring too much in the way of investment and too much in the way of changing the problem to fit the solution.

Ultimately, the goal of the research is the architecture of a solution which can be implemented here and now and be useful immediately. To this end, we operate under a few limitations which also make our work distinct from what others have presented earlier:

- There are no tradable 'coins' or other such tokens in the system we propose.
- We don't consider a microgrid implementation, but we put our work within what exists considering energy infrastructure on the ground, here and now.
- We don't add any computational costs in excess of what traditional servers impose.
- The solution we propose doesn't require significant alterations to the legal frameworks.

B. The Overall System Structure and Goals

For purposes of this paper, we will focus on a specific use-case chosen for being realistic but simple. Simplicity is there as an aid to understanding: the system can adapt to greater complexity but is easier to understand in this simplified form. The use-case we are considering is of a situation with a somewhat monolithic power distribution landscape in which we have many consumers, multiple producers, and multiple prosumers, and a single distribution provider with a single, unified grid connecting everyone. This distribution provider serves as a common carrier for all participants in the system and a provider of last resort.

A problem for would-be blockchain architectures in energy trading is that, while power is trivially metered and thus technically reducible to joule-tokens in a blockchain, the iron rules of its distribution and the significant difficulties of its storage mean that trivial trading is not possible. After all, a shortfall of a good on a market produces an increased price, a shortfall of electrical power leads to grid collapse. The input and output of the grid must match at all times. This has two implications. First, the only items that can be sensibly traded are, in essence, futures, i.e., promises to supply electricity at a given price in a given timeframe. Second, the system needs a failsafe: a guarantor of the power grid's integrity no matter what happens on the market. In this case, it must be the power distribution company itself.

Given this situation, market participants cannot in truth send power to each other. The way the grid works they can only receive power or send it. The power grid accepts the obligation to always accept the surplus made by producers (at a nominal rate), and to always provide the agreed-upon power to all consumers (at a specified rate). This represents the floor of the market and guarantees that the failure state of the solution is a system operating exactly as it does now.

Any consumer can register a need for a certain amount of electricity in a given time period, and any producer or prosumer can place a sealed bid into the system during a short bidding period. Once the bidding closes, the orders and bids are settled, and the consumer accepts the obligation to accept a certain amount of power and the producer/prosumer accepts the obligation to put into the system the exact same amount of power. Naturally, if both keep their ends of the bargain the matter is settled and a money transfer is made. If either defaults, the grid operator accepts the defaulted-upon burden. Of course, to reduce the instance of such behavior two things are needed: limits and disincentives. Limits stop producers and especially prosumers from taking excessive positions in the futures market based on their previous record in fulfilling their obligation and their attested production capacities. Disincentives make the defaulting party liable for the punitive costs of fulfilling their obligation for them. This means that all participants in the market are incentivized not to make deals they can't keep and prevented from making deals they are unlikely to keep.

The way this system serves everyone is in that it allows the consumer to buy electricity at a more advantageous rate than the default cost offered by the power distribution company. Likewise, it allows the producer and, more importantly, the prosumer to sell their surplus at prices that are larger than the nominal fee paid to them normally. The margin between the price paid for surplus power and the price paid for power from the distribution company is where trading profit can be made. This scenario describes a direct sale, but there is no reason that this system could not support speculators who can buy these supply/demand contracts on the open market, resell them among themselves, and fulfill them when their time comes. Such speculators could turn superior knowledge of power consumption trends into profit and in turn provide the market greater liquidity and price stability.

A secondary, but equally important use-case is the provable purchase of green power. As matters stand, unless one has generation capacities on-site there is no way to prove that, say, a factory uses a certain percentage of green power to make something. This can be needed in case of regulatory demand, qualifying for a tax break, or for marketing reasons. Generally speaking, in any energy-intensive enterprise, it's highly unlikely onsite power generation capacities will be sufficient. This means power must be bought, and kilowatt-hours don't come with tags differentiating between solar, wind, and coal. The system we propose allows the precise logging of the origin of all the power in the system and allows for verifiable claims that a given product, say, has been manufactured with 100% renewable energy.

For this system to have short settlement times and brief trading windows while being acceptable to prosumers, it needs to be highly autonomous. Therefore, the typical user of this system needs to only configure the system to fit their preferences, picking the desired savings or increased green energy usage and the acceptable level of risk in trading and allowing the system therefore to engage in autonomous operation. This will endeavor to, based on the settings, get the best possible deal for the user allowing them to passively reduce their bill, make some money selling their renewable surplus, or increase the use of renewable energy in their day-to-day.

C. The Proposed System Architecture

This subsection deals with the software architecture of the system under the assumption that the grid already allows us to track the power consumed by any given user and the power emitted into the system by any given user using built-in sensors. This, given modern infrastructure, is true in a large number of cases and certainly for all prosumers.

The architecture of the proposed system is presented in Fig. 3. Most of the system's conventional part can be implemented through software best practices in common use in the industry today. That means that the heart of the conventional part of the system is an application server exposing its functionality over the REST protocol to front-ends implemented as web and mobile applications which consume the functionality exposed by the application server over REST. The application server communicates with a database cluster to ensure reliable, scalable data storage. A typical technology stack for a solution of this nature is React for the Web front-end, React-native for the mobile application, Node.js for the application server, and MongoDB for the NoSQL document-centric database storage. This technology stack is of course amenable to change due to software engineering concerns.

The distributed ledger component's function is that of a secure, distributed database with smart contracts defining ways in which the data stored in the database may be altered and by whom. The question is how to design this subcomponent to allow it to fulfill all the needs of the system in general.

The first thing to determine is the precise nature of the blockchain/distributed ledger solution to use. In this paper, we propose the use of a private, permissioned DLT solution with a semi-open structure. The blockchains most commonly mentioned, such as Bitcoin [2] and Ethereum [9], are public, meaning that any operator may create a node of their own and, as long as they follow the protocol of the blockchain, they become a part of its operation. This is maximally scalable and decentralized, but it is a very poor fit for the legal framework in which such a system must operate. For the whole mechanism to function adequately, identities within a system must be associated with full legal identities and with specific pieces of power transmission and generation hardware.

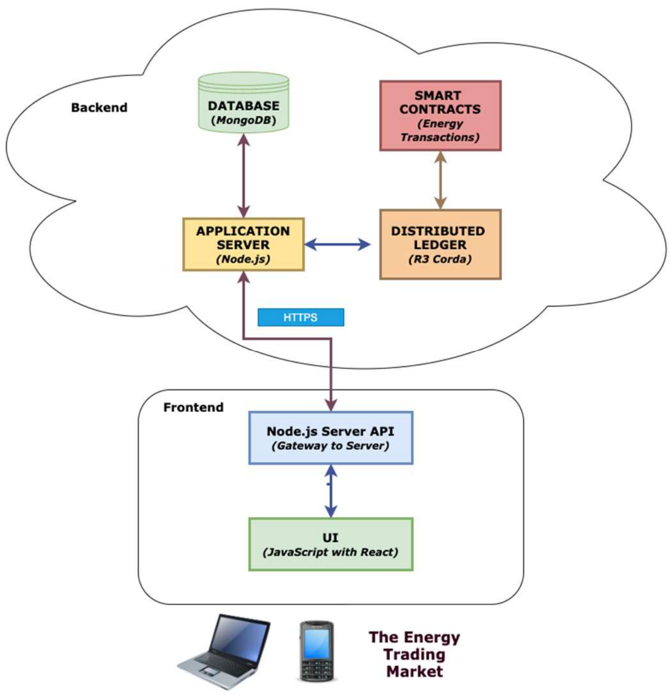

Fig. 3. The architecture and the technology stack of the proposed information system supporting decentralized energy trading.

Thus, a private ledger is required. However, we propose that the best results would be achieved with semi-open design in which anyone fulfilling certain requirements is allowed to operate a node and join the network.

Furthermore, it is evident that the relations between the various participants of the network are asymmetrical with different roles apportioned to different participants. Therefore, we cannot employ a permissionless distributed ledger as our basis, as such a DLT assigns the same role and allows the same rights to all its participants. Thus, we need a permissioned distributed ledger in which different powers are given to different participants. There are multiple implementations of such DLTs available [10, 11]. The DLT implementation we use in our system is the R3 Corda. The choice of Corda was motivated by the goal of creating a lean distributed ledger which complies easily with industry standards and can operate on a "per transaction" level. In such a setting, Corda is found to be a superior solution over Hyperledger Fabric [25, 26], which was used as the basis of other similar energy trading systems based on private permissioned DLTs [6, 15].

D. The Participants in the DLT Peer-to-Peer Network

The classes of participants that we defined in the Corda peer-to-peer network of our distributed ledger are:

- **Grid authority**. The grid authority is any institution which is responsible for the grid and monitors the sensors attached to it. The fact that this is a singular entity everyone trusts is antithetical, admittedly, to the spirit of decentralization of blockchains, but in most cases there is only one grid and thus only one institution responsible for it.
- **Power distribution company**. A company that buys electricity in bulk and sells it according to a fixed schedule of costs. It serves this system as the purchaser and seller of last resort. It can be combined with the grid authority in case of a monolithic power distribution system.
- **Marketplace**. A marketplace is a specific participant which offers trading management services to participants. It manages the order book and performs settlement, as needed. In simpler systems it can be unified with the power distribution company.
- **Producer**. An enterprise primarily engaged in the production of electricity for consumption. Usually has a bulk agreement with a power distribution company and, as such, may not be a part of the blockchain network despite being a part of the grid.
- **Prosumer**. A private individual who possesses some power generating capacity, typically renewable power generating capacity who, aside from using power, also sells surplus to the grid. The principal user of this system.
- **Consumer**. A private individual or company who needs electrical power and wishes to purchase it.
- **Verification agency**. A private enterprise that can publish and verify information onto the distributed ledger. A typical example could be a private agency which, through direct physical inspection can confirm installed capacity for a prosumer or producer.

Verification agencies allow for a limited, scalable decentralization of the system.

- **Speculator**. A private individual or enterprise who purchases power supply agreements/futures on the open market and resells them in order to make a profit.

Typically each participant in a blockchain network of this type will have their own node, that is to say a computer under their control which implements the protocol of the blockchain and makes sure no state change gets written into the ledger that runs contrary to the agreed-upon rules. This, however, is impractical. Certainly, the grid and the large companies can maintain their own servers. The cost is, for a large organization, negligible. But an individual prosumer is already operating on slim margins of profit: the surplus generated is a windfall, not a steady income, and the costs of running one's own node are constant and they mount. Furthermore, this introduces another thing to manage and pay attention to which runs contrary to the turnkey ambitions of this solution.

Therefore, we propose the existence of aggregator nodes. These nodes function in place of the individual nodes of arbitrary subsets of participants and hold in trust a key derived from the private key of the prosumer. Transactions signed with this key are counted as signed by the prosumer, giving the aggregator node the 'power of attorney' for these purposes. However, the prosumer retains control because they can terminate their relationship with an aggregator node at any point with a single on-chain transaction, revoking the power of the key to verify transactions after that moment. On the flip side, the protocol of the network can be such that aggregator nodes must, on request, relinquish all data they have on a given participant they are managing in an agreed-upon format. An aggregator node can be operated like a business, essentially selling blockchain access in much the same way an ISP sells internet access. These two technical solutions: easy key revoking and easy data mobility mean that migrating from one aggregator to another is trivial, allowing for market mechanisms to swiftly deal with underperforming aggregators.

With the system working as described some prosumer's automated trading agent can reference current production, area under solar panels, and the weather forecast for tomorrow and offer certified-green energy for a specific time-slot tomorrow. It does this on a local marketplace. The offer has to be co-signed by the prosumer's aggregator node, the marketplace node, and a verifier node. A verifier node is specifically there to make sure that the rules of the system are followed and can be maintained by any entity that's trusted enough. Certainly the power distribution companies will, at a minimum, run their verifier nodes and so can the marketplaces. The verifier node must certify that the prosumer is in good standing and the offer fits within the limit the prosumer must operate under.

A speculator may notice this and decide to buy the obligation on the market and sends the request to the marketplace where it is signed by the marketplace, a verifier node which checks for speculator limits and good standing status, and finally the prosumer's aggregator node. Once it is fully signed, this triggers an external integration system to effect a money transfer using either existing banking and e-payment infrastructure or through any desired crypto-currency. The fact that the speculator now owns the obligation is written into the ledger. The prosumer owes the speculator a given amount of power in a given time.

If they fail to deliver as much power as agreed-upon, the grid authority will deliver it, and charge a penalty to the prosumer. The speculator in turn can sell the power-debt to another speculator or to a consumer. If the speculator cannot sell the power-debt by its settlement slot it must either accept the power itself, spending it, or the grid will do so and the speculator will pay the penalty cost. This way while you can trade freely with future obligations once final settlement time comes the rules of the power grid must be followed with inputs and outputs being equal.

IV. Conclusions

In this paper we discussed a different approach to implementing a decentralized energy trading system based on a distributed ledger in such a way that the system may develop maximally organically. As part of introducing our problem, we showed how distributed ledger and blockchain solutions are a natural fit to this problem space and outlined the problems such solutions may cause.

We discussed previous work and existing solutions in the field of DLT applications in the energy sector and outlined a different approach, prioritizing different goals. The most important of these goals are organic growth, scalability over time, as well as avoiding any system which requires a high degree of complexity, adoption, and infrastructure to be in any way operational. We showed how these goals require certain architectural and technical features and constrain our choice of technology stack. Lastly, we outlined a basic system architecture which could accomplish these goals and the technology stack required to implement such a solution.

Our future work proceeds along three lines: experimentation, specification, and extension. Experimentally, we will seek to build prototypes of our system, not focused on its utility but on its scalability. We will create distributed ledger networks of varying configuration which accomplish a simulacrum of the transactions a trading system like this will need, we will subject them to various levels of stress which compare to real-world usage scenarios and we will carefully monitor resource consumption and bottleneck. The goal is to have a strict economic metric showing minimal costs per transaction and allowing the implementation of the system to make economic plans to scale.

In the field of specification we will work on further developing the architecture of this system. Blockchain and distributed ledger solutions must, due to their very high security and reliability, are amenable to careful specification. This allows us to have a complete workable design for our system before the implementation task can be started.

Lastly, in the field of extension we will attempt to improve the core technology we rely upon to better suit the sort of private semi-open permissioned distributed ledger systems we are to use. Of particular interest is safe data acquisition, reliable third-party verification of facts, and crucially effective secret bidding over requests or offers within our system. Hiding data in distributed ledger systems, even private permissioned ones, is much harder than guaranteeing their integrity which is comparatively easy. As a result we are investigating zero knowledge cryptographic protocols to ensure the possibility of secret bidding.

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Advancements on Real-Time Simulation for High Switching Frequency Power Electronics Applications

(Invited Paper)

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***Abstract*—This paper presents an outlook about controller hardware-in-the-loop technology and how recent advancements in time resolution improved real-time simulation accuracy for testing high switching frequency power electronics applications. To illustrate that, the control of a dual active bridge converter (DAB) is taken as an example. The DAB converter is emulated on Typhoon HIL device, while the control algorithm is implemented on a digital signal processor from Texas Instruments. Real-time simulations are performed, highlighting the increased precision of the results obtained with the novel switch-level gate-drive signal oversampling.**

***Index Terms*—controller hardware-in-the-loop, dual active bridge, time resolution, power electronics, real-time simulation.**

I. Introduction

One of the key features that enabled the paradigm shift from centralized generation to distributed generation based on renewable energy sources was the accelerated development and continuous advancements on power electronics (PE) technology, allowing to achieve rapid cost reduction as well as increased reliability and improved power quality [1]. As a consequence, engineers are continuously challenged to design and implement different solutions more and more efficiently, which calls for different tools and can be specially demanding considering the need to comply with different requirements, such as grid codes and electric vehicle (EV) integration standards [2], [3]. In this direction, the strategy of waiting until late stages of a project to verify the integration of different hardware and software, as well as to assess the performance of the systems against test protocols, is no longer suitable. Even if scaled prototypes are considered, building the infrastructure can be time-consuming and expensive, and the test flexibility would still be limited by hardware constraints and also by the need to establish proper instrumentation and safety precautions [4]–[6].

For these reasons, the use of hardware-in-the-loop (HIL) for development and testing is an important alternative. This approach adds flexibility and security, besides reducing the time spent in different parts of the development cycle. Ergo, it has been a standard procedure in the automotive industry for more than two decades and it has also been recognized as a viable and cost-effective method for testing and pre-commissioning of microgrids [7], [8].

Considering PE industry, Controller-HIL (C-HIL) is an usual approach, where the power part can be simulated in real time, while the control and management systems, as well as the protection devices, can be implemented in the exact same platforms that will be embedded in the real apparatus. In this way, it possible to have a safe and high fidelity testing environment, where advanced control strategies and the interactions between different systems can be rapidly assessed without risking to damage the devices, reducing time and cost, besides improving test coverage and reproducibility [8], [9]. On the other hand, PE applications may encompass various switches operating at very high switching frequencies, especially considering the increasing use of wide bandgap devices in sectors such as the e-mobility industry. As a result, in order to capture the effects caused by the switching behavior, one has dynamically complex electrical systems that are really demanding to simulate with high fidelity in real time, requiring high resolution sampling of the gate drive signals (GDS) and very short simulation time steps and, therefore, advanced processing capability and ultralow latency [10], [11].

In this direction, this paper shows how C-HIL technology advanced, improving time resolution and therefore real-time simulation accuracy for high switching frequency applications. First, challenges related to the GDS sampling resolution are discussed and the Global GDS Oversampling method is introduced. A Boost converter operating at 80 kHz is used to illustrate the improvements on the accuracy as a result of this approach. Then, the Switch-level Oversampling method is presented, which allows to deal with more demanding high-switching frequency applications. To illustrate that, a dual active bridge (DAB) converter operating at 250 kHz is taken as a case study. The converter is emulated on the Typhoon HIL404 device, which is built for advanced motor drive and automotive applications, being able to reach simulation steps down to 200 ns with input sampling resolution of 3.5 ns. The control algorithm is implemented in the digital signal processor (DSP) TMS320F28379D, from Texas Instruments. Real-time simulations are performed and the accuracy of the obtained results is analyzed.

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II. Real-time Simulation for PE

Power electronics plants can be modeled based on ideal switches, neglecting dynamics associated to the transitions between switching states. Therefore, the semiconductors are either conducting or blocked, and the commutation between these two states is ideally fast. Nevertheless, real-time simulation devices run in discrete time and typically employ linear state-space equation solvers with fixed time step. To take into account the switching nature of the PE converters, a piece-wise linear approach can be used. In this scenario, the simulation dynamically changes among a finite number of modes, which are linear time-invariant models defined based on the possible states of the semiconductors (i.e., the reachable submodel topologies). Therefore, one has a fixed state-space representation over each simulation time step, for which the matrices can be computed offline during the compilation process and then stored in the solver memory [10].

On the other hand, note that the number of modes grows exponentially with the number of switches, which can lead to high memory resource requirements. To mitigate that, PE converters can be organized as pre-packaged components optimized for real-time execution, with an specialized run time logic that allows to reduce number of reachable modes. In addition, FPGA-based multi-core processors can be used, taking advantage of parallel computing to not only reduce the memory requirements but also to reduce the simulation step size. Those strategies are employed in the Typhoon HIL devices, as the ones used to obtain the results that will be presented in this paper.

As mentioned in the introduction, PE encompass a number of applications which require high-power converters that are operated at high frequencies, demanding high time resolution to achieve accurate simulation results. In this direction, considering fixed time step solvers, if the digital inputs are sampled only at the beginning of each simulation step, the sampling period of the pulse-width modulation signals is equal to the simulation time step. In addition, considering C-HIL applications, the simulation clock is not synchronized with the outputs of the connected digital controller. Therefore, since switching events can only be detected in the simulation step after the event has occurred, there is an inaccuracy to identify the exact instant where the digital input changed its state, leading to variable delays that cause imprecise duty cycle detection and hence inaccurate simulation results. The resulting sampling error depends on when the GDS changes with respect to the simulation steps, and the latency will be in the range from one to two simulation steps. This is shown in Figure 1, where DI represents the digital input (GDS) and X illustrates the state change due to the input event.

Ideally, in offline simulations, these outcomes could be mitigated by arbitrarily reducing the simulation time step at the expense of longer execution times, which is not viable for real-time simulators [13]. Thus, even FPGA based simulators are limited to simulation time steps of hundreds nano seconds, which still poses limitations to the accuracy of simulations for high switching frequency converters.

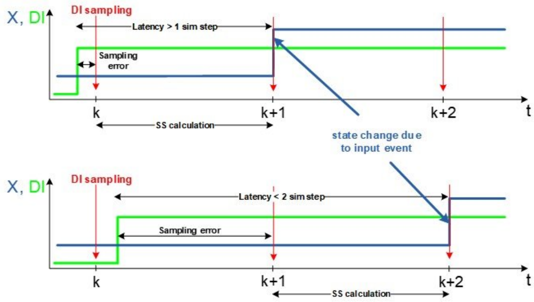

Fig. 1. Sampling error without GDS Oversampling [12].

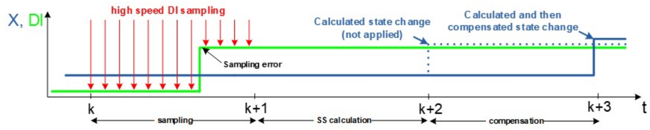

Fig. 2. Illustrative representation of the GDS Global Oversampling [12].

In this regard, although being able to reduce the simulation time step is important, additional strategies to enhance sampled GDS time resolution are also key features, as will be detailed in the next section [14].

III. Strategies for Time Resolution Enhancement

In the following subsections, two strategies for time resolution enhancement will be discussed, namely, the Global GDS Oversampling and the Switch-level GDS Oversampling.

A. Global GDS Oversampling

As mentioned before, the larger the simulation time steps, the larger the GDS sampling error can be, which will translate to larger errors in the state variables calculation. In order to meet high accuracy requirements with limited simulation step sizes, time resolution can be improved by using the Global GDS Oversampling method. In this approach, the driving signals are sampled multiple times within one simulation step, which allows to attenuate the sampling errors. Also, the switching events are time stamped, i.e, the time of the GDS transition is precisely captured, and then used to compensate the state variables [13], [15]. Figure 2 illustrates the Global GDS Oversampling method.

The Global GDS Oversampling algorithm can be summarized by the following steps [12]:

1. Sampling the GDS multiple times within a simulation step and identifying the instant when the change in the digital input occurs.
2. Calculation of the state variables without updating the GDS input. Meanwhile, information about the time when the GDS actually changed is used to calculate the value of states that will be used for the compensation in the next simulation step. These values are not visible at the outputs.

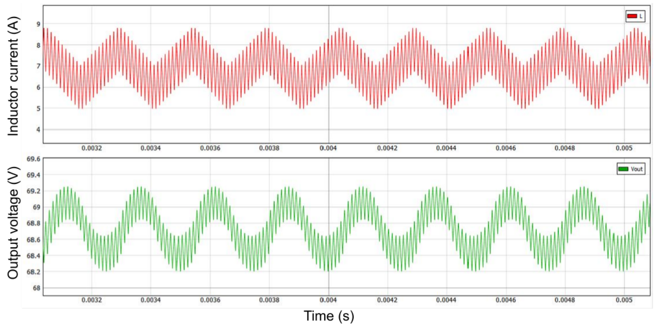

Fig. 3. Boost converter operating at 80 kHz: input current and output voltage without GDS oversampling.

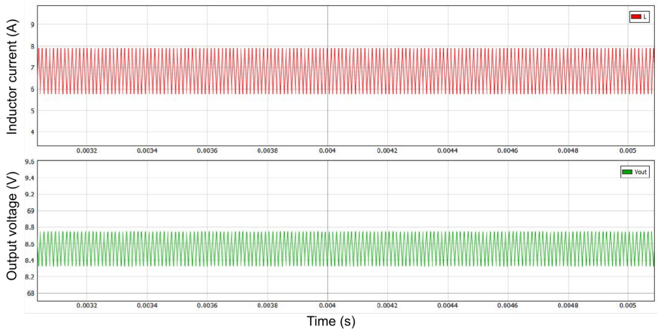

Fig. 4. Boost converter operating at 80 kHz: input current and output voltage with Global GDS oversampling enabled.

3. Third phase is the compensation of states. The temporary calculated states from the previously simulated step and information about the time when GDS changed are used to calculate new state output. After calculation and compensation, the correct value of the state will be present at the output.

To illustrate the improvements on simulation accuracy obtained with the Global GDS Oversampling method, let us consider a Boost converter operating in open-loop with a fixed duty cycle. The converter is driven by an external controller with switching frequency set to 80 kHz, while the real-time simulation runs on a Typhoon HIL402, with time step of 500 ns and GDS sampling period of 6.25 ns. Open-loop operation is chosen to emphasize the effects of the oversampling method without including controller dynamics in the comparison. Figure 3 shows the input current and the output voltage of the converter operating without GDS oversampling. In these results, we can see that the insufficient sampling resolution of the driving signal led to low frequency fluctuations on the converter states, which is an undesired behavior. On the other hand, when the Global GDS Oversampling feature is enabled, one has the results shown in Figure 4. Clearly, we can see that the low frequency fluctuations are mitigated, leading to the expected steady state behaviors.

As shown in the previous results, the Global GDS Oversampling method can significantly improve effective time resolution and therefore extend the range of switching frequencies that can be supported with high accuracy. However, this method leads to an increase in the computational burden and also to the need for an additional time step dedicated for compensation of the state variables. Therefore, the calculation time becomes prohibitive if multiple switching events occur, posing a limit on the number of GDS transitions that can be handled in a single simulation step [13], [15]. In cases where more than one GDS transition usually happen per sub-circuit within a simulation time step, higher accuracy can be obtained by employing oversampling methods that operate at the component level, as will be described in the next subsection.

B. *Switch-level GDS Oversampling*

Differently from previous method, the Switch-level GDS Oversampling is implemented at component level. This means that, instead of relying on the compensation of the state variables after the GDS transition is identified, it actually restructures the power converter model. For that, instead of purely using the ideal switch concept, the switching transitions of every externally commuted switch are modeled by means of controlled voltage and current sources, whose values are defined taking into account the average value of the GDS over the simulation time step. This average value (duty cycle) is calculated based on the digital input oversampling. Therefore, if the GDS resolution is high enough so that the quantization error can be neglected, it is possible to compensate all GDS transitions within that simulation step. Moreover, since the simulation step period is small in comparison to the switching period, the switching ripple will be preserved [13].

To illustrate that, let us consider an IGBT leg, as shown in Figure 5(a). Figure 5(b) shows the implementation of this IGBT Leg component using the Switch-level GDS Oversampling method. Notice that a pair of diodes is also included to support direction-dependent current flow and natural commutation, as well as to enable discontinuous conduction mode.

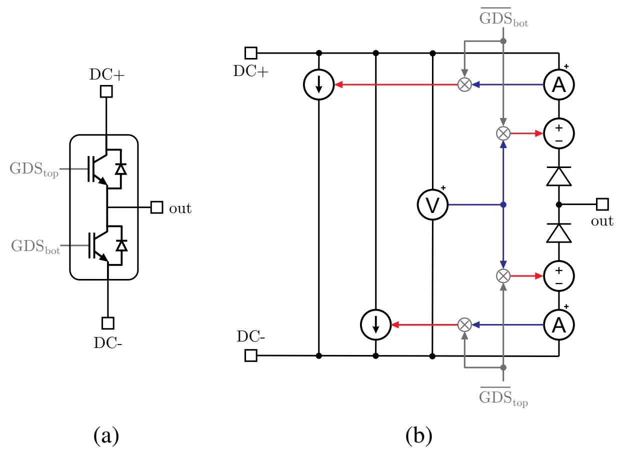

Fig. 5. IGBT leg: (a) ideal component; (b) implementation based on the Switch-level GDS Oversampling method.

For the IGBT leg shown in Figure 5, the Switch-level GDS Oversampling working principle can be summarized by the following steps:

1. Calculation of the average switching signals over the simulation time step ($\overline{\mathrm{GDS}}_{\mathrm{bot}}$ and $\overline{\mathrm{GDS}}_{\mathrm{top}}$) for every controllable switch. Recall that duty cycles are calculated very precisely thanks to small GDS oversampling period.
2. The converter receives information about duty cycles of the gate drive signals. Together with current and voltage measurements, these information are used to control the current and voltage sources and to define the converter‘s output, as shown in Figure 5(b).

As mentioned before, this method allows to compensate all GDS transitions within one simulation step, which is an advantage when compared to the Global GDS Oversampling. Nevertheless, due to algorithm complexity, it also includes a delay of one simulation step between GDS inputs and the state outputs. Moreover, since the model has to be restructured including controlled sources and diodes, it is more complex and computationally expensive then the previous approach.

It is important to recall that while a large variety of models works well with Global GDS Oversampling, Switch-level GDS Oversampling method is indicated for those models which rely on high switching frequencies and where more than one GDS transition often happen during one simulation step. A Typical example are the DAB converters. This case study will be presented in the next section, together with a comparison between the two aforementioned oversampling methods.

IV. Case Study: DAB Converter

The DAB converter was proposed in [16] as a high-power-density bidirectional DC/DC topology. By means of soft switching, the converter is capable of reducing switching losses, therefore enabling operation with high switching frequency. The topology of the DAB converter comprises two single-phase full-bridge inverters and a high-frequency transformer, as illustrated in Figure 6. The series inductor L_D is also highlighted in the figure and, in practice, it represents the leakage inductance of the transformer [17].

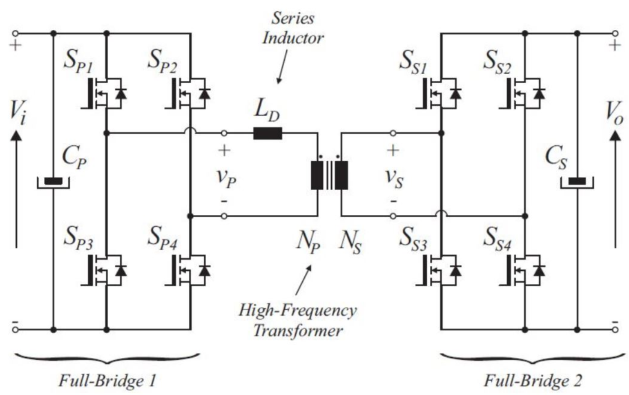

Fig. 6. Topology of the DAB converter [17].

Taking advantage of characteristics such as efficiency, reliability and inherent galvanic isolation, DAB converters have been used in different cutting-edge applications, such as uninterrupted power supplies, microgrids and bidirectional EV chargers. For instance, [18] presents a discrete non-linear controller to regulate the output voltage of a DAB converter operating at 20 kHz, taking into account parametric variations. Suitable results are obtained by means of C-HIL real-time simulations using Typhoon HIL402 device. Regarding EV applications, [6] provides an overview of the advantages of DAB converters for grid-to-vehicle and vehicle-to-grid applications. The system is emulated using Typhoon HIL602 device, and high quality real-time simulation results are provided.

In order to control the DAB converter, the conventional strategy is based on the two-level modulation with phase shift, called single phase shift (SPS). Using this strategy, the power flow can be controlled by changing the phase difference between the carrier signals of the two inverter bridges, while keeping a constant duty cycle. Nevertheless, even with a simple control structure such as SPS, DAB converters operating at high frequencies can be really demanding to simulate in real-time with high precision.

To illustrate that, let us take as a case study the DAB converter with parameters detailed in Table I. Notice that two different switching frequencies (f_{sw}) are considered, in order to compare the simulation performance with the two oversampling methods under different operating conditions.

TABLE I
Case study: parameters of the DAB converter

Parameters	Values	
Maximum power	100 kW	
Input and output voltages	$V_i = 800$ V and $V_o = 400$ V	
Transformer ratio (N_p:N_s)	$1:1$	
Series resistance	$R_D = 100$ mΩ	
Switching frequencies	$f_{sw1} = 50$ kHz	$f_{sw2} = 250$ kHz
Series inductor	$L_{D1} = 8\ \mu$H	$L_{D2} = 1.6\ \mu$H

V. Real-Time Simulation Results

In this section, C-HIL real-time simulation results are presented for the DAB with parameters given in Table I. The converter is emulated on the Typhoon HIL404 device, with a simulation time step of 250 ns and GDS sampling period of 3.5 ns, employing the oversampling methods presented in Section III. Once again, open-loop operation is considered to avoid that controller performance influences the assessment of the simulation accuracy. The SPS modulation is implemented in the DSP TMS320F28379D, from Texas Instruments.

A. Operation with switching frequency of 50 kHz

Initially, consider operation of the DAB converter with switching frequency of 50 kHz and a phase shift PS=50^o. For real-time simulation employing the Global GDS Oversampling method, Figure 7 shows the current through the series inductor L_D, as well as the voltages at the primary and secondary of the transformer (V_p and V_s, respectively). Although the

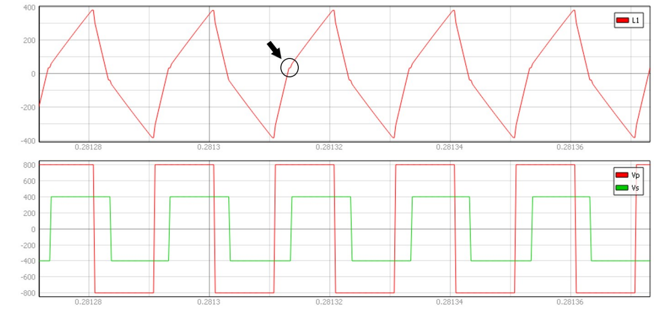

Fig. 7. Operation with $f_{sw} = 50$ kHz and PS $= 50^o$ using Global GDS Oversampling method: (top) current through L_D; (bottom) voltages at the primary and secondary of the transformer.

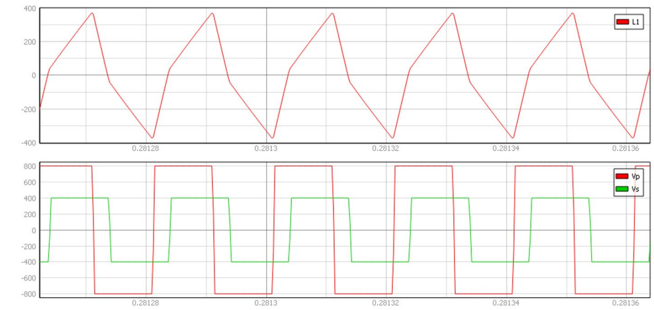

Fig. 8. Operation with $f_{sw} = 50$ kHz and PS $= 50^o$ using Switch-level GDS Oversampling method: (top) current through L_D; (bottom) voltages at the primary and secondary of the transformer.

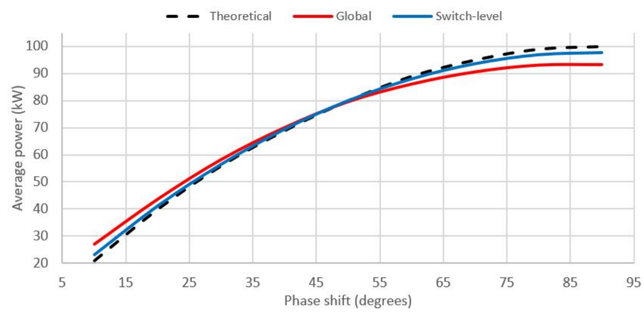

Fig. 9. Average output power as function of the phase shift angle for operation with switching frequency of 50 kHz.

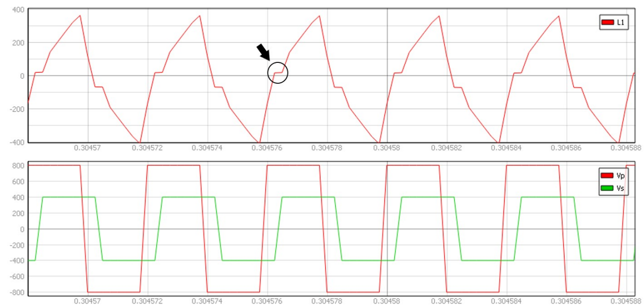

Fig. 10. Operation with $f_{sw} = 250$ kHz and PS $= 50^o$ using Global GDS Oversampling method: (top) current through L_D; (bottom) voltages at the primary and secondary of the transformer.

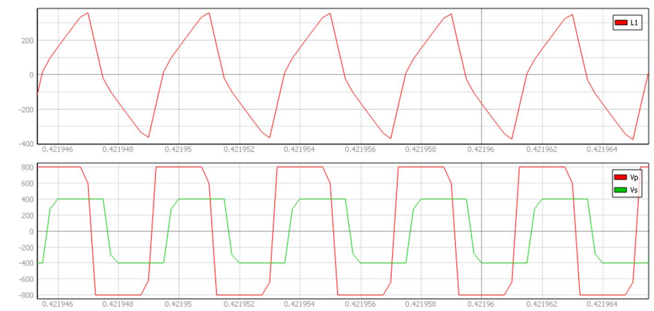

Fig. 11. Operation with $f_{sw} = 250$ kHz and PS $= 50^o$ Switch-level GDS Oversampling method: (top) current through L_D; (bottom) voltages at the primary and secondary of the transformer.

overall results are suitable, it is possible to see that there is an undesired behavior on the current waveforms close to the zero-crossing region, which can be attributed to the multiple GDS transitions and high switching frequency.

On the other hand, Figure 8 shows the waveforms for the same operating conditions, but now obtained with real-time simulation employing the Switch-level GDS Oversampling. One can notice that the undesired behavior pointed out in the previous current waveform is no longer existent, leading to more accurate results. To better illustrate how this affect the overall accuracy of the simulation in different operation points, Figure 9 shows the average output power as function of the phase shift angle employing both oversampling methods. As a reference, the theoretical output power is also plotted [18]. It is possible to verify that both oversampling methods are able to follow the theoretical curve with good precision. Nevertheless, the switch-level GDS oversampling method leads to a slightly better accuracy when compared to the Global oversampling, specially when the phase shift approaches limit values.

B. Operation with $250\ kHz$

Let us now consider operation of the DAB converter with 250 kHz, while maintaining the phase shift at 50^o. For the real-time simulation employing the Global GDS Oversampling method, Figure 10 shows the current and voltages waveforms. Differently from Figure 7, we can notice now a larger imprecision in the current waveform, which is caused by higher GDS sampling errors associated to the significantly higher switching frequency. In opposition, by employing the Switch-level GDS Oversampling method it is possible to properly compensate multiple GDS transitions within a simulation time step, leading to the current waveform shown in Figure 11, where the undesired behavior seen in the previous result was eliminated. The effect of the Switch-level GDS oversampling method can also be seen comparing the voltage waveforms in Figure 10 to the respective ones in Figure 11.

Figure 12 shows the average output power as function of the phase shift angle employing both oversampling methods for operation with 250 kHz. As expected, the Switch-level GDS Oversampling leads to very accurate results. However, differ-

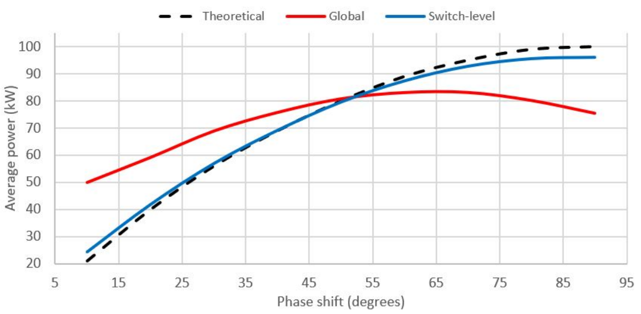

Fig. 12. Average output power as function of the phase shift angle for operation with switching frequency of 250 kHz.

ently from what was concluded for operation with 50 kHz, the Global GDS Oversampling is no longer able to ensure suitable results for the entire range of operation.

Finally, Table II shows a comparison of the computational resource utilization when running without oversampling and also when employing the aforementioned oversampling approaches. As expected, although able to achieve more accurate results, the Switch-level GDS Oversampling method is more complex and computationally expensive, requiring a higher time slot and matrix memory utilization then the Global GDS Oversampling method. It is worth to notice that the utilization values presented in Table II consider that the converter stage is emulated in a single core. Nevertheless, using Typhoon HIL404 device, circuits can be partitioned into up to 4 cores, allowing to reduce hardware utilization and emulate considerably larger systems.

TABLE II
COMPARISON OF THE COMPUTATIONAL RESOURCE UTILIZATION

	None	Global	Switch-Level
Time slot utilization	72.86%	84.29%	98.57%
Matrix memory utilization	34.47%	34.47%	61.94%
Computational latency (simulation steps)	1	2	2

VI. CONCLUSION

This paper presented how enhancements on sampling resolution enabled the use of C-HIL technology to achieve high fidelity real-time simulation results for high switching frequency applications. Firstly, the Global GDS Oversampling method was introduced, and results obtained for a boost converter confirmed that this approach can mitigate the insufficient sampling resolution of the driving signal, improving the accuracy of the simulation for PE applications. Then, the Switch-level GDS Oversampling method was presented, detailing how it is able to compensate multiple switching events within a simulation time step. A DAB converter was taken as case study to illustrate the performance of both oversampling methods, confirming that the presented approaches allow to significantly extend the range of switching frequencies that can be handled with high accuracy by C-HIL real-time simulation.

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HIL-based certification for converter controllers: Advantages, challenges and outlooks

(Invited Paper)

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***Abstract*—Hardware in the Loop (HIL) testing is widely used in automotive, aerospace, and robotics. However, the use of HIL in power electronics is still in its early stages of expansion due to the growing need for advanced grid support functions of distributed energy resources (DER) and microgrids. This paper presents the advantages, challenges, and outlooks of HIL-based certification for converter controllers. It will cover the types of existing HIL tests, the HIL base certification of controllers, and finally, some examples of industry use cases that successfully employ HIL from product development to pre-certification and certification.**

***Index Terms*—Distributed energy resources, Hardware-in-the-loop, power electronics, product development, certification**

I. Introduction

Hardware in the loop (HIL) test methodology is widely applied in automotive [1], [2], aerospace [3], [4] and robotics [5], [6]. In the last decade we observed accelerated HIL adoption for power electronics and microgrid applications; mainly driven by significant deployment of inverter-based distributed energy resources (DERs). DER proliferation brought the idea that they should take an active role to perform ancillary functionalities such as supporting grid stability, power quality, and reliability despite simply feeding power into the electric grid, [7]. Those functionalities are usually referred to as advanced grid support (AGS). To achieve this goal in a coordinated way, some revisions of standards and grid codes included requirements for DER to deliver extra grid supporting functions [8], [9], [10], [11], [12]. Also, the grid support capability does not apply for DER alone but also for microgrids that could contain different power sources, storage systems, and high priority loads, for instance. In this case, there is an extra effort to achieve this goal due to costs to design, deploy and test a microgrid.

Furthermore, DER can autonomously respond to grid demands of providing reactive/active power support, withstand under/over voltage ride through, etc. In this scenario, the complexity of requirements the manufacturers have to comply with will increase depending on how many markets they will be selling a specific product, [13]. Each market has regional requirements that usually demand product configuration case-by-case and a final test from an accredited laboratory. However, it is recurrent the interactions between the product manufacturer and the testing laboratory until the converter controller complies with the requirement of each standard. Regarding the microgrid's higher complexity, there is a risk in the final commissioning stage when deploying in the field. Integration of different sources requires careful configuration and intense testing to avoid unwanted interactions among the devices under all operating scenarios, [14].

Moreover, advancements in FPGA and CPU technologies paved the way towards real-time simulators for fast dynamic systems such as power electronics, where it is necessary to have real-time simulation time steps in the sub-microsecond range. Fig. 1 contains the different testbed platforms available and the trade-off between test fidelity and test coverage. The test fidelity represents how accurate the testbed reflects the behavior of the deployed system and the test coverage represents the range of test conditions that can be safely executed. The traditional development procedure consists of employing a simulation tool, building the prototype, and performing limited and full power laboratory tests. The simulation tool has good test coverage flexibility but provides limited test fidelity, [15]. HIL testing can be deployed to increase test fidelity while maintaining high test coverage. In the power electronics field, for example, the power stage could be simulated in real-time, while the controller remains the same as it will be if embedded in the real system. This type of HIL methodology is called controller hardware-in-the-loop (C-HIL). If the equipment under test (EUT) is a full-size, full-power converter, it has to be interfaced with the real-time simulation through high power amplifiers. This system is called power hardware-in-the-

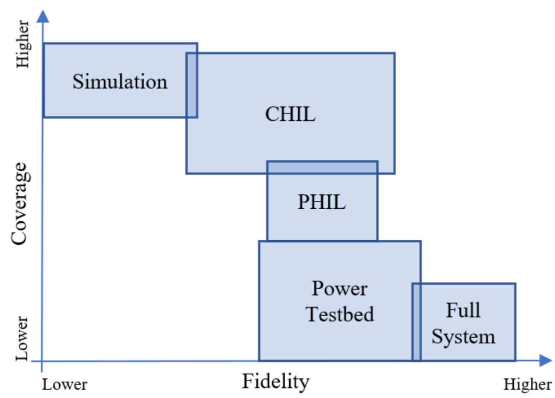

Fig. 1. Comparison between testbed types, adapted from [15].

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loop (PHIL). PHIL is used where a full-power component of a system has to be tested within the larger system, for example. The next possible testbed would be the power testbed. This testing type has a higher test fidelity but also has the drawback of reduced test coverage, once the test is limited to the test bench equipment and laboratory operators' knowledge. Finally, the full system test has the highest test fidelity and the lowest test coverage. This type of test represents the real system test in the final installation point, a wind turbine in its final power plant, for example. Recently, some studies were conducted to review the traditional certification process to include HIL-based tests as part of the certification testing, [16]. Also, the power electronics industry increasingly applies HIL in the product development cycle, starting from early research to pre-certification testing.

In this scenario, to reduce the time and cost to deploy a DER or a microgrid, C-HIL testing can be applied to test controllers, protections, and AGS. The C-HIL scheme can provide a broad test coverage, similar to a computational simulation, and test fidelity, close to PHIL or a power testbed, if the models are well validated. This paper will present some use cases that apply C-HIL-base certification for converters controllers from laboratories and industry. It will further address some highlights of the HIL-based certification advantages, challenges, and future outlook, and finally, a conclusion.

II. Use cases

This section presents some use cases that apply HIL-based testing capable of certifying converter controllers.

A. Austrian Institute of Technology and Sandia National Laboratories

The first use case [7] is a partnership between the Austrian Institute of Technology (AIT) and the Sandia National Laboratories (Sandia). They developed C-HIL testing for rapid and concurrent development of converter controls for interconnection standards, Fig. 2. This C-HIL testbed platform applies the Typhoon HIL602 (already updated by Typhoon HIL604) integrated with the SunSpec System Validation Platform (SVP) and the Equipment Under Test (EUT) for testing UL 1741 SA requirements [8].

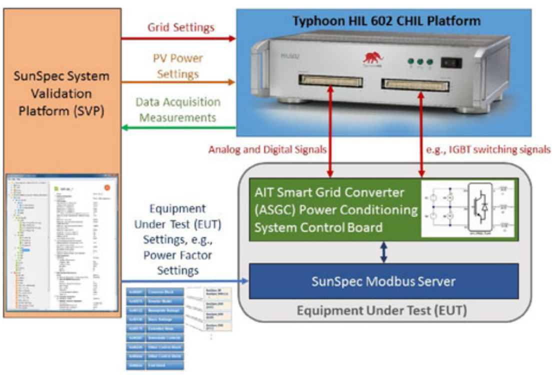

Fig. 2. AIT and Sandia C-HIL testing, [7].

In this application, the EUT represents a two-quadrant 34.5-kW grid-tie PV inverter that can provide a broad range of AGS. The EUT operating modes and settings are controlled by the smart grid controller via SunSpec Modbus Server. The SVP was designed as UL 1741 SA [8] control center. Thus the SVP enables portability of the test sequences, capability of autonomous testing, and reduction of configuration time.

Fig. 3 shows the power factor (PF) test results. This function requires a change in the power factor value settings in three different power levels, and each of these power factor values is measured three times. The black dashed lines in the active–reactive power (P–Q) plane indicate the target power factors, the red dashed lines indicate boundary levels, and the four colored markers represent the EUT output for each of the PF levels. The EUT accurately reached the PF target within the passing bounds in all but three tests at PF=-0.20, [7].

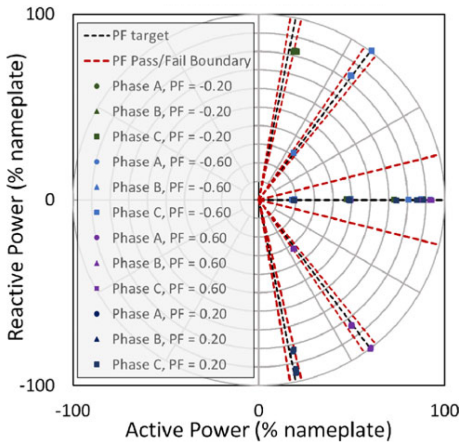

Fig. 3. PF test results on a P-Q plane, [7].

Fig. 4 shows the frequency-watt (FW) test. This function is designed to support bulk system operation in the case of high generation or load tripping. The function is typically programmed to only reduce power in over-frequency scenarios for PV systems in order to prevent system instability. The black dashed lines indicate the target output power, the red dashed lines indicate boundary levels, and the three colored markers represent the EUT output, [7]. Again the results from C-HIL testing are inside the expected boundaries.

B. Austrian Institute of Technology

The second use case is from AIT. They developed a C-HIL testing for pre-certification of grid code compliance for solar inverters, [17]. The platform consists of software automating the test procedures (called Pre-Cert Toolbox) running in the Typhoon HIL602 (already updated by Typhoon HIL604), an EUT in form of the converter controller board connected to a digital real-time simulation system and a simulation model of the power stage, grid and DC sources, Fig. 5.

The fidelity of the simulation is mainly determined by the time resolution of the model and the accurate representation of electrical components (IGBT switches, magnetic, loads, etc). Each of these aspects needs to be considered to ensure realistic

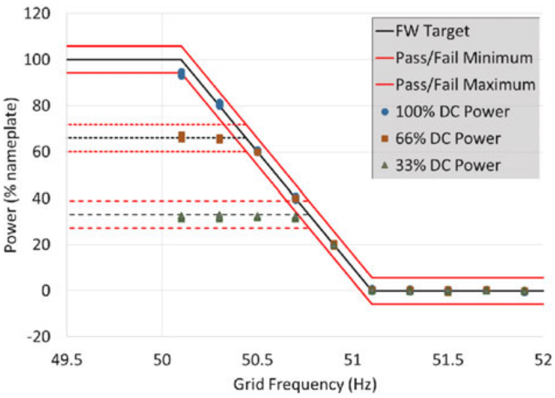

Fig. 4. EUT Frequency-Watt response, [7].

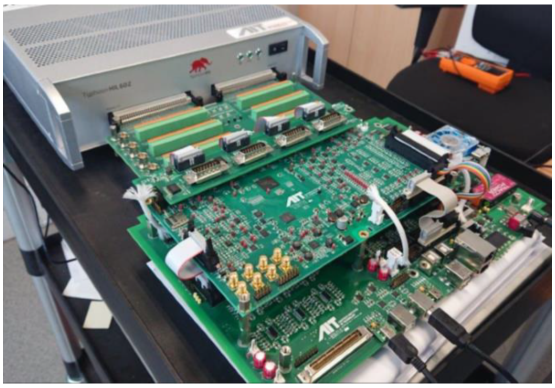

Fig. 5. View of the converter controller board connected to Typhoon HIL via an interface board, [17].

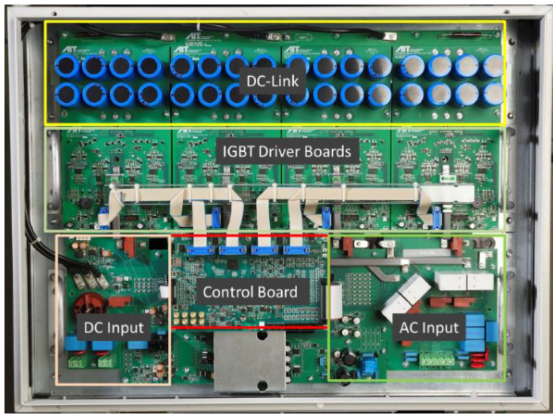

Fig. 6. View of the full-scale inverter (34.5 kVA DC-AC) showing DC link (yellow), IGBT power boards (light green), control board (red), DC input (white) and AC input boards (green), [17].

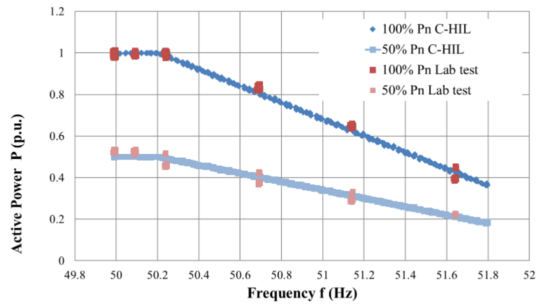

Fig. 7. Comparison of the results from C-HIL and power testbed for Frequency-Watt, [17].

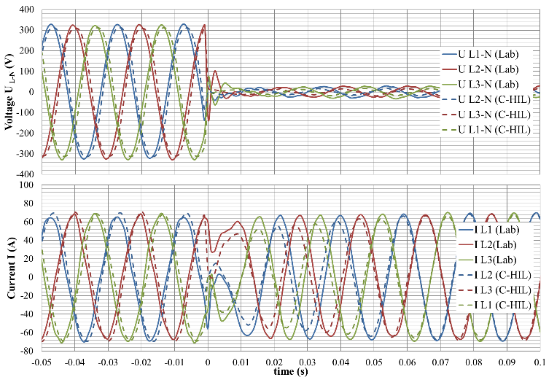

Fig. 8. Comparison of the results from C-HIL vs power testbed for a transient UVRT, [17].

behavior and accurate results from the C-HIL testbed. The C-HIL testbed implements the full set of test items defined in widely used test specifications in Europe as VDE 0124-100 [11] and FGW TR3 [12].

The C-HIL results were compared with the traditional power testbed. In the traditional test, the converter controller board is connected to the DC-AC 34.5 kVA, 3-phase 4 wire, neutral-point-clamped inverter with IGBT switches, Fig. 6.

Fig. 7 shows the comparison of the measured response from C-HIL and real laboratory testing for the frequency-watt (FW) test. The complete sequence is repeated for two active power levels, 100% and 50% of the rated power (Pn). Fig. 8 shows the comparison of the measured response from C-HIL and real laboratory testing for the Under-Voltage Ride Through Test (UVRT). Both tests were performed using a procedure defined in FGW TR3, [12], where the converter controller was programmed to provide the required reactive current Ib according to the grid voltage drop as defined in [18].

In both cases, Fig. 7 and 8, it is possible to verify the correlation of the results, both in steady-state and transient behavior. This validates the model, hence results from C-HIL will very likely e reproduced in the power laboratory.

C. Hitachi ABB Power Grids

The third use case is the microgrid and controller test by Hitachi ABB e-mesh solution. The e-mesh solution is a digital concept that allows the management of distributed energy resources from the converter level through the microgrid system [19]. The battery storage system for this application could be up to 1 MW, [20] and by applying Typhoon HIL604 C-HIL testbed in the e-mesh environment it is possible to better design the microgrid and converter controller to cover the desired needs in the early stage of the development of the project. Before the C-HIL methodology, it was usual to do on-site testing. However, that implies a limited time frame to run the tests and a limited number of test cases that can be executed. In the C-HIL testing, it is possible to simulate some specific conditions, such as a grid disconnection event, and pre-certificate the controllers, [21]. In this way, it is possible to verify the response of converters controllers and monitor the response of the battery energy storage system to keep the grid alive with limited disturbances, Fig. 9.

Another great benefit of using C-HIL is to automate all the necessary tests. By doing so, it becomes easy and inexpensive to run all the required tests and receive a full report before sending the converter to the certification laboratory. It allows the company to run pre-certification tests, fix any issues in the converter firmware, and run all the tests again to guarantee that the new firmware version did not cause unexpected errors in other operating conditions.

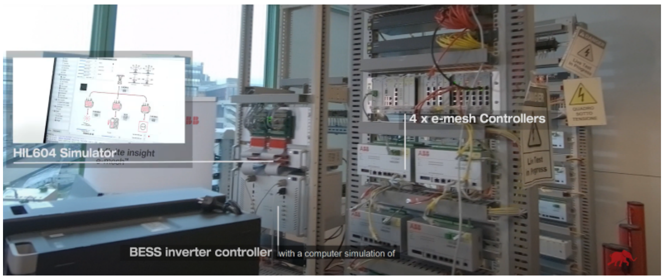

Fig. 9. E-mesh C-HIL testing, [21].

D. EPC Power

The fourth use case is the converter controller test by EPC Power. The EPC Power laboratory infrastructure allows the development and testing of power electronics converters on the megawatts scale. However, the power testbed operation time is expensive, time-consuming, hazardous for humans and adjacent equipment. To overcome these issues it was developed a C-HIL testbed with the Typhoon HIL602 (already updated by Typhoon HIL604), the interface board, and the converter controller board running the same inverter software like the one in the final product, Fig. 10, [22]. Additionally, the C-HIL testbed allowed control engineers to develop the firmware in parallel to the hardware team, reducing the development time by at least 6 weeks. After the hardware was done, it was possible to test the converter with full power within a couple of days.

An exciting development case was troubleshooting a resonance issue with the output filter of the inverter against a specific grid impedance. The resonance did not occur in the pure simulation software, but only in the full system commissioning. When the parameters were loaded and tested using the C-HIL testbed the same resonance appeared allowing its mitigation, [22].

Regarding the certification tests, the C-HIL testing allows the pre-certification of the converter controller before going to the traditional laboratory power testbed. For instance, the anti-islanding tests that consume a third of the total traditional test time can be performed in a couple of minutes when using the C-HIL testbed. The UL 1741 SA certification of the 375 kW and 500 kW inverter was initially performed on the C-HIL testbed. After the satisfactory performance of the controller, full power tests were performed, following the standard procedure, where no changes to the firmware were necessary, [22].

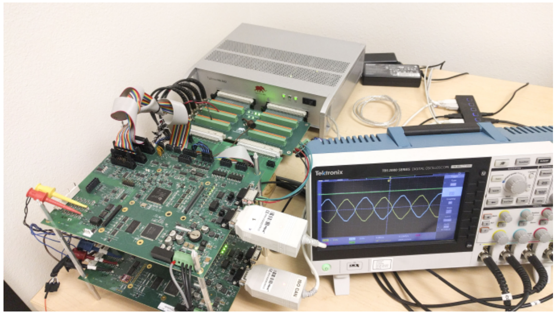

Fig. 10. EPC Power C-HIL testing, [22].

E. Schneider Electric

The fifth use case is the converter controller testing by Schneider Electric. The Schneider laboratory infrastructure allows the development and testing of power electronics hybrid inverters for residential storage. Like the previous use case, Schneider Electric also experienced the setback when developing a converter controller for different standards and markets. The certification process was time-consuming, expensive, thus, a C-HIL testbed was built. The testbed comprised Typhoon HIL602+, the interface board, and the converter controller boards. This platform can perform pre-certification tests and speed up development. Fig. 11 shows the example of an anti-islanding C-HIL schematic diagram for controller pre-certification. They also created an automated test execution environment so every time the firmware is updated, a full regression test is performed on C-HIL testbed. Finally, the C-HIL application was expanded to test different microgrid configurations often encountered in the field [23].

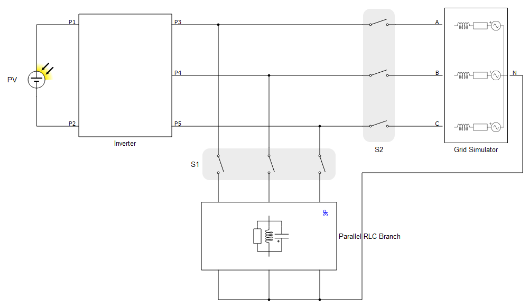

Fig. 11. Example of C-HIL testing for anti-islanding.

III. Advantages, challenges and outlook

This section address the advantages, challenges, and outlooks from the point of view of testing laboratory and industry.

A. Advantages

The advantages of the HIL-based approach over traditional power testbeds are remarkable, not only for testing laboratories but also for the industry. The common advantages between both would be: It is possible to reduce the infrastructure needs for testing, reduce the time needed for testing, there is no risk of damaging any equipment, it is possible to achieve test conditions that are not feasible in the field or the laboratory, and updating the firmware is inexpensive if needed. It also will allow the flexibility to operate a range of systems (single-phase, three-phase, etc), different rated power, and advanced grid support functions. The testing laboratory will have a well-defined, repeatable, standardized test procedure with minimal chances for human error. It also will be able to expand the test coverage they can offer for other standards, grid codes, and application-specific requirements. The industry will be able to evaluate control logic and interoperability interfaces prior to integration with hardware, perform a quick check of project changes, and speed up the development of products even with different standards and grid codes.

B. Challenges

Regarding the general challenges, it is possible to highlight that this is a new tool for most laboratories and industries. Thus it will require an initial investment in equipment and training. However, the main challenge would be to change the culture of testing or developing products. Also, the controller-simulator interface would need to be validated and perhaps even certified due to the profound impact on test results it might have.The testing laboratory will have to develop a way to validate the C-HIL model to ensure that the obtained results are trustworthy. It could be performed with a benchmark between the real vs C-HIL test in a well-defined set of key operation points, for instance. In the same way, the industry will have to develop a methodology to create the converter/microgrid model to be validated and tested in the C-HIL testbed.

C. Outlook

The outlook for this technology in the field of power electronics, microgrids, and power systems is to become widely adopted by testing laboratories and the industry. Several studies from testing laboratories and experiences from the industry already validated numerous benefits of applying HIL-based pre-certification for converter controllers in several applications, from converter-level to the microgrid-level. However, even without the C-HIL based certification being included in the traditional certification process, the industry use cases have demonstrated how helpful it is in shortening and streamlining the certification process by providing means of running accredited laboratory-grade tests in-house. Once the C-HIL test technology becoming well-adapted, the standard bodies could provide traditional standard documents together with the required testing code. It would simplify the process of grid code compliance testing, nudging the academia to develop new control strategies able to bring additional grid support capabilities.

IV. Conclusion

The HIL testing methodology is widely used in many areas such as robotics, automotive, and aerospace. Recent advancements in FPGA technology allowed the creation of real-time simulators for fast dynamic systems necessary for power electronics. Additionally, the increasing presence of DER connected to the electric grid and their capability of performing AGS lead to standards and grid codes revisions to include extra grid support functions. In this scenario, the complexity of requirements manufacturers have to comply with increases depending on which markets they are selling a product. Therefore, HIL-based testing provides a highly effective solution for converter control verification against an ever-increasing number of grid code requirements. It also allows seamless, risk-free test automation, ensuring repeatability of the test procedure and regression testing.

This paper presented several examples where C-HIL pre-certification of converter controllers was implemented with success. The examples covered certification laboratories and industries. They confirmed that the HIL-based certification and pre-certification can improve the DER development process, enhancing quality, and reducing costs and time-to-market. Thus, this technology should be considered as part of the traditional certification process. Most of the use cases were listed as early generation HIL simulators that still showed a satisfactory level of fidelity. Meanwhile, the setups were updated to the latest generation devices able to provide results that are even closer to the actual field measurements.

The main advantages of HIL-based product certification are the ability to reduce the infrastructure needs for testing, the time needed for testing, the risk of damaging the equipment, and the possibility to achieve test conditions that are not feasible in a tests laboratory. Complete HIL-based product certification also requires additional steps in the industrial process, such as models and interface validation, which might be a challenge, changing the culture of testing or developing products and validating the C-HIL model, the simulation interface, for example, could be a challenge. Further, some studies from testing laboratories and experiences from the industry already validate the benefits of applying HIL-based pre-certification for converter controllers. The applications covered the converters controller, as well as microgrids with several converters. Nevertheless, the presented examples confirm that benefits significantly outweigh the added effort and we expect accelerated adoption from both, become increasingly adopted from the testing laboratories and the industry.

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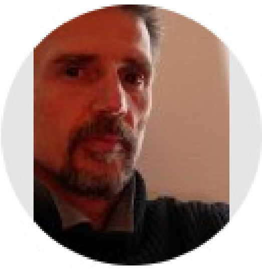
IL

INVITED LECTURES

IL1.1
Thierry Meynard, France

SELF DESIGNING BLOCKS: TURN YOUR SIMULATION SOFTWARE INTO A PRE-DESIGN TOOL

Abstract – Simulation software allow finding the input and output signals produced by a given set of devices connected in a given configuration and controlled with a given pattern. Is it possible to invert the process : can we determine which components, topology and control should be used to produce a given set of input/output signals? Self-designing blocks are a first answer to this problem. Composed of a visible layer with an elementary piece of circuit and a hidden data-flow layer with a set of local design equations, they can be assembled freely and connected to input/output power sources including user-defined requirements. Connecting these blocks apparently builds a standard circuit, but it also creates automatically a system-level design algorithm by assembling through hidden connections the local pieces of code included in each block. These blocks can be an aid for junior engineers or to speed-up preliminary design, but it could also be a way to encapsulate the know how of specialists of different subsystems, component and topology to share more widely their knowledge and make it available in a homogenous form to a wider public.



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Thierry Meynard (Fellow, IEEE) graduated from the ENSEEIHT (École Nationale Supérieure D'électrotechnique, D'électronique, D'informatique, D'hydraulique et des Télécommunications), Toulouse, France, in 1985, and received the Ph.D. degree in electrical engineering from the National Polytechnic Institute of Toulouse, Toulouse, France, in 1988.,In 1988, he was a Doctor in Electrical Engineering with the Institut National Polytechnique de Toulouse, Toulouse, France, and was then an Invited Researcher with the Université du Québec à Trois-Rivières, Trois-Rivières, Canada, in 1989. He joined the Centre National de la Recherche Scientifique (CNRS), as a Fulltime Researcher in 1990, and was the Head of the Static Converter Group from 1994 to 2001.

From 2010 to 2018, he was an Associate Director with the National Program Three-Dimensional Power Hybrid Integration (3-DPHI). He is currently a Directeur de Recherches with CNRS, Laboratoire Laplace, Toulouse, France, but in parallel he has been also involved in several industry-related activities. From 2000 to 2016, he was a Part-time Consultant with Cirtem. In 2016, he cofounded and became a Scientific Advisor with the company Power Design Technologies that develops PowerForge, the software for designing of two- and multilevel power converters. And in January 2020, the consulting company “EIRL Thierry Meynard” was created to help theoretical knowledge to become industrial products. He is coinventor of several topologies of multilevel converter used by ABB, Alstom, Cirtem, General Electric, Schneider Electric: “Flying capacitor,” “Stacked MultiCell,” “5LANPC,” “AC/AC chopper,” and “xPlexed choppers.” His main research interests are related to the series and parallel multicell converters, magnetic components, and development of design tools for power electronics. (Based on document published on 19 October 2020).

IL1.2
Alessandro Lidozzi, Italy

PHIL – POWER HARDWARE IN THE LOOP FOR THE REAL-TIME POWER EMULATION OF ELECTRICAL MACHINES

Abstract – The real-time emulation of power electronics systems has today reached levels of precision and accuracy hardly imaginable only a decade ago. The main beneficiary of the introduction of Hardware-In-the-Loop (HIL) simulators on the market has been the development of control algorithms. The possibility of verification and the flexibility in the reconfiguration of systems without hardware, has perfected the development of increasingly complex regulation strategies, testing them in total safety environment and with reduced costs due to the absence of the experimental setup. The next step was the introduction of power amplifiers alongside HIL solvers: the power simulation of complex converters is now possible on a large scale. However, the electrical machine emulation sector has benefited least from the introduction of HIL systems. If on the one hand it is now possible to simulate an electric machine in real time in a completely virtual system, on the other hand it is not yet possible to fully emulate its behavior in power through PHIL, and therefore through power amplifiers. The power emulation of electrical machines will be the leitmotif that will guide through the Power Hardware In the Loop (PHIL) systems for static emulation of rotating electrical machines.

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Prof. Alessandro Lidozzi received the Electronic Engineering degree and the Ph.D. degree from the Roma Tre University, Rome, Italy, in 2003 and 2007, respectively.
Since 2017, he has been an Associate Professor with the C-PED, ROMA TRE University. His research interests are mainly focused on power converters and electrical machines modeling and control, Hardware-In-the-Loop simulators and Power-Hardware-In-the-Loop emulators, graphical programming of FPGA and development of high-performance control platforms based on combined DSP-FPGA targets.

IL1.3
Gerald Deboy, Austria

ON THE TRUE VALUE OF WIDE BANDGAP POWER DEVICES FOR LOW AND HIGH POWER APPLICATIONS

Abstract – Based on the physical properties of power devices based on wide bandgap materials we will analyze in this contribution their true value in comparison to their silicon counterparts. Even though we can compare FoMs such as switching losses and their perspective on device level, a value-based evaluation needs to draw conclusions on system level taking into account topology, control and required ruggedness features. We are using advanced Pareto front analysis techniques to model thousands of possible designs for a given task to find best matches along the dimensions of power density, efficiency and cost.
The talk will present use cases ranging from low power applications such as quick charging of mobile phones to high power applications in server/telecom and EV charging.

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Dr. Gerald Deboy received the M.S. and Ph.D. degree in physics from the Technical University Munich in 1991 and 1996 respectively. He joined Siemens Corporate Research and Development in 1992 and the Semiconductor Division of Siemens in 1995, which became Infineon Technologies later on. His research interests were focused on the development of new device concepts for power electronics, especially the revolutionary COOLMOS™ technology. From 2004 onward he was heading the Technical marketing department for power semiconductors and ICs within the Infineon Technologies Austria AG. Since 2009 he is leading a business development group specializing on new fields for power electronics. He is a Sr. member of IEEE and has served as a member of the Technical Committee for Power Devices and Integrated Circuits within the Electron Device Society. He has authored and coauthored more than 90 papers in national and international journals including contributions to three student text books. He holds currently 130 granted international patents and has more applications pending.

T1

POWER CONVERTERS AND DEVICES

Paper No. T1.1-1

MINIMIZATION OF COMMUTATION LOSSES IN LLC RESONANT CONVERTER WITH GAN HEMTS AND SI BASED MOSFETS

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Abstract: *Highly efficient and high-power density power electronics applications require semiconductor devices with minimized power losses. Traditional Si based MOSFET transistors are limited by maximum operating frequency unlike GaN transistors. The combination of high critical breakdown field and high electron velocity and mobility in the GaN material system provided a path to highly efficient end compact power conversion applications. This paper provides brief comparation of Si MOSFETs and GaN transistors in high-frequency highpower density application as LLC resonant converter which is increasingly represented in the industry. Overlapping gate to source signals method for commutation losses reduction is presented. The same method is examined on couple of Si and GaN transistors available on the market first in Ltspice simulation package and further on LLC GaN HEMT's resonant converter developed prototype. The experimental results of commutation loss reduction are presented.*
Key Words: ***GaN transistors, LLC resonant tank, dead-time analysis, high efficiency, high-power density***

Paper No. T1.1-2

ANALYSIS AND MODELING OF TEMPERATURE DEPENDENCE OF I-V BEHAVIOR IN SILICON CARBIDE MOSFETS

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Abstract: *In this paper, we present a physics-based simulation model for SiC MOSFETs which is vaid from -55 °C to 175 °C. Using the proposed physics-based formulation we find for the first time the variation in key device parameters with temperature from -55 °C to 175 °C. It is found that the presence of a large interface charge density affects variation of threshold voltage, and mobility of the channel region of the SiC device. The mobility and saturation velocity of the drift region varies differently with temperature as drift region is away from the interface. A good model agreement between model and measured data is obtained for full I-V plane across three temperatures.*
Index Terms: ***SiC MOSFETs, SPICE models, Compact models, Temperature effects SiC.***

Paper No. T1.1-3

SIC MOSFET JUNCTION TEMPERATURE ESTIMATION BASED ON OUTPUT CHARACTERISTICS INTEGRATED ON GATE-DRIVER

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Abstract: *This paper is focused on developing the approach for junction temperature (T_J) estimation by knowing relevant switch information on the gate-driver (GD). The device switch-current I_d and the on-state drain-to-source $V_{ds;on}$ enable the online T_J estimation. The knowledge of T_J can enable active thermal control as well as condition monitoring of the SiC MOSFET device, tackling the long-term reliability aspects. With the aid of a FPGA on GD, a look-up table in FLASH memory containing device output characteristics is assessed, enabling real-time T_J monitoring for both devices in the commercial SiC MOSFET half-bridge module configuration. Following the developed gatedriver prototype, the T_J is verified with maximum error less than 5 °C having excellent repeatability of ±1:2 °C and is furthermore verified in continuous operation showing promising results.*
Index Terms: ***SiC MOSFET, gate-driver, junction temperature, Rogowski, on-state voltage measurement, wire-bond degradation.***

Paper No. T1.1-4

TEST BENCH SETUP FOR CHARACTERIZATION OF GAN HEMT

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Abstract: *This paper presents a setup to characterize GaN HEMTS devices under short-circuit events and the degradation of some of their parameters. First, the previous literature in the field is introduced. Both, the behavior under single and repetitive short-circuits and failure mechanisms are discussed. Then, a systematic method is proposed to "on-board" measure the critical electrical parameters and analyze the behavior of DUTs under short-circuit failures to build a reliability model. Subsequently, multiple tests with different conditions have been performed to characterize in detail GaN HEMTs. Finally, pure short-circuit tests have been performed to identify critical parameters and aging indicators. The reliability challenge of GaN devices could be addressed by having on-board, in-system prognostics, and device health monitoring techniques to predict device failures well ahead of time.*
Index Terms: ***Short circuit, device degradation, E-mode GaN HEMT, reliability, measurement, health monitoring.***

Paper No. T1.1-5

GAN AND SUPERJUNCTION MOSFET TRANSISTOR SWITCHING IN A RESONANT SWITCHED-CAPACITOR CONVERTER

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Abstract: *The paper presents switching process comparison among the gallium nitride (GaN) and the Superjunction (SJ) MOSFET transistors applied in the resonant switched-capacitor (SC) DC-DC converter. The topology belongs to the class of circuits where losses and EMI generation associated with an output capacitance of transistors are significant. An effect of the output capacitance of switches on the converter's operation is examined by the switching waveforms analysis. An impact of temperature is demonstrated as well. Methods of improvement of switching quality by application of zero-voltage-switching (ZVS) mode and application of GaN switches are discussed. The paper bases on experimental results.*
Index Terms: ***Gallium nitride transistor, DC-DC converter, Superjunction MOSFET, C_{oss} losses, switching losses***

Paper No. T1.1-6

ANALYTICAL PFC BOOST INDUCTOR POWER LOSS CALCULATION METHOD IN CCM

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Abstract: *This paper proposes an analytical approach for calculation of power loss incurred across an inductor of the boost-based power factor correction converter working into the continuous conduction mode of the current. Despite the fact the method presented herein is limited to the ferrites only, it overcomes many complicated formulae with regards to the inductor power loss, which makes it suitable for simple and straight-forward implementation into the commercial designs. The method accuracy is verified against power loss obtained from the FFT analysis of the inductor current.*
Keywords: ***power factor correction, inductor, power loss, winding loss, core loss, fringing factor, boost converter, switchmode power supply.***

Paper No. T1.1-7

ANALYTICAL DESIGN OPTIMIZATION OF PFC BOOST INDUCTOR IN CCM

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Abstract: *This paper describes in details an analytical design optimization procedure of the PFC Boost inductor working in continuous conduction mode of the current. The method finds an optimal solution based on the inductor's minimum power loss and its geometrical volume, the factors, which depend on assumed PFC working conditions. Moreover, the method sweeps through the magnetic flux densities and inductor current ripples assuring rejection of these inductors, which are not possible to build, otherwise delivering 2D and 3D matrices of optimal designs.*
Keywords: ***power factor correction, inductor optimization, inductor, power loss, winding loss, core loss, fringing factor, boost converter, switch-mode power supply.***

Paper No. T1.1-8

MODELING AND SIMULATION OF POWER THYRISTORS IN POWER SUPPLY FOR INDUCTION HEATING WITH RESPECT TO THEIR FAILURE RATES AND RELIABILITY

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Abstract: *This paper discusses the issues related to the accurate modeling and simulation of the operation of rectifiers and inverter thyristors in a high-power induction heating system. Based on the obtained results, a comparison is made with respect to of the values of some parameters. Simulation studies were used to determine the losses in high-power thyristors needed to calculate their failure rates and reliability levels.*
Keywords: ***failure rates, induction heating, reliability, thyristors, PSpice, macromodel.***

Paper No. T1.2-1

ANALYSIS, MODELING, AND SIMULATION OF THE MULTIPLE OUTPUT FLYBACK CONVERTER USED IN VARIOUS MOTOR DRIVE APPLICATIONS

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Abstract: *Flyback converters are highly preferred due to their affordable costs in industrial, and automotive applications such as electric motor drives where multiple isolated outputs are required. A detailed analysis approach has been proposed to model and simulate a multi-output Flyback DC-DC converter circuit operating in continuous conduction mode (CCM). The originality of the method comes from modeling main critical components such as multiple output Flyback transformer thoroughly. Modified Nodal Method is used in order to obtain the system equations. Simulation results are presented as an illustration of the proposed modeling approach.*
Keywords: ***Multiple Output Flyback, DC-DC Converter, Modified Nodal Analysis, Modeling, Simulation, Motor Drive***

Paper No. T1.2-2

ACTIVE-CLAMPED FLYBACK DC-DC CONVERTER IN THREE-PHASE APPLICATION

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Abstract: *The active-clamped flyback (ACF) dc-dc converter is typically used in applications with universal singlephase mains input. In this paper, design notes, simulation and experimental results of an ACF, supplied from rectified threephase mains, are presented. Additionally, notes on simulation and measurement of the transformer magnetizing inductance are provided too. This ACF is designed to provide 5.5 V at its output with voltage-conversion ratio in range from 83.6 to 116.4. It was planned to use it as an auxiliary stand-by power supply of a wireless inductive-charging system. A 13 W prototype was built and tested. Maximum achieved efficiencies at 460 V and 640 V dc voltage inputs, with 100 % load, were 72.6 % and 69.1 %, respectively. The known fact that converters with high voltage-conversion ratio might suffer from lower efficiencies is, unfortunately, confirmed with the ACF topology as well. However, resulting efficiency, that is comparable with classical Flyback dc-dc converter, reduced EMI, ZVS operation and good thermal behavior could justify usage of the ACF in threephase applications that are not cost-sensitive.*
Keywords: ***Active-clamped, flyback, high voltage-conversion ratio, magnetizing-inductance measurement, simulation, transformer design, three-phase application***

Paper No. T1.2-3

ANALYSIS, MODELING AND SIMULATION OF TWO STAGE BUCK-BOOST CONVERTER WITH SWITCHED-CAPACITOR

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Abstract: I*n this paper, an efficient approach is proposed for the analysis, modeling and simulation of a two-stage switched-capacitor buck-boost converter, one of the new prototypes of DC/DC conversion technology. Switch and diode elements are considered ideal for a better understanding of the proposed method for efficient analysis of the two-stage switched-capacitor buck-boost converter. However, the proposed method is also valid for circuit analysis with non-ideal elements. The method allows performing the analysis on a single equation system despite the changing topologies caused by the switches on states and off states of the switches. In order to obtain system equations, the basis of the analysis, the modified nodal analysis method (MNA) is used, and the switches are included directly in the system equations. The system of equations is solved in a computer environment with the help of numerical methods and the study is supported with simulation.*
Keywords: ***Switched-Capacitor, Buck-Boost, DC-DC Converter, Modified Nodal Analysis, Modeling, Simulation***

Paper No. T1.2-4

A NEW TAPPED INDUCTOR QUADRATIC DC-DC CONVERTER

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Abstract: *In this paper a new quadratic Boost converter with coupled inductors is presented. The static conversion ratio is calculated together with the dc inductor currents and capacitor voltages. The state-space large signal and small signal models are derived and the control-to-output and the audiosusceptibility transfer functions are determined. The theoretical concepts were verified through computer simulation.*
Keywords: ***quadratic dc/dc converter, tapped inductor, ideal transformer, static conversion ratio, small-signal transfer functions***.

Paper No. T1.2-5

GENERALISED FOURIER SERIES MODEL FOR DUAL ACTIVE BRIDGE DC/DC CONVERTER BASED ON TRIPLE PHASE SHIFT MODULATION METHOD

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Abstract: *This paper presents a generic model for the dual active bridge DC/DC converter. The model is based on the Fourier series of the switching functions of the converter. The switching functions are firstly derived with all the possible control variables identified for the converter. The triple phase shift modulation control method is realised for this work. Other modulation methods such as the phase shift control, dual phase shift control and pulse-width modulation control can be derived from the triple phase shift control model. The dynamic harmonic model of the DC capacitor voltages, DC currents, AC voltages and the AC inductor current are derived. The harmonic model is verified using MATLAB/Simulink software to match the derived model with a detailed switched model of the dual active bridge DC/DC converter. Further, a 500 W 24/100 V prototype is built to confirm the work.*
Index Terms: ***Dual active bridge (DAB), DAB model, Harmonic model, Triple phase shift, Generalised model***

Paper No. T1.2-6

A BUCK CONVERTER SUITABLE IN LOW STEP-DOWN APPLICATIONS

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Abstract: *A new buck-type dc-dc converter with one active switch and two diodes is presented. Deriving the static conversion ratio value, it results that the proposed topology is well suited in applications that require an output voltage lower but close to the input voltage. The efficiency of this new stepdown converter is above 90% over a wide duty cycle range, starting from small values of the duty cycle. The main equations in steady state are obtained by performing dc analysis of the converter. By evaluating the semiconductor device stresses and comparing the characteristics of the proposed converter to those of other step-down topologies, it is revealed that the new topology exhibits better features in many aspects. Based on the design equations, a prototype was built, simulated and experimentally tested. The simulations and the theoretical considerations are confirmed by the experimental results and thus proving the feasibility of the proposed buck converter.*
Keywords: ***step-down converter, duty cycle, static conversion ratio, voltage and current stresses, efficiency***

Paper No. T1.2-7

COMPARATIVE ANALYSIS OF INPUT-SERIES-OUTPUT-SERIES PARITAL POWER RATED DC TO DC CONVERTERS

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Abstract: *This paper analyses the possibilities of the inputseries-output-series partial power converter configuration with auxiliary series resonant balancer converter. In comparison to the standard converter topologies, the differences between processed powers, as well as differences between powers processed by the inductors are presented in boost, buck and buck-boost cases. Additionally, in the case of the boost topologies, the more in-depth analysis of the power losses is shown. Consequently, the benefits regarding the converter efficiency of the input-series-output-series boost partial power rated converted are discussed.*
Keywords: ***partial power, differential power, efficiency, topology comparison***

Paper No. T1.2-8

THE TRANSIENT REGIME OF A DC RELAY SUPPLIED A CHARGED CONDENSER

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Abstract: *This paper analyzes the transient charging regime of a capacitor whose capacity is much higher than that of the capacitor with which it is connected in series and whose capacity is much lower than that of the charging capacitor. It establishes the evolution in time of the capacitor voltage taking into account the power losses in its dielectric. The power losses in the capacitor dielectric occur in the diagram analyzed by an electrical resistor. Also, because the capacitor is charged by connecting to a DC voltage source obtained by rectification, in the equivalent electrical circuit the direct resistance of the rectifier diodes is not neglected.*
Keywords: ***protection equipment, real condenser, transient regime, real source, Borel's theorems***

Paper No. T1.3-1

ANALYSIS AND DESIGN OF PARTIAL-POWER RATED SINGLE-PHASE DIODE BOOST RECTIFIER

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Abstract: *A single-phase diode boost rectifier is proposed in this paper. The core of the proposed rectifier is a multiswitch dc-dc converter with two terminals; an input and an output. The input is connected in parallel with the dc bus capacitor, while the output is connected between the rectifier plus rail and the dc bus plus rail. The converter controls the rectifier current and the dc bus voltage. The rectifier current is controlled constant or pseudo-constant in order to reduce the input current total harmonic distortion (THD). The dc bus voltage is boosted above the mains peak voltage. In contrast to the ordinary single-switch boost rectifiers, the switches of the proposed boost rectifier are rated on a fraction of the dc bus voltage and a fraction of the input current. It makes this topology compact and efficient. Power rating, size and losses depend on the dc bus voltage to rectifier voltage ratio. For example, if the ratio is low, the efficiency is over 99%. The proposed boost rectifier has been analyzed and experimentally verified on a 4 kW prototype variable speed drive. The results are presented and discussed.*

Paper No. T1.3-2

DESIGN OF A SIC MOSFET 6-PHASE BOOST RECTIFIER

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Abstract: *This paper focuses on the analysis and the design of a power electronic conversion system with reference to wind offshore applications. The proposed conversion system consists of a 6-phase AC-DC converter based on the SiC power semiconductors, to be used to control the achievable power from the wind turbine electrical generator. This system is suitable for applications where reliability and fault tolerance capabilities are the main targets. Voltage and current ratings have been determined to select the power module; furthermore, the analytical analysis to estimate the DC-bus rms current and voltage ripples is carried out. After that, the power loss equations have been derived in order to estimate the efficiency of the conversion. To validate the proposed hardware design, analytical results have been compared to simulation ones using Plexim/PLECS tool in Matlab/Simulink environment.*

Keywords: ***AC-DC converter, power semiconductors, rms current, wind offshore.***

Paper No. T1.3-3

BRAKING ENERGY RECOVERY BY MODULAR MULTILEVEL CONVERTERS IN MVDC RAILWAY ELECTRIFICATION SYSTEMS

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Abstract: *DC railway electrification systems traditionally rely on transformer-rectifier groups to inject power into the catenary. This technology is well established and can be up-scaled for the upcoming medium voltage DC lines (MVDC) that are proposed to operate at 9 kVdc. However, the operation of MVDC railway lines could be reinforced by means of four quadrant substations. As such, Modular Multilevel Converters (MMCs) are envisioned as a serious alternative. They are expected to provide an outstanding flexibility in terms of load flow control, owing to their voltage regulation capability and their bi-directional nature. Additionally, they would improve the interconnection with AC utility networks, by providing robust isolation of perturbations and independent control of the active and reactive power. Due to their four quadrant operation, MMCs are also expected to be extremely beneficial during faults (e.g. short-circuits) and significantly increase the resilience of the system. This paper illustrates to what extent MMCs could be used to recover the energy regenerated by locomotives while braking. To this end, the work was carried on a Real-Time Hardware-In-the-Loop (RT-HIL) replica of a section of a railway line.*
Keywords: MVDC, railways, power electronics

Paper No. T1.3-4

INCREASING CURRENT LOOP PERFORMANCE USING VARIABLE ACCURACY FEEDBACK FOR GAN INVERTERS

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Abstract: *With the appearance of wide-bandgap power electronic devices such as SiC and GaN, the pulse-width modulation frequency is growing. In modern servodrives based on GaN devices it can reach 100 kHz and more. However, the performance of the drive is now limited by the delay in the current feedback rather than the modulation frequency. When using shunt current sensing with delta-sigma modulation, the delay in feedback can be adjusted with simultaneous change of the measurement accuracy. This paper proposes to use inaccurate but fast feedback when error between reference of the motor current and its actual value is big, and to use accurate but slow feedback in case of small error. This requires simultaneous change of the current controller parameters. The performance of the system was examined using model of the servodrive and showed twice higher cutoff frequency of the current loop.*
Keywords: ***current loop, shunt current sensing, GaN, servodrive, delta-sigma modulation, adaptive controller***

Paper No. T1.3-5

NEW THREE-LEVEL SOFT TURN-OFF T-TYPE NPC INVERTER

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Abstract: *This paper presents research results of the novel three-level T-type neutral point clamped inverter (T-NPC) with an active auxiliary switching circuits (AASC) for soft turn-off operation. Application of the AASC allows for significant losses reduction in high voltage IGBT switches. It improves the turnoff process where faster collector current decrease and slower collector-emitter voltage rise is achieved. The presented concept is the novel solution which allows for substantial optimization of volume of auxiliary resonant chokes in relation to the established soft-switching concept. In the proposed solution the resonant chokes are used for charging of auxiliary snubber capacitors but do not conduct the load current. The paper presents the basic concept of the inverter with the AASC, the mechanism of losses reduction and the concept of switching. The AASC converter can operate with the classic phase disposition (PD) PWM. The presented concept of the inverter paper is verified by simulations results.*
Keywords: ***T-type inverter, multilevel inverter, soft switching, switching losses, IGBT, high efficiency***

Paper No. T1.3-6

1:1 RESONANT SWITCHED CAPACITOR WITH CAPACITIVE-BASED ISOLATION

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Abstract: *In power electronics, galvanic isolation is required for safety reasons, and when large DC or AC voltages have to be withstood between the input and output of a power converter. Galvanic isolation in the form of a magnetic transformer prevents failures in one side of the converter to be transferred to the other side and provides voltage transformation. Transformers are used for power applications, but optocouplers or capacitive barriers can be used to transfer control signals. However, the main limitation of transformers is that they are heavy, bulky, and lossy, and, as a result, transformer-less topologies conventionally achieve better performance. In this paper, a topology is proposed where galvanic isolation is obtained through capacitors rated to the maximum common-mode voltage, rather than relying on transformers. First, the fundamental principles of the idea are discussed. The operation of the proposed 1:1 resonant switched capacitor converter is introduced, emphasizing the effects of varying common-mode voltages. Later, zero-voltage switching is covered, and finally, the operation is validated in simulation.*
Keywords: ***Resonant converters, switched capacitors, zero voltage switching, isolation.***

T2

AUTOMOTIVE AND INDUSTRIAL DRIVES

Paper No. T2.1-1

ANALYSIS OF POWER DISTRIBUTION SYSTEMS BASED ON LOW-VOLTAGE DC/DC POWER SUPPLIES FOR AUTOMATED GUIDED VEHICLES (AGV)

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Abstract: *Modern factories are increasingly using automated guided vehicles (AGV) or mobile robots for transport. To increase their run-time, most of them now have energy recovery systems that feed the kinetic energy of the braking process back into the storage system. In most cases, the storage system is a Li-ion battery, which is thus subjected to increased stress. To cope with this issue, Super-Capacitors can be used in combination with batteries. In this paper, the standard battery solutions will be compared with the combined Super-Capacitor and battery solutions. A recommendation for the use of the different topologies based on general system characteristics is provided.*
Index Terms: ***AGV, automated guided vehicles, AMR, autonomous mobile robots, battery, DC/DC, Li-ion, MR, mobile robots, partial power, power distribution systems, SuperCapacitor, Ultra-Capacitor***

Paper No. T2.1-2

ANALYSIS OF NON-REGENERATIVE RESISTIVE DYNAMIC BRAKING BEHAVIOR OF PMSM

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Abstract: *Safety is a crucial issue in industrial and motion control applications where electric motors are used. It is necessary to ensure safe stopping of motion systems for human, environmental and device safety when motor control become dysfunctional, for example in the event of power cut, system fault, necessity of emergency stop. For safe stopping, several braking methods can be used. In this paper, resistive dynamic braking method is modeled and analyzed with Forward Euler Method in MATLAB. Deceleration profile and power dissipation graphs are obtained for various conditions such as different speeds. Finally, results are compared to each other and evaluated.*
Keywords: ***PMSM, Non-regenerative Resistive Dynamic Braking, Electrical Machine, Electrical Drive***

Paper No. T2.1-3

MATLAB/SIMULINK BASED ENERGY CONSUMPTION PREDICTION OF ELECTRIC VEHICLES

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Abstract: *Transport electrification represents one of the key aspects of achieving carbon neutrality. Despite the decreasing price of electric vehicles, the transition to electric vehicles is progressing relatively slowly. The main reasons delaying transport electrification are associated with the long charging time of electric vehicles, limited charging infrastructure, along the so-called range anxiety manifesting itself in driver's uncertainty on whether the vehicle can reach the target destination successfully. Energy consumption prediction plays an important role in reducing range anxiety by providing the driver an accurate estimate of the remaining range. This paper presents a MATLAB/Simulink model for the energy consumption prediction of electric vehicles on a designated route. The developed model is a physical model relying on longitudinal vehicle dynamics which can be easily personalized according to different models of electric vehicles. The developed model is tested on a standard FTP75 driving cycle using the available data on Tesla Model S.*
Keywords: ***electric vehicles, energy consumption prediction, MATLAB/Simulink***

Paper No. T2.1-4

MODELLING OF THREE-PHASE INTERLEAVED DC-DC CONVERTER FOR HYBRID ENERGY STORAGE APPLICATION IN ELECTRIC VEHICLES

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Abstract: *Hybrid energy storages (HES) is becoming more compelling solution for electric vehicles (EV), as battery technologies fail to meet expected requirements. Enhanced longevity, better power density and longer range are only a few of the advantages that HES offers in comparison to the pure battery based storage. Since supercapacitors are recognized as one of the most prominent technologies for HES, selection of an adequate power converter becomes an issue. This paper illustrate the possibilities for the implementation of the interleaved DC-DC converter together with supercapacitor in HES. More precisely paper offers the modelling and simulation results of the converter subjected to the operation regimes specific for HES in standard electric vehicle.*
Keywords: ***electric vehicles, hybrid energy storage, supercapacitor, lithium-ion batteries.***

Paper No. T2.1-5

EXTENDED SVM FOR DIRECT MATRIX CONVERTER BASED DRIVE OPERATING UNDER UNBALANCED GRID CONDITIONS

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Abstract: *Space Vector Modulation (SVM) for direct matrix converter (DMC) with advanced features, such as elimination of high-frequency common-mode voltage and unity grid power factor is attracting increased research interest. However, disturbances on the grid side of matrix converter are directly transferred to the output load, due to no DC-link storage element. Consequently, THD of both output and input currents increases. In this paper, SVM is further extended to suppress disturbance propagation to the output. Using DSRFPLL (Double Synchronous Reference Frame PLL) structure, positive and negative sequence component of grid voltage can be extracted quickly and accurately. Furthermore, proposed modulation technique eliminates the influence of negative sequence component, in the open loop manner without causing any additional delay. Simulation results are provided to verify the proposed method. It is concluded that proposed extended SVM can maintain balanced output currents and achieve sinusoidal input currents in the same time, even under unbalanced grid conditions.*
Keywords: ***Common-mode voltage, matrix converter (MC), open-end-winding machine, space vector modulation (SVM), unbalanced, unity power factor***

Paper No. T2.1-6

REVITALIZATION AND MODERNIZATION OF DRAGLINE EXCAVATORS WITH LIMITED BUDGET

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Abstract: *Different approaches to revitalization and modernization of dragline excavator drives are possible. Modern AC drives with induction motors, existing DC motors with armature current thyristor converters and WardLeonard drives with modern thyristor converters offer same performance of the drives, but at different cost for equipment and different time required for adaptation of the mechanical supporting structures. Experimental results obtained on recently modernized excavator with cost effective approach, Ward-Leonard drive are presented in the paper.*
Keywords: ***excavators, AC drives, DC drives, Ward-Leonard drives, modernization***

T3

ELECTRICAL MACHINES

Paper No. T3.1-1

NON-LINEAR OBSERVER BASED STATOR INTER-TURN SHORTCIRCUIT FAULT DETECTION IN 3-Φ INDUCTION MOTOR

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Abstract: *In this paper, a model-based stator inter-turn short-circuit fault detection in three-phase induction motor is proposed. A modified mathematical model of the faulty induction motor based on stator fluxes is derived. This is believed to be a novel contribution, as researchers haven't used stator flux based induction motor model for inter-turn shortcircuit fault detection. State estimation of induction motor is carried out using conventional non-linear Kalman observer. Residual-sequence obtained from the non-linear Kalman observer is used as fault identifier. Dynamic computations are carried on 10-hp induction motor using MATLAB R2021a software. The presented simulation results validate the efficacy of the proposed fault detection strategy.*
Keywords: ***Extended Kalman filter, fault detection, Nonlinear systems, state estimation, state observers, squirrel-cage induction motors.***

Paper No. T3.1-2

FCS-MPC OF A DMC-FED INDUCTION MACHINE WITH UNITY INPUT POWER FACTOR USING ROTATING VECTORS

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Abstract: *This paper proposes a Finite Control Set-Model Predictive Control (FCS-MPC) of an induction machine fed by a Direct Matrix Converter (DMC). The number of possible switching configurations of a MC represents a notable challenge in implementing MPC for the DMC. In this paper, the inclusion of rotating vectors in the control set and the exclusion of some voltage vectors groups are investigated. The input power factor is fixed to one, the control scheme is explained and simulation results are presented and discussed. These simulation results allowed us to demonstrate the feasibility and the flexibility of the MPC scheme regarding constraints and changing the control set. This work can be considered significant due to the fact that control objectives were attained with less computations.*
Keywords: ***Model Predictive Control, Direct Matrix Converter, Induction Machine, Power Factor, Control Set.***

Paper No. T3.1-3

DESIGN PROCEDURE FOR HIGH-FREQUENCY TRANSFORMER IN LLC RESONANT TOPOLOGY

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Abstract: *Renewable energy sources expansion demands increased standards in safe and energy efficient switching power converters. This paper discusses procedure for step-by-step design of low power high-frequency transformer that provides galvanic isolation of the DC/DC resonant converter. It includes a selection of operating frequency and a detailed overview of the design process that focuses on compact solution while obtaining minimal power losses. The estimation of the transformer parameters is realized in FEM analysis and compared to the ones measured on the developed prototype. Finally, the results of the tests employed on the implementation of such transformer in LLC resonant converter of 1 kW rated power, 200 kHz and 60 V input voltage are shown.*
Keywords: ***HF transformer, transformer design, ferrites, litz wire***

Paper No. T3.1-4

INFLUENCE OF PHASE COUPLING ON THE PERFORMANCE OF 8/6 SRM

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Abstract: *To improve the performance of a Switched Reluctance Motor (SRM), simultaneous excitation of multiple phases is required. This paper offers a detailed analysis of the mutual flux between the phases in an 8/6 SRM depending on whether the magnetic polarities of excited phases are the same or opposite. The analysis is performed based on static characteristics obtained using a machine model in a Finite Element Method (FEM) software. Furthermore, considering that the magnetic symmetry between phases cannot be achieved in an 8/6 SRM when using an Asymmetrical HalfBridge Converter (AHBC), the resulting phase interactions are highly pronounced and are studied by analyzing transient flux linkages, phase currents, energy conversion loops and torque.*
Keywords: ***switched reluctance motor (SRM), multiphase excitation, finite element method (FEM).***

Paper No. T3.1-5

INDUCTANCE IDENTIFICATION OF THE SURFACE PERMANENT MAGNET SYNCHRONOUS MACHINES WITH SINUSOIDAL VOLTAGE TEST SIGNALS

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Abstract: *In this paper, a simple and reliable technique for inductance identification of the Surface Permanent Magnet Synchronous Machine is presented. The identification technique is based on the injection of sinusoidal voltage test signals into the reference axis of the dq reference frame, in order to determine the dq inductances. The proposed technique belongs to self-commissioning techniques, which can be implemented on standard drives since it does not require additional equipment. The technique is validated and evaluated through computer simulations. Additionally obtained results are compared to initial parameters obtained from the standard inductances determination test and with the results from the automatic parameter identification procedure of the standard industrial drive.*
Keywords: ***SPMSM drive, self-commissioning, parameter identification, dq inductance, signal injection.***

Paper No. T3.1-6

MINIMIZATION OF AN ELECTROMAGNETIC TORQUE RIPPLE OF A FIVE-PHASE IM OPERATED UNDER ONE-PHASE FAULT

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Abstract: *The presented paper deals with the five-phase induction motor (IM) having star connected stator winding, which is working under one phase supply failure. Computation of the motor electromagnetic quantities are made using the space vector theory in the complex plane. Analysis is done assuming, the motor is supplied by a pulse width modulation (PWM) controlled inverter with sufficiently high modulation frequency. Only the first stator voltage harmonics is taken into consideration. On the base of measured the IM parameters, trajectories of stator and rotor current space vectors were investigated. On their basis, the motor electromagnetic torque ripple waveform for failure supply mode is derived. Finally a possibility to reduce torque ripple in failure state is shown.*
Index Terms: ***Space vector, Five phase, Induction machine, Torque ripple, Star connection, One phase fault, Four phase operation***

T4

CONTROL AND MEASUREMENT

Paper No. T4.1-1

MINIMUM DEVIATION CONTROLLER FOR INDIRECT ENERGY TRANSFER CONVERTERS

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Abstract: *This paper introduces a practical single-mode minimum deviation controller for indirect energy transfer converters. It provides theoretically minimum possible output voltage deviation during load transients. The controller has an outer voltage loop, providing half-duty ratio signals, that is triggered by an inner current loop. This controller behaves the same way in steady state and during transients. The effectiveness of the controller is verified experimentally, with a 5 V to 8 V, 16 W, 250 kHz boost converter prototype. The results demonstrate virtually minimal output voltage deviation. In comparison with a PID compensator that has a relatively high bandwidth of one-tenth of the switching frequency, the presented controller has about 2 times smaller deviation allowing for an equivalent output capacitor reduction.*
Keywords: ***Digital control, minimum deviation controller, switched mode power supplies***

Paper No. T4.1-2

CONTROL ALGORITHMS FOR MATRIX CONVERTERS WITH LOW MATHEMATICAL COMPLEXITY

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Abstract: *Due to the degrees of freedom inherent in matrix converter modulation, there are a large number of different, seemingly contradictory modulation strategies. This work contributes to a systematization of at least a subset of the strategies. For this purpose, a systematic derivation of direct control algorithms is performed. "Direct" is meant in the sense that the duty cycles are computed using only basic arithmetic. Since such algorithms do not invoke mathematical library functions, they can be easily implemented in embedded processors or programmable logic.*

Due to their direct computability and systematic derivation from theory, the algorithms can be regarded as archetypes of matrix converter modulation and can be a valuable aid in comparing different control algorithms.
Index Terms: ***Matrix converters, Algorithm, Classification***

Paper No. T4.1-3

ALGORITHM AND BLOCK DIAGRAM OF AN ELECTRONIC SYSTEM FOR CONTROL OF ENERGY FLOWS IN RESIDENTIAL PREMISES

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Abstract: *An algorithm for the operation of an electronic system for managing energy flows in a residential premises has been developed, where criteria for achieving the required comfort temperature have been implemented. Based on the developed algorithms, a structural diagram of the electronic system for managing energy flows in residential premises has been synthesized. By controlling the energy source, the goal is to achieve the desired comfort temperature, with reduced electricity consumption.*
Keywords: ***electronic system, energy flows, residential premises***

Paper No. T4.1-4

HALF-BRIDGE VOLTAGE SOURCE INVERTER CONTROL DEVELOPMENT USING HIL SYSTEM

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Abstract:*The paper deals with a HIL (Hardware In the Loop) system or so-called Rapid Control Prototyping (RCP) tools, used in a single-phase half-bridge Voltage Source Inverter (VSI) control development. The control algorithm is developed for the ATMEL ATmega2560 microcontroller. The code is implemented to the microcontroller via Arduino development board. A control board mock-up is assembled for control algorithm validation. HIL system is used as an RCP tool for testing. Furthermore, the VSI model is done in a HIL Schematic Editor and HIL SCADA software environment. The system functionality is tested for two selected operation points. Waveforms are recorded, and the voltage spectrum analysis is performed via external low-voltage spectrum analyzer. The shortcomings of developed system are addressed and the solution for them is proposed.*
Keywords: ***hardware in the loop, rapid control prototyping, voltage source inverter, control algorithm, development board***

Paper No. T4.1-5

INFLUENCE OF SYSTEM DELAY ON CURRENT CONTROLLER STABILITY AND PERFORMANCE AT GRID-SIDE INVERTER WITH LCL FILTER

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Abstract: *This paper presents a brief overview of digital current control methods for three-phase grid-side inverters with the LCL filter.An analytical approach of modeling the LCL filter for the needs of the current regulator design is presented. The dependence of system performance on induced delay is shown, as well as following stability analysis. Digital current controllers based on grid or inverter side current feedback are designed using inverse dynamics concepts. Designed controllers are tested on Hardware-in-the-loop HIL402 device. Obtained results are discussed and suggestions are provided in terms of the practical implementation of the control system.*
Index Terms: ***LCL-filter, grid-side three-phase inverters, digital current control, Nyquist criterion***

Paper No. T4.1-6

ANALYSIS AND DSP IMPLEMENTATION OF MULTI-SAMPLED THREE-PHASE CURRENT CONTROLLERS

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Abstract: *This paper presents a method for current control of three-phase systems, realized using the multi-sampled pulsewidth modulator (MS-PWM). The feedback signal is highly oversampled and filtered to obtain its average value with high noise suppression. Independently, the control update rate is chosen to be higher than double the switching frequency, which reduces delays due to calculation and digital modulation. In this way, the proposed strategy offers improved dynamic response compared to standard double-update PWM, while offering a high quality feedback signal, robust to noise sampling and aliasing. The analysis is verified using a standard digital signal processor TI f28379d and a Typhoon HIL 402 hardware-in-the-loop system that emulates an electric drive with a high-speed BLDC motor.*
Index Terms: ***Current control, Digital Pulse-Width Modulators (DPWM), Multi-sampled Pulse-Width Modulators (MSPWM)***

Paper No. T4.1-7

AUTOMATIC SYSTEM FOR SAVING COOKING GAS

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Abstract: *Conservation of natural resources, namely gas, which together with oil is one of the most widely used but depletable energy resources, is a mandatory activity for both technology users and developers. This goal can be achieved by developing new technologies and new devices capable to use alternative sources of energy, and also to save up the conventional ones. In order to upgrade the above mentioned works we have built an automatic system capable to maintain the necessary cooking temperature of the pot using the Seebeck effect after the pot, or pan, was heated at respective temperature using natural gas as combustible. As far as we know such automatic system was not reported in literature. Further development of our system is mentioned in the last chapter of this article.*
Keywords: ***Automatic system, Seebeck effect, natural gas, cooking pot, microcontroller, Arduino.***

Paper No. T4.2-1

PREDICTIVE CONTROL OF AN INDUCTION MACHINE FED BY A VOLTAGE SOURCE INVERTER

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Abstract: *Predictive control techniques have emerged as a suitable solution for the control of drive systems. In this paper, a predictive control strategy for the flux and torque control of an induction machine fed by a voltage source inverter is presented. The algorithm selects an available commutation state for the converter which minimizes a cost function, and this state is applied in the next sampling time. Simulated results in Matlab/Simulink demonstrate the feasibility of the strategy showing a good tracking of the variables to their respective references and sinusoidal stator machine currents.*
Index Terms: ***Induction machine, model predictive control, predictive torque control, voltage source inverter***.

Paper No. T4.2-2

THE SELECTION OF COST FUNCTIONS IN MODEL PREDICTIVE CONTROL APPLICATIONS

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Abstract: *In model predictive control strategies, the cost function selection is the most relevant aspects to obtain a good performance of the full system. In this paper a study of the most common cost functions used for the control of two level voltage source inverters is presented. The paper compares several cost function alternatives that could be considered for different power electronic converter applications. The results show that Model Predictive Control is a suitable alternative for the implementation of different control objectives in power converters.*
Index Terms: ***Cost function, model predictive control, predictive current control, voltage source inverter.***

Paper No. T4.2-3

IMPROVEMENT OF PMSM CONTROL USING REINFORCEMENT LEARNING DEEP DETERMINISTIC POLICY GRADIENT AGENT

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Abstract: *Based on the advantage of using the reinforcement learning on process control, provided by the fact that it is not necessary to know the exact mathematical model and the structure of its uncertainties, this article approaches the possibility of improving the performances of the Permanent Magnet Synchronous Motor (PMSM) control system based on the Field Oriented Control (FOC) type control strategy, by using the correction signals provided by a trained reinforcement learning agent, which will be added to the control signals* u_d*,* u_q*, and* i_{qref} *. The type of reinforcement learning used is the Deep Deterministic Policy Gradient (DDPG). The combination possibilities of these control structures are presented, and their superiority over the FOCtype control strategy is validated by numerical simulations.*
Keywords: ***permanent magnet motors, field oriented control, reinforcement learning, intelligent agent, deep neural networks.***

Paper No. T4.2-4

TUNING OF PI SPEED CONTROLLER FOR PMSM CONTROL SYSTEM USING COMPUTATIONAL INTELLIGENCE

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Abstract: *Starting from the classic Field Oriented Control (FOC) structure of a Permanent Magnet Synchronous Motor (PMSM), this article presents the comparative performance of the control system when the tuning of the PI-type speed controller is performed both in the conventional way (using the Ziegler-Nichols method supplemented by the trial and error method), and using three computational intelligence specific algorithms, namely: Genetic Algorithm (GA), Simulated Annealing (SA) algorithm, Reinforcement Learning (RL) - Twin Delayed Deep Deterministic Policy Gradient (TD3) agent algorithm. The superiority of the results of the use of computational intelligence algorithms for tuning the PI-type speed controller is demonstrated by numerical simulations performed in the Matlab/Simulink development environment.*
Keywords: ***permanent magnet motors, genetic algorithm, simulated annealing, reinforcement learning, computational intelligence.***

Paper No. T4.2-5

APPROACHES TO REDUCING OF THE ACTIVE POWER MEASUREMENT ERROR FOR A METHOD BASED ON AVERAGING OF INSTANTANEOUS POWER

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Abstract: *The method based on averaging of instantaneous power characterizes a number of advantages. This method is simple to implement, simple to analyze the error for the case of sinusoidal and polyharmonic signals, and is capable of performing high accuracy measurements. The paper analyzes the existing approaches to reducing the active power measurement error by this method and proposes two novel approaches. The first of the proposed approaches is based on performing additional low-pass filtration of the active power measurement results. A moving average filter, an cascaded integrator-comb (CIC) filter and a combined filter (CIC filter and an additional filter-compensator) are proposed as an output filter. This approach allows to reduce the static measurement error without additional frequency measurement and additional adjusting of the measuring transducer parameters. The second approach is based on performing multiple measurements of active power at fixed time intervals and averaging the measurement results. This approach is simple to implement. For both approaches, analytical relationships have been obtained that make it possible to estimate the active power error for the case of it application. Variants of combining of existing and proposed error reduction approaches are considered, which significantly increases the measurement accuracy.*
Keywords: ***active power, frequency deviation, measurement error, digital filtration, phase shift, CIC filter***

Paper No. T4.2-6

METHOD OF REDUCING OF THE COMPLEX SPECTRUM MEASUREMENT ERROR IN CASE OF APPLYING OF THE QUADRATURE DEMODULATION TECHNIQUE

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Abstract: *The quadrature demodulation technique can be applied to measure the frequency, amplitude and phase spectrum of electric power grid signals. This measurement method has a number of advantages: simplicity of analysis of measurement error, the ability to increase the measurement accuracy (by applying a higher order digital filter), and simplicity of simulation. One of the disadvantages of this method is the relatively large dynamic error component caused by the application of post-filter or by the reference frequency adjustment (both approaches allows to reduce the signal parameters measurement error). In this paper we propose an alternative approach that makes it possible to achieve a significant reduction of the measurement error without increasing the filter order. For the proposed approach, an increase of the dynamic error component is not observed. The proposed approach consists in compensating the amplitude and phase spectrum measurement results by applying analytical dependences and frequency measurement results. In this paper, analytical expressions are obtained that make possible to estimate the maximum value of the spectrum error in case of applying the proposed approach. The influence of the frequency measurement error on the accuracy of the proposed method of the spectrum measurement error correction is estimated. By Matlab and Simulink software, a simulation modeling has been performed, which makes it possible to assess the reliability of the obtained analytical expressions and the effectiveness of the proposed approach. When performing simulation, sinusoidal, polyharmonic (line spectrum) signals and a sinusoidal signal distorted by white noise are considered.*
Keywords: ***quadrature demodulation, digital filtration, measurement error, frequency deviation, simulation modeling***

Paper No. T4.2-7

ANALYSIS OF THE INFLUENCE OF NON-SIMULTANEOUS SAMPLING ON THE MEASUREMENT OF THREE-PHASE INSTANTANEOUS POWER

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Abstract: *This paper analyses the influence of analog to digital conversion delays in the measurement of three-phase voltages and currents used for calculation of instantaneous power. Stringent hardware requirements of simultaneous sampling sometimes make measuring three voltages and currents at the same time impossible. Commonly available hardware for analog to digital conversion introduces multiplexed channels, with a single or dual analog to digital converter. The sample time delays between the measured channels introduce the error in calculated three-phase instantaneous active power. Both analytical and numerical analysis of the error in the presence of higher harmonics is presented.*
Keywords: ***power measurement, analog to digital converter, sample time delay, instantaneous power***

T6

POWER QUALITY

Paper No. T6.1-1

CALCULATION AND SPECTRAL ANALYSIS OF DC-LINK CURRENT FOR THREE PHASE PWM INVERTER

Jianxia Sun, Cheng Lin
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Abstract: *Due to the effect of high-frequency switches, the dc-link current of the PWM inverter contains a large number of harmonic components, which results in ripple fluctuations of dc bus voltage and directly affects the quality and reliability of the power supply system. According to the Double Fourier Series method, we deduce the expressions of the dc-link current, which include the low frequency and high frequency parts. Besides, the effect of the output current harmonics on the dc-link current is considered, which improves the accuracy of the expression. Based on the derived expressions, we quantize the spectrum of the dc-link current. From the view of magnitude, we deduce the specific harmonic distribution in the frequency domain. The quantized spectrum of dc-link current provides the guideline for the dc filter design, which can reduce the system volume and cost. Finally, the theoretical analysis of dc-link current is verified by the Fast Fourier Transform analysis results obtained by the simulation model platform.*
Keywords*: PWM inverter, harmonic, Double Fourier Series*

Paper No. T6.1-2

VOLTAGE SAGS DURATION PROBABILITY DISTRIBUTION FUNCTION

Vladimir A. Katić, Srđan Lj. Milićević, Aleksandar M. Stanisavljević
Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia

Abstract: *This paper aims to present a probability distribution function for voltage sags. A large number of real grid recordings, originally obtained by authors, measurements provided by Prof. Math Bollen or presented in the literature are analyzed. Two types of probability functions, Weibull and lognormal are considered for five cases of measurement results from different countries. Averaged probability distribution functions are proposed. Their applications for the optimization of the artificially generated voltage sags database can be used further for the training of neural networks for power quality characterization.*
Keywords: *Power distribution faults, Probability, Probability distribution, lognormal distribution, Weibull distribution*

Paper No. T6.1-3

COMPARISON OF SINUSOIDAL PWM TECHNIQUES IN TERMS OF HARMONIC ANALYSIS IN THREE AND FIVE LEVEL DIODE CLAMPED INVERTER

Ufuk Badak, Ali Bekir Yıldız
Kocaeli University, Engineering Faculty Electrical Engineering, Umuttepe Campus Kocaeli, Turkey

Abstract: *In inverter applications requiring high power and high voltage, the voltage stress on the switching elements of conventional inverters is high. Multilevel inverters are preferred over conventional inverters to reduce this voltage stress. Within the scope of this article, a study on Diode Clamped Multi-Level Inverter is presented. The Phase Disposition, Phase Opposition Displacement and Alternative Phase Opposition Displacement which are the Sinusoidal Pulse Width Modulation arrays, present different comparative modulation on the fivelevel diode clamped inverter. In this study, inverter topologies were shown according to the number of levels, current paths were determined according to the number of levels, different modulation techniques for triggering the switching element were explained, and harmonic analysis was performed in Phase Disposition, Phase Opposition Displacement and Alternative Phase Opposition Displacement arrays in no-load and RL-load state according to the determined level numbers. The whole study was conducted in Matlab / Simulink environment and according to the simulation results, a five-level diode clamped inverter with a total harmonic distortion value of 16.82% in the no-load condition and PD array gave the best result.*
Keywords: ***Diode Clamped Multi Level Inverter, Sinusoidal Pulse Width Modulation , Total Harmonic Distortion.***

Paper No. T6.1-4

APPLICATION OF THE PV SYSTEMS FOR NON-LINEAR LOAD CURRENT COMPENSATION

Viktor Trifunjagić, Vladimir A. Katić, Aleksandar M. Stanisavljević
University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

Abstract: *Non-linear loads, that are nowadays widely used have an effect of raising the level of current harmonics, and subsequently voltage harmonics in the grid. At the same time, the implementation of PV systems is spreading over households enabling additional supply and the inclusion of ancillary services. This paper investigates the possibility of the application of PV systems as an active power filter to improve the quality of electricity in the residential part of the electricity network. The Matlab/Simulink model was developed and tested for the average residential network. The results show that such a possibility is justified and can have positive effects.*
Keywords: ***harmonics, PV systems, power quality, active power filtering***

21st INTERNATIONAL SYMPOSIUM on POWER ELECTRONICS - Ee 2021

NOVI SAD, SERBIA, October 27th – 30th, 2021

Paper No. T6.1-5

TRAINING AN LSTM VOLTAGE SAGS CLASSIFICATOR ON A SYNTHETIC DATASET

Radovan Turović, Dinu Dragan, Aleksandar Stanisavljević, Gorana Gojić, Veljko Petrović, Vladimir Katić, Dušan Gajić
University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

Abstract: *In this paper, an end-to-end deep learning method for voltage sag classification using a Long Short-Term Memory (LSTM) neural network is proposed. The network receives an unmodified three-phase voltage signal sequence as an input and outputs a label to indicate if a signal is not faulted or there is one of the seven standard voltage sag types present, labeled from A to G respectively. A database of over 450,000 synthetically generated signals is generated for network training purposes. When tested on synthetic signals, the network achieves an accuracy of over 92%, while it reports lower accuracy on real-world signals. However, the network has demonstrated the ability to generalize on measured signals despite being trained on synthetic signals, and mainly correctly classifies signal segments of serious severities which present the opportunity to improve the classification accuracy of arbitrary measured signals by training the network on an even larger synthetic dataset. The source code following the paper is available at https://bitbucket.org/sara_e21/voltage-sagclassifier.*

Keywords: ***Neural networks, Artificial intelligence, Power quality, Voltage sags (dips) classification, Dataset generation, Deep learning, Recurrent neural network***

T7

RENEWABLE & DISTRIBUTED ENERGY SOURCES

21st INTERNATIONAL SYMPOSIUM on POWER ELECTRONICS - Ee 2021

NOVI SAD, SERBIA, October 27th – 30th, 2021

Paper No. T7.1-1

MULTI-LEVEL, PARTIAL POWER PROCESSING AND WBG DEVICES - FUTURE OF 1500-V PHOTOVOLTAIC SYSTEMS

Branislav Stevanović, Pedro Alou, Miroslav Vasić
Universidad Politécnica de Madrid (UPM), Centro de Electronica Industrial (CEI), Madrid, Spain

Abstract: *A brief review of the current market and industry trends of photovoltaics is presented in this work with a clear focus on the 1500-V grid-connected PV systems. The bottleneck for the further improvement of the efficiency, cost and penetration of the photovoltaics in the global renewable energy production is detected in the power conditioning units. The key solution for this issue is recognized in the emerging new classes of 650-V and 900-V WBG devices in combination with highly popular and investigated concepts in the last years - multi-level and partial power processing. Results of the full-multivariable optimization of some topological solutions presented in the literature are discussed. According to the analysis presented and to the results reported in the existing literature, predictions and guidelines are suggested for the further development of PV systems.*
Keywords: ***Photovoltaics, 1500-V, Multi-Level, Partial Power Processing, WBG Devices***

Paper No. T7.1-2

PROBABILISTIC LOAD FLOW CALCULATION USING HALTON QUASI-RANDOM NUMBERS IN MODERN POWER SYSTEMS WITH WIND AND SOLAR GENERATION

Filip Mišurović, Saša Mujović
Faculty of Electrical Engineering, University of Montenegro, Podgorica, Montenegro

Abstract: *Rising penetration of renewable resources in power systems through integration of distributed generation (DG) confronts traditional deterministic load flow (DLF) analysis with serious uncertainties and challenges. This claim is a direct consequence of variable energy production capability of the DGs whose operation strongly depends on weather conditions. The DLF approach gives only a snapshot of the state of the system at certain moment neglecting the all uncertainties arising from variable generation capabilities of DGs and volatility of consumption. Therefore, for the sake of such analyses another approach, namely, probabilistic load flow (PLF) should be adopted. The main issue regarding the application of PLF is the balance between method accuracy and efficiency. This paper is aimed to confirm the applicability of PLF method combining Monte Carlo simulations with Halton sequences for the modern power systems with integrated wind and solar generation. To that end, modified IEEE 14 bus test system was taken as a base for analysis and simulations, as well as deriving of key findings. Results have shown significant reduction of calculation time in comparison to basic Monte Carlo method, while keeping the method's precision.*
Keywords*: Distributed generation, Halton sequence, Load flow, Monte Carlo methods, Probabilistic logic, Uncertainty.*

Paper No. T7.1-3

SITING AND SIZING OF RENEWABLE ENERGY SOURCES: A CASE STUDY ON MONTENEGRO

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Abstract: *Due to a variety of negative effects associated with renewable energy sources, extensive studies need to be carried out before their integration into the power system, determining the optimal location, size, and type of generation capacities. This paper presents a techno-economic analysis of the available potential of renewable energy sources, focusing on the transmission system of Montenegro. The maps of the statistical climate indicators of wind and solar energy have been processed concerning the technical, economical, and environmental criteria to perform an accurate estimation of the available potential. After performing the zonal division of the maps of available renewable potential, by employing a multiobjective optimization approach, optimal plant size has been determined for each zone. The obtained results can be used as a starting point for further planning studies.*
Keywords: ***renewable energy sources, techno-economic analysis, multiobjective optimization***

Paper No. T7.1-4

AN IMPROVED DIRECT VOLTAGE COMPONENT EXTRACTION METHOD FOR GRID CONNECTED CONVERTERS

Ruzica Cvetanovic, Zarko Janda[1]
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[1]Automation & Control, Electrical Engineering Institute Nikola Tesla, Belgrade, Serbia

Abstract: *As a consequence of an upward trend in the renewable energy's share over the last few years, technical specifications for the integration of grid side inverters are becoming more and more harsh. With the aim of satisfying the grid connection requirements, an adequate synchronization algorithm, capable of providing satisfactory performance in the presence of imbalance and harmonics, is essential. In this paper, we introduce a novel algorithm for very fast extraction of the direct voltage component. Using a finite number of grid voltage samples, a system of algebraic equations is solved and sine and cosine factors are obtained. These are further processed by the square root and arctan functions to acquire information about the amplitude and angle of the direct sequence component. An appropriate method for frequency estimation from the direct sequence angle is necessary for the operation of the synchronization algorithm presented in this paper. An all-pass filter (APF) based synchronous reference frame phase locked-loop (SRF PLL) is used as a benchmark for the proposed finite sample count (FSC) algorithm, to evaluate its performance in simulations and experiments. Experimental validation is realized on a standard DSP platform. A grid simulator is used to provide analog grid voltage signals.*
Index Terms: ***All-pass filter (APF), grid-connected converters, phase locked loop (PLL), synchronization, sequence detection.***

21st INTERNATIONAL SYMPOSIUM on POWER ELECTRONICS - Ee 2021

NOVI SAD, SERBIA, October 27th – 30th, 2021

Paper No. T7.1-5

GIS FOR PUBLIC LIGHTING INSTALLATIONS

Sanja Špica, Milan Čeliković, Srđan Popov
University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

Abstract: *This paper describes the practical realization of the Geographic Information System (GIS) on public lighting installation, exploiting and using geospatial data to achieve efficient operation and to manage lighting data and information while reducing planning and decision time and costs. GIS is used to organize geospatial data of the public lighting system on State Road IB 23 in the Republic of Serbia. The section of IB 23, Užice – Bela Zemlja is the part of the road which was recently reconstructed using modern lighting solutions, such as LED. The exact locations and characteristics of each individual luminaire on this 15 km long section of the road are used to create a GIS database. Adequate geospatial and technical data, organized in such a way may greatly improve maintenance planning, which will lead to much cost-effective and less timeconsuming management of the public lighting installation system.*
Keywords: ***GIS, public lighting, state road IB 23, planning, LED lights, QGIS***

IS

INDUSTRY SESSION

IS-1.1

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IS-1.3

The Renewable Energy Sources for smart sustainable health Centers, University Education and other public buildings (RESCUE), Interreg-IPA CBC Croatia-Serbia project

Dumnić Boris, University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia
Šljivac Damir, University of Osijek, Fac. of Elec.Eng., Comp.Sc. and Infor.Tech., Osijek, Croatia
Stojkov Marinko, University of Slavonski Brod, Slavonski Brod, Croatia
Varda Nikolina, Clinical Hospital Center, Osijek, Croatia
Lukić Radisav, Clinical Center of Vojvodina, Novi Sad, Serbia

TT

TUTORIALS

TT-1
Huai Wang, Denmark
Shuai Zhao, Denmark

AI-ASSISTED CONDITION AND HEALTH MONITORING IN POWER ELECTRONICS

Abstract – Artificial Intelligence (AI) plays an increasing role in solving the optimization, regression, and classification problems in condition and health monitoring of power electronic converters. The outcomes from the condition and health monitoring are essential to operation optimization and predictive maintenance. This tutorial will cover three sub-topics: 1) introduction to condition and health monitoring in power electronics and its engineering problems; 2) introduction to AI methods and the motivation to apply them for the associated engineering problems; 3) case studies in parameter estimations, early failure prediction, and remaining useful lifetime prediction for power electronic applications.

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Huai Wang is currently Professor at the Center of Reliable Power Electronics (CORPE) at Aalborg University, Denmark. His research addresses the fundamental challenges in modeling and validation of power electronic component failure mechanisms, and application issues in system-level predictability, condition monitoring, circuit architecture, and robustness design. He also leads a project on light-AI for cognitive power electronics. His team collaborates with various industry companies across the value chain, from power electronic materials, components to systems.
Prof. Wang lectures three short-term Industrial/PhD courses on Reliability of Power Electronic Systems, Design FMEA in Power Electronics, and Capacitors in Power Electronics Applications at Aalborg University. He has contributed more than 120 journal papers and co-edited a book on the Reliability of Power Electronic Converter Systems in 2015. He has given 25 tutorials at leading power electronics conferences (e.g., PCIM Europe, APEC, ECCE, etc.) and more than 80 invited talks. Prof. Wang received his PhD degree from the City University of Hong Kong, Hong Kong, China, and B. E. degree from the Huazhong University of Science and Technology, Wuhan, China. He was a short-term visiting scientist with the Massachusetts Institute of Technology (MIT), USA, and ETH Zurich, Switzerland. He was with the ABB Corporate Research Center, Baden, Switzerland, in 2009. Dr. Wang received the Richard M. Bass Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society in 2016 for the contribution to reliability of power electronic converter systems. He serves as General Chair of IEEE IFEC 2020 and Associate Editor of IEEE Transactions on Power Electronics.

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Shuai Zhao is currently a postdoctoral researcher with the Center of Reliable Power Electronics (CORPE), Department of Energy Technology, Aalborg University, Denmark. He received the BE (Hons), ME, and Ph.D. degrees in information and communication engineering from Northwestern Polytechnical University, Xi'an, China, in 2011, 2014, and 2018, respectively. From Sep. 2014 to Sep. 2016, he was a visiting Ph.D. student with the Department of Mechanical and Industrial Engineering at the University of Toronto, Toronto, ON, Canada, with a scholarship from the China Scholarship Council (CSC).
In Aug. 2018, he was a visiting scholar with the Power Electronics and Drives Laboratory, Department of Electrical and Computer Science at the University of Texas at Dallas, Richardson, TX, USA. His research interests include system informatics, intelligent condition monitoring, diagnostics & prognostics, and tailored AI tools for power electronic systems. the value chain, from power electronic materials, components to systems.

TT-2

Miroslav Vasić, Spain
Luis Gómez Navajas, Spain
Javier Galindos Vicente, Spain

DESIGN CHALLENGES FOR HIGH-PERFORMANCE GAN BASED CONVERTERS IN MULTI-MHZ APPLICATIONS

Abstract – Nowadays Silicon (Si) semiconductors present high reliability and maturity, however, the limits in terms of power density, operation temperature, and switching frequency are close to being reached. Gallium Nitride (GaN) power devices promise superior operation at higher junction temperatures, in harsh conditions such as the space, and superior conduction and switching properties than traditional Si technology. Although the theoretical electrical properties of GaN devices are far superior to those of Silicon, all their benefits have not been exploited yet. In order to fully empower the emerging GaN based power electronics applications and unleash the full potential of GaN devices, it is necessary to fully understand what is behind (or inside) a GaN HEMT, as well as their design and reliability challenges.

We were expecting to move the switching frequencies to MHz range, but it looks like that it is more complex than expected. What are the design challenges if you want to design a 20 MHz inverter? How the single event failures influence the health of your GaN converter? How to proceed with further application development? These are the questions in front of us, and this Tutorial will try to respond them. It will cover two fundamental aspects, device theory and practical design issues, starting with a comprehensive introduction to GaN devices and their applications, to provide the attendees with the fundamental knowledge of GaN devices advantages, as well as basic know-how related to practical GaN based circuit design. Afterwards we will present the applications which can clearly benefit from GaN employment, clearly identifying the problems that we have seen during the development. The tutorial is based on the results published by the speakers and other researchers in the field, as well as on our latest designs and accomplished experimental results.

1. Basic GaN HEMT physics
    - GaN and SiC high expectations
    - How does a HEMT work?
    - Gate engineering
    - Dynamic channel resistance
2. Practical challenges
    - Package parasitics
    - Device driver
    - Layout and PCB issues
    - Thermal management
3. High Frequency Applications of interest
    - High frequency PA – Envelope Tracking
    - Ultra-Compact Power Converters
    - High Speed PA
    - High Frequency challenges
        - PWM generation
        - Delay effect
        - Magnetic material
        - CM noise
4. Reliability challenges
    - GaN HEMT characterization
    - Building the setup
    - Measuring channel resistance
    - Characterization under short-circuit events
5. Conclusions

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Miroslav Vasić was born in Serbia in 1981. He received the B.S. degree from the School of Electrical Engineering, University of Belgrade, Belgrade, Serbia, in 2005. Since then he has been working at Centro de Electrónica Industrial at ETSII (UPM) where he received his M.S. in 2007 and his Ph.D. degree in 2010. He has been working as assistant professor at UPM since 2015.
His research interest includes application of power converters and their optimization. In the recent years great part of his research activities has been related to the research of new semiconductor devices based on GaN and their impact on power electronics.

Miroslav Vasić has published more than 70 peer-reviewed technical papers at conferences and in IEEE journals. In 2012 he received the Semikron Innovation Award for the teamwork on “RF Power Amplifier with Increased Efficiency and Bandwidth.” In 2015 he received a medal from Spanish Royal Academy of Engineering as a recognition of his research trajectory and in 2016 he received UPM Research Projection Award for the best young researcher at Universidad Politécnica de Madrid.
Miroslav actively serves as a reviewer in several IEEE journals such as IEEE Transactions on Power Electronic and IEEE Transactions on Industrial Electronics and as an Associated Editor in IEEE Journal of Emerging and Selected Topics in Power Electronics and IEEE Transactions on Vehicular Technology. Since 2021 he acts as the Vice-chair of the IEEE PELS TC 10- Design Methodologies.

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Luis Gómez Navajas was born in Jaraíz de la Vera, Spain, in 1997. He received the bachelor degree in industrial engineering from the Universidad Politecnica de Madrid, Madrid, Spain, in 2019. He is currently studying the double Master in industrial engineering and industrial electronics in the Universidad Politecnica de Madrid, Madrid, Spain.
Since 2018, he has been a research student at the Centro de Electrónica Industrial (CEI), Madrid. His current research interests include high frequency converters with carrier phase-shifted modulation and compact GaN based design to drive capacitive loads.

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Javier Galindos Vicente Received the B.S. degree in Industrial Engineering with a minor in Control and Industrial Electronics from ETSII-UPM, Madrid, Spain in 2020. He has done his Bachelor Thesis researching on the field of Power Electronics with GaN devices. (Spanish patent under evaluation). He is currently studying an MSc in Digital Manufacturing at EIT Digital (UPM-TalTech). At the same time, he is involved in a research project with AIRBUS D&S and UPM to characterize failure mechanism of GaN devices. His main interests include power electronics and AI.

21. Savetovanje
Energetska elektronika – Ee2021

S1

ENERGETSKA ELEKTRONIKA: ELEKTRIČNI POGONI I OBNOVLJIVI IZVORI

Paper No. S1-1

ENERGETSKA ELEKTRONIKA – SIMPOZIJUM U GODINAMA JUBILEJA

Vladimir A. Katić[1], Dragomir Nikolić[2], Zoltan Čorba[3], Aleksandar Stanisavljević[4], Ljubinka Gerić[5], Jadranka Galić[6]
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Kratak sadržaj: *Naučni skup simpozijum/savetovanje Energetska elektronika se već skoro pola veka održava i po tome je jedan od najdugovečnijih u Srbiji. U tom dugom periodu on je prolazio kroz više faza da bi od nacionalnog savetovanja prerastao u vrhunsku međunarodnu konferenciju. U radu je dat prikaz razvoja ovog skupa kroz ključne odrednice, odnosno brojeve radova, autora/koautora, kao i analizu ovih statističkih podataka. Detaljniji podaci nalaze se na web sajtu skupa* www.dee.uns.ac.rs *odnosno glavnog organizatora Društva za energetsku elektroniku Srbije* www.dee.org.rs
Ključne reči: ***Energetska elektronika, Simpozijum/Savetovanje, Istorijat***

Paper No. S1-2

IMPLEMENTACIJA FN ELEKTRANA U ZDRAVSTVENE I OBRAZOVNE CENTRE KROZ REGIONALNU SARADNJU HRVATSKA - SRBIJA

Zoltan Čorba[1], Boris Dumnić[1], Bane Popadić[1], Dragan Milićević[1], Matej Žnidarec[2], Marinko Stojkov[3]
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[2]Sveučilište Josipa Jurja Strossmayera, Fakultet elektrotehnike, računarstva i informacionih tehnologija, Osjek, Hrvatska
[3]Sveučilište u Slavonskom Brodu, Strojarski fakultet u Slavonskom Brodu, Slavonski Brod, Hrvatska

Kratak sadržaj: *Rad se bavi integracijom fotonaponskih (FN) elektrana u zdravstvene i obrazovne institucije u okviru IPA projekta RESCUE. Značaj projekta se ogleda u promociji obnovljivih izvora energije (OIE) i povećanju energetske efikasnosti objekata. Mogućnost implementacije OIE je posebno usmereno ka javnim ustanovama. U radu se opisuju karakteristike, procena proizvodnje i doprinos smanjenju ugljen-dioksida FN elektrana koje su izgrađene u Novom Sadu, Osjeku i Slavonskom Brodu.*
Ključne reči: ***FN elektrane/Javne institucije/Efikasnost***

Paper No. S1-3

PRIKAZ RADA U LABORATORIJI ZA MIKROELEKTRONIKU FAKULTETA TEHNIČKIH NAUKA

Mirjana Damnjanović[1], Milica Kisić[2]
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Kratak sadržaj: *Laboratorija za mikroelektroniku je jedna od nastavno-istraživačkih laboratorija Katedre za elektroniku na Fakultetu tehničkih nauka. U njoj je smeštena oprema za karakterizaciju elektrotehničkih materijala, elektronskih komponenti i kola, kao i za izradu kola u tehnologiji štampanih ploča (PCB), 3D aditivnoj tehnologiji, fleksibilnoj i tekstilnoj elektronici. U Laboratoriji se obučavaju za rad studenti završnih godina akademskih studija i studenti doktorskih studija. Takođe, zaposleni imaju priliku da u Laboratoriji rade svoja istraživanja.*
Ključne reči: ***Mikroelektronika/Istraživački rad/Merne metode***

Paper No. S1-4

LABORATORIJA ZA OPTOELEKTRONIKU – LABORATORIJSKE VEŽBE I ISKUSTVA

Miloš Jovanović[1], Aleksandar Stefanov[2], Marko Vasiljević Toskić[3], Stefan Panzalović[4], Jovan S. Bajić[5]
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Kratak sadržaj: *U radu je predstavljena grana elektronike koja se bavi izučavanjem prirode svetlosti i njenih osobina. Predstavljen je način učenja kroz eksperimentalne laboratorijske vežbe u cilju približavanja gradiva studentima kroz praktičan rad u laboratoriji. Opisan je izgled laboratorije i pojedina aparatura koja se koristi pri izvođenju laboratorijskih vežbi. Nakon toga opisana je metodologija izvođenja laboratorijskih vežbi, gde je dat spisak i sadržaj vežbi koje se trenutno izvode u laboratoriji. Na samom kraju upoređena su iskustva studenata koji su pohađali laboratorijske vežbe unutar laboratorije, u poređenju sa studentima koji su laboratorijske vežbe pohađali online.*
Ključne reči: ***Optoelektronika/Laboratorija/Vežbe***

Paper No. S1-5

ENERGETSKA ELEKTRONIKA - PREGLED KNJIGA, ČASOPISA I NAUČNIH SKUPOVA

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Kratak sadržaj: *Energetska elektronika je oblast elektrotehnike koja se intenzivno razvija još od šezdesetih godina prošlog veka. Taj trend je naročito izražen poslednjih godina sa proširenjem opsega njene primene na priključenje obnovljivih izvora, električne mreže, pogon vozila sa nultom emisijom i dr. Broj objavljenih knjiga, kao i radova u časopisima koji tretiraju ovu tematiku ubrzano raste. Takođe, sve više naučnih skupova u svom naslovu imaju ovu oblast i privlače veliku pažnju istraživača, eksperata i inženjera iz privrede. Autori su smatrali da je prikladno da se napravi jedan pregled stanja u ovoj oblasti sa ovog aspekta. S obzirom da postojeći broj odrednica bi značajno opteretion obim ovog rada, pregled se ograničio samo na one knjige, časopise i skupove koji su međunarodnog karaktera, na engleskom jeziku i koji u svom naslovu imaju reči „Power Electronics". U radu je dat prikaz postojećih knjiga, publikacija i naučnih skupova uvažavajući pomenuto ograničenje, njihovih osnovnih karakteristika uz odgovarajuće komentare. Autori se nadaju da će on korisno poslužiti svima, koji se bave energetskom elektronikom da sagledaju obim publikacija, kao i da imaju pregled svetskih naučnih skupova na ovu temu.*
Ključne reči: ***Energetska elektronika, Knjige, Časopisi, Naučni skupovi***

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