# Concurrent Operation of Wireless and Wired Power Transfer System with a Single Converter/Inverter

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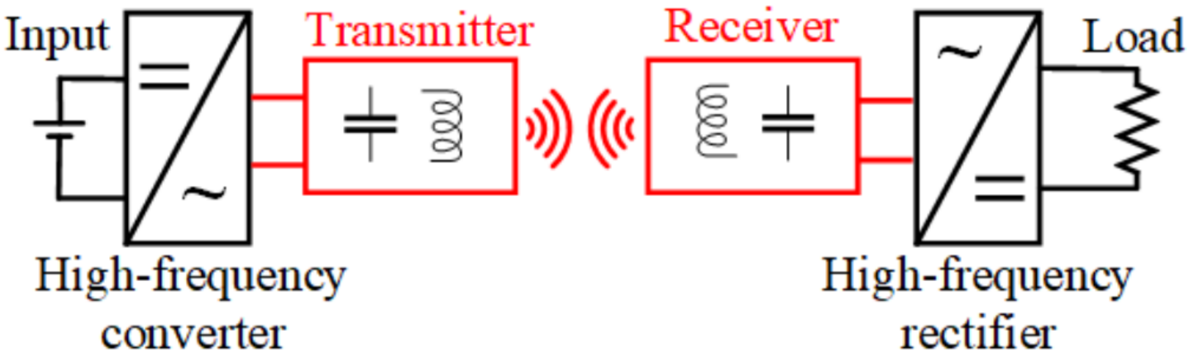
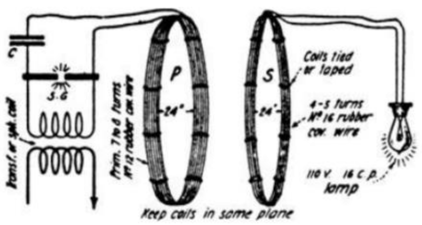
20/10/2022

# Wireless Power Transfer



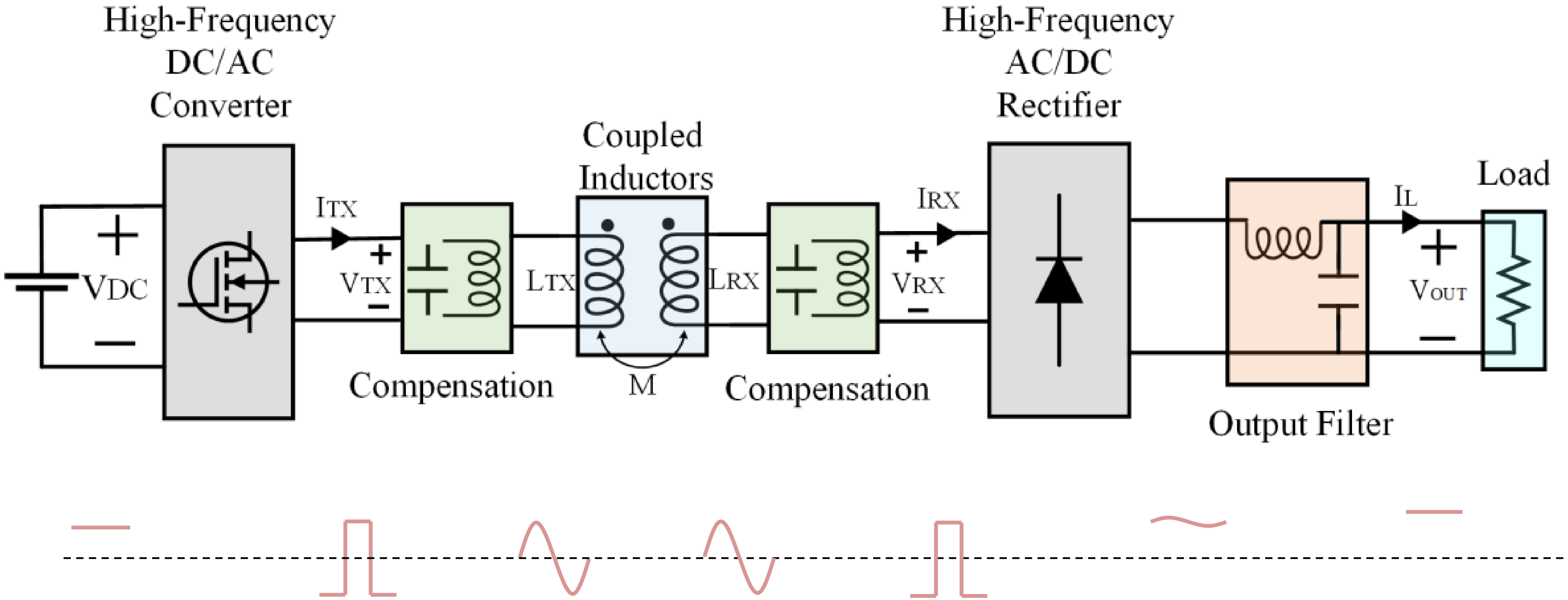

1. DC/AC Converter
2. Compensation Circuits
3. Transmitter/Receiver Coils
4. AC/DC Rectifiers



Tesla's WPT System

| | Inductive Power Transfer | Capacitive Power Transfer |
|---|---|---|
| Transfer Type | Varying MF | Varying EF |
| Power Ratings | High | Low |
| Frequencies | Low | High |
| Efficiency | High | High |
| Distance | Moderate | Low |

# Inductive Power Transfer System



Look at Mendeley : PowerLab/Enes/WPT-Motor

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# Simultaneous Information/ Power Transfer

1. Simultaneous Wireless Information and Power Transfer (SWIPT): Recent Advances and Future Challenges (2018)
2. Integrated Resonant Structure for Simultaneous Wireless Power Transfer and Data Telemetry(2012)
3. A Simultaneous Wireless Power and Data Transmission Method for Multi-Output WPT Systems: Analysis, Design, and Experimental Verification (2020)

# Selective Power Transfer

1. Selective Omnidirectional Magnetic Resonant Coupling Wireless Power Transfer With Multiple-Receiver System(2018)
2. Design and Analysis of Wireless Switched Reluctance Motor Drives(2019)
3. Frequency Splitting-Based Wireless Power Transfer and Simultaneous Propulsion Generation to Multiple Micro-Robots(2018)
4. Comparative Analysis of Frequency-Selective Wireless Power Transfer for Multiple-Rx Systems(2020)
5. A Frequency-Selective EMI Reduction Method for Tightly Coupled Wireless Power Transfer Systems Using Resonant Frequency Control of a Shielding Coil in Smartphone Application(2020)
6. Selective Wireless Power Transfer for Smart Power Distribution in a Miniature-Sized Multiple-Receiver System(2016)
7. A Multifrequency Superposition Methodology to Achieve High Efficiency and Targeted Power Distribution for a Multiload MCRWPT System(2018)
8. Cross Interference Minimization and Simultaneous Wireless Power Transfer to Multiple Frequency Loads Using Frequency Bifurcation Approach

# Slip-Ring Applications

1. A Primary-Side Control Method of Wireless Power Transfer for Motor Electric Excitation(2019)
2. Wireless DC Motor Drives with Selectability and Controllability(2017)
3. An Airborne Radar Power Supply With Contactless Transfer of Energy—Part I: Rotating Transformer (2007)
4. Aerodynamic Fluid Bearings for Translational and Rotating Capacitors in Noncontact Capacitive Power Transfer Systems(2014)
5. Synchronous Generator Brushless Field Excitation and Voltage Regulation via Capacitive Coupling Through Journal Bearings(2017)
6. Operation of an Electrical Excited Synchronous Machine by Contactless Energy Transfer to the Rotor(2018)
7. A Rotation-Lightweight Wireless Power Transfer System for Solar Wing Driving(2019)
8. Wireless Power Transfer for Smart Industrial and Home Applications(2019)
9. Use of the Rotating Rectifier Board as a Capacitive Power Coupler for Brushless Wound Field Synchronous Machines(2022)

# Single-Stage Power Transfers

1. A High-Efficiency GaN-Based Single-Stage 6.78 MHz Transmitter for Wireless Power Transfer Applications(2019)
2. Cooperative Integration of RF Energy Harvesting and Dedicated WPT for Wireless Sensor Networks(2019)
3. A Three-Phase Single-Stage AC–DC Wireless-Power-Transfer Converter With Power Factor Correction and Bus Voltage Control(2020)
4. Individually Regulated Multiple-Output WPT System With a Single PWM and Single Transformer (2020)

# Concurrent Power Transfer

1. Multifrequency Inductive Power Transfer(2014)
2. Wireless Power Transfer With Concurrent 200-kHz and 6.78-MHz Operation in a Single-Transmitter Device (2016)
3. Gan-Based Dual-Mode Wireless Power Transfer Using Multifrequency Programmed Pulse Width Modulation (2017)
4. A Multifrequency Superposition Methodology to Achieve High Efficiency and Targeted Power Distribution for a Multiload MCRWPT System (2018)
5. Cross Interference Minimization and Simultaneous Wireless Power Transfer to Multiple Frequency Loads Using Frequency Bifurcation Approach(2019)
6. A Gallium Nitride (GaN)-Based Single-Inductor Multiple-Output (SIMO) Inverter With Multi-Frequency AC Outputs (2019)
7. Single-Inductor Multiple-Output (SIMO) Buck Hybrid Converter for Simultaneous Wireless and Wired Power Transfer(2020)
8. Generalized methodology to generate, amplify and compensate multi-frequency power for a single-inverter-based MF-MR-S-WPT system (2020)
9. Concurrent Wireless Power Transfer to Multiple Receivers With Additional Resonant Frequencies and Reduced Power Switches (2020)
10. Multifrequency and Multiload MCR-WPT System Using Hybrid Modulation Waves SPWM Control Method (2021)
11. Multi-Frequency Multi-Amplitude Superposition Modulation Method With Phase Shift Optimization for Single Inverter of Wireless Power Transfer System (2021)
12. Design and Control of a Decoupled Multichannel Wireless Power Transfer System Based on Multilevel Inverters (2022)
13. A Dual-Frequency Three-Dimensional WPT System with Directional Power Transfer Capability at Two Separately Regulated Outputs (2022)

# Aim : Merging Concurrent Power Transfer System with Slip Ring Applications

## Concurrent Power Transfer

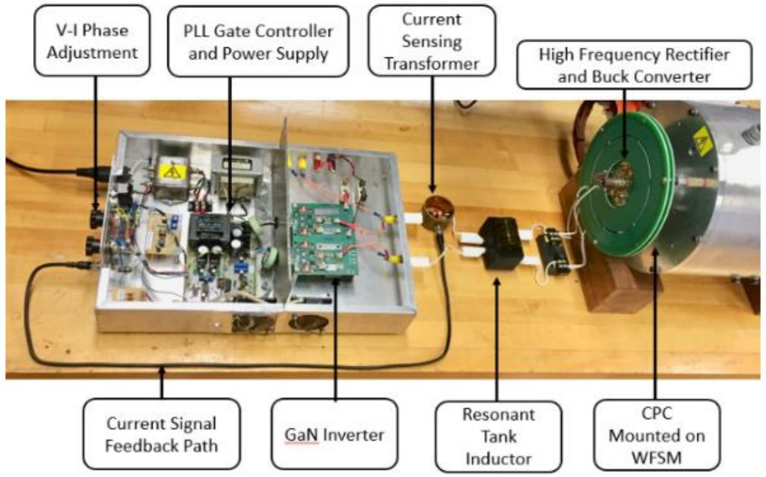
### Motivations:

1. To increase power
2. To reduce switching components
3. To increase DC-link utilization rate
4. To provide operation for more than one standards

### Topologies:

1. Multi-converter and multi-resonant
2. Single-converter and multi-resonant
3. Single-converter and multi-load

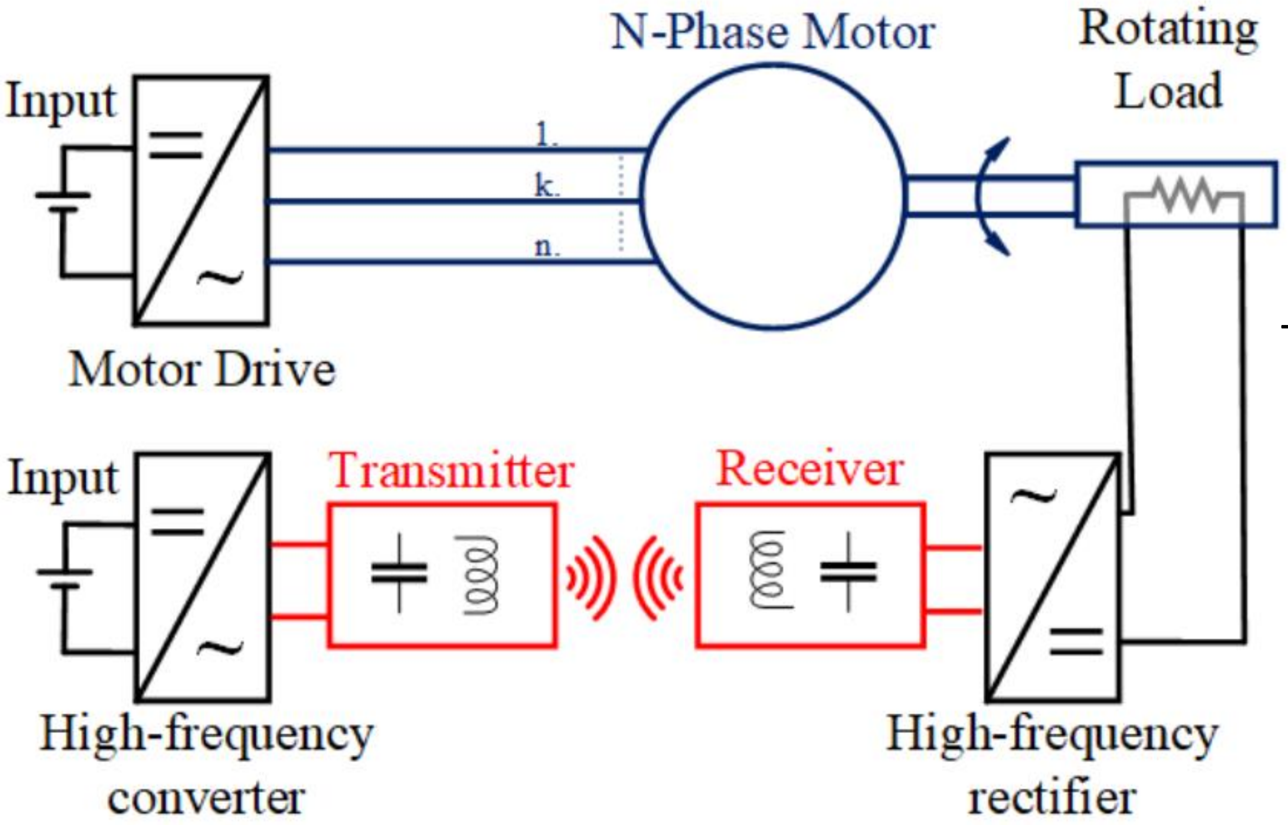
## Contactless Slip Rings




### Motivations:

1. To eliminate carbon brushes requiring periodic maintenance
2. To eliminate brushless exciters that are not suitable for variable speed drives

# Conventional Inductive Power Transfer Based Contactless Slip Ring




Two converters:

1. To drive the motor
2. To excite the Tx coil

Motor → attenuated in motor current

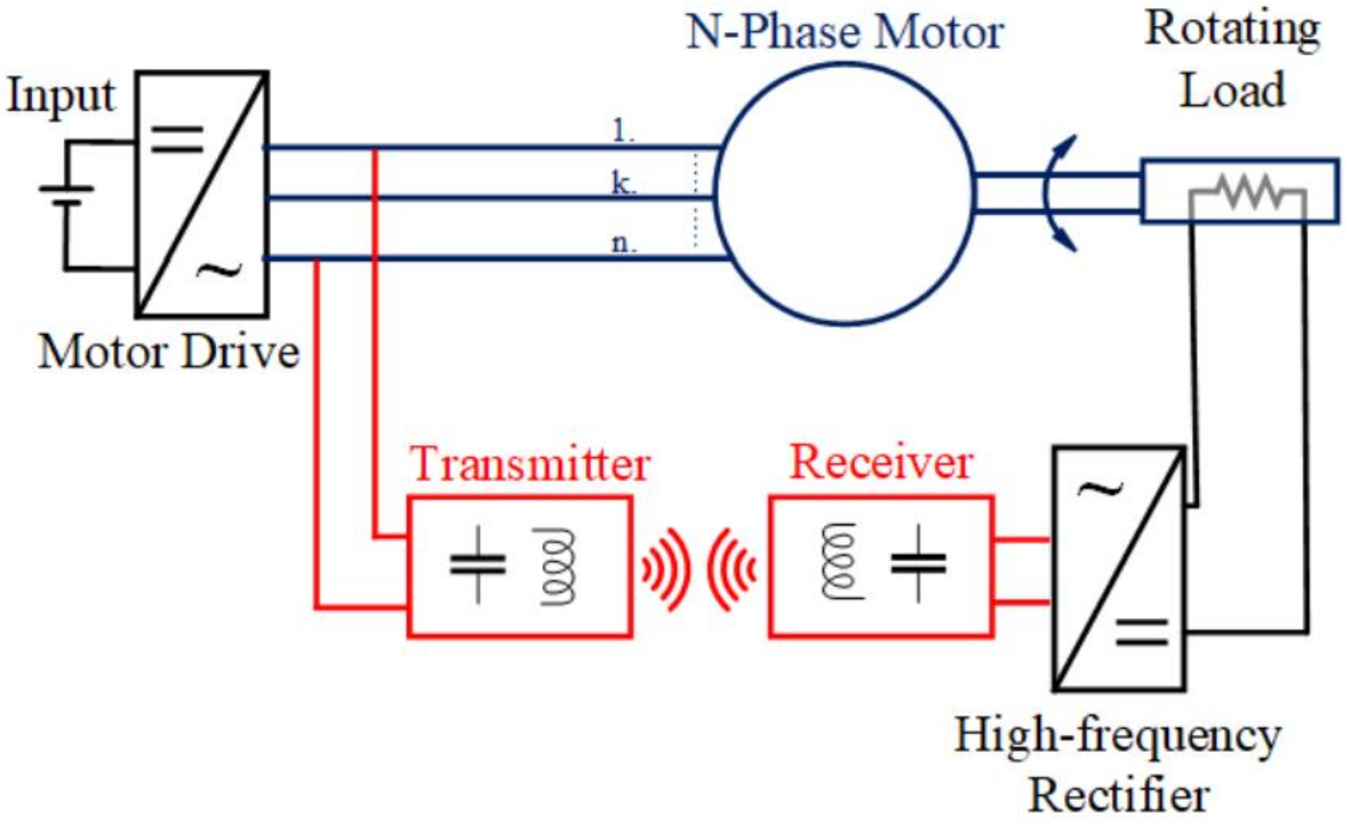
The motor drive → generating low and high frequencies

Motor → used to drive

The WPT converter → generating high frequency

The WPT system →behaves like band-pass filter

# Proposed Inductive Power Transfer Based Contactless Slip Ring



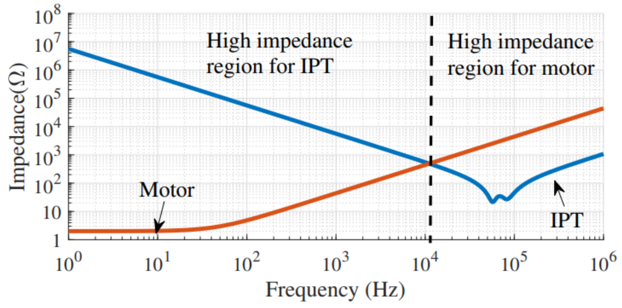

The motor drive → generating high frequency

combining

The WPT system →behaves like band-pass filter

No longer required

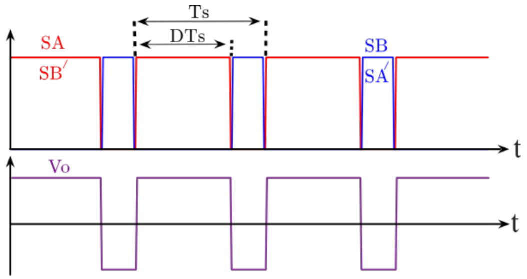
~~The WPT converter → generating high frequency~~



# Challenge: Independent Control of Motor and Contactless Slip Ring Power

Motor:

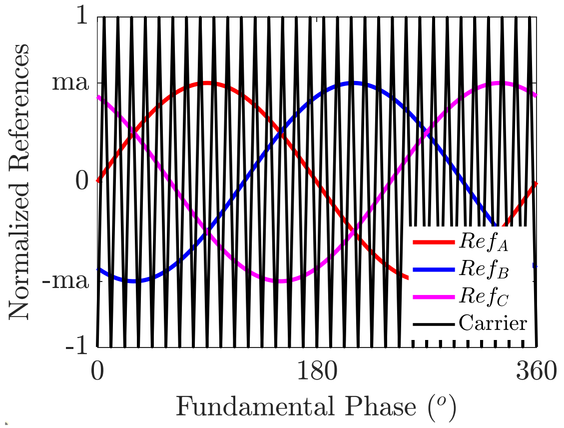
1. DC motor
2. AC motor




Control:

Pulse Width Modulation

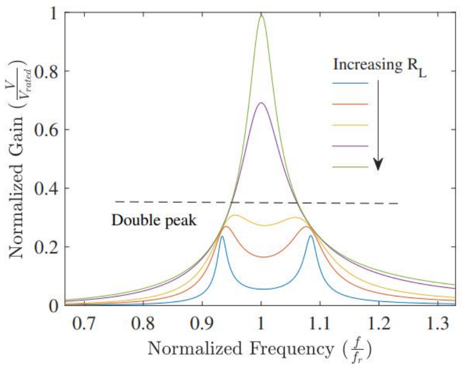
- Unipolar PWM
- Bipolar PWM
- SPWM
- SVPWM
- DPWM




WPT:

1. Transmitter (Primary Side) Control
   - Duty Cycle Control
   - Phase Shift Control
   - Switching Frequency Control

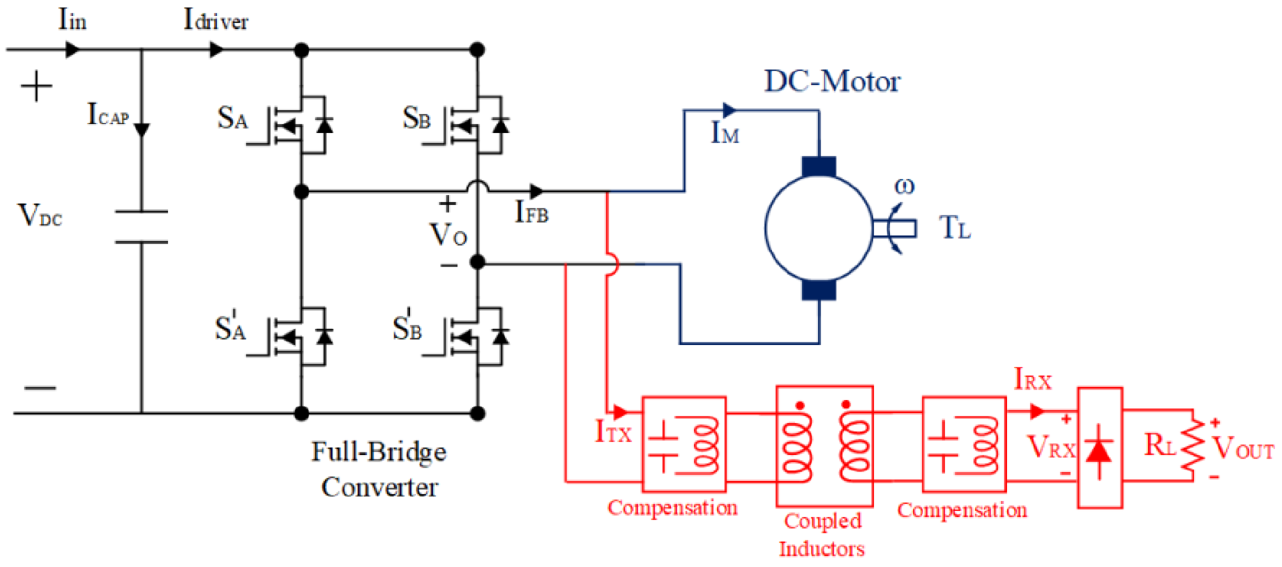
2. Receiver (Secondary Side) Control
   - Additional active converter
   - Active rectifier

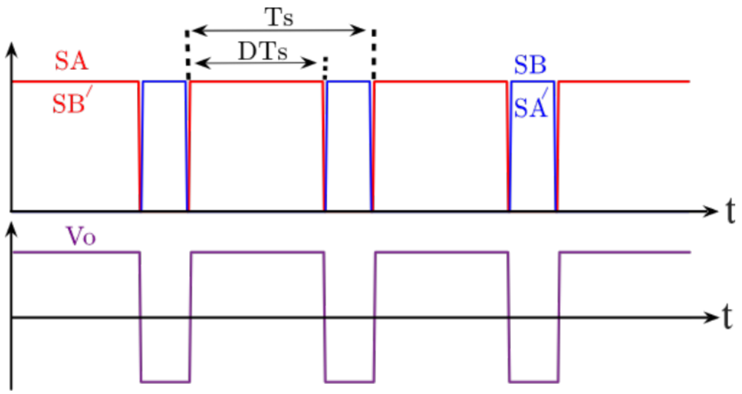


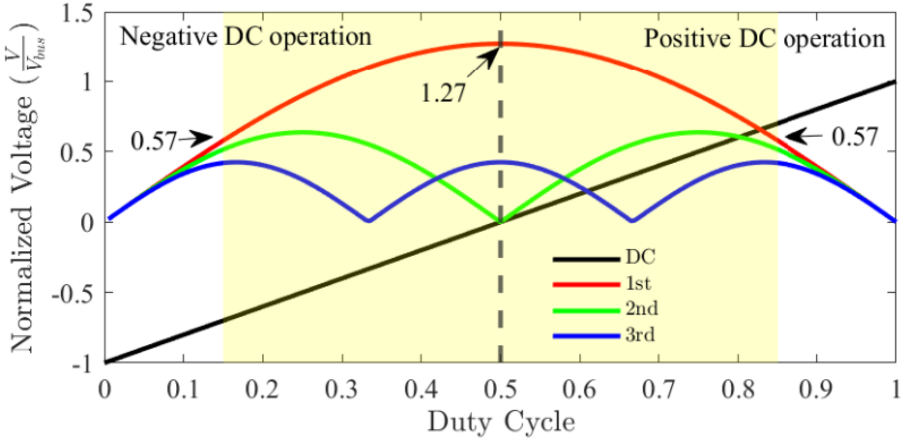
# DC Motor Drives

$$S_A = S_B'$$

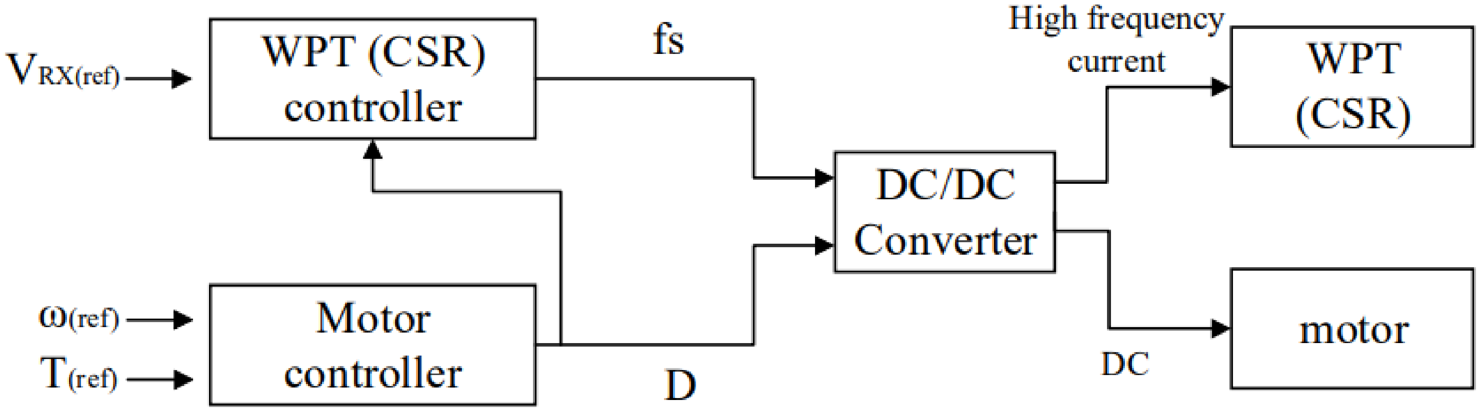
$$S(t) = \mathrm{D} + \sum_{\mathrm{k}=1}^{\infty} \frac{2}{\mathrm{k}\pi} \sin(\mathrm{k}\pi\mathrm{D})\cos(2\pi\mathrm{k}\mathrm{f_s}\mathrm{t})$$

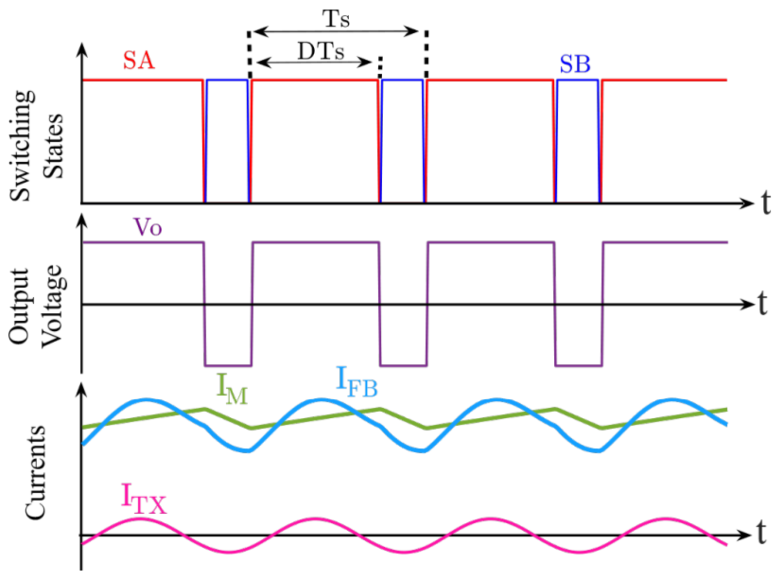


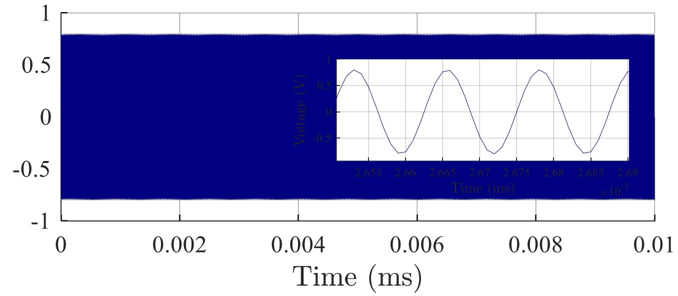



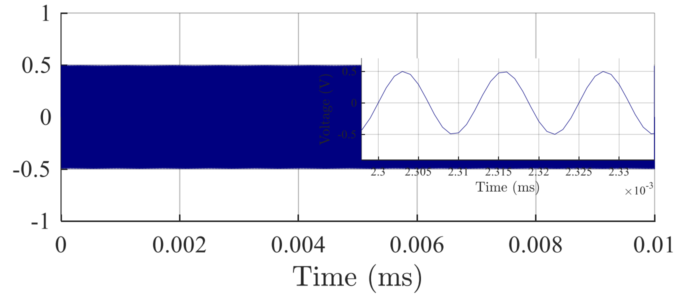



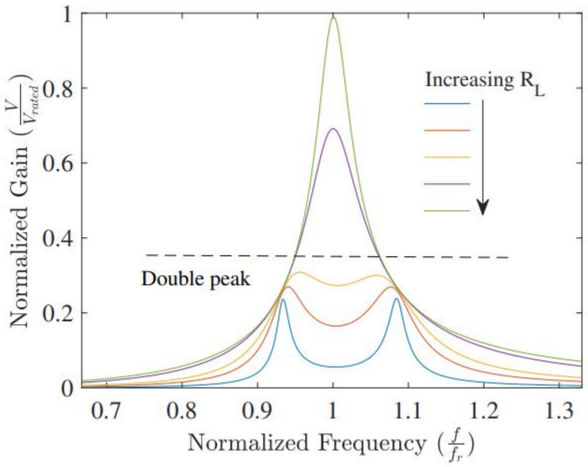
# Control Method



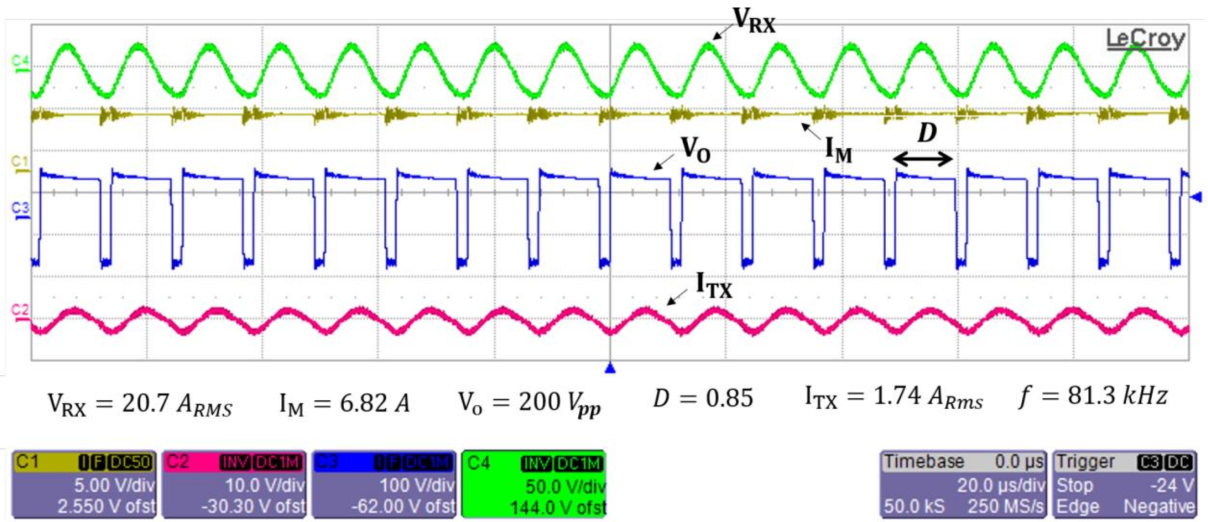



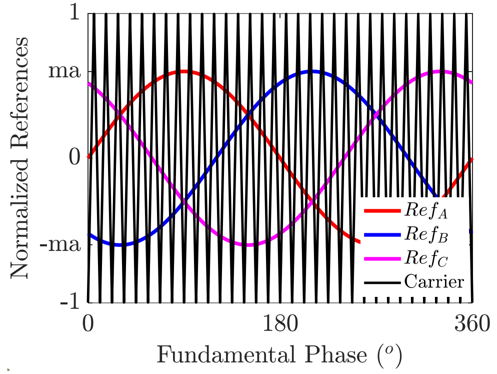



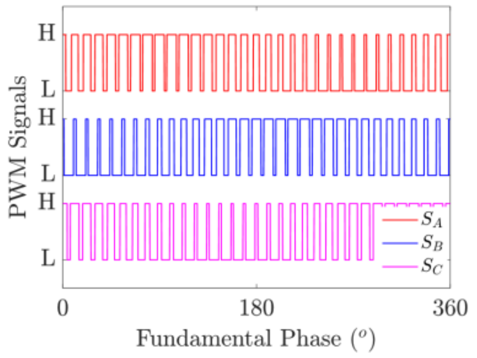
# Concurrent Operation

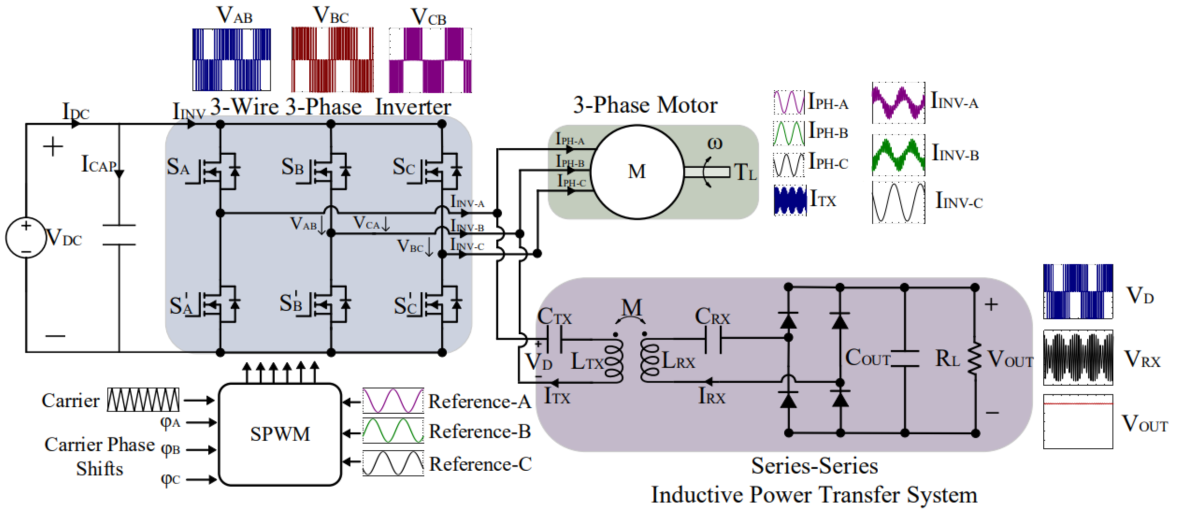


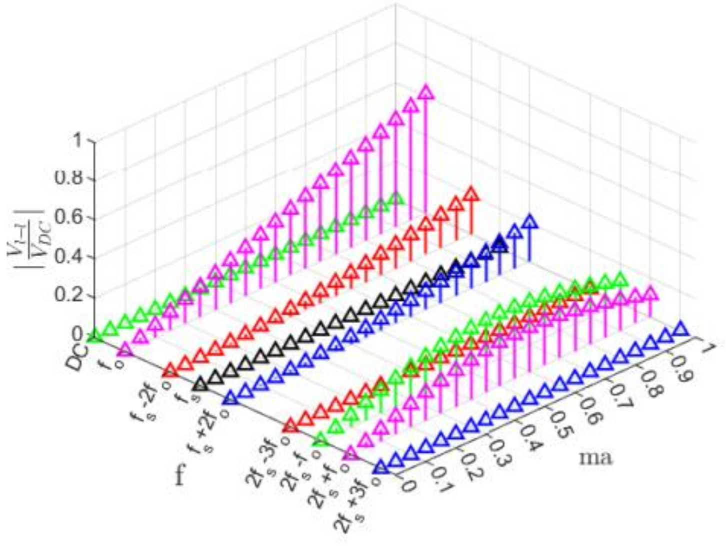

| | Cases | | | | | | |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G |
| **Frequency (kHz)** | 95 | 90 | 90 | 95 | 90 | 90 | 97.5 |
| **Duty Cycle** | 0.6 | 0.75 | 0.75 | 0.6 | 0.6 | 0.6 | 0.5 |
| **Load Torque (N.m)** | 0.24 | 0.27 | 0.37 | 0.21 | 0.21 | 0.17 | - |
| **Motor Power (W)** | 125 | 179 | 244 | 109 | 110 | 89 | - |
| **IPT Power (W)** | 50 | 51 | 51 | 50 | 90 | 90 | 52.7 |

# AC Motor Drives



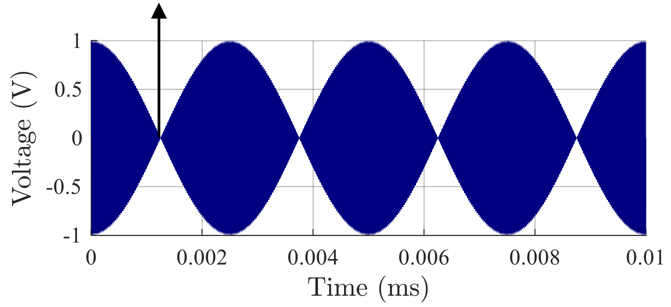



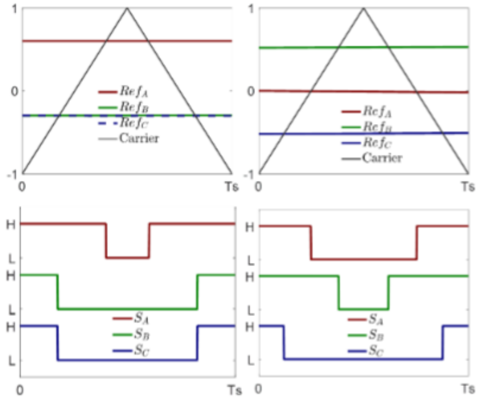

| Frequency | Leg A | Leg B | Leg C | Sequence |
|---|---|---|---|---|
| $f_o$ | $0^o$ | $120^o$ | $-120^o$ | Positive |
| $f_s - 2f_o$ | $0^o$ | $120^o$ | $-120^o$ | Positive |
| $f_s$ | $0^o$ | $0^o$ | $0^o$ | Zero |
| $f_s + 2f_o$ | $0^o$ | $-120^o$ | $120^o$ | Negative |

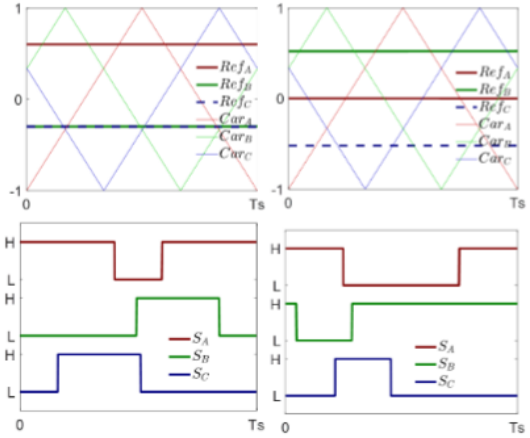
There is no transferred power at some time points if only side band exist

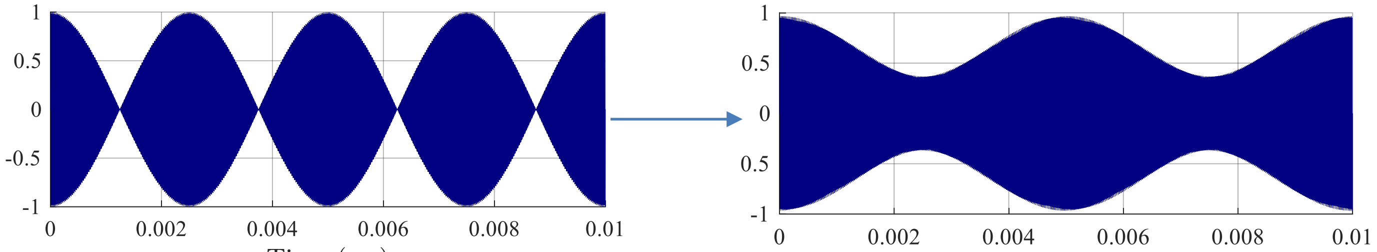



*no component at* $f_s$

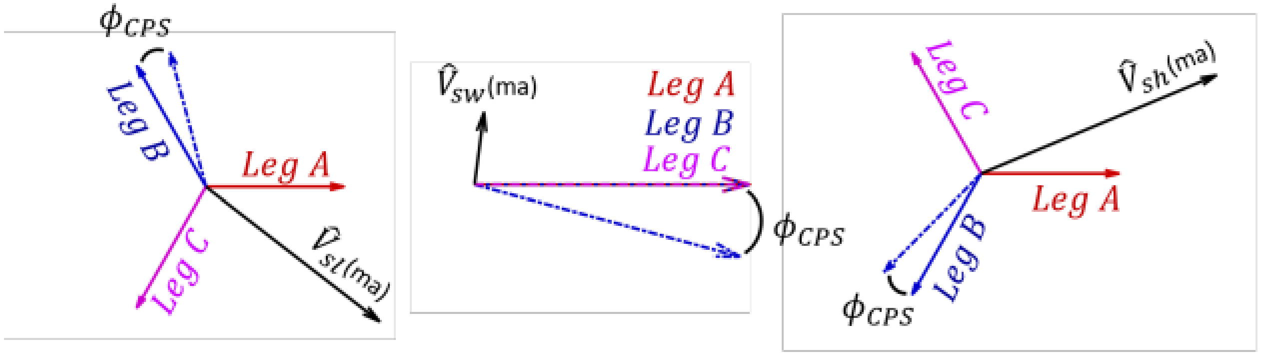
# Carrier Phase Shift



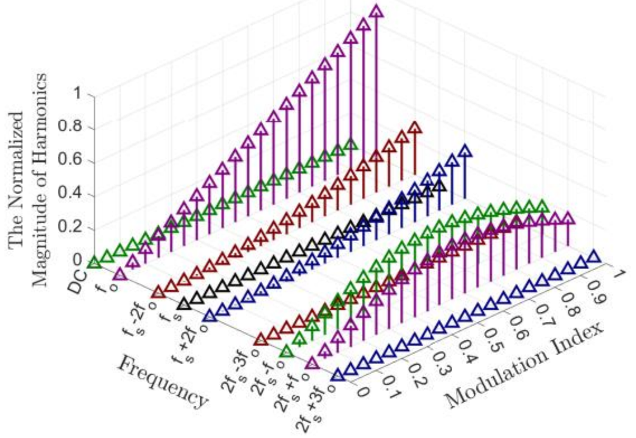




| Frequency | Leg A | Leg B | Leg C |
|---|---|---|---|
| $f_o$ | $0^o$ | $120^o$ | $-120^o$ |
| $f_s - 2f_o$ | $0^o + \phi_A$ | $120^o + \phi_B$ | $-120^o + \phi_C$ |
| $f_s$ | $0^o + \phi_A$ | $0^o + \phi_B$ | $0^o + \phi_C$ |
| $f_s + 2f_o$ | $0^o + \phi_A$ | $-120^o \phi_B$ | $120^o + \phi_C$ |

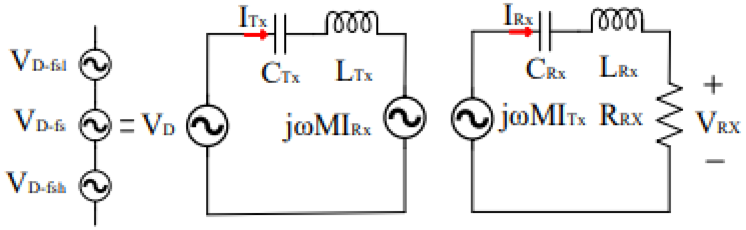


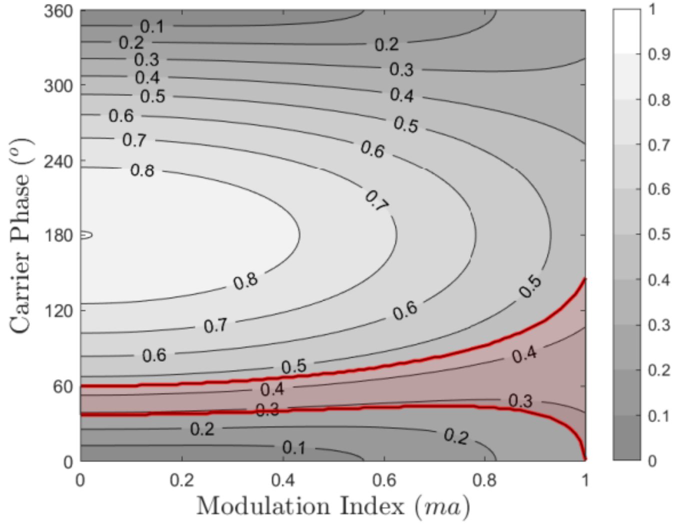

$|Leg\ A, B, C| = \frac{2}{\pi} J_2(m_a \frac{\pi}{2})$ $|Leg\ A, B, C| = \frac{2}{\pi} J_o(m_a \frac{\pi}{2})$ $|Leg\ A, B, C| = \frac{2}{\pi} J_2(m_a \frac{\pi}{2})$

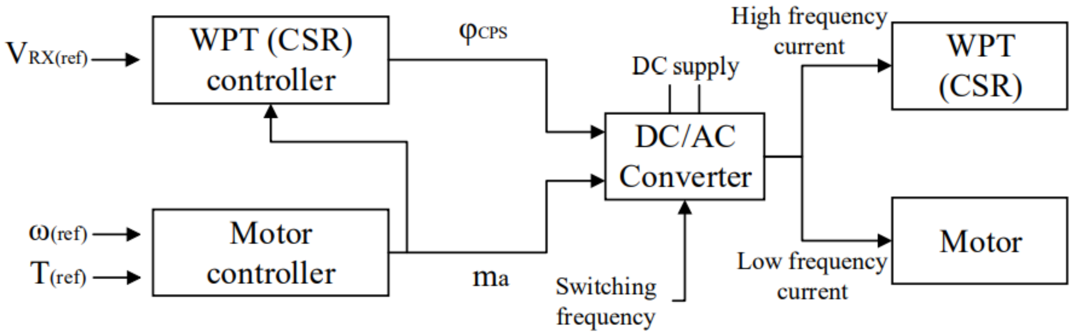
# Primary Side Voltage Control




$$\textit{Carrier phases}\begin{cases}\phi_{cA} = 0\\ \phi_{cB} = \phi_{CPS}\\ \phi_{cC} = 0\end{cases}$$



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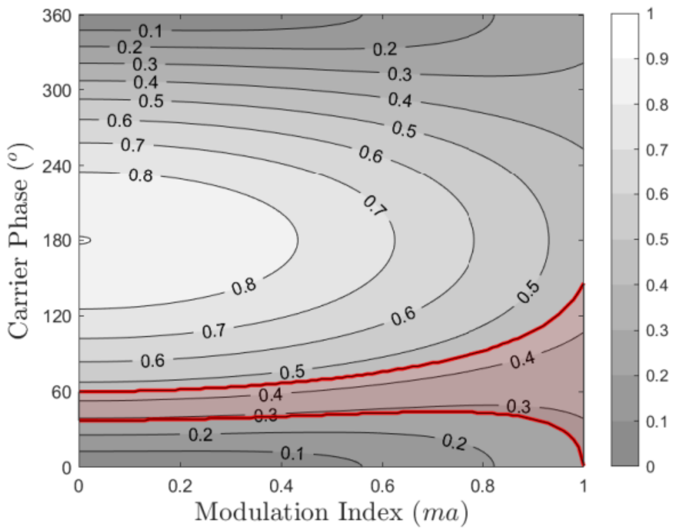
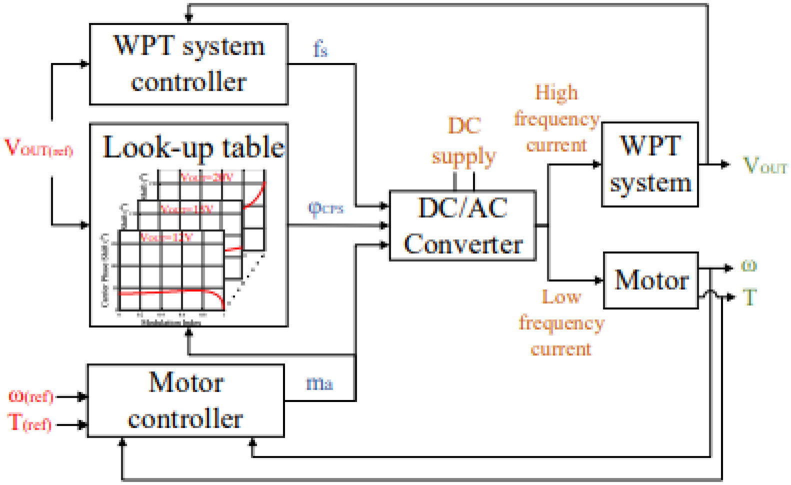
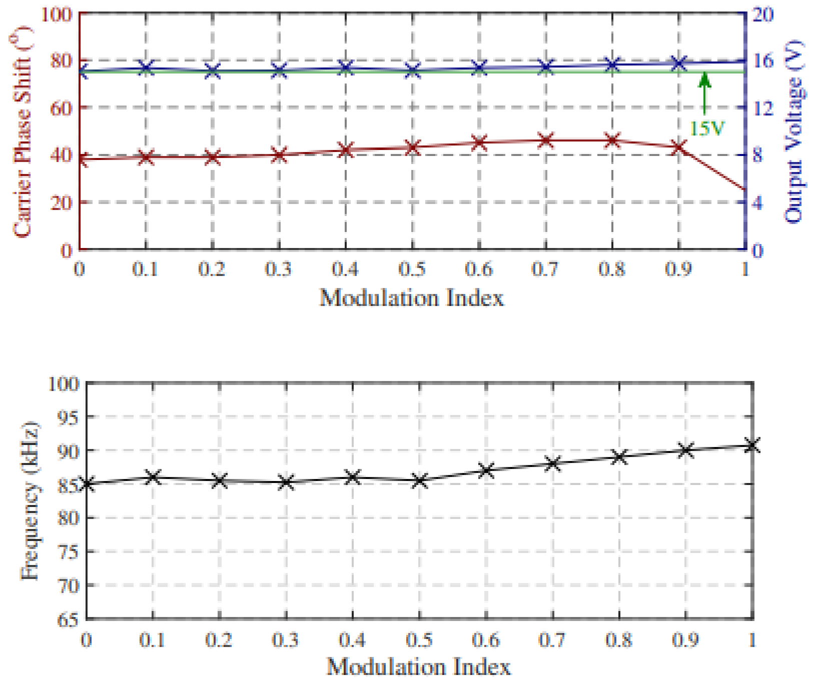
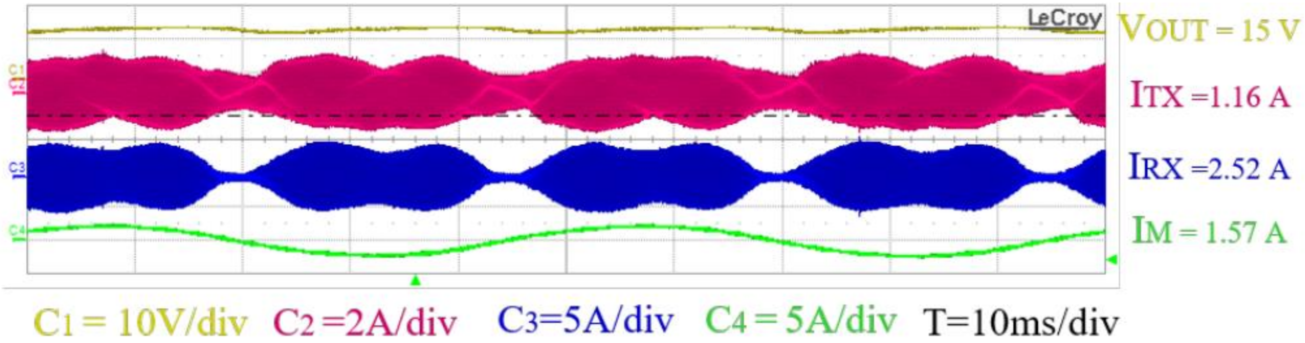
# Output Voltage Regulation

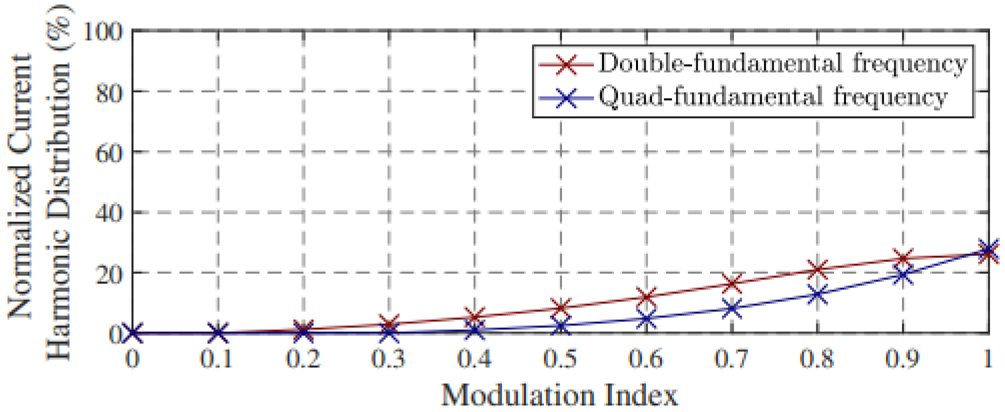


# Low-frequency Ripple at the Output Voltage



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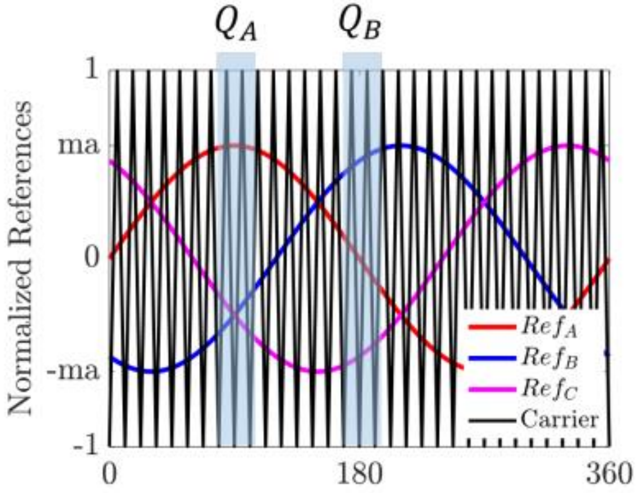
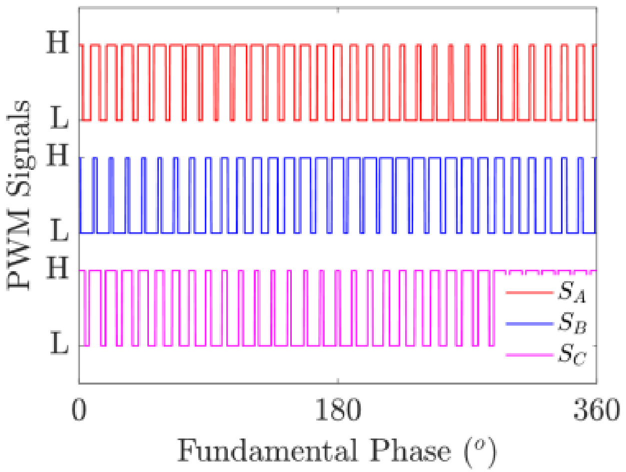
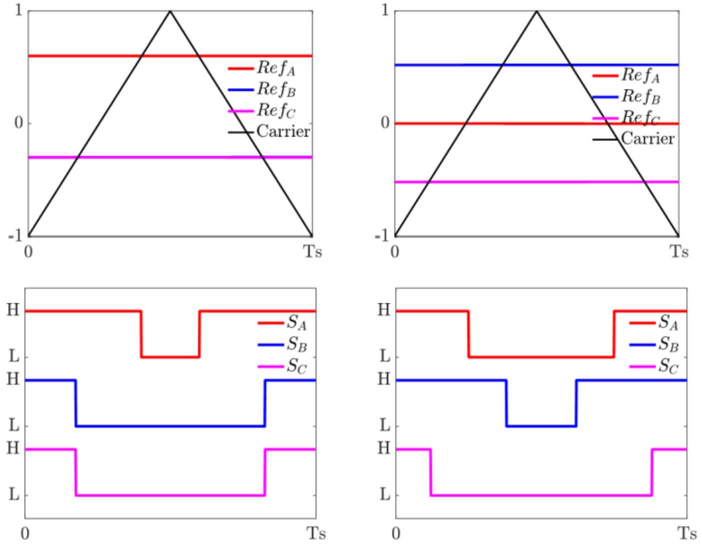
# Real-time algorithm



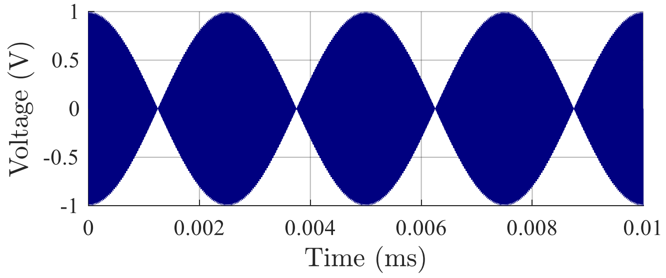



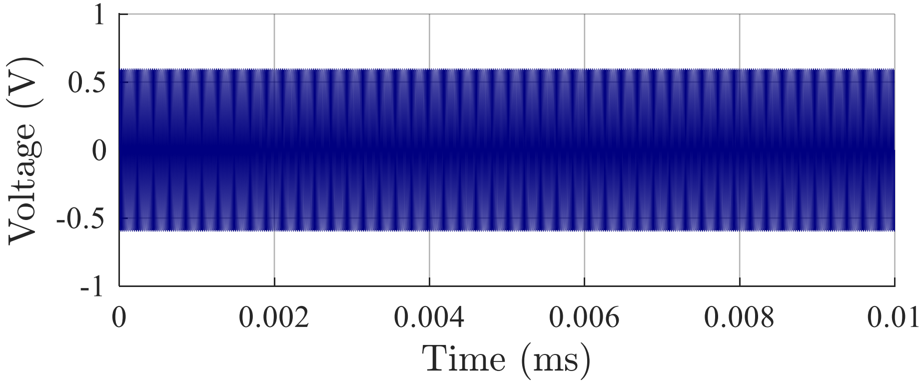




$Q_A$ ($\theta_f = 120^o$) $Q_B = (\theta_f = 180^o)$

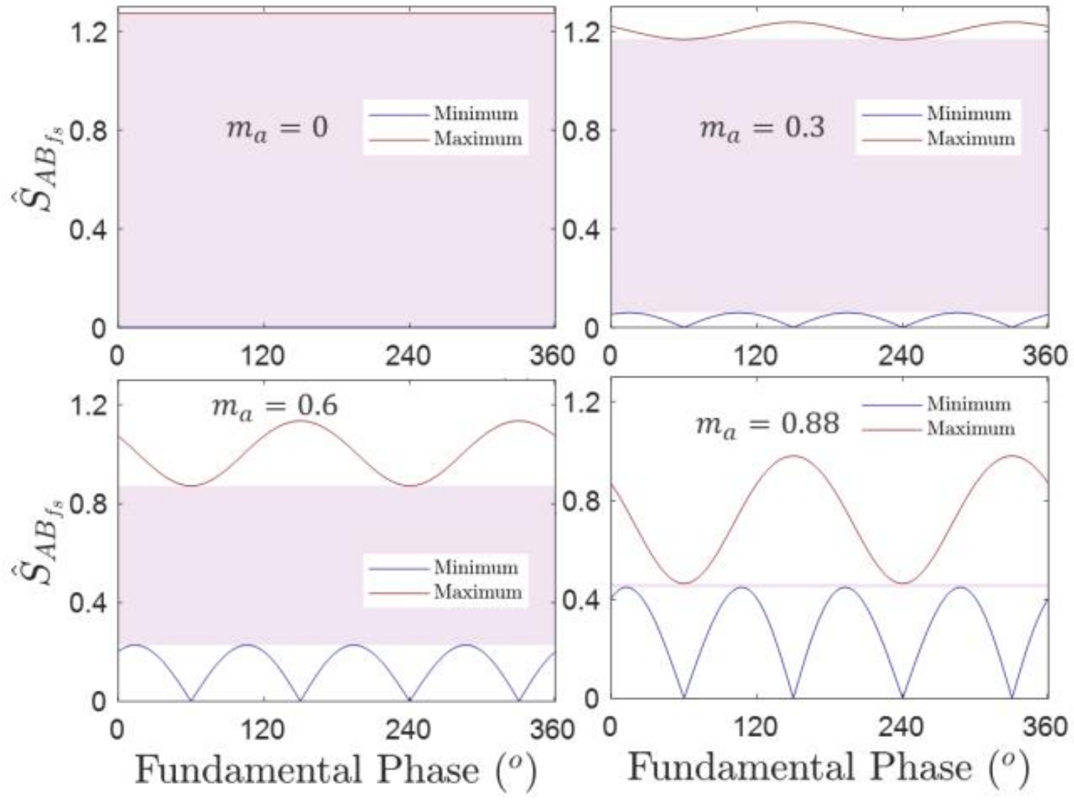
$$\hat{S}_{AB_{f_s}} = \frac{2}{\pi}\sqrt{\begin{array}{c}\sin(\pi D_A)^2+\sin(\pi D_B)^2\\ -2(\sin(\pi D_A)(\sin(\pi D_B)\cos(\phi_A-\phi_B)\end{array}}$$

$$\begin{aligned} S_{AB}(t)^{f_s} &= S_A(t)^{f_s} - S_B(t)^{f_s} \\ &= \frac{2}{\pi}\sin(\pi D_A)\cos(2\pi f_s t + \phi_{C-A}) \\ &\quad - \frac{2}{\pi}\sin(\pi D_B)\cos(2\pi f_s t + \phi_{C-B}) \end{aligned}$$



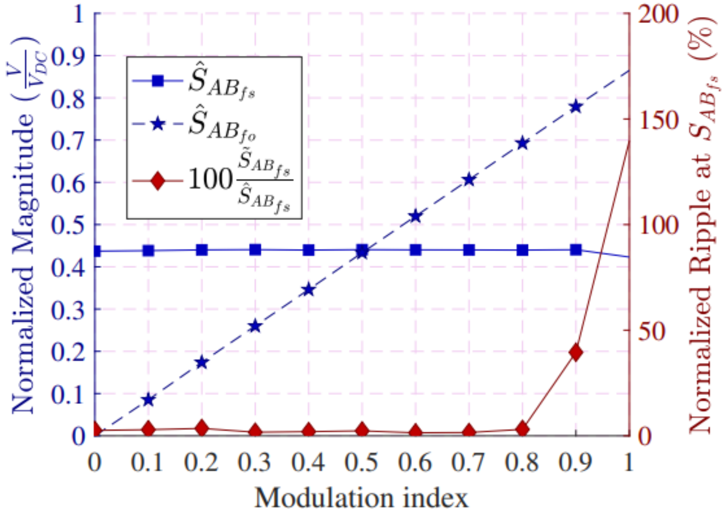



# Restrictions

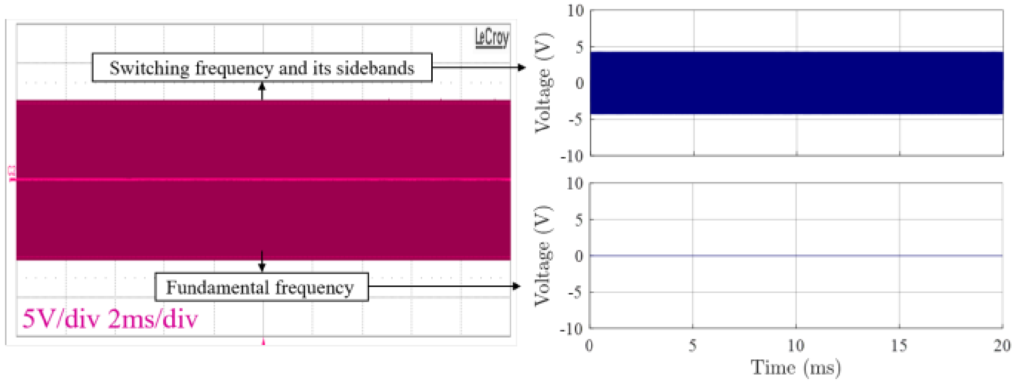



$$\frac{2}{\pi}|sin(\pi D_A) - sin(\pi D_B)| < \hat{S}_{AB_{fs}} < \frac{2}{\pi}|sin(\pi D_A) + sin(\pi D_B)|$$

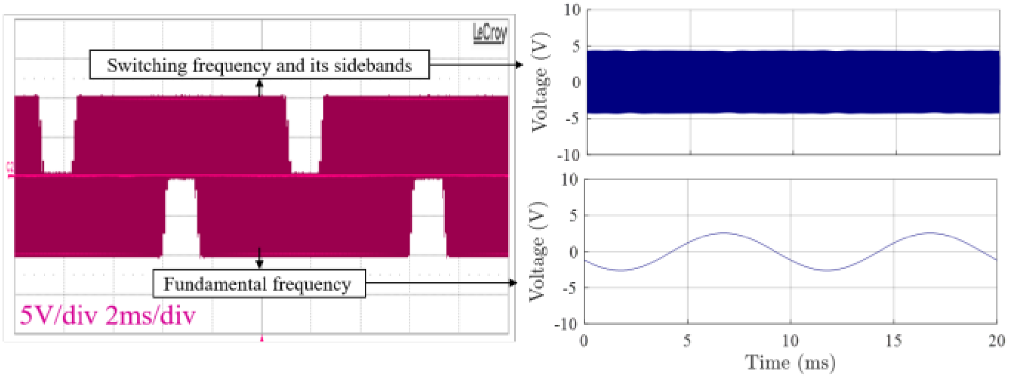
$\hat{S}_{AB_{fs}} = 0.43$ !    $m_a < 0.88$



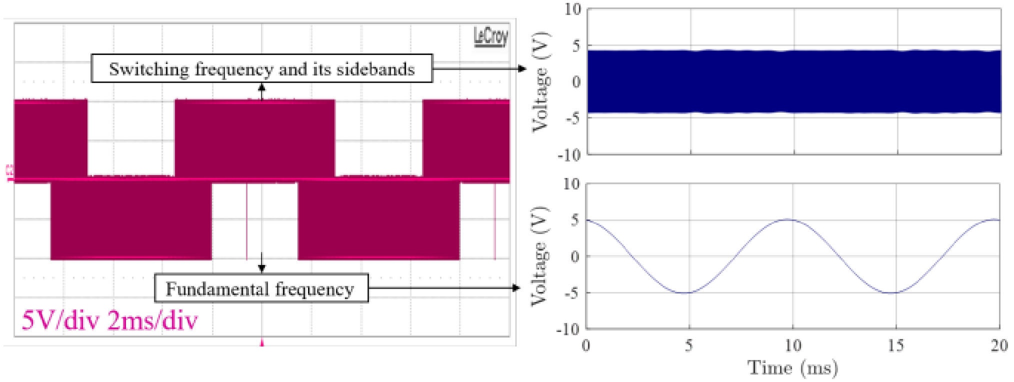
# Experimental Validation



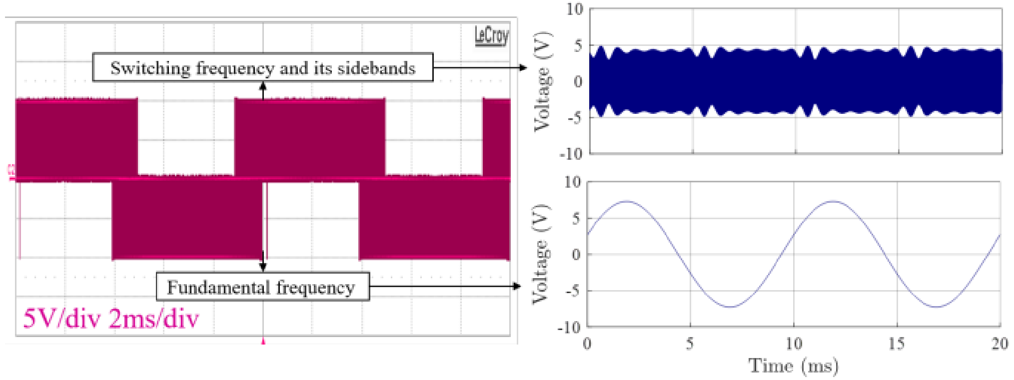

(a) $m_A = 0.$




(b) $m_A = 0.3.$




(c) $m_A = 0.6.$




(d) $m_A = 0.86.$

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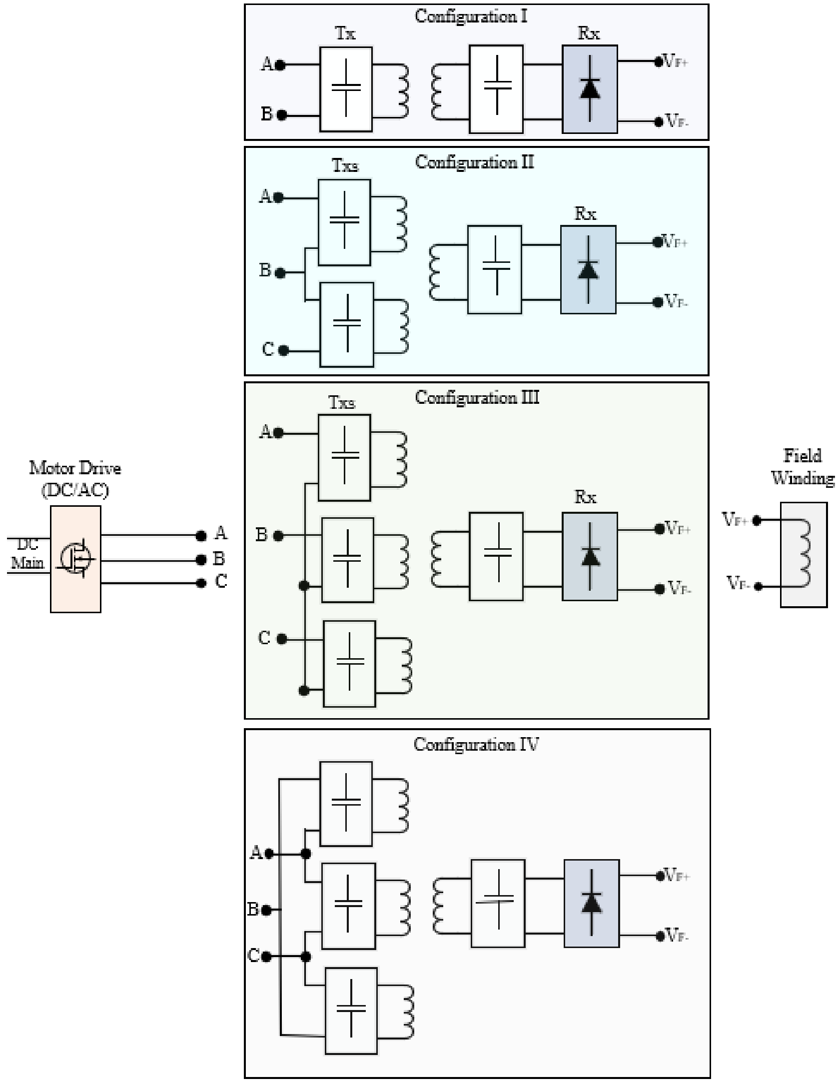
# Future Works

- Motor drives have more than 2 wires
- Conventional WPT systems have 2 wires input

↓

- Multi-phase WPT systems




## Motivations:

1. To increase DC-link utilization rate
2. To increase power
3. To break the restrictions

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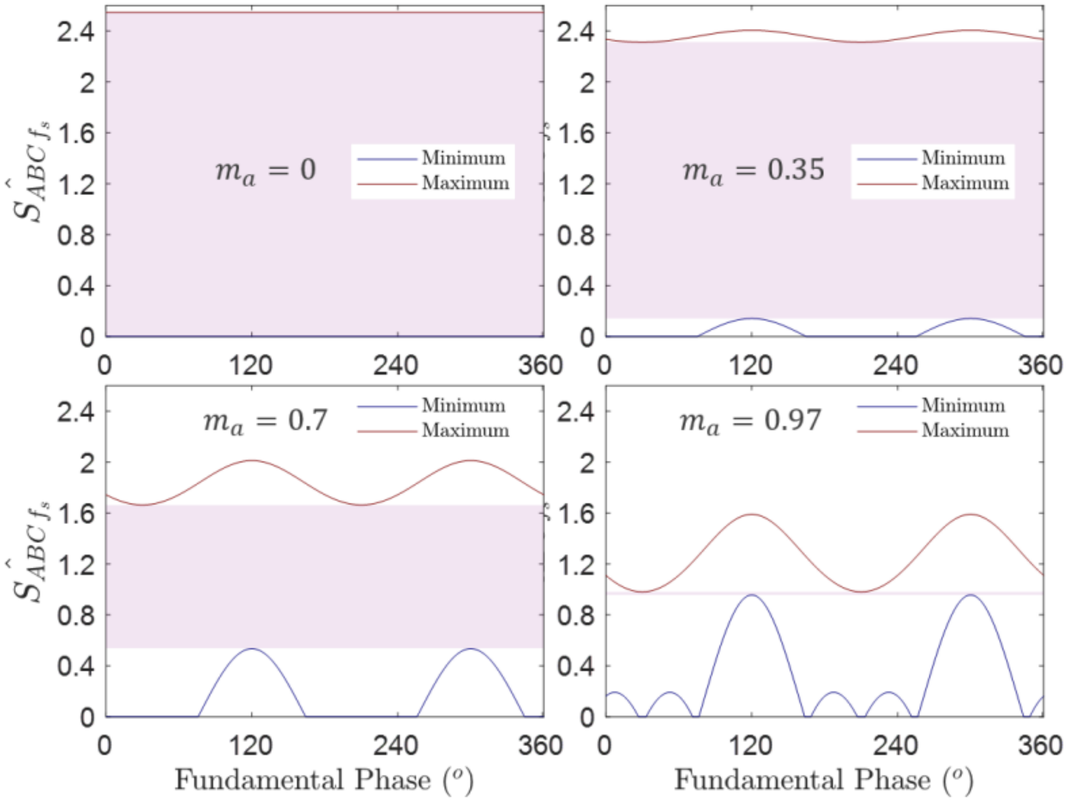
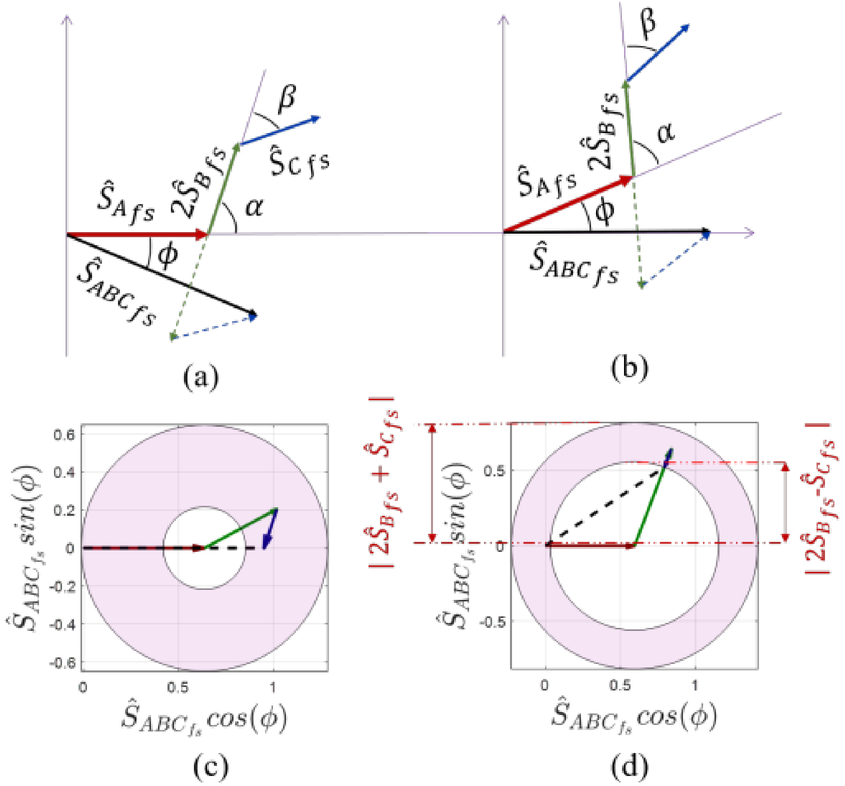
# Future Works



# Challenge- Calculation Burden!

$$\phi_{C-A} = \phi$$
$$\phi_{C-B} = \phi + \alpha$$
$$\phi_{C-C} = \phi + \alpha + \beta$$

**if** $\hat{S}_{ABC_{fs}} < \hat{S}_{A_{fs}} - |2\hat{S}_{B_{fs}} - \hat{S}_{C_{fs}}|$ **then**

$\phi = 0;$

**if** $\hat{S}_{ABC_{fs}} > \hat{S}_{A_{fs}} + |2\hat{S}_{B_{fs}} - \hat{S}_{C_{fs}}|$ **then**

$\phi = 0;$ (19)

**else**

$$\phi = acos\left(\frac{\hat{S}^2_{A_{fs}} - (2\hat{S}_{B_{fs}} - \hat{S}_{C_{fs}})^2 + \hat{S}^2_{ABC_{fs}}}{2\hat{S}_{A_{fs}}\hat{S}_{ABC_{fs}}}\right)$$

$$\alpha = 2tan^{-1}\left(\frac{(\sigma_2 + \sigma_1)\sigma_4}{4\hat{S}_{B_{fs}}\hat{S}_{C_{fs}}}\right)$$
$$\beta = 2tan^{-1}\left(\frac{(\sigma_2 - \sigma_1)\sigma_4}{4\hat{S}_{B_{fs}}\hat{S}_{C_{fs}}}\right) \tag{21}$$

where

$$\sigma_4 = \hat{S}^2_{A_{fs}} - \hat{S}^2_{B_{fs}} - \hat{S}^2_{C_{fs}} + \hat{S}^2_{ABC_{fs}} - 2\hat{S}_{A_{fs}}\hat{S}_{ABC_{fs}}cos(\phi) + 2\hat{S}_{B_{fs}}\hat{S}_{C_{fs}} \tag{22}$$

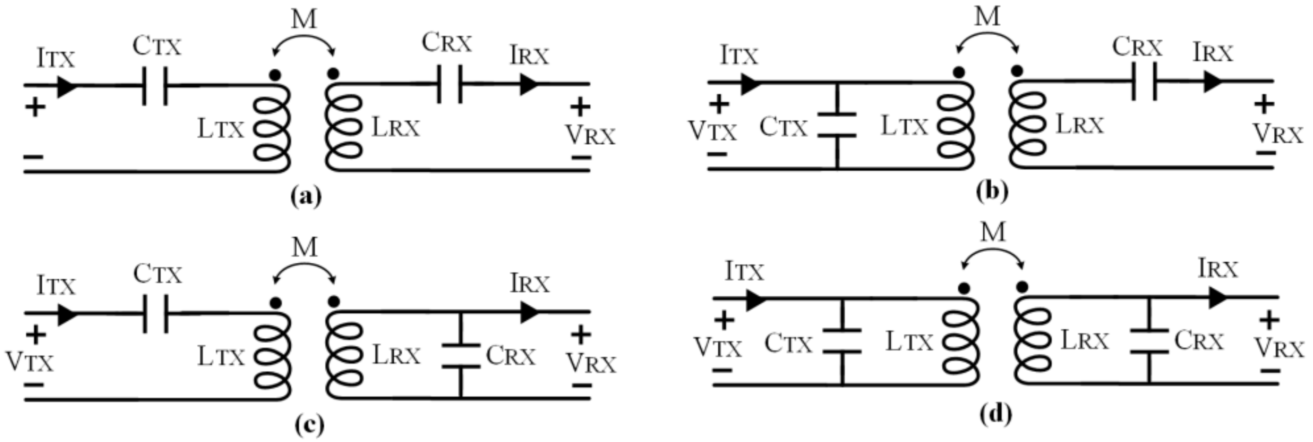
$$\sigma_3 = \sigma_4\Big(\hat{S}^2_{A_{fs}} + \hat{S}^2_{B_{fs}} - \hat{S}^2_{C_{fs}} + \hat{S}^2_{ABC_{fs}} - 2\hat{S}_{A_{fs}}\hat{S}_{B_{fs}} - \hat{S}_{A_{fs}}\hat{S}_{ABC_{fs}}cos(\phi) + \hat{S}_{B_{fs}}\hat{S}_{ABC_{fs}}cos(\phi)\Big) \tag{23}$$

$$\sigma_2 = \frac{8\hat{S}^2_{B_{fs}}\hat{S}_{C_{fs}}\hat{S}_{ABC_{fs}}sin(\phi)}{\sigma_3} \tag{24}$$

$$\sigma_1 = \frac{4\hat{S}_{B_{fs}}\hat{S}_{C_{fs}}\sqrt{\sigma_4\Big(-\hat{S}^2_{A_{fs}} + \hat{S}^2_{B_{fs}} + \hat{S}^2_{C_{fs}} - \hat{S}^2_{ABC_{fs}} + 2\hat{S}_{B_{fs}}\hat{S}_{C_{fs}} + 2\hat{S}_{A_{fs}}\hat{S}_{ABC_{fs}}cos(\phi)\Big)}}{\sigma_3} \tag{25}$$

Thanks!

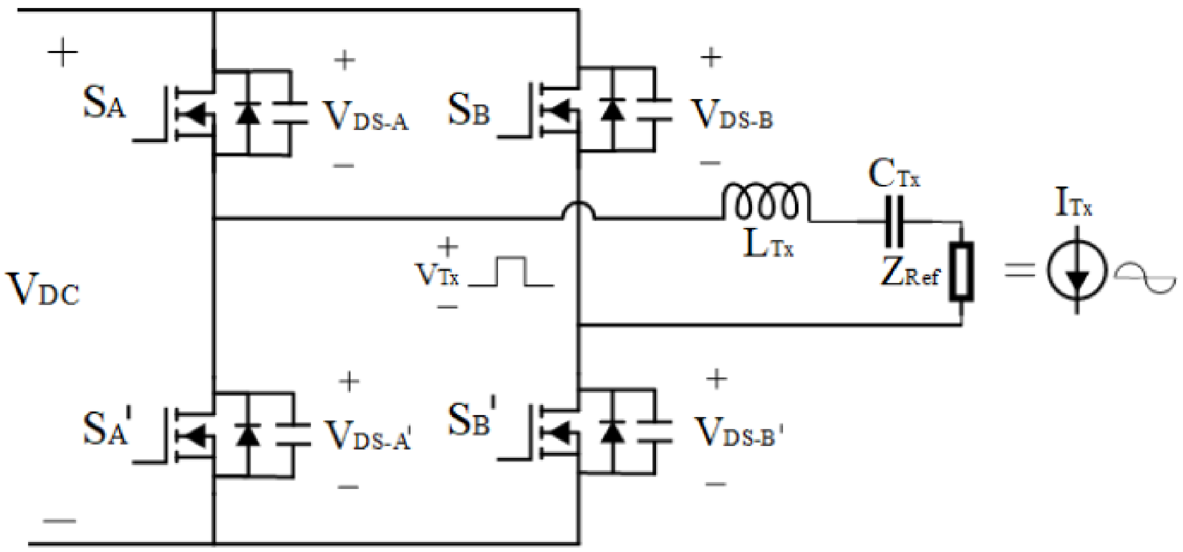
# Compensation Topologies

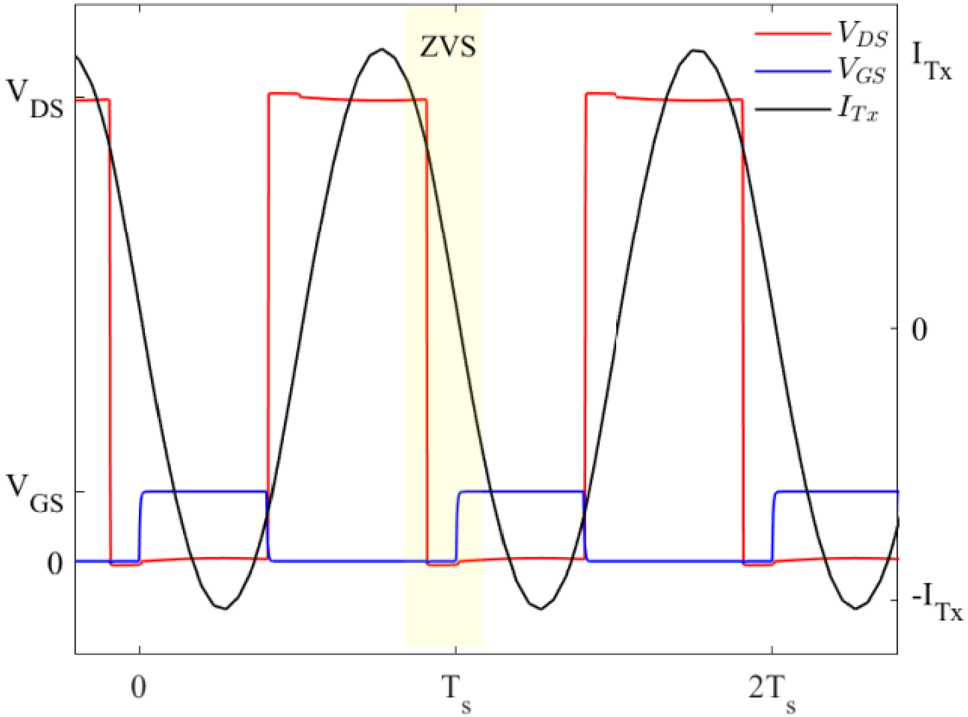



**a)** Series-series
**b)** Parallel-series
**c)** Series-parallel
**d)** Parallel-parallel

| **Series-Series Compensation** | |
|---|---|
| Source Type | Voltage Source |
| Resonant frequency | Load Independent |
| Resonant frequency | Coupling Independent |
| No load operation | Short Circuit |
| Capacitor Size | Large |

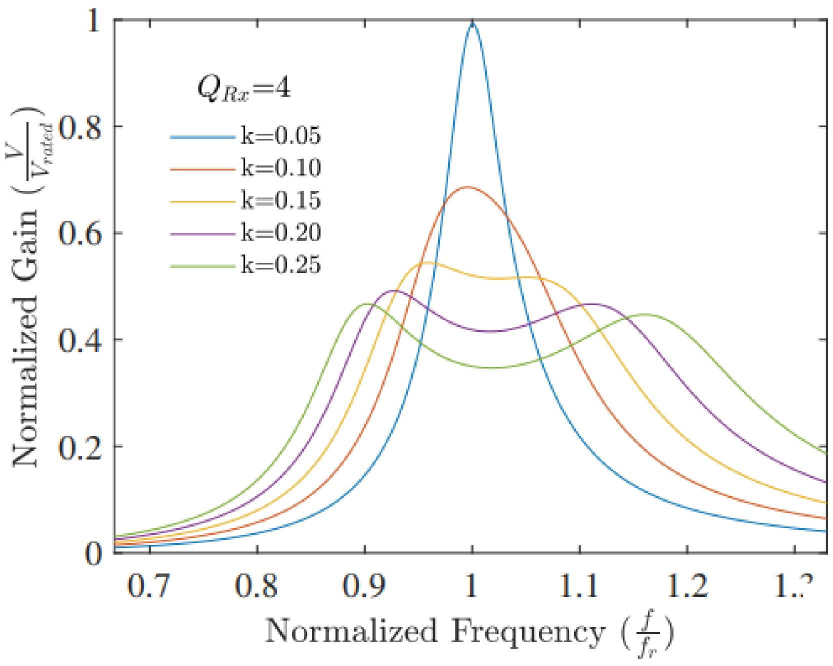
# Zero Voltage Switching




Inductive region → The capacitance of the switches discharges by the load current during dead time.

# Bifurcation Phenomenon




Double-peak

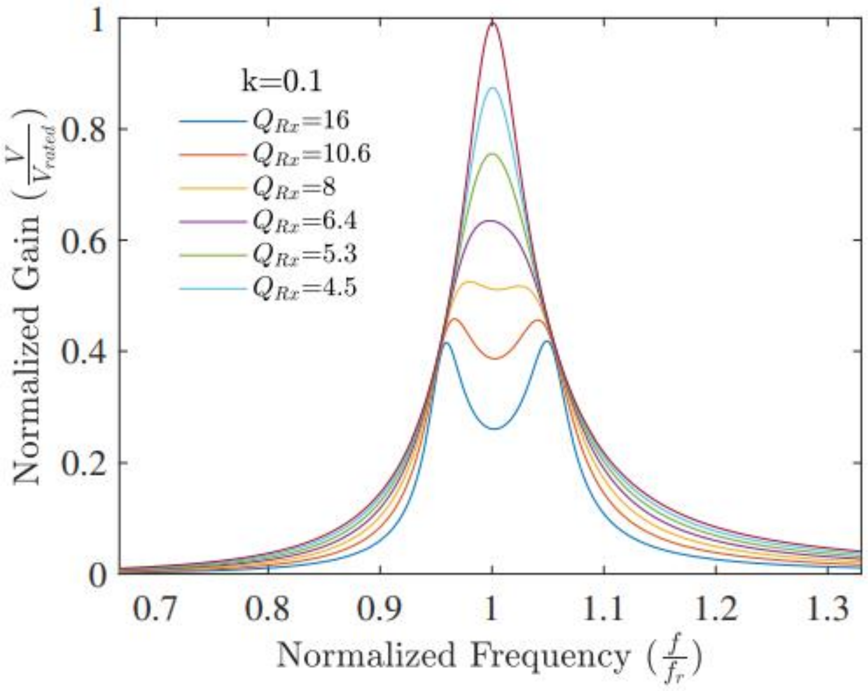
↓

~~$f_{op} > f_r$ → Inductive region~~

↓

- Making control difficult
- Decreasing efficiency

$$k_c = \frac{1}{Q_{Rx}}\sqrt{1 - \frac{1}{4Q_{Rx}^2}}$$



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# Wireless Power Transfer System Design Procedure

| The Rated Voltages and Powers | |
|---|---|
| Input Voltage ($V_{BUS}$) | 100 $V_{DC}$ |
| IPT Output Voltage ($V_{RX}$) | 20 $V_{RMS}$ |
| Motor Output Power ($P_M$) | 500 W |
| IPT Output Power ($P_o$) | 50 W |

| The Motor Parameters | |
|---|---|
| Armature resistance ($R_a$) | 2 Ω |
| Armature inductance ($L_a$) | 7 mH |
| Motor electrical time constant ($T_s$) | 3.5 ms |

| The Drive Parameters | |
|---|---|
| Duty cycle($D$) | 0.15 – 0.85 |
| Switching frequency ($f_s$) | $<$ 100 kHz |
| Switching period ($T_s$) | $>$ 10 $\mu$s |

$$V_{o,1^{st}}(rms) = \frac{4}{\sqrt{2}\pi} V_{Bus} sin(\pi D)$$

$$\downarrow$$

$$0.15 < D < 0.85$$

$$40\ V_{RMS} < V_{o,1^{st}}(rms) < 90\ V_{RMS}$$

$D = 0.15$

$D = 0.85$

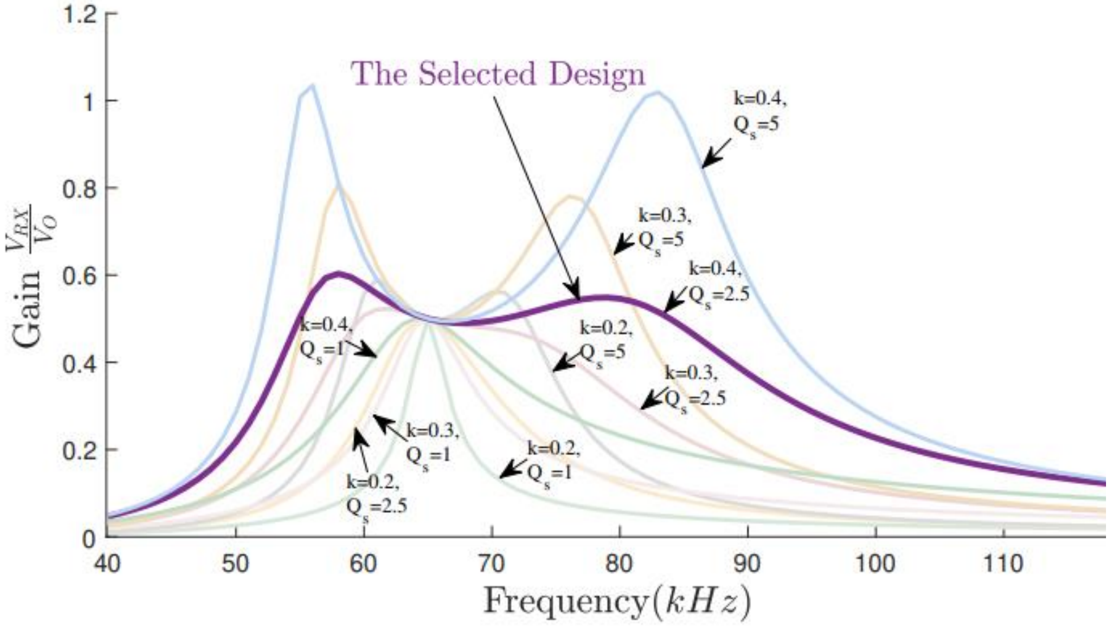
$D = 0.5$

$$Q_{RX} \longrightarrow \mathrm{L_{RX}} = \frac{\mathrm{Q_{RX}R_L}}{\omega_o} \longrightarrow \mathrm{M} = \frac{\mathrm{V_{RX}V_{o,1^{st}}}}{\mathrm{P_o}\omega_o}$$

$$\downarrow$$

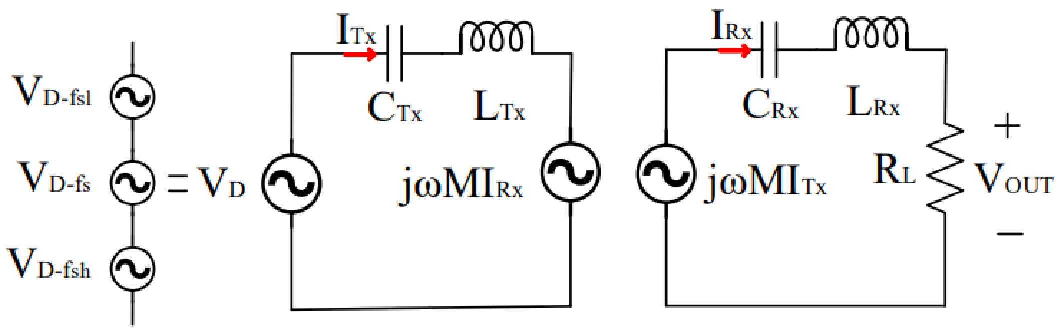
$$\mathrm{C_{TX,RX}} = \frac{1}{\mathrm{L_{TX,RX}}\omega_o^2} \longleftarrow \mathrm{L_{TX}} = \frac{\mathrm{V_{o,1^{st}}^2}}{\mathrm{k^2}\omega_o^2\mathrm{Q_{RX}}} \longleftarrow k$$

# Wireless Power Transfer System Design




| | |
|---|---|
| **Receiver quality factor ($Q_{RX}$)** | 2.6 |
| **Resonant frequency ($f_0$)** | 65 kHz |
| **Coupling factor (k)** | 0.40 |
| **Load resistance ($R_L$)** | 8 Ω |
| **Receiver coil inductance ($L_{RX}$)** | 51 $\mu$H |
| **Mutual inductance (M)** | 41 $\mu$H |
| **Transmitter coil inductance ($L_{TX}$)** | 205 $\mu$H |
| **Receiver resonant capacitance ($C_{TX}$)** | 115 nF |
| **Transmitter resonant capacitance ($C_{RX}$)** | 29 nF |
| **Voltage gain at $f_o$** | 0.5 |

# Wireless Power Transfer System Design




$$\omega_{rl} = \omega_r \sqrt{\frac{1}{1+k}}$$

$$\omega_{rh} = \omega_r \sqrt{\frac{1}{1-k}}$$

$$A_{WPT} = \left| \frac{V_{OUT}}{V_{IN}} \right|$$

$$\frac{dA_{WPT}}{dR_L} = 0$$

$$L_{Rx} = \frac{Q_{Rx} R_L}{\omega_{rh}} \longrightarrow A_{WPT(\omega_{rh})} = \left| \sqrt{\frac{L_{Rx}}{L_{Tx}}} \right| \longrightarrow L_{Tx} = \frac{L_{Rx}}{A^2_{WPT(\omega_{rh})}}$$

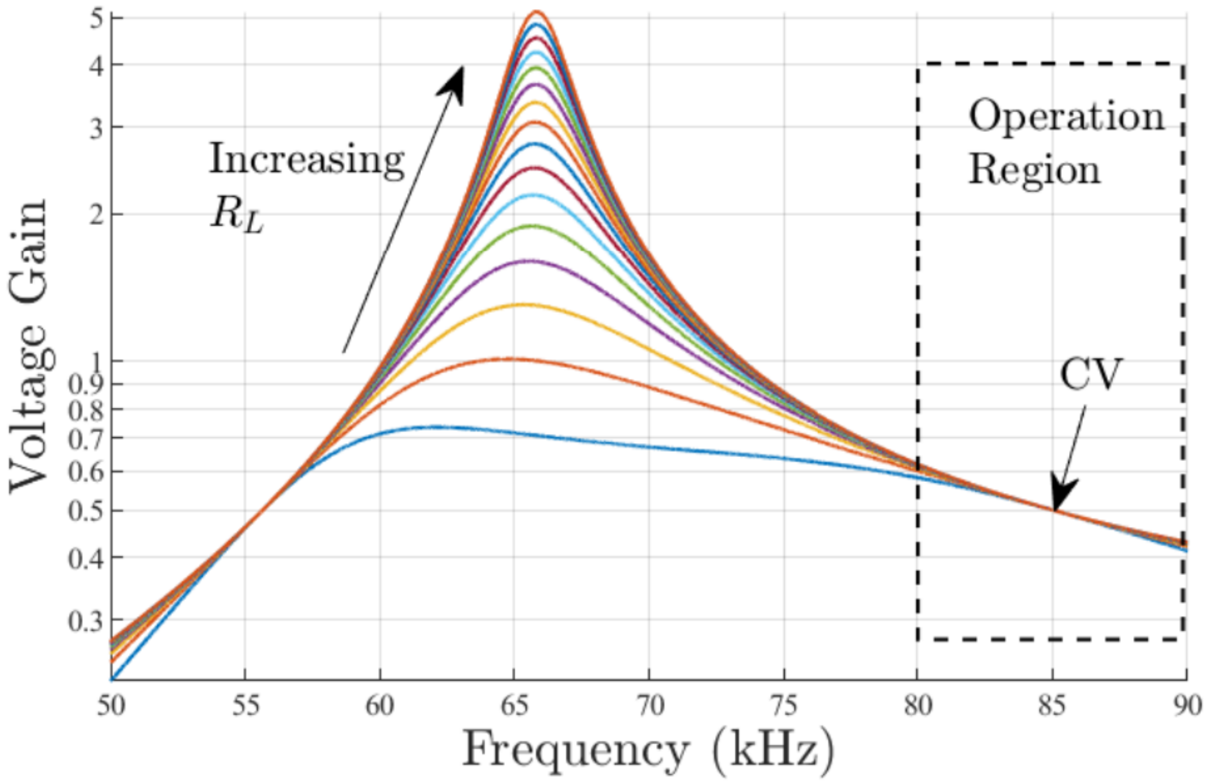
$$\downarrow$$

$$C_{Tx} = \frac{1}{\omega_r^2 L_{Tx}} \qquad \longleftarrow \qquad M = k\sqrt{L_{Tx} L_{Rx}}$$

$$C_{Rx} = \frac{1}{\omega_r^2 L_{Rx}}$$

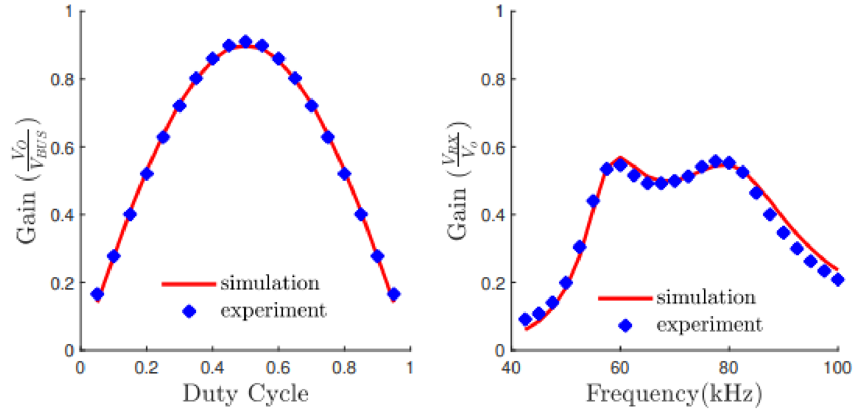
# Wireless Power Transfer System Design

| Initial/Choosen Parameters | Values | Derived Parameters | Values |
|---|---|---|---|
| $P_{rated}$ | 24 W | $A_{WPT}$ | 0.5 |
| $V_D$ | 30 $V_{RMS}$ | $R_L$ | 9.3 Ω |
| $V_{out}$ | 15 $V_{RMS}$ | $L_{Rx}$ | 50 $\mu H$ |
| $f_{rh}$ | 85 kHz | $L_{Tx}$ | 200 $\mu H$ |
| $Q_{Rx}$ | 2.9 | M | 40 $\mu H$ |
| $k$ | 0.4 | $f_r$ | 65.85 kHz |
| | | $C_{Tx}$ | 29.2 nF |
| | | $C_{Rx}$ | 117 nF |

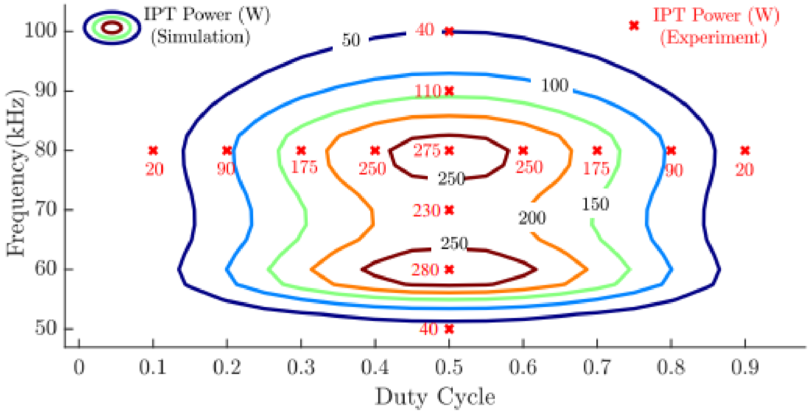


# Experimental Results- WPT System Validation

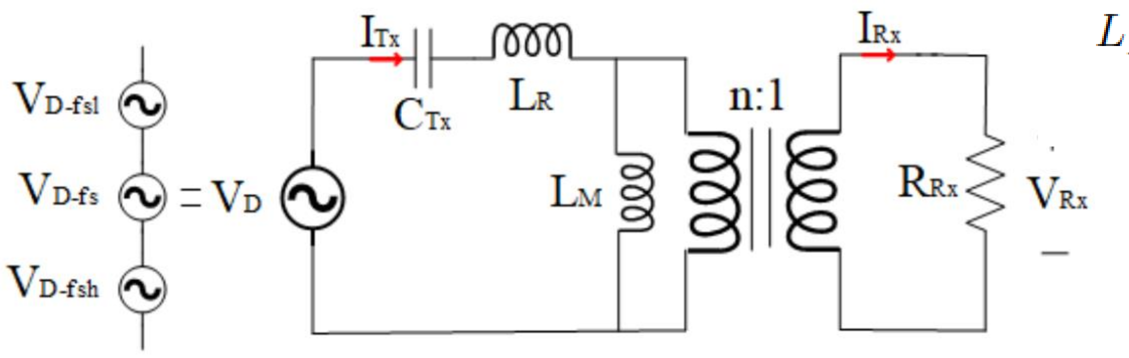
| | Design values | Measured values |
|---|---|---|
| Transmitter inductance | $204\mu H$ | $205\mu H$ |
| Receiver inductance | $52\mu H$ | $51\mu H$ |
| Mutual inductance | $41\mu H$ | $40\mu H$ |




(a) Duty cycle-gain characteristic of WPT at 80 kHz. (b) Frequency-gain characteristic of WPT ($D$ = 0.5).



# Wireless Power Transfer System Design




$$L_{Rx} = Q\frac{R_{Rx}}{\omega_r} \longrightarrow n = k\sqrt{\frac{L_{Tx}}{L_{Rx}}} \longrightarrow L_{Tx} = \frac{n^2}{k^2}L_{Rx}$$

$$n = \frac{V_D}{V_{Rx}}$$

$$C_{Tx} = \frac{1}{\sqrt{\omega_r^2 L_R}}$$

| Initial/Choosen Parameters | Values | Derived Parameters | Values | Experimental Values |
|---|---|---|---|---|
| $P_{rated}$ | 30 W | $V_{Rx}$ | 7.56 | - |
| $V_D$ | 40 $V_{RMS}$ | $R_{Rx}$ | 0.97 Ω | - |
| $V_{OUT}$ | 6 $V_{DC}$ | n | 5.95 | - |
| $f_{rh}$ | 60 kHz | $L_{Tx}$ | 1510 $\mu H$ | - |
| $Q_{Rx}$ | 2.5 | $L_{Rx}$ | 6.5 $\mu H$ | - |
| $k$ | 0.7 | M | 42 $\mu H$ | - |
| $R_L$ | 1.2 Ω | $C_{Tx}$ | 6.7 nF | - |