



# Soft-Switching Motor Drive for Electric Vehicles

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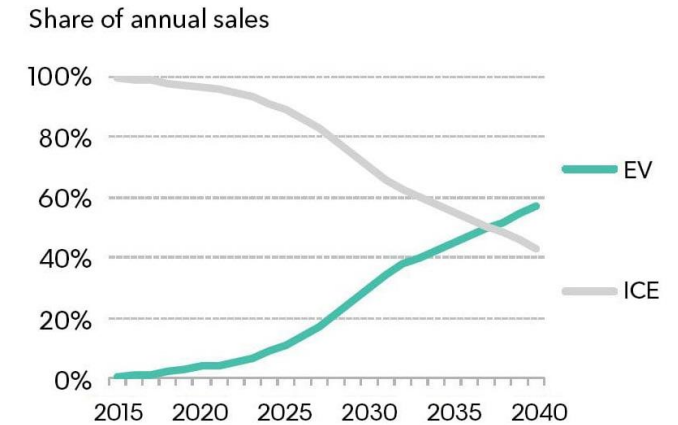
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# Electric Vehicles – Opportunities

- Electric vehicles (EV) market is rapidly expanding [1]:
  - 3% of global light-vehicle sales in 2017
  - Projected to reach 56% by 2040
- Drivetrains are a critical component of EV applications and greatly impact the overall vehicle performance [2]:
  - \$90+ billions in combined investment commitment from major car manufacturers under 5 years to develop next generation of EV technologies, including drivetrains

- [1]: Electric Vehicle Outlook 2019 | Bloomberg New Energy Finance - <https://about.bnef.com/electric-vehicle-outlook/>
- [2]: Global carmakers to invest at least \$90 billion in electric vehicles - *Reuters*, 16-Jan-2018

Global EV and ICE share of long-term passenger vehicle sales



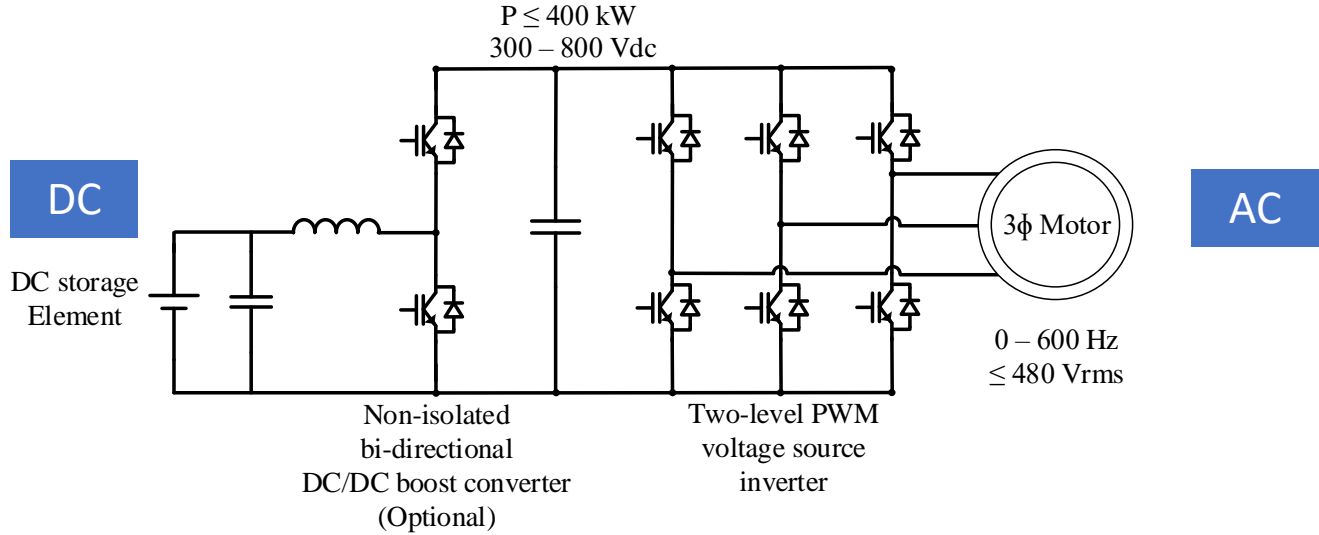
Source: BloombergNEF



**BMW i3**

# Electric Vehicle Motor Drive – Existing Technology

- Electric vehicle motor drives are a critical component of vehicle drivetrain
- Motor drives connect DC battery to three-phase motor (AC) used for propulsion
- Industry standard is hard-switched two-level PWM voltage source inverter (VSI)
- VSI suffers from well-known issues:
  - EMI, dv/dt, reflected waves, overvoltage and motor bearing stress
  - Poor efficiency profile & large fault currents
- Numerous mitigation techniques have been devised for Si-based motor drives:
  - EMI filters and dv/dt filters, reinforced insulation motor design, ruggedized Si IGBT design with improved short-circuit withstanding capabilities, etc.
- **Mitigation techniques increases system complexity & cost, and do not directly apply to SiC and Wide-bandgap semiconductors**



Typical EV drivetrain using DC-DC bi-directional boost converter (optional) and standard two-level voltage source inverter

# Electric Vehicle Motor Drives - State of the Art

- Review of commercial electric vehicle drivetrain [1]:

	2004 Toyota Prius (50kW)	2008 Lexus LS600h (110 kW)	2010 Toyota Prius (60 kW)	2012 Nissan Leaf (80 kW)	2014 Honda Accord (124 kW)	2016 BMW i3 (125 kW)	2017 Toyota Prius (53 kW)
Peak power density (kW/L)	4.5	10.6	5.9	5.7	12.1	18.5	11.5
Peak specific power (kW/kg)	3.8	7.7	6.9	4.9	9.1	14.1	8.6
DC Bus voltage (V)	500	650	650	375	700	355	600

- Best-in-class vehicle (as of 2019): 2016 BWM i3 with 18.5 kW/L
- Far from 2025 DOE/US Drive target: 100 kW/L
- Disruptive changes to conventional drivetrain approach likely required to reach this target
- SiC technology is promising yet very challenging to leverage with hard-switched VSIs



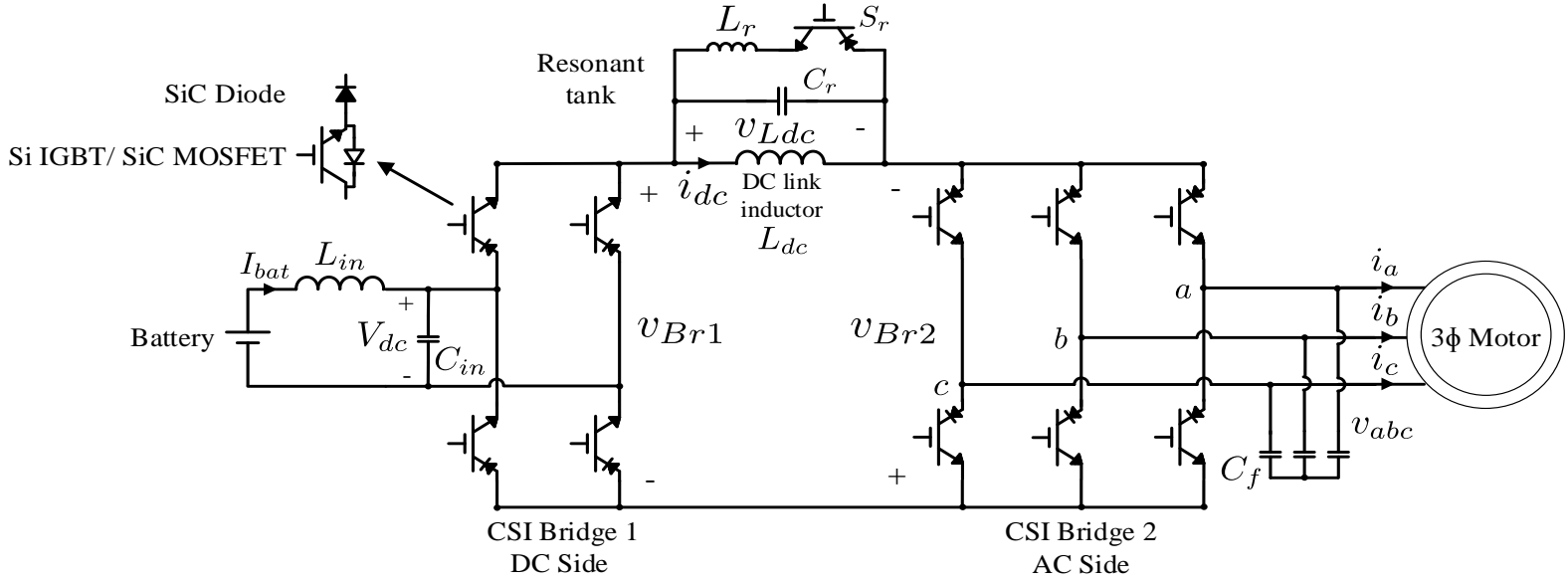
2014 Honda Accord Drivetrain – 17.5 kg, 12.4 L

Limited power density because of inherent limitations of the PWM VSI technology used today

[1]: S. Chowdhury et al., "Enabling Technologies for Compact Integrated Electric Drives for Automotive Traction Applications," in 2019 IEEE Transportation Electrification Conference and Expo (ITEC), 2019, pp. 1–8

# Proposed Soft-Switching Current Source Inverter

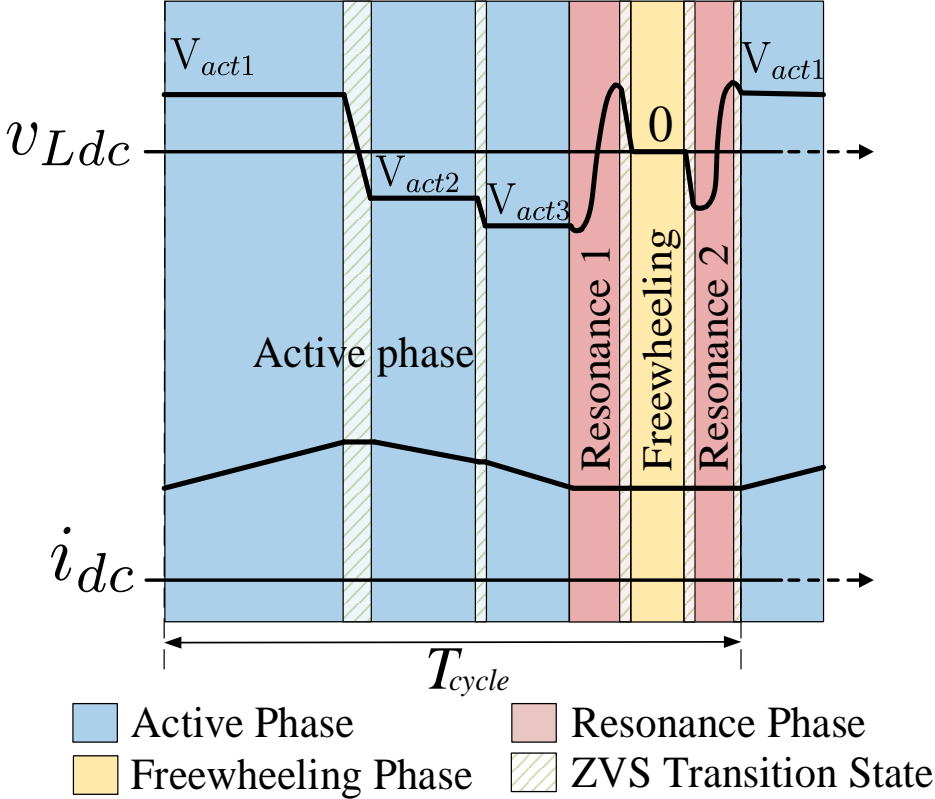
- Use **soft-switching current source inverter (SSCSI) topology** for next-generation EV powertrain:
  - Builds from well known current source inverter
  - **Minimal and self-contained topology** with bi-directional power flow capabilities, and buck-boost functionality
  - Resonant elements ( $L_r, C_r, S_r$ ) rated to handle **only a fraction of the processed power**
  - **Intrinsic dv/dt control for low EMI** – including with latest SiC devices – **without additional dv/dt filters**
  - Soft-switching under all motor regimes for **increased conversion efficiency**
  - High switching frequency, no DC-link capacitor for **power-dense design**



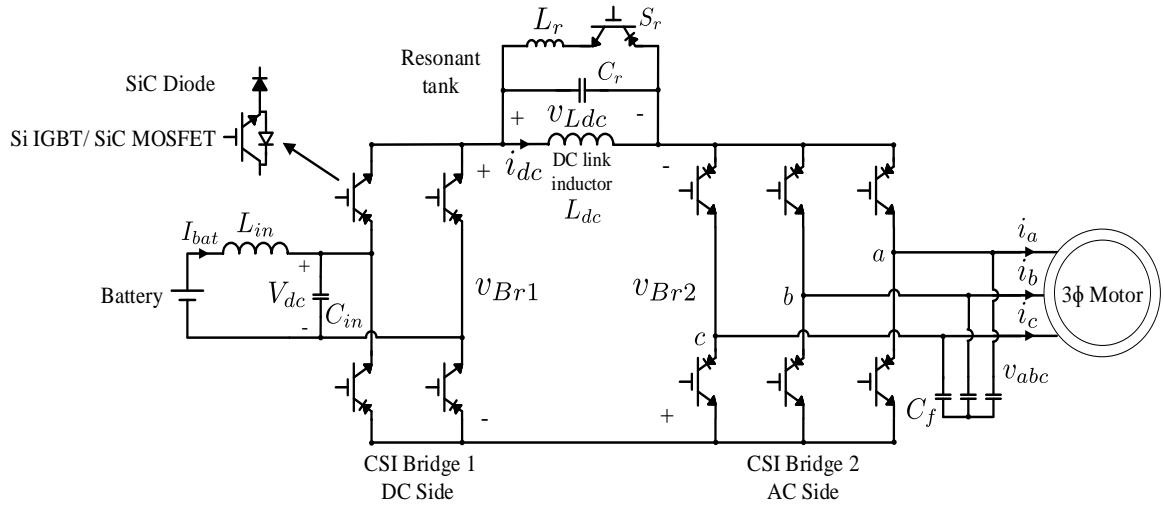
Proposed Soft-Switching Current Source Inverter (SSCSI) for EV drivetrains

# SSCSI – Operating Principles

- Typical Switching cycle of the SSSCI includes three main phases and a ‘ZVS transition’ state [1]:



Typical SSSCI Switching Cycle



- **Active phase:** energy transfer with sources/loads
- **Resonance phase:** unique to SSSCI and required for ZVS operation
- **ZVS transition state:** Zero-voltage switching mechanism in SSSCI
- **Freewheeling phase:** pad switching cycle to keep constant switching frequency
- Resonant tank designed to ensure:

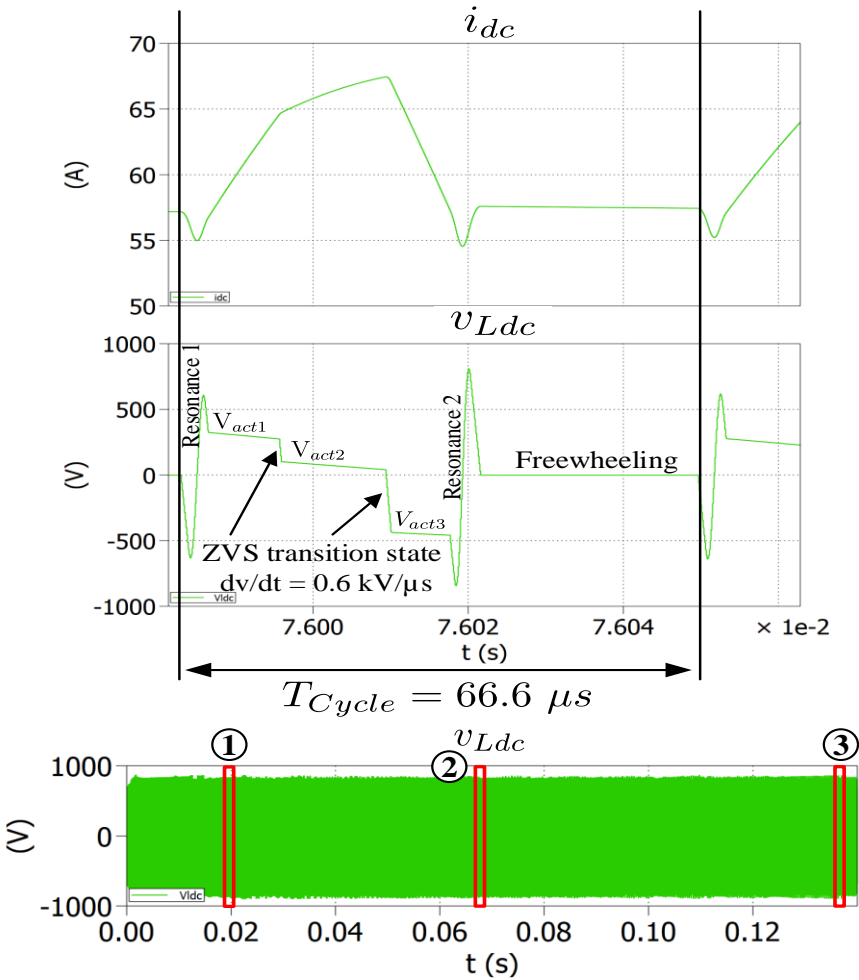
$$t_{Active\_phase} \gg t_{ZVS\_state} + t_{Resonance\_phase}$$

[1] M. J. Mauger, P. Kandula and D. Divan, "Soft-Switching Current Source Inverter for Next-Generation Electric Vehicle Drivetrains," 2020 IEEE Transportation Electrification Conference & Expo (ITEC), 2020, pp. 651-658, doi: 10.1109/ITEC48692.2020.9161493.

# Validation of the Proposed SSCSI Motor Drive

- Simulation study of a 25 kVA SSCSI EV motor drive with V/f control and frequency excursion of 0-500Hz

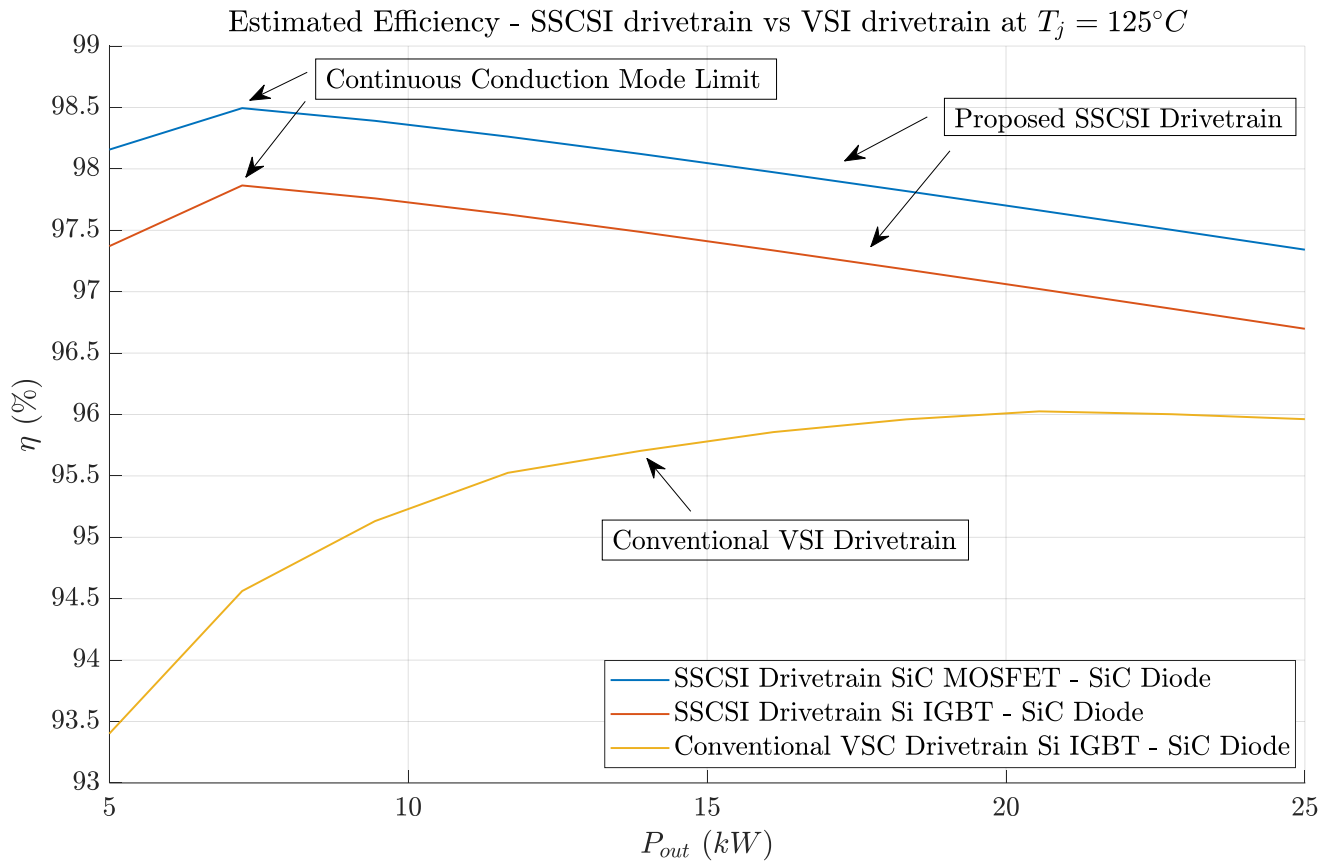
Observation 2 (10 kVA, 300 Vrms)



Parameter	Value	Parameter	Value
Rated power	25 kVA	$L_{dc}$	350 $\mu H$
Nominal battery voltage	500 Vdc	$C_{in} \ \& \ C_f$	28 $\mu F$
Nominal output voltage	480 Vrms LL	$L_{in}$	220 $\mu H$
Nominal DC-link current	60 A	$C_r$	100 nF
Switching frequency	15 kHz	$L_r$	2.8 $\mu H$

- Stable operation under buck and boost conversion mode**
- Output  $THD_V = 5\%$ , Input  $THD_I = 5.5\%$
- Minimum passive element sizes** with very low stored energy (<1 J in DC-link, 10 J in combined filter capacitance)
- Minimum and controlled devices voltage stress**
- Soft-switching confirmed throughout cycle, across entire voltage and loading ranges.** Critical for EV motor drive applications.

# Efficiency Profiles – SSCSI vs VSI EV Motor Drives



Parameter	SSCSI	VSI
Rated power	25 kVA	25 kVA
Nominal battery voltage	500 Vdc	500 Vdc
Nominal output voltage	480 Vrms LL	480 Vrms LL
Nominal DC-link	50 A	750 V
Switching frequency	15 kHz	15 kHz

0.8% - 4% efficiency gains with Si  
1.4% - 5% efficiency gains using SiC

- Using **identical Si IGBTs and SiC diode**, **SSCSI efficiency is higher than conventional VSI** across the entire power range.
- Unique SSCSI efficiency profiles where **efficiency increases as Pout decreases**.
- Similar efficiency trends expected under all machine regimes.
- **SSCSI set to outperform VSI on typical driving cycle.**

# ■ Conclusions

- Proposed soft-switching topology (SSCSI) for next-generation electric vehicle motor drive with:
  - Minimal and self-contained topology
  - Bi-directional DC-AC conversion with buck-boost capability
  - Soft-switching operation under all machine regimes
  - Intrinsic  $dv/dt$  control for low EMI, including with SiC devices
  - High switching frequency
  - Filtered input/output waveforms with low THD and common-mode voltage
  - No bulky DC-link capacitor
  - Benign failure mode
- SSSCI offers numerous system benefits:
  - High power density
  - Unique efficiency profiles with up to 5% efficiency gains over traditional VSI topology
  - High temperature operation
  - Simplified electric motor design
  - Increased driving range

# Thank you for your attention

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