# Control and Optimization of Power in LLC Converter Using Phase Control

By

Nagasri Kollipara

B.Tech., JNTU,

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**Thesis Advisor**

**Dr. Marian K Kazimierczuk**

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# Contents



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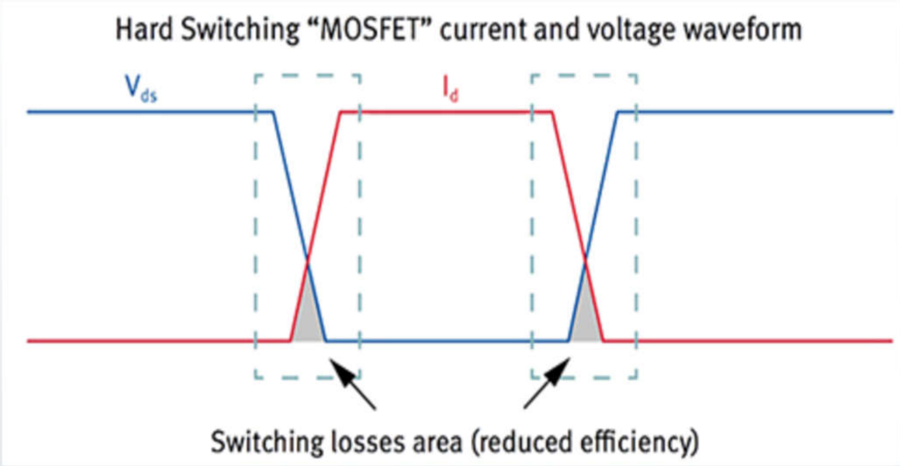
# Conventional PWM Converters

- In non-isolated voltage regulators, high switching losses occur due to simultaneous occurrence of voltage and current stress across MOSFET during turn-on and turn-off transitions
- Switches exhibits high switching losses due to high amount of stress during load current transfer



# Hard Switching

- Switching losses increases linearly with switching frequency, which contributes major portion of loss at high switching frequencies
- Due to high amount of stress, switches need to be transitioned forcibly (Hard-switching)
- Work around :
  - Switches required to maintain high **di/dt** and **dv/dt** to minimize switching losses. Changes in circuit layout to reduce stray components
  - Increase turn on/off speeds (Extremely fast FETs required)
  - Use of snubbers (R,L and C components) can help to soften switching waveforms
  - Implement soft switching techniques such as in quasi resonant converter

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# Snubber Usage

- Turn-on cycle:
  - Low di/dt
  - Low turn-on losses
  - Low recovery current
  - But, switch voltage rating drastically increases during turn-off period
- Turn-off cycle:
  - Low dv/dt and
  - Low turn-off switching losses

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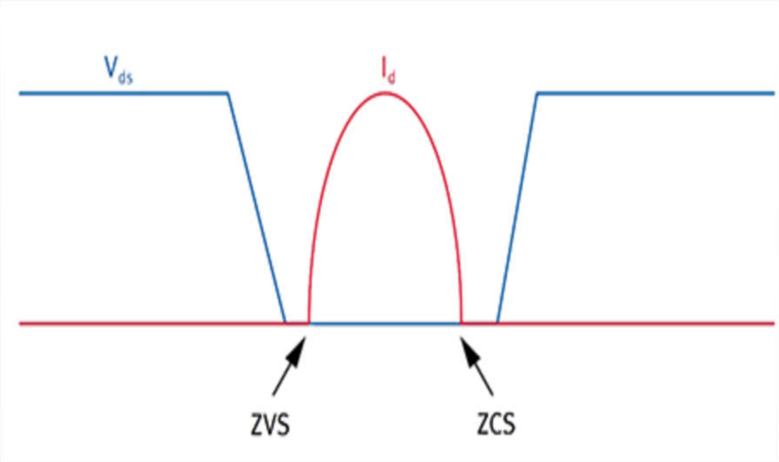
# Soft Switching

Eliminates overlap between voltage and current which helps minimizing losses.

**Zero Voltage Switching (ZVS):**

- Voltage falls to zero before MOSFET turns ON or OFF
- Maintains zero- loss transition in turn-on and very low loss transition in turn-off state
- Parallel capacitor can be used as a loss less snubber




**Zero Current Switching (ZCS):**

- Switch current is brought to zero before MOSFET is OFF
- Maintains zero- loss transition in turn-off and very low loss transition in turn-on states
- Series inductor is used as loss less snubber

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# Classification of Soft-Switching Technique

- Load Resonant Converters –
  - Load is a part of resonant circuit. So, load carries resonant current or voltage across resonant components
  - Power transfer to load is controlled by circuit's switching frequency
- Quasi Resonant Converters-
  - These are called as resonant power converters
  - L-C resonance defines the shape of voltage or current across switch to achieve ZVS or ZCS condition
- Resonant Transition Converters-
  - More useful in DC-AC inverters
  - LC resonance helps to maintain ZVS or ZCS to change the AC inverter state

# Thesis Objective

- Understanding the Quasi Resonant Converters
- Implement frequency and phase control techniques to resonant converters
- Analyze the dead-time transition (ZVS) condition
- Calculating the optimal frequency to achieve high efficiency at light loads
- Calculate the switching losses, conduction losses for frequency and phase controlled circuit
- Investigate the best suitable technique for system control

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# Resonant Power Converters

- The basic strategy of resonant power converters are to:
  - Eliminate and reduce switching losses
  - Achieve high efficiency
  - Lower EMI
- It is possible to achieve it through ZVS and ZCS by making voltage or current across switch to zero during switching transitions
- **Resonant converter types**
  - Series Resonant Converter:
    - Capacitor as a output filter (High efficiency from full load to light load)
    - Maximum gain is achieved only at resonant frequency
    - Not suitable for low voltage applications, Output filter should be large to handle current ripple

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# Resonant Power Converters

- Parallel Resonant Converter:
  - ❑Inductor as an output filter
  - ❑Suitable for low voltage applications
  - ❑Suffers from fixed device current which doesn’t change with load current
- Series Parallel Resonant Converters:
  - ❑Combination of SRC with additional capacitor/inductor as a tank circuit
  - ❑Can be referred as LLC resonant converter
  - ❑Suitable for wide input range applications

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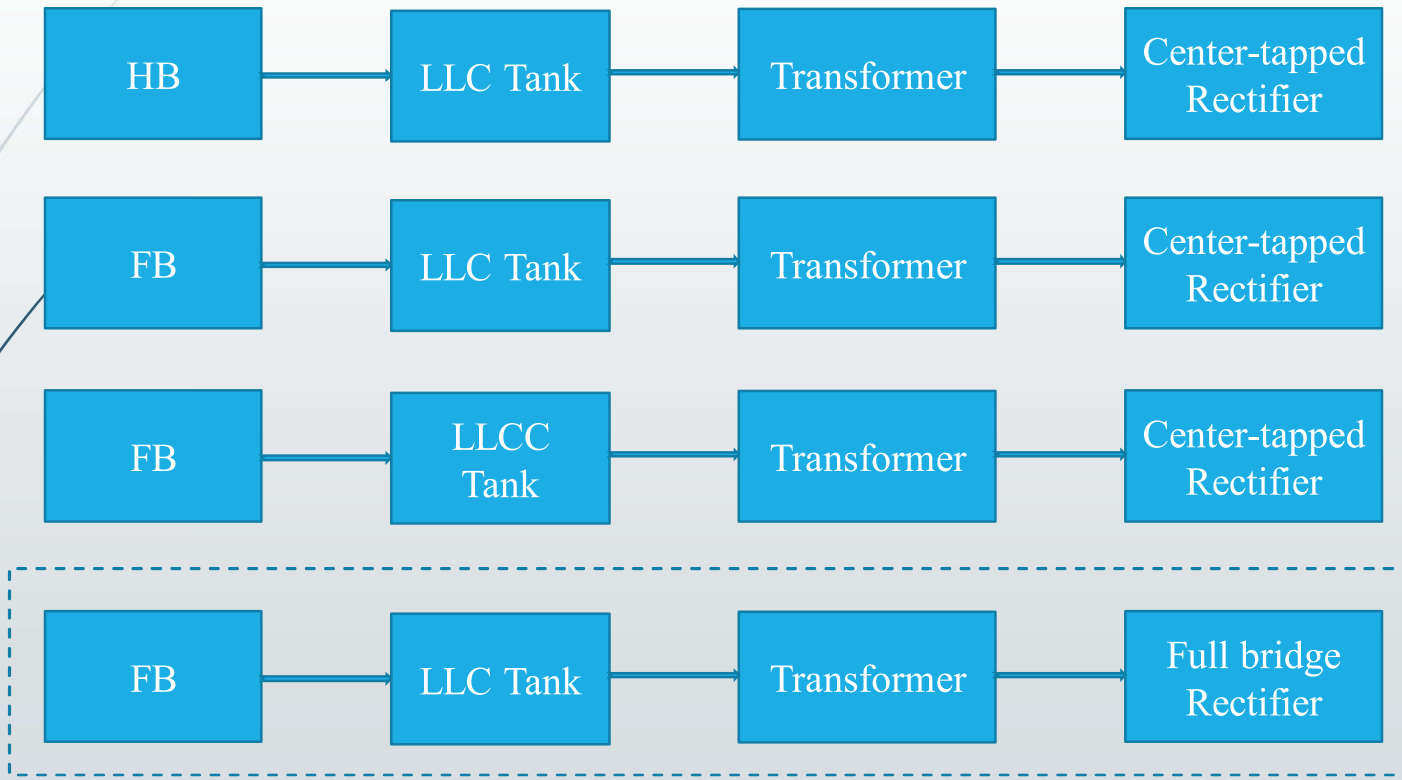
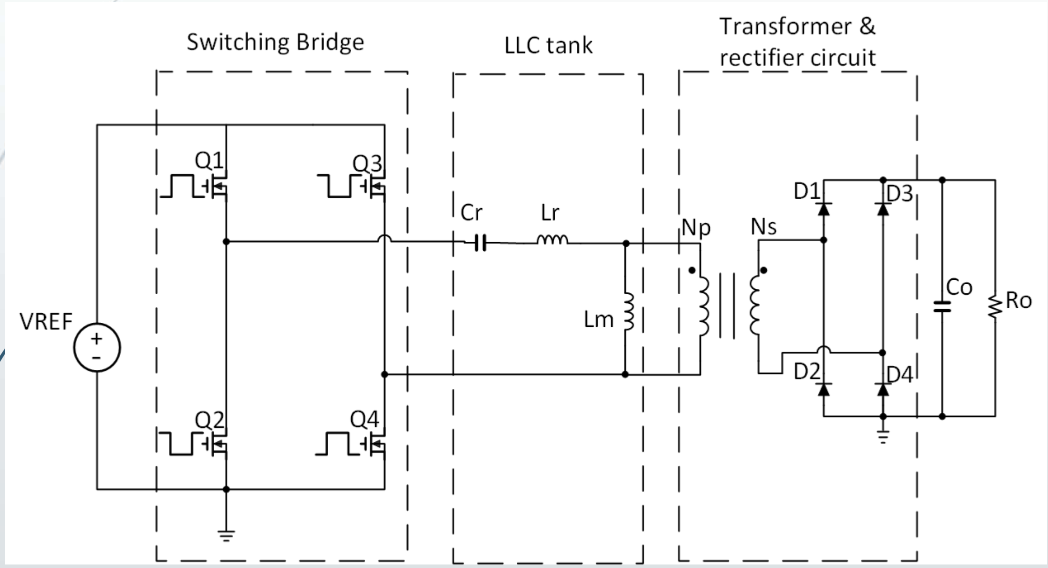
# LLC Resonant Power Converters

- Combination of two inductors and one capacitor (L-L-C)
- Offers narrow range of switching frequencies along with capability to maintain ZVS and ZCS for optimal efficiency
- Improves light load efficiency with optimal selection of components
- Improves Electromagnetic Compatibility (EMC)
- LLC power converters uses frequency modulation technique

# Rationale for this work



# LLC Converter Schematic




- Full bridge switching circuit
- LLC resonant tank
- Rectifier circuit
- Output capacitor and fixed load resistor
- No active output voltage feedback loop for simplicity

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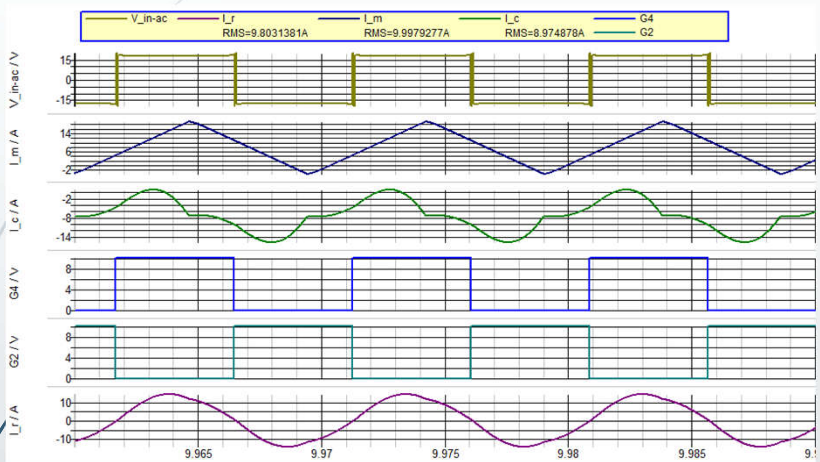
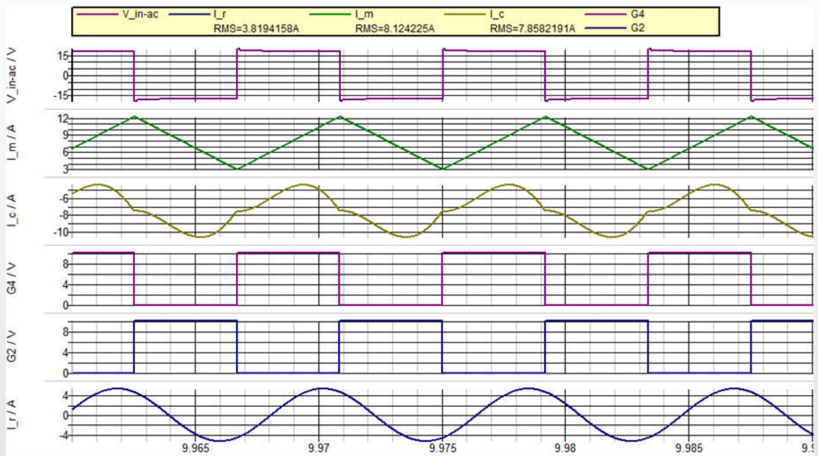
# RMS currents of FM LLC with varying frequency for a fixed load resistance

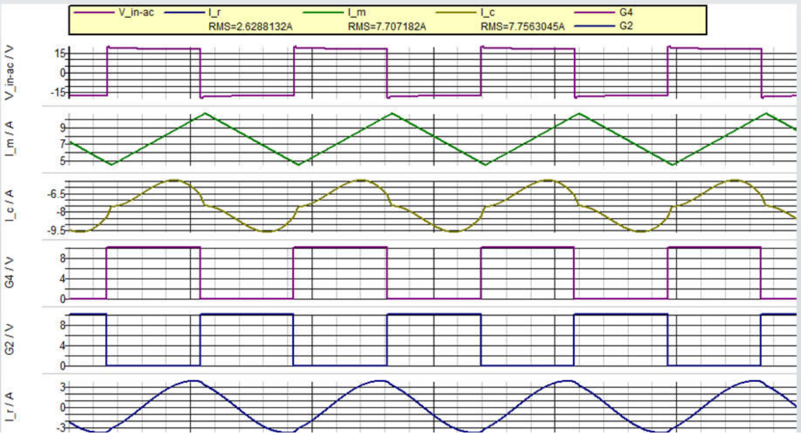
108kHz




120kHz

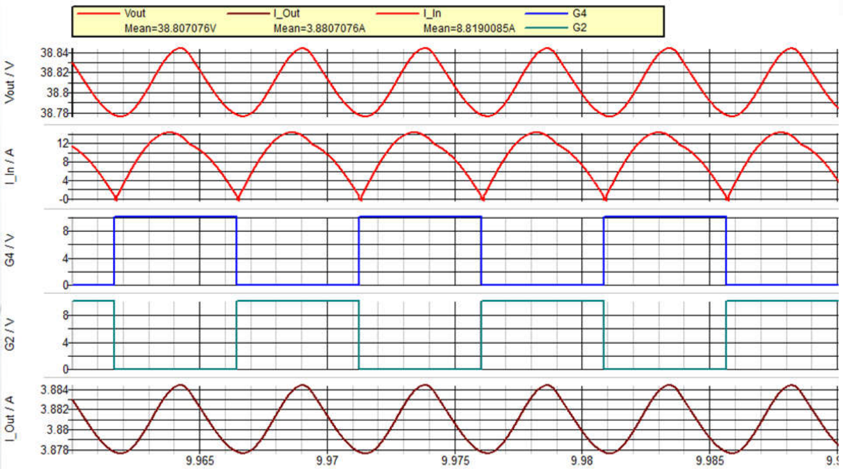



130 kHz

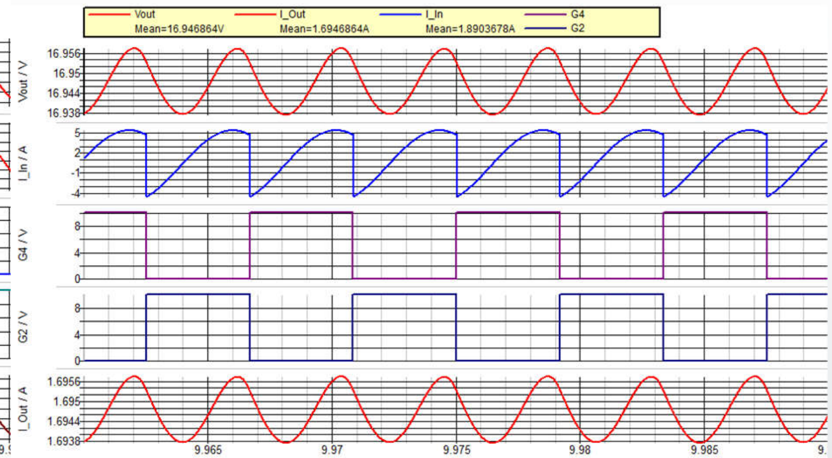


# Output voltage and current waveforms

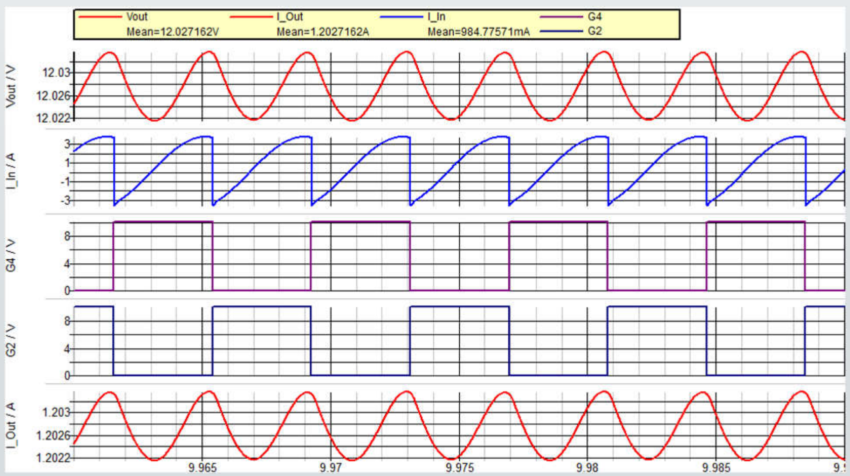
104.3 kHz




120 kHz




130 kHz

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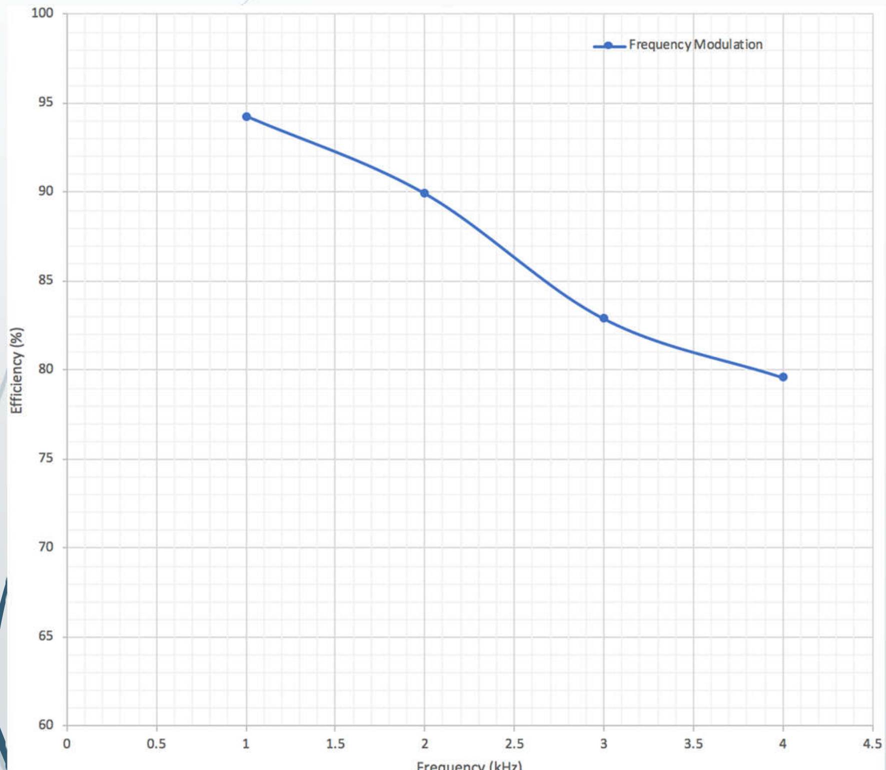
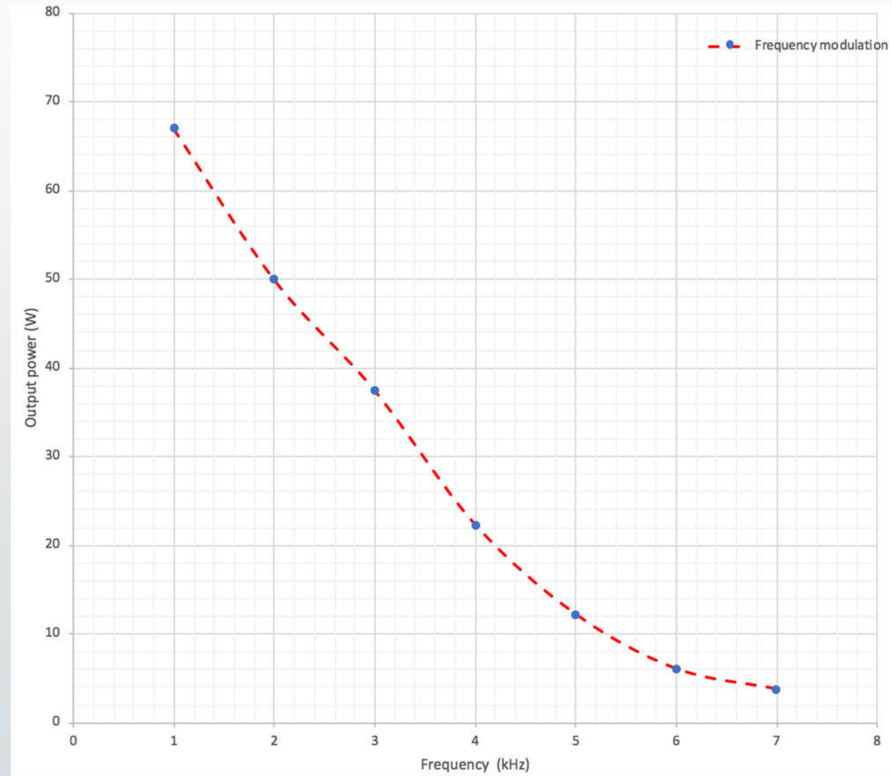
# Efficiency and Power for frequency modulated LLC obtained from simulations



# Drawbacks of Frequency Modulation

- Variable frequency technique generates wide frequency range of Electromagnetic Interference (EMI)
- Non-optimum utilization of magnetic components at light loads
- Can't achieve wide input range because operating point is determined by design parameters
- Problems during start-up, light load and short circuit operation.
- For wide range of input, system may require very high frequency operation which can be harder to control and to limit interference.
- Fails to maintain monotonicity of the control power to output transfer function

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# Application of Phase Control

With known disadvantages of LLC converter using frequency modulation discussed above, present days research concentrates on phase shift control technique for resonant converters.

This thesis presents phase shift modulated technique for full–bridge LLC resonant converter :

- Understanding the dead-time transition (ZVS) condition
- First harmonic approximated (FHA) analysis as a function of input voltage and phase
- Impact of Magnetization current at different phase angles
- Understanding the switching losses, conduction losses and output power at different loads.
- Future scope to expand for a wider range of voltage gain and input voltage

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# Phase Control Technical Expectations

- Phase control techniques in full-bridge circuit is expected to improve the monotonicity of the power supply's control to output transfer function
- Improves power supply efficiency especially at light loads
- Able to maintain ZVS condition for wider range of operating conditions
- Less impact when operated below resonant frequency
- Reduces EMI/EMC

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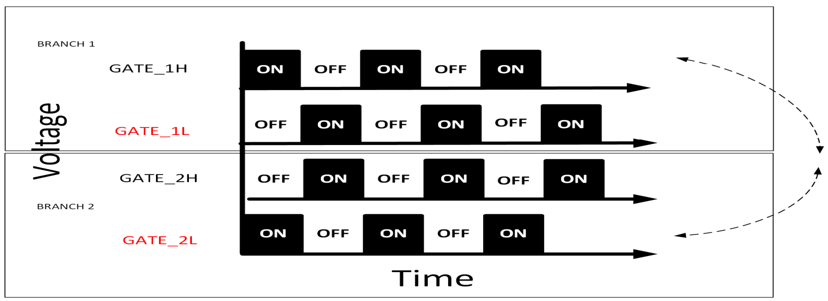
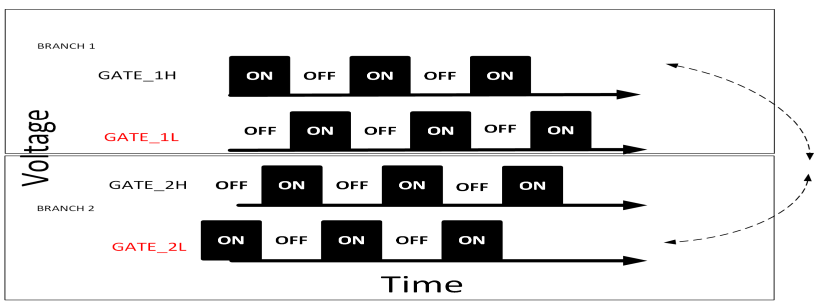
# Phase shift control




**"Phase = 180"**

Full power transferred to LC (or LLC) resonant circuit (in effect, input supply voltage is maximum)

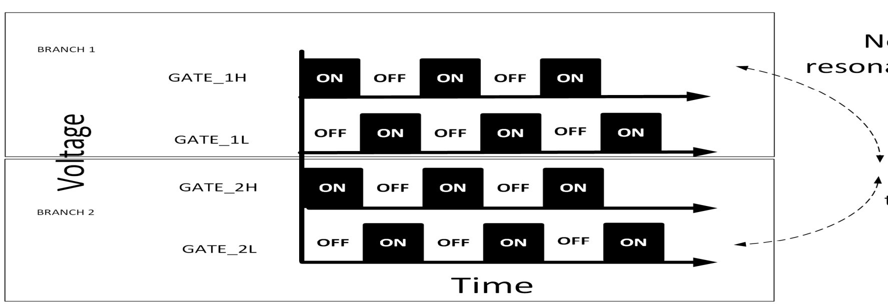
Whenever top Fet of Branch 1 is conducting (ON), it finds lower Fet of Branch 2 conducting (ON), so FULL power is transferred from supply rail VIN to resonant LC circuit




**"Phase = 90"**

Partial power transferred to LC (or LLC) resonant circuit (in effect, input supply voltage is halved)

For roughly half the time top Fet of Branch 1 is conducting (ON), it finds lower Fet of Branch 2 conducting (ON), so HALF power is transferred from supply rail VIN to resonant LC circuit



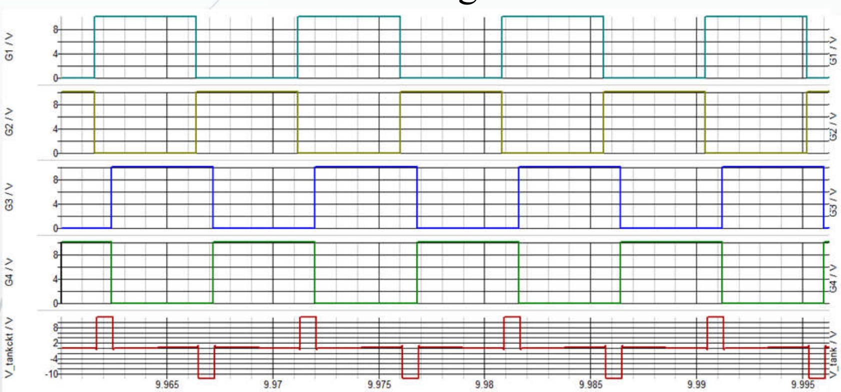

**"Phase = 0"**

No power transferred ever to LC (or LLC) resonant circuit (in effect, input supply voltage is zero)

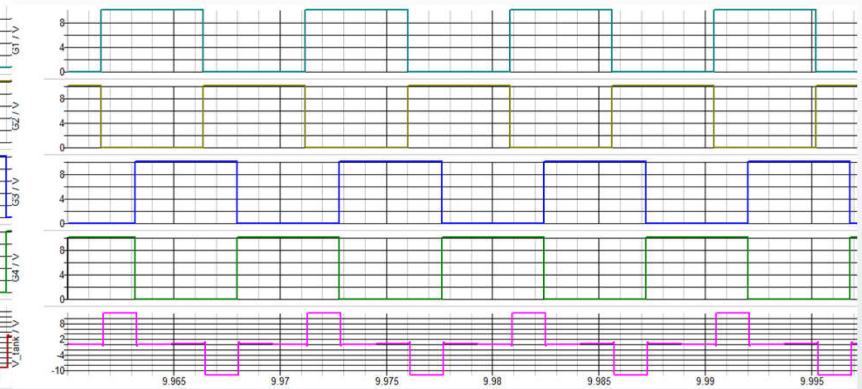
Whenever top Fet of Branch 1 is conducting (ON), it finds lower Fet of Branch 2 non-conducting (OFF), so NO power is ever transferred from supply rail VIN to resonant LC circuit

# LLC tank pulse at varying phases

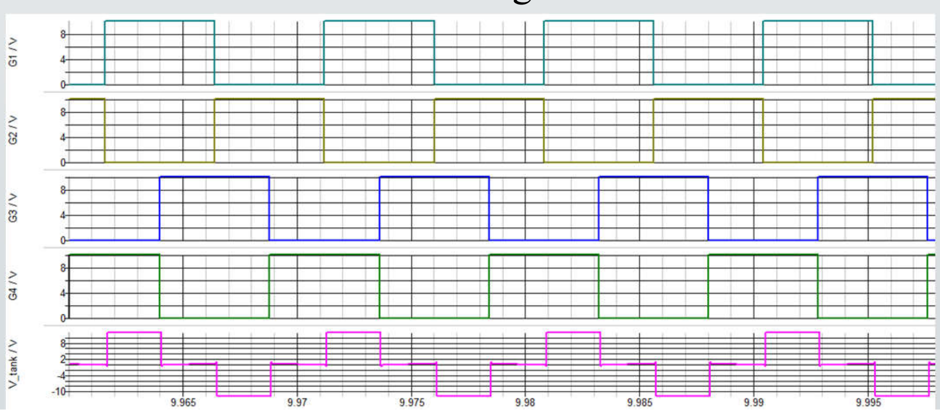
Gate and tank signal at $30^{o}$




Gate and tank signal at $60^{o}$




Gate and tank signal at $90^{o}$

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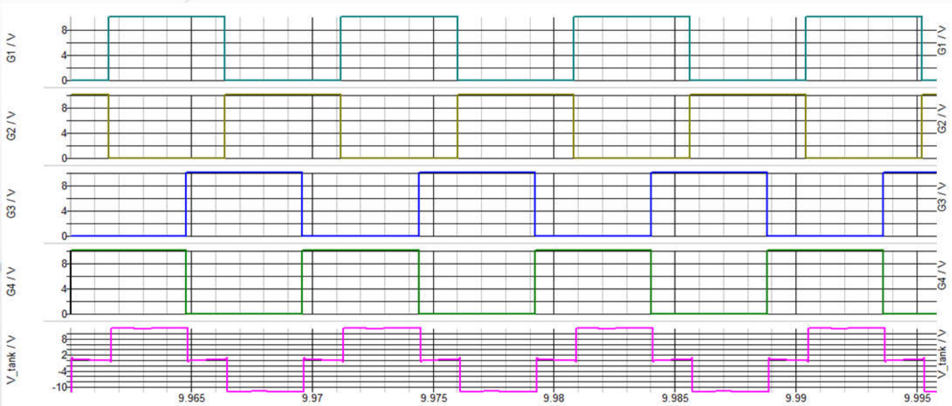
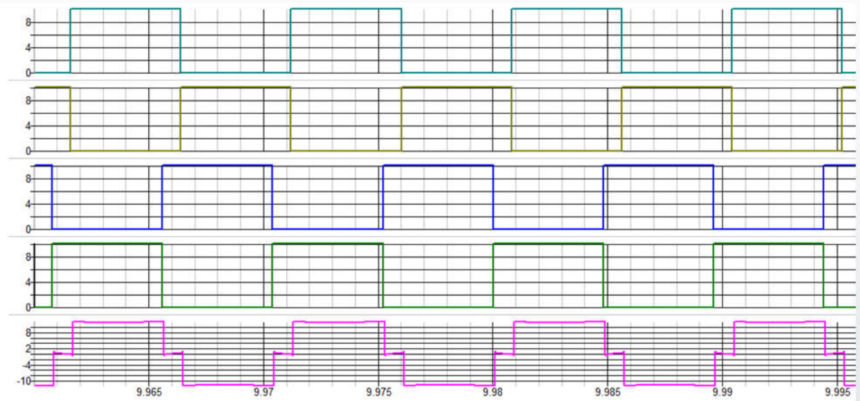
# LLC tank pulse at varying phases

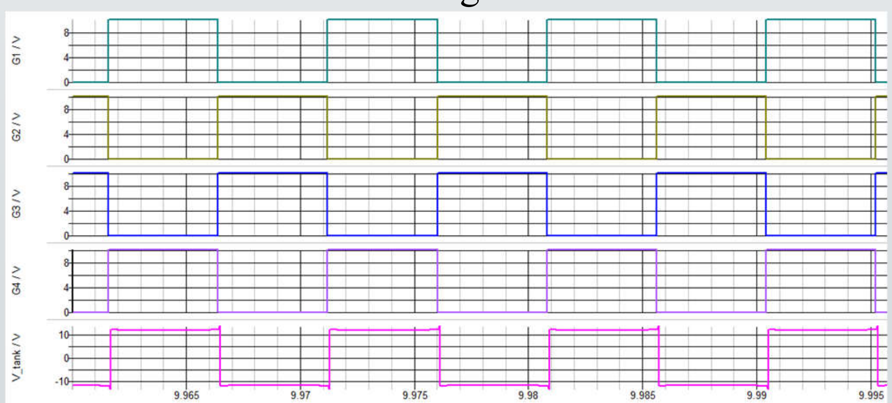
Gate and tank signal at 120$^o$




Gate and tank signal at 150$^o$




Gate and tank signal at 180$^o$

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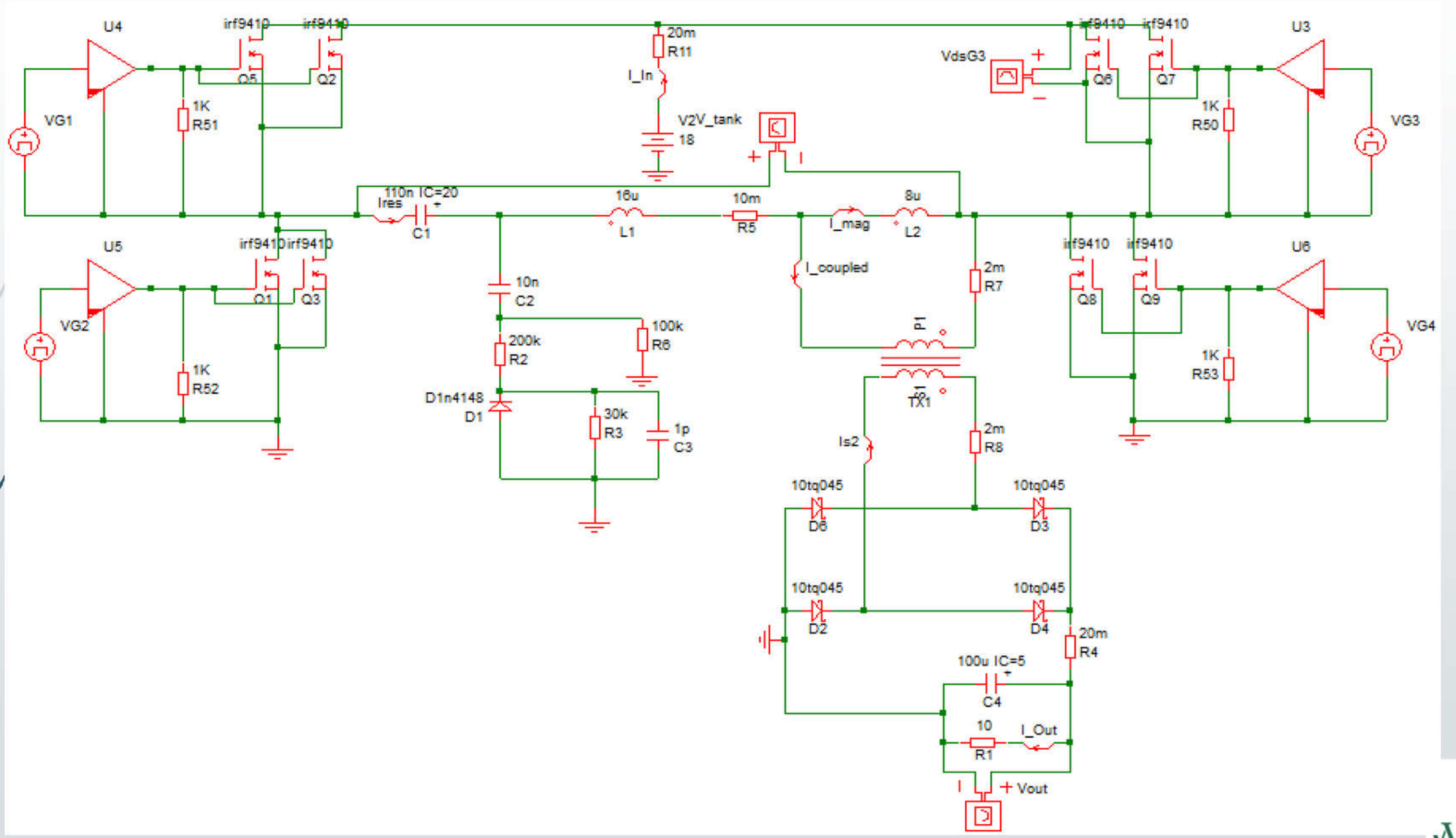
# SIMPLIS schematic of LLC circuit

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# Design Specifications

| | |
|---|---|
| Input voltage ($V_{in}$) | 18 V |
| Output power ($P_{out}$) | 150 W |
| Switching frequency ($f_s$) | 104.3 kHz |
| Resonant capacitor ($C_r$) | 110nF |
| Leakage Inductor ($L_r$) | 16uH |
| Magnetization Inductor ($L_m$) | 8uH |
| Load Resistance ($R_L$) | 10 |
| Transformer specification | Lp =Ls =100mH, Np : Ns =1 |
| Initial Deadtime | 100ns |

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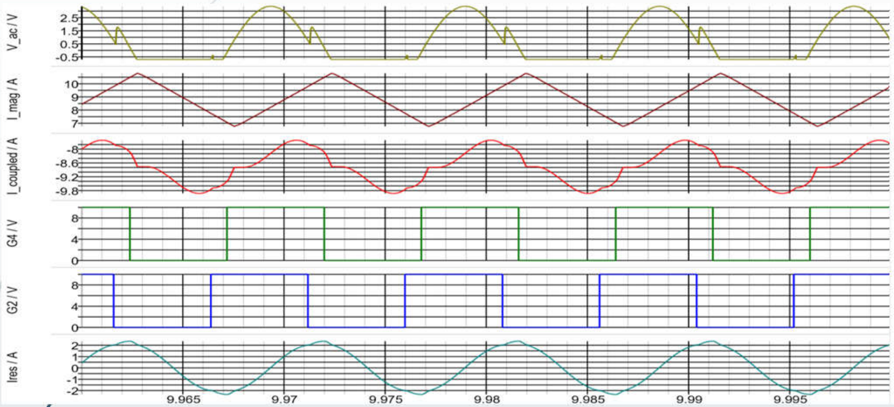
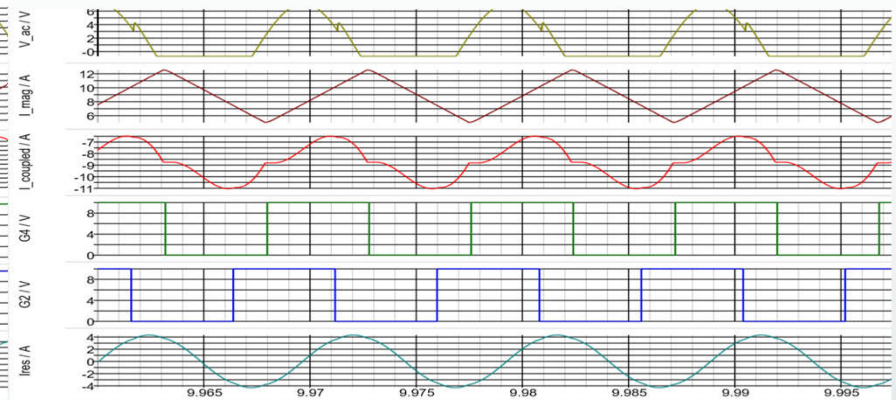
# RMS currents of PSM LLC at 30$^o$, 60$^o$, 90$^0$

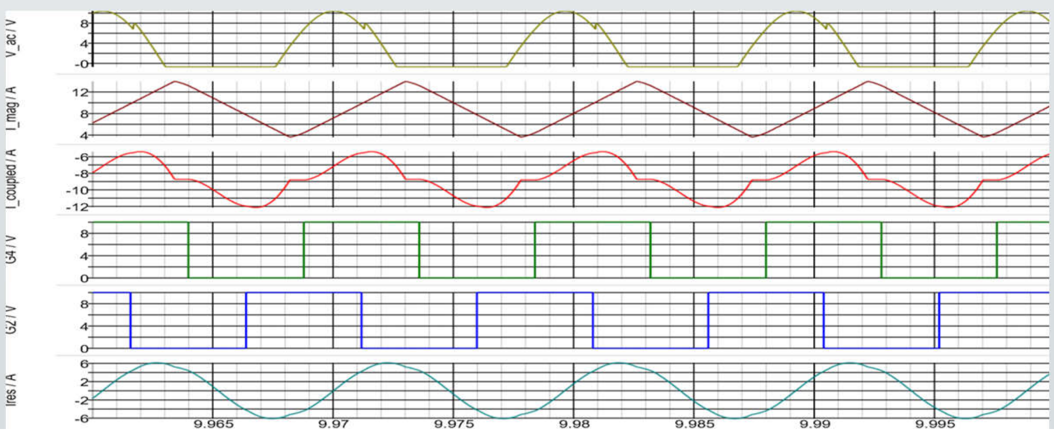
Leakage and Magnetization current at 30$^0$




Leakage and Magnetization current at 60$^0$




Leakage and Magnetization current at 90$^0$

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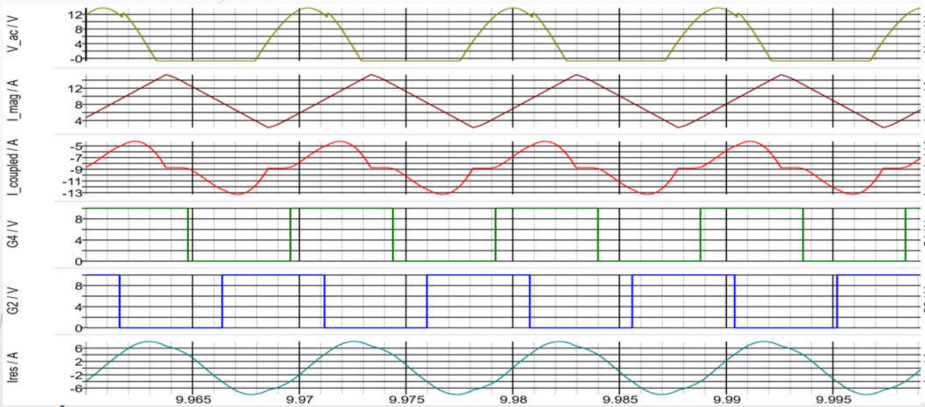
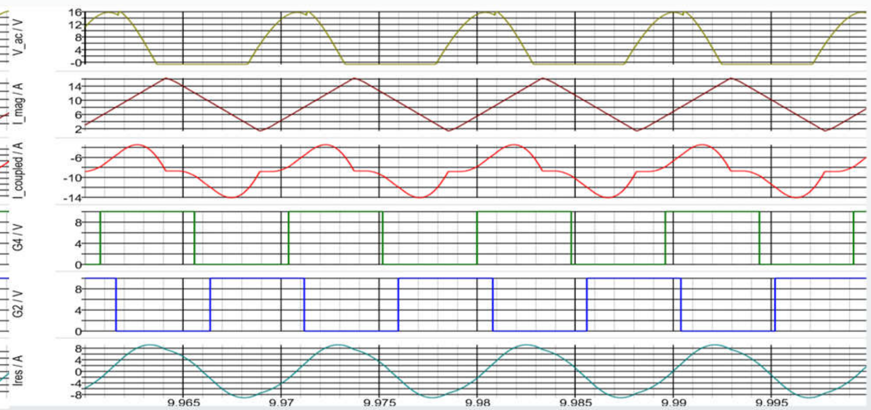
# RMS currents of PSM LLC at 120$^{o}$, 150$^{o}$, 180$^{o}$

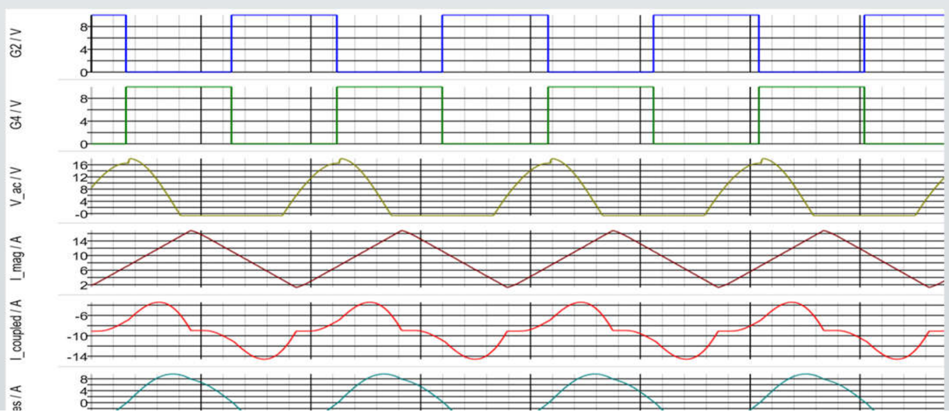
Leakage and Magnetization current at 120$^{0}$




Leakage and Magnetization current at 150$^{0}$




Leakage and Magnetization current at 180$^{0}$

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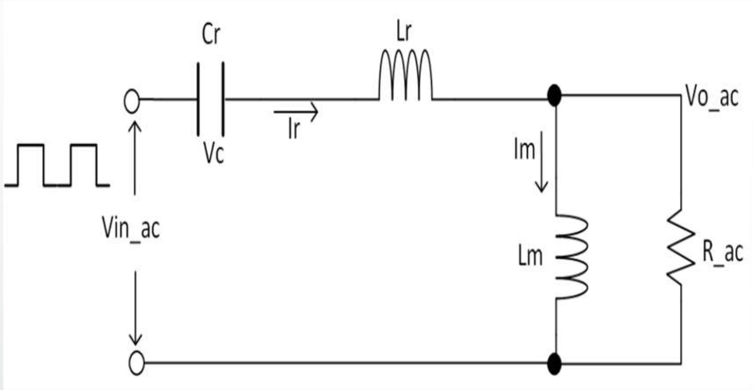
# First Harmonic Approximated Analysis

- First Harmonic Approximated analysis is used calculate the transfer function from input to output voltage as a function of the load
- With FHA analysis, resonant tank's higher order harmonics are neglected and fundamental harmonics are utilized to calculate the voltage gain.
- When switching frequency is nearly equal to resonant frequency, resonant tank easily filters out higher order harmonics.
- For optimum power, LLC circuit operation has to be operated with a switching frequency nearly equal to resonant frequency.

# FHA analysis of PSM LLC circuit

Voltage across resonant tank is given by

$$V_{in-ac} = V_{in} + \frac{4V_{in}}{\pi} \sum_{n=1,3,5} \frac{1}{n} \sin(n2\pi f_s t)$$




Fundamental harmonic component is given by

$$V_{in-ac\ (FHA)} = \frac{4V_{in}}{\pi} \sin(2\pi f_s t)$$

Average current reflected on tank circuit is

$$I_{o-ac} = I_o \sin(n2\pi f_s t)$$

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# FHA analysis of PSM LLC circuit

Equivalent Load Resistance:

$$R_{ac} = \frac{8n^2}{\pi^2} R_L$$

Input Impedance of tank circuit:

$$Z_{in-ac} = \frac{1}{j\omega C_r} + j\omega L_r \; + \frac{j\omega L_m R_{ac}}{j\omega L_m + R_{ac}}$$

Output Impedance of tank circuit:

$$Z_{out-ac} = \frac{j\omega L_m R_{ac}}{j\omega L_m + R_{ac}}$$

Voltage gain:

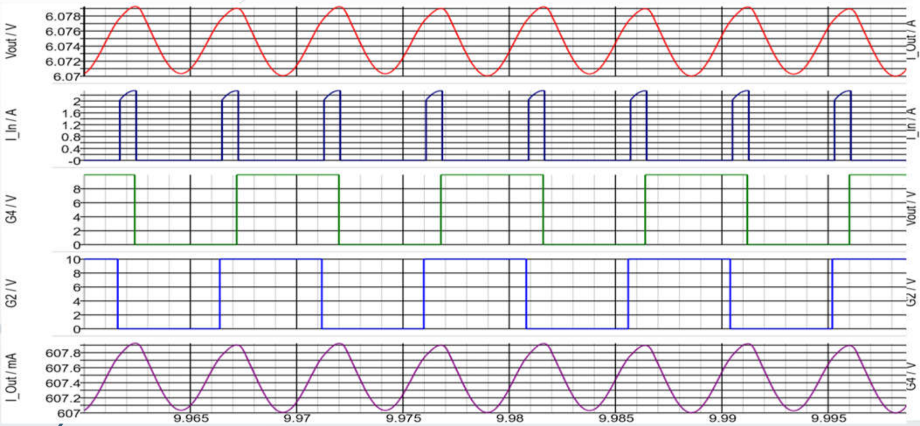
$$M = \frac{Z_{in-ac}}{Z_{out-ac}}$$

# Output scaling factor for constant $R_{LOAD}$

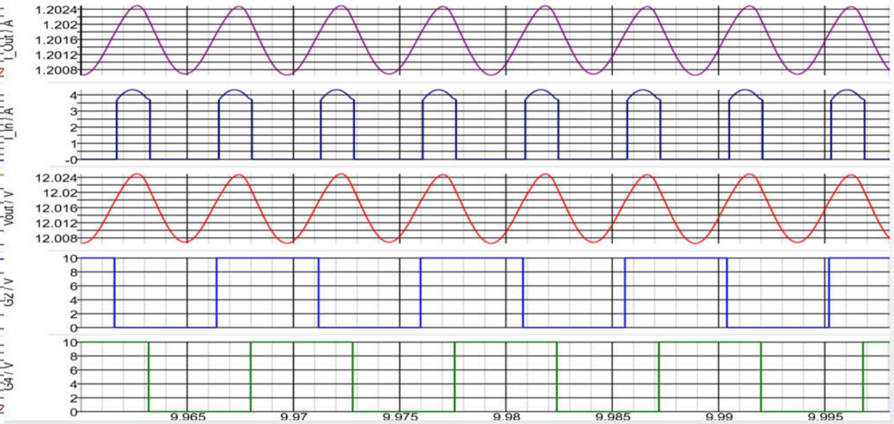
| Phase | Duty Cycle (D) | Sin($\pi D$) $factor$ | Tank Voltage (V) (Theoretical) | (Simulation) | Error (V) ($\Delta$) |
|---|---|---|---|---|---|
| 30 | 0.083 | 0.257 | 5.908 | 6.726 | 0.818 |
| 60 | 0.16 | 0.4813 | 11.04 | 9.74 | 1.297 |
| 90 | 0.25 | 0.707 | 16.2058 | 11.99 | 4.214 |
| 120 | 0.3 | 0.8093 | 18.54 | 13.877 | 4.664 |
| 150 | 0.416 | 0.965 | 22.11 | 15.74 | 6.37 |
| 180 | 0.5 | 1 | 22.918 | 17.645 | 5.273 |

# Output voltage and current waveforms

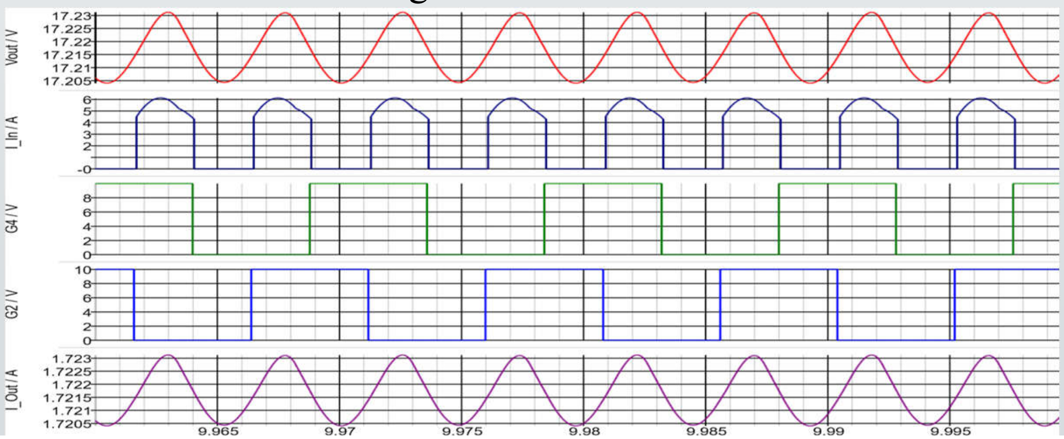
Voltage and current at $30^o$




Voltage and current at $60^o$




Voltage and current at $90^o$

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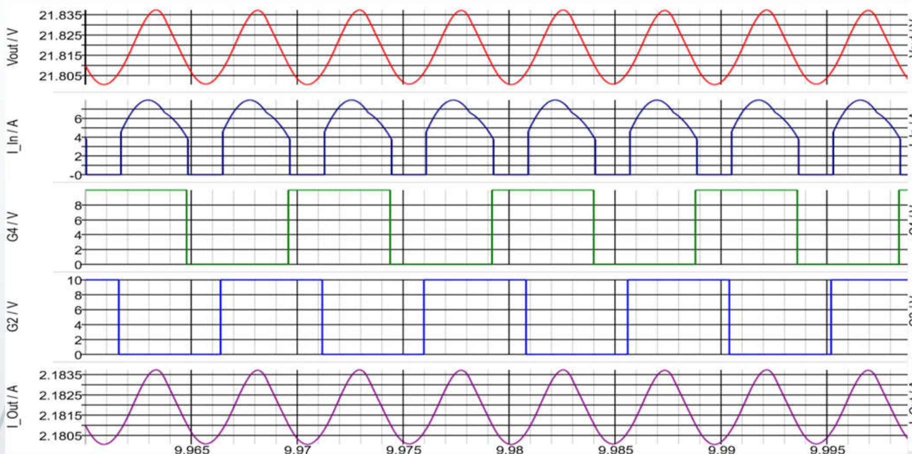
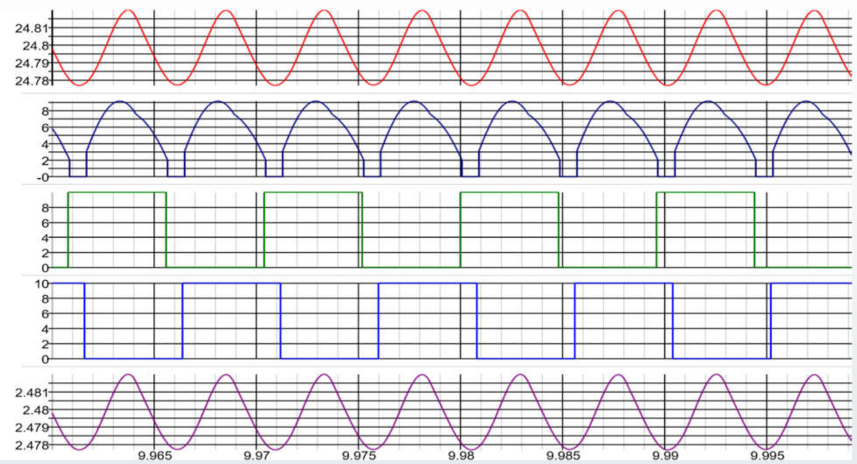
# Output voltage and current waveforms

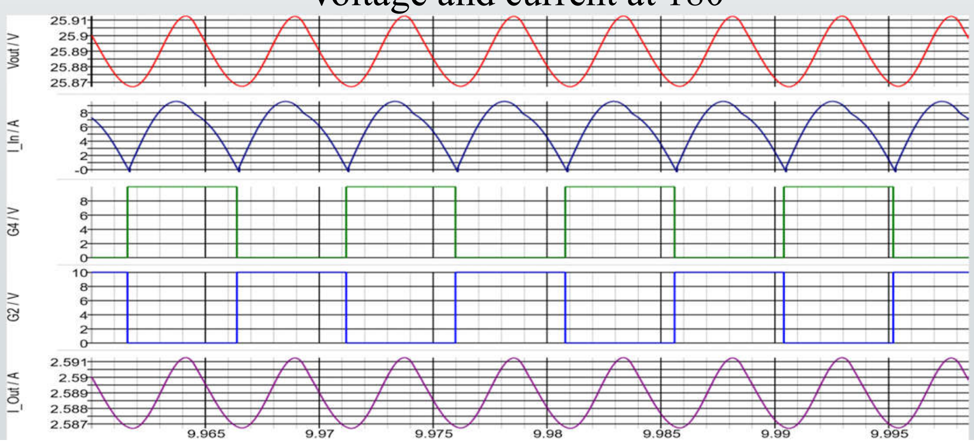
Voltage and current at 120º




Voltage and current at 150º




Voltage and current at 180º



# Comparisons

Comparing with classical frequency modulation :-

- Phase modulation improves efficiency at light loads
- Improves electromagnetic spectrum of emissions
- Easier control architecture (Fixed frequency)
- Matches the transmitter's maximum power characteristics to actual power requirements

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# Comparison

Frequency modulated

| Frequency (Hz) | Magnetization current (A) | Leakage current (A) |
| --- | --- | --- |
| 104.3k | 9.99 | 8.97 |
| 108k | 9.166 | 8.913 |
| 120k | 7.673 | 7.858 |
| 135k | 7.426 | 7.481 |
| 145k | 7.43 | 7.34 |

Phase shift modulated

| Phase (Degree) | Magnetization current (A) | Coupled current (A) |
| --- | --- | --- |
| 30 | 7.604 | 8.7 |
| 60 | 8.049 | 8.35 |
| 90 | 8.6 | 7.93 |
| 120 | 9.28 | 8.355 |
| 150 | 9.7 | 8.7 |
| 180 | 9.99 | 8.97 |

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# Comparison – Output power and efficiency

Frequency modulated LLC converter

| Frequency | $P_{in}$ | $P_{out}$ | Efficiency |
|---|---|---|---|
| 104.3k | 158.74 | 150.6 | 94.27 |
| 108k | 125.64 | 114.11 | 89.93 |
| 120k | 34.02 | 28.72 | 84.42 |
| 135k | 13.572 | 11.246 | 82.86 |
| 145k | 9.756 | 7.605 | 77.96 |

Phase shift modulated LLC converter

| Phase | $P_{in}$ | $P_{out}$ | Efficiency |
|---|---|---|---|
| 30 | 7.83 | 7.177 | 91.66 |
| 60 | 31.914 | 30.588 | 95.845 |
| 90 | 66.06 | 64.158 | 97.12 |
| 120 | 107.1 | 104.4 | 97.47 |
| 150 | 142.362 | 136.69 | 96.012 |
| 180 | 158.742 | 150.6 | 94.27 |

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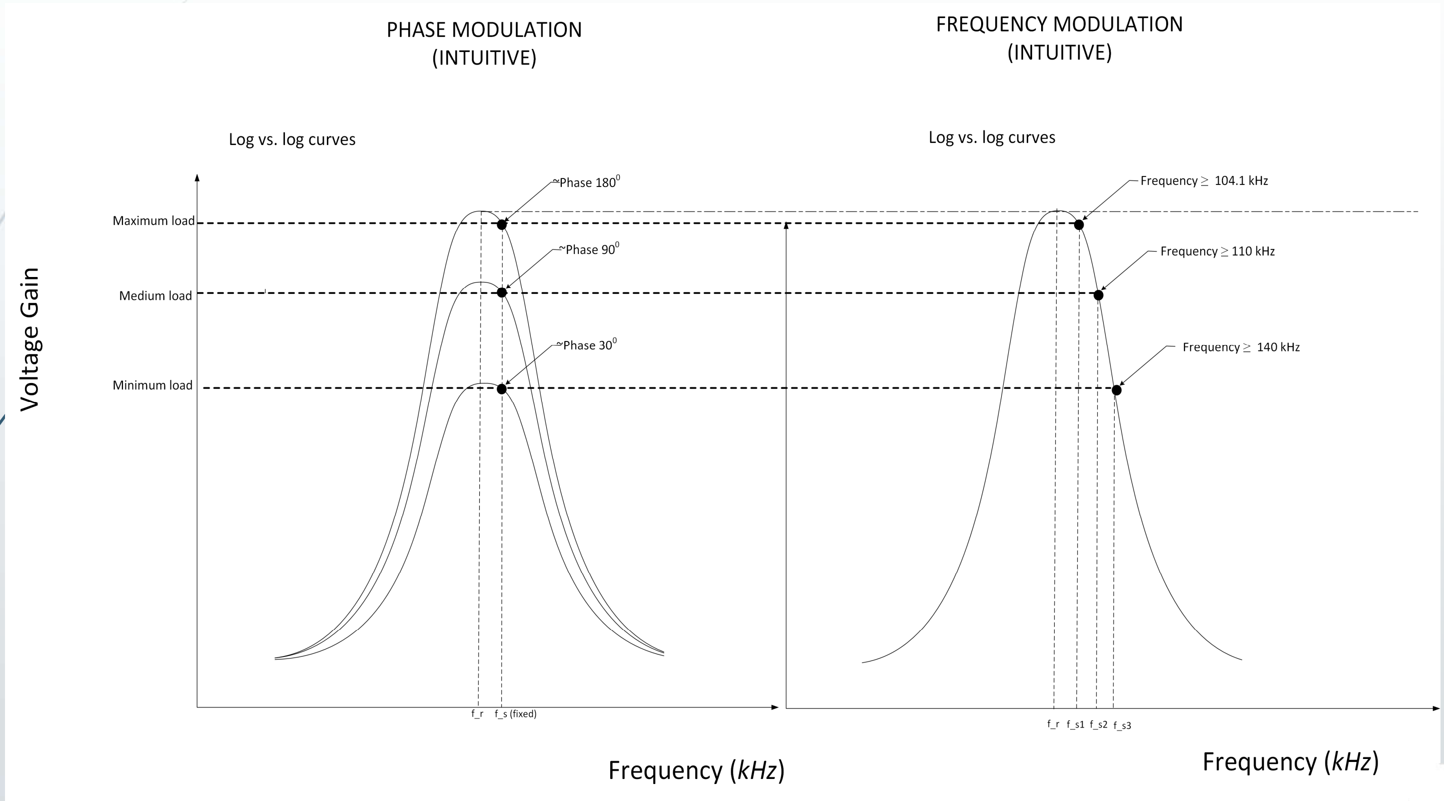
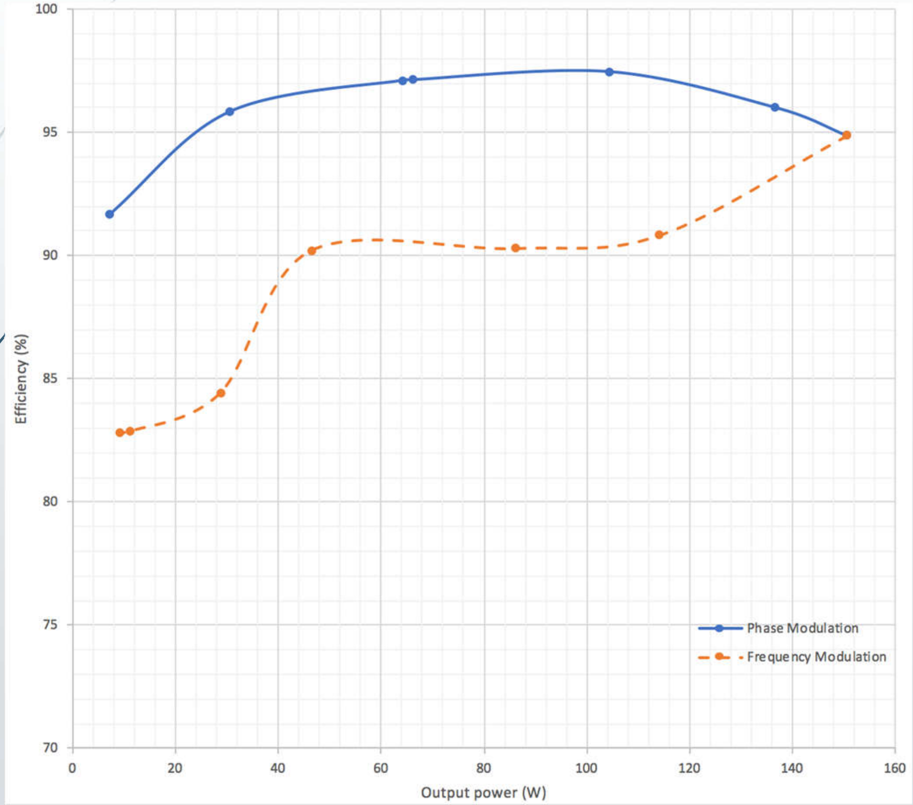
# Gain comparison



# Efficiency comparison




**At full load:**
Frequency controlled – 94.86%
Phase shift controlled – 94.86%

**At light load:**
Frequency controlled – 82.86%
Phase shift controlled – 91.66%

**Maximum efficiency:**
Frequency controlled – 94.86%
Phase shift controlled – 97.47%

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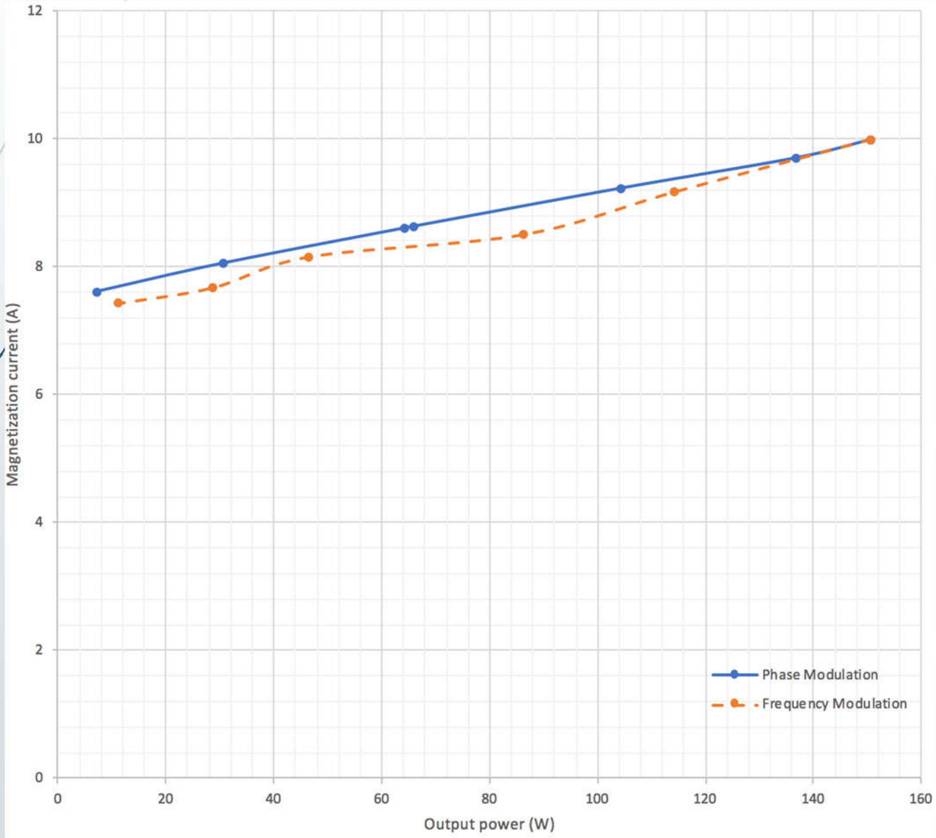
# Loss comparison

- To compare the performance FM and PSM controlled circuit, following reference points chosen

**Output power = 66 W , Input voltage = 18 V, Output voltage = 25.699 V**

| Parameter | Frequency modulation | Phase shift controlled |
|---|---|---|
| Switching frequency(Hz) | 112k | 104.3k |
| Phase (°) | 180 | 91.5 |
| Input power (W) | 71.46 | 67.98 |
| Efficiency (%) | 92.37 | 97.14 |
| Conduction losses (W) | 3.546 | 1.813 |
| Driving losses (W) | 0.028 | 0.0132 |
| Turn-off losses (W) | 0.558 | 0.506 |
| Total power losses (W) | 4.132 | 1.958 |

# Magnetization current vs Output power




- ❑ At a fixed frequency operation, phase control exhibits monotonicity of control power and optimal utilization of magnetic components. Also, minimum losses are observed even through phase variation.
- ❑ Whereas in frequency control technique, tank energy changes with frequency variation which generates glitches/spikes due to increased conduction losses across switch

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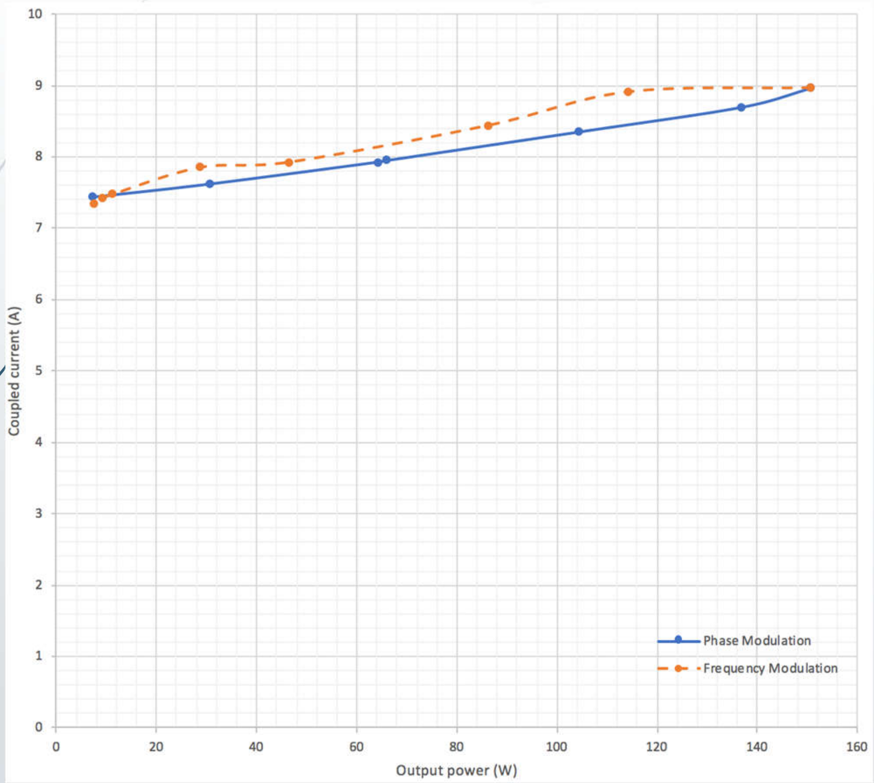
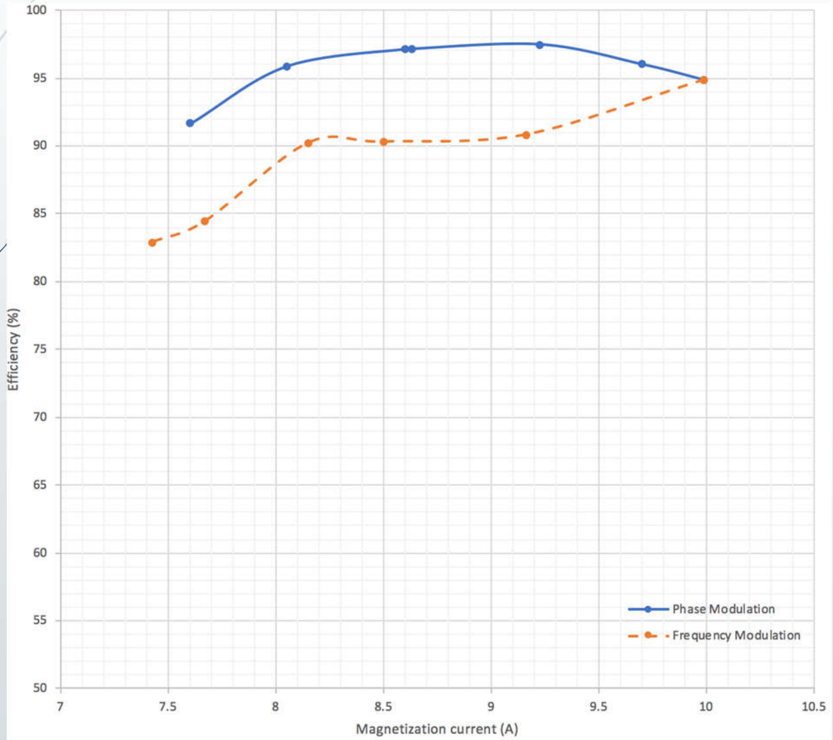
# Coupled current vs output power




Magnetization current recorded low in frequency controlled compared to phase controlled circuit, there is a significant amount of current leaked which is not contributed to deliver power towards load

# Efficiency vs Magnetization Current




Because of controlled magnetization current in PSM circuit, significant amount of power is being delivered to load always. This is a key contributing factor to observe greater efficiency than FM converter.

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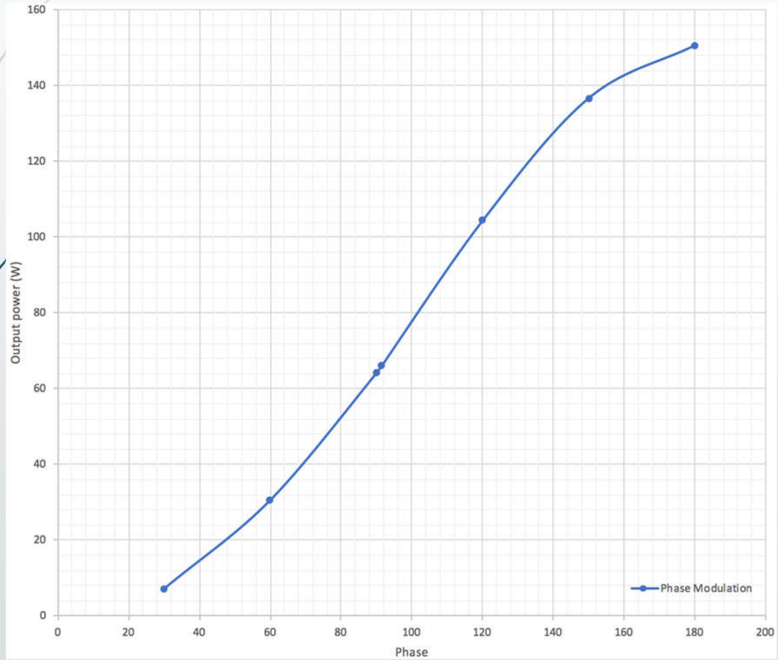
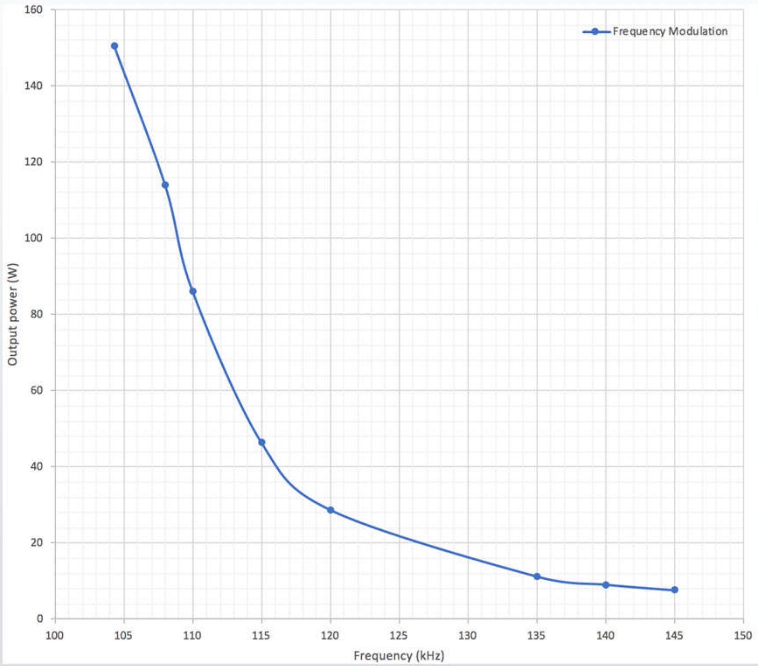
# Output power comparison

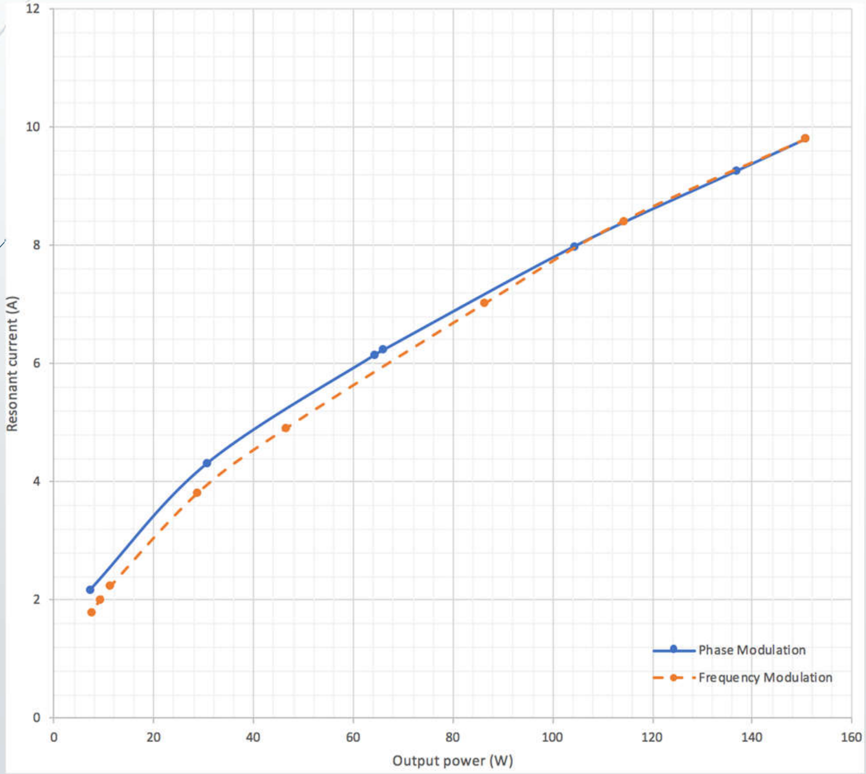
Phase shift modulated




Frequency modulated



# Resonant current vs Output power



# Conclusion

- Frequency modulated LLC resonant converter was presented with fixed $R_{LOAD}$ for simplicity
- Phase control technique for LLC converter was investigated
- Efficiency of phase controlled LLC converter vs. frequency modulated LLC converter was compared
- At a fixed frequency operation, phase control exhibits monotonicity of control power and optimal utilization of magnetic components.
- Minimum losses are observed across wide range of phase angle
- Phase modulation exhibits much better characteristics than frequency modulation based on iterative simulations

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## Contributions

- First harmonic approximated analysis was used to study Phase Control of LLC boost converter.
- Comparative study of LLC circuit behavior with frequency and phase control technique.
- Modelled rectifier circuit to LLC tank, for optimum operation, to understand ZVS condition at varying phases for PSM LLC.
- Implementing V_ac tracking, we can track the best operating point for wider range of input for PSM technique.

# Future Work

- Perform experimental comparison of frequency and phase control technique for LLC converter
- Study applicability of PSM LLC converters to Wireless Power Transfer (WPT) technology
- Implement active feedback loop and study the stability of PSM controlled resonant circuit over a wide load range.
- Study line regulation characteristics.

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# Questions

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# Thank you

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