Power Electronics for Inductive Power Transfer Systems

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System Overview

Power Supply Unit → Inverter → Gate Drive (Resonant) → Tx → Rx → Rectifier → Load Emulation (optional) → Battery

Inductive Link

Transmitting End → Receiving End
Coils with ferrite cores (EV charging pads) can be heavy and not very portable.

Their directed magnetic flux leads to restricted freedom of movement.

Air-core coils, with their wide flux coverage, are more suitable for IPT applications as: drones or unmanned aerial vehicles (UAV) chargers, wireless office.

By resonating the receiving coil at the frequency of the transmitted magnetic field, link efficiency is improved.
**Equations describing the Link:**

1. $\eta_{\text{link, max}} = \frac{k^2 Q_{\text{TX}} Q_{\text{RX}}}{(1 + \sqrt{1 + k^2 Q_{\text{TX}} Q_{\text{RX}}})^2}$
2. $\alpha = \omega C_{\text{RX}} R_{\text{LOAD}}$
3. $\alpha_{\text{par}} = \frac{Q_{\text{RX}}}{\sqrt{1 + k^2 Q_{\text{TX}} Q_{\text{RX}}}}$
4. $\alpha_{\text{ser}} = \frac{\sqrt{1 + k^2 Q_{\text{TX}} Q_{\text{RX}}}}{Q_{\text{RX}}}$
5. $Q = \frac{\omega L}{R}$
● Increase frequency to maximise Q factors.
● Maximum frequency at the point after which far-field radiation begins to dominate.
● Switching losses of power electronics may rise, so despite improved link efficiency, overall efficiency may decrease.
● Efficient high frequency soft-switching power electronic topologies are required, with fast semiconductor devices.
Hard Switched Topologies:

- Switching losses decrease system’s efficiency.
- Induced coil current with high harmonic distortion.

Advantages of Class-D Operation:

- Switching losses can be minimised after proper selection of semiconductors and passive filters.
- Simple design.
- Low component stress regarding the required output voltage and current.
- Tolerant to load variations.

Advantages of Class-E Operation:

- Minimizes switching losses.
- Semiconductor can reach higher switching frequencies.
- Simple gate drive circuit.
- Presents a linear load to the inductive link (rectifier).
## FET Transistors

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Tech</th>
<th>Model</th>
<th>$V_{DS,MAX}$ (V)</th>
<th>$R_{DS,ON}$ (Ω)</th>
<th>$t_R$, $t_F$ (ns)</th>
<th>$R_{G,ext}$ (Ω)</th>
<th>$V_{GS}$ (V)</th>
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<tbody>
<tr>
<td>IXYS</td>
<td>Si</td>
<td>102N12A</td>
<td>1000</td>
<td>0.95</td>
<td>3, 8</td>
<td>0.2</td>
<td>0/+15</td>
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<td></td>
<td></td>
<td>201N25A</td>
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<td>5, 8</td>
<td>0.2</td>
<td>0/+15</td>
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<tr>
<td>Vishay</td>
<td>Si</td>
<td>SiS892ADN</td>
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<td>0.033</td>
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<td>1</td>
<td>0/+10</td>
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<tr>
<td>Cree</td>
<td>SiC</td>
<td>C2M0280120D</td>
<td>1200</td>
<td>0.28</td>
<td>7.6, 9.9</td>
<td>2.5</td>
<td>-5/+20</td>
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<tr>
<td>EPC</td>
<td>GaN</td>
<td>EPC8009</td>
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<td>0/+5</td>
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<tr>
<td>GaN Systems</td>
<td>GaN</td>
<td>GS66508T</td>
<td>650</td>
<td>0.055</td>
<td>N/A</td>
<td>1.5</td>
<td>0/+7</td>
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</tbody>
</table>

**IXYS**

**VISHAY**

**CREE**

**EPC**

**GaN Systems**
## Semiconductor Technology

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Tech</th>
<th>Model</th>
<th>$V_{D,\text{MAX}}$ (V)</th>
<th>$i_{F,\text{MAX}}$ (A)</th>
<th>$Q_c$ (nC)</th>
<th>$C_{D,\text{max}}$ (pF)</th>
<th>$C_{D,\text{min}}$ (pF)</th>
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</thead>
<tbody>
<tr>
<td>Cree</td>
<td>SiC</td>
<td>C3D10170A</td>
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<td>10</td>
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<td>C3D10060A</td>
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<tr>
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<td>3</td>
<td>N/A</td>
<td>360</td>
<td>~60</td>
</tr>
</tbody>
</table>

**CREE**
- TO-220-2
- PowerQFN 3.3x3.3

**NXP**
- SOD128
Transmitting End

Power Supply Unit → Inverter → Gate Drive (Resonant) → Rx → Rectifier → Load Emulation (optional) → Battery

Receiving End

Inductive Link
Class-E inverter:

- In theory more efficient than Class-D.
- Zero-voltage switching minimises turn on losses.
- At optimal reflected load zero rate of change of voltage is achieved with maximum output power capability.
- Transformation of loaded coil impedance to decrease current stress in the utilised MOSFET.
- Suboptimal Class-E operation at lower than optimal $R_L$ (coupling factor decreases) – still efficient switching.
- Class-E operation ceases at loads greater than optimal.
Saturable Reactors:

- By controlling the frequency of operation and saturating the secondary side of high impedance ratio transformers (saturable reactor), Class-E operation is recovered when $R_L$ exceeds the optimal load value.

![Diagram of inverter circuit with saturable reactor](image-url)
Class-EF\textsubscript{2/3} Inverter:

- Hybrid inverters that combine the improved switch voltage and current waveforms of Class-F inverters with the efficient switching of Class-E inverters.
- Switch voltage and current stresses are reduced according to design method.
- Efficiency, output power and power output capability become higher than the Class-E.
- Sensitive to $R_L$ variations (like Class-E).
- Sensitivity analysis ongoing project.
Transmitting End

Power Supply Unit → Inverter → Gate Drive (Resonant) → Rx → Rectifier → Load Emulation (optional) → Battery

Inductive Link

Receiving End
Main loss mechanisms in the Class-E semi-resonant inverter are conduction and gate drive losses. Conduction losses could be reduced if the IXYS FET is replaced by a Cree SiC MOSFET due to lower $R_{DS,ON}$. Resonant gate drive allows low power driving of SiC device at MHz frequencies despite high $V_{GS}$ requirements.

<table>
<thead>
<tr>
<th>Model</th>
<th>$V_{DS,MAX}$ (V)</th>
<th>$R_{DS,ON}$ (Ω)</th>
<th>$C_{iss}$ (pF)</th>
<th>$R_{G,ext}$ (Ω)</th>
<th>$V_{GS}$ (V)</th>
<th>$P_{G,C}$ (W)</th>
<th>$P_{G,R,C}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si - IXYS</td>
<td>102N12A</td>
<td>1000</td>
<td>0.95</td>
<td>2000</td>
<td>0.3</td>
<td>0/+10</td>
<td>1.35</td>
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<tr>
<td>SiC - Cree</td>
<td>C2M0280120D</td>
<td>1200</td>
<td>0.28</td>
<td>259</td>
<td>11.4</td>
<td>-5/+20</td>
<td>1.1</td>
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</table>
Experimental Results:

- Cree C2M0280120D SiC MOSFET was chosen as the MOSFET in the semi-resonance Class-E inverter.

- EPC8009 Gallium Nitride (GaN) MOSFET from EPC was chosen for all four switches for the gate drive.

- Transmitting end efficiency begins at 70% at 10-W delivered to ac load and increases up to 94% at 100-W ac load power.
Underpinning Research

Receiving End

Power Supply Unit → Inverter → Gate Drive (Resonant) → Tx → Rx → Rectifier → Load Emulation (optional) → Battery

Inductive Link

Transmitting End → Receiving End
Design Requirements:

- Specific $R_{LOAD}$ provides maximal link efficiency.
- Deployed rectifier must present $R_{LOAD}$.
- Efficient at the frequency of operation.
- Comply with the output type of the tuned resonant tank:
  - Current output when series tuned
  - Voltage output when parallel tuned

Parallel Resonance:

Series Resonance:
Rectifiers

Half Wave Resonant Class-E:

Design Equations:
\[ R_{dc} = 2M^2 R_{LOAD} \]
\[ L_r = \frac{R_{dc}}{\omega_o Q_{rect}} \quad C_r = \frac{1}{\omega_r^2 L_r} \quad A = \frac{\omega_o}{\omega_r} \]

Half Wave Class-D:

Design Equation:
\[ R_{dc} = \frac{\pi^2 R_{LOAD}}{2} \]

Half Wave Class-E:

Design Equations:
\[ R_{dc} = \frac{R_{LOAD}}{2M^2 I} \quad C_d = \frac{Q_{rect}}{\omega R_{dc}} \]
Test Rig:

- Voltage driven multi-frequency Class-D inverter supplying power to the resonant tank and rectifier.
- Inverter output emulates induced emf in Rx coil.
- All the odd harmonics except the first are filtered by the series tuned coil.
- Product of inverter's output voltage and output current is the input power to the Rx end.
- Input resistance is calculated using the measured power and input current.
Experimental Results: Resonant Class-E

- Comparison between Class-E resonant rectifiers at 6.78-MHz, operating \textit{at} and \textit{below} resonance.
- Operation below resonance more efficient with peak estimated efficiency at 90\% when 120-W were delivered to the dc load.
- Input impedance dependent on output voltage.
- The total harmonic distortion (THD) of the link’s spectrum when utilizing the rectifier was calculated to verify the resistive nature of the topology: THD of generated magnetic field: 0.17\%.
Experimental Results: Current driven Class-D and -E

- Current driven Class-D and Class-E were compared for IPT applications at 6.78-MHz when utilising Cree SiC diodes (C3D10060A).
- Both rectifiers achieved their highest efficiency at high voltage operation, Class-D: 95% and Class-E: 92%.
- Junction capacitance of diodes introduced a frequency-dependent impedance in the Class-D and a small error in the required input resistance value of the Class-E.

Class-D; Vertical: 50 V/div; Horizontal: 100 ns/div

Class-E; Vertical: 100 V/div; Horizontal: 100 ns/div
Underpinning Research

Receiving End

Power Supply Unit
Inverter
Gate Drive (Resonant)
Tx
Rectifier
Load Emulation (optional)
Battery

Transmitting End
Inductive Link
Receiving End
DC Load Emulation

Parallel Resonance || $Q_{Rx} = 1100$

Series Resonance || $Q_{Rx} = 1100$

- $k^2Q_{Tx} = 2.00E-02$
- $k^2Q_{Tx} = 6.32E-02$
- $k^2Q_{Tx} = 2.00E-01$
- $k^2Q_{Tx} = 6.32E-01$
- $k^2Q_{Tx} = 2.00E+00$
- $k^2Q_{Tx} = 6.32E+00$
- $k^2Q_{Tx} = 2.00E+01$
Magnetic Link Optimisation

Power Supply Unit → Inverter → Gate Drive (Resonant) → Inductive Link → Rectifier → Load Emulation (optional) → Battery

Tx Rx
Artificial magnetic conductors can give increased link efficiency and provide shielding.

- Reduce flux concentration behind the coils.
- Designs have been developed making use of permeable substrates and lumped capacitor loading that can operate at MHz IPT frequencies.
Research Summary:

- Coil design.
- Artificial magnetic conductor shielding.
- High-frequency inverters.
- High-frequency rectifiers.
- System optimisation for several IPT applications.

http://www.imperial.ac.uk/wireless-power/