

## High-efficiency power conversion with silicon

### Presenter:

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### Brief description:

A primary aim in the design of power conversion circuitry is to attain high efficiency. Advantages include reduced lifetime energy consumption and reduced cooling requirements. The main candidate power semiconductor devices for applications such as:

- grid-tie inverters;
- industrial machine drives;
- electric vehicle drives;

are generally considered to fall into these categories:

- silicon IGBTs and fast recovery diodes, or
- emerging devices, typically the silicon carbide (SiC) MOSFET.

Of the two, the latter is seen as a higher-cost option with improved performance in terms of efficiency and consequent systems-level benefits, but with implementation challenges such as more rigorous gate-driver requirements. However, this tutorial will examine whether silicon technology has been fully exploited. To this end, the silicon super-junction (SJ) MOSFET will be considered from an applications standpoint to assess whether it offers a useful third option on the performance-cost curve. The SJ MOSFET has been used extensively in SMPSs where it can enable very high efficiencies to be attained. However, the topologies used in the applications addressed here generally fall within the voltage source converter (VSC) category. For the following reasons, the SJ MOSFET presents significant challenges if it is to be advantageously deployed in VSCs.

- The device's intrinsic diode has a highly adverse reverse recovery characteristic.
- The output capacitance of the device has an extremely non-linear characteristic. Whilst beneficial in single-ended circuits, for example, SMPS power factor correction stages, it is highly problematic in VSCs.

Several solutions will be presented and discussed. A key feature of the tutorial is that the theory presented will be supported by several hardware examples of SJ devices successfully deployed in VSCs.

### Outline:

The tutorial will be organized into the following main sections:

The challenges encountered - and solutions in the literature - when using silicon super-junction (SJ) MOSFETs in VSCs will be reviewed in detail.

A simple equation will be presented that gives the minimum losses attainable with SJ MOSFETs in hard-switched VSCs.

A taxonomy of techniques for advantageously deploying SJ MOSFETs in VSCs, including multilevel variants, will be presented. A flowchart-based design methodology will be presented. This will describe how low-cost ancillary circuitry can be optimally located within a VSC to enable it to advantageously use SJ devices.

Whilst the VSC is the most commonly implemented topology family, the current source converter (CSC) and Z-source converter (ZSC) are alternatives. The potential systems-level advantages of deploying the SJ MOSFET in CSCs and ZSCs will be considered.

The very particular design challenges presented by the passive components needed to facilitate the deployment of SJ devices in VSCs will be identified and discussed.

An approach for informing the optimum die area selection when using SJ MOSFETs in high-efficiency power converters will be discussed. Traditional figures of merit are of limited relevance when applying SJ devices in VSCs, and a revisited figure of merit will be presented.

Practical examples of techniques being applied to address the challenges shown by the SJ MOSFET will be presented. As well as in two-level VSCs, these will be demonstrated in multilevel and ZSC topologies.

Whilst work on the SJ MOSFET will be presented in the tutorial, its potential applicability to emerging devices will also be discussed.

Finally, ongoing research in the field will be covered and several areas identified for future research will be highlighted.

## **Relevant publications:**

*Recent relevant publications (since 2014) have included:*

1. M. Rana and N. McNeill, "High-frequency and high-efficiency bidirectional DC-DC converter for electric vehicle supercapacitor systems", appearing at 6<sup>th</sup> IET Hybrid and Electric Vehicles Conference (HEVC 2016), London, UK, November 2016
2. J. Kitson and N. McNeill, "A high efficiency voltage-fed quasi Z-source inverter with discontinuous input current using super-junction MOSFETs", Proceedings, 8<sup>th</sup> IET Power Electronics, Machines and Drives Conference (PEMD 2016), Glasgow, Scotland, UK, April 2016
3. A. Hopkins, N. McNeill and P. H. Mellor, "Drain current injection circuitry for enabling the deployment of super-junction MOSFETs in a 5kW bidirectional DC-DC converter", Proceedings, 8<sup>th</sup> IET Power Electronics, Machines and Drives Conference (PEMD 2016), Glasgow, Scotland, UK, April 2016
4. J. Kitson and N. McNeill, "Circuit for clamping bridge over-voltages in a voltage-fed quasi Z-source converter", IET Electronics Letters, Vol. 52, No. 7, pp. 551-553, 1 April 2016
5. N. McNeill, X. Yuan and P. Anthony, "High-efficiency NPC multilevel converter using super-junction MOSFETs", IEEE Transactions on Industrial Electronics, Vol. 63, No. 1, pp. 25-37, January 2016
6. Hopkins, N. McNeill, P. Anthony and P. H. Mellor, "High efficiency bidirectional 5kW DC-DC converter with super-junction MOSFETs for electric vehicle super-capacitor systems", Proceedings, 7<sup>th</sup> IEEE Energy Conversion Congress and Exposition (ECCE 2015), Montreal, QC, Canada, September 2015
7. A. Hopkins, N. McNeill, P. Anthony and P. H. Mellor, "Figure of merit for selecting super-junction MOSFETs in high efficiency voltage source converters", Proceedings, 7<sup>th</sup> IEEE Energy Conversion Congress and Exposition (ECCE 2015), Montreal, QC, Canada, September 2015
8. N. McNeill, X. Yuan and P. Anthony, "High-efficiency multilevel converter technology for electric vehicle applications using super-junction MOSFETs", Proceedings, 5<sup>th</sup> IET Hybrid and Electric Vehicles Conference (HEVC 2014), London, UK, November 2014
9. P. Anthony and N. McNeill, "The efficient deployment of silicon super-junction MOSFETs as synchronous rectifiers", Proceedings, 7<sup>th</sup> IET Power Electronics, Machines and Drives Conference (PEMD 2014), Manchester, UK, April 2014
10. N. McNeill, P. Anthony and N. Oswald, "Ultra-high efficiency machine drive inverter using super-junction MOSFETs", Proceedings, 7<sup>th</sup> IET Power Electronics, Machines and Drives Conference (PEMD 2014), Manchester, UK, April 2014

*The work in presented in these publications has been carried out under UK EPSRC awards including:*

1. "Ultra-Efficient Grid-Tie Inverter Technology", Award no. EP/K019333/1, £98,795, 2013
2. "Underpinning Power Electronics 2012: Converters Theme", Award no. EP/K035096/1, £2,018,422 between five UK universities, 2013

## **Presenter's biography:**

Neville McNeill has a PhD in power electronics, is a Chartered Engineer and has worked in the electric vehicle and renewable energy industries. He was at the University of Bristol for twelve years until August 2016 where he was latterly Senior Lecturer in Power Electronics. Since September 2016 he has been Senior Research Fellow in Power Electronics at the University of Strathclyde. His main current research interest is in high-efficiency multi-kilowatt power electronic conversion for electric vehicle, aerospace and renewable energy applications.