RESONANT LLC CONVERTER

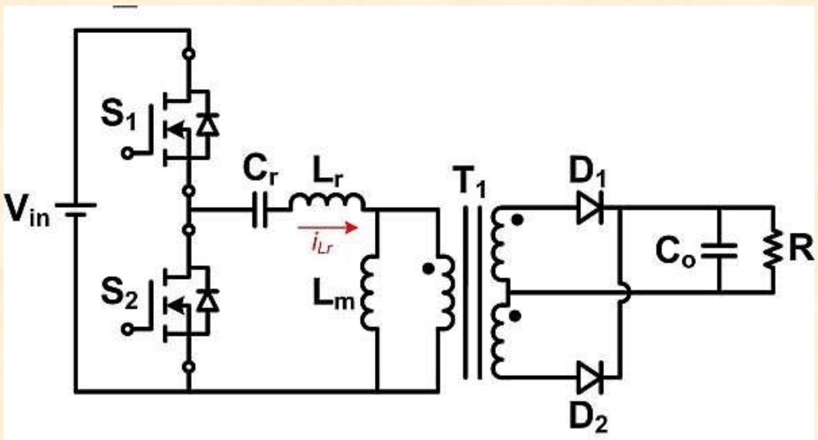
ANALYSIS, SIMULATION AND SIMPLIFIED DESIGN OF LLC CONVERTER

1. FOREWORD

`Below is simplified schematic of LLC converter.

Design of every LLC converter starts with transfer function plot showing graphs of different Q (quality factor) values for a specified relationship M of resonant inductance Lr to magnetizing inductance Lm. But how to derive the transfer function?

It is difficult, if possible, to simulate the schematic below and derive its transfer function as it is nonlinear circuit. It has square wave input voltage and diode rectifier.



In order to linearize the circuit some assumptions are made.

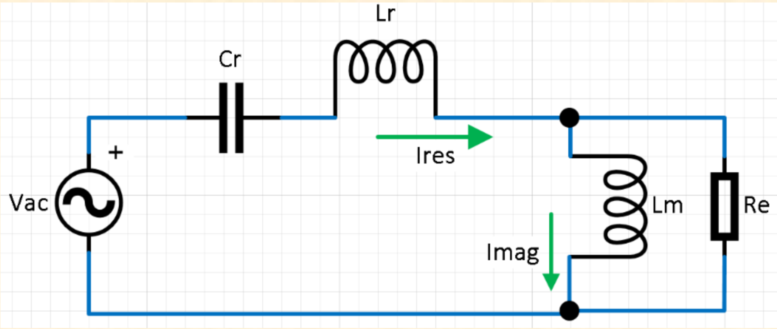
2. LINEARIZE THE CIRCUIT: FIRST HARMONIC APPROXIMATION AND RAC CONCEPTS

Resonant circuit in the LLC converter is actually a filter. When we apply square wave voltage at resonant frequency to it we will see sinusoidal current. As the current in the resonant circuit is sinusoidal at resonant frequency and LLC converter switching frequency is swinging around the resonant frequency, we can assume that our current is sinusoidal and only first harmonic is present (First Harmonic Approximation). Therefore, we can replace square wave voltage on the input of the resonant circuit with AC voltage source Vac.

Its RMS value for half bridge $Vac = \frac{\sqrt{2}}{\pi} * Vdc$

Next, we replace diode rectifier, transformer and load resistance with an equivalent resistance.

$Re = \frac{8*n^2}{\pi} * Rout$, (by professor Robert Steigerwald), where n is the transformer turns ratio



3. DERIVING TRANSFER FUNCTION AND FORMULA FOR CURRENT WITH MATHCAD

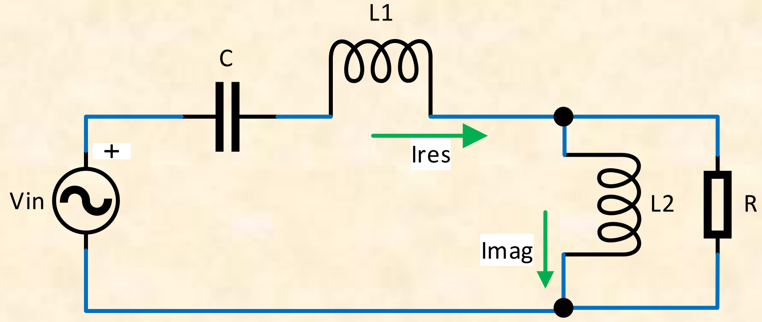
Now we have got linear circuit and we can derive transfer function and function for resonance current.

I am using the ratio between Lm and Lr, M =Lm/Lr equal to 6. Most of the designs use range of 6 to 10 and we can adjust it later during design to optimize it.

In order to be able to use the results for any design I am using normalized values here for all components and values.

As you can see L2(Lm) is 1, and L1(Lr) is 0.16 or 6 times smaller.

Normalized resonant frequency is equal to 1.



$L1 := 0.16$

$L2 := 1$

$Fr := 1$

$C := 0.16$

$j := \sqrt{-1}$

$Fx := 0.1, 0.101 .. 10$

$R := 1$

$Vin := 1$

$s(j) := j \cdot 2 \cdot \pi \cdot Fx$

$$Zrl(Fx) := j \cdot 2 \cdot \pi \cdot Fx \cdot L2 \cdot \frac{R}{j \cdot 2 \cdot \pi \cdot Fx \cdot L2 + R}$$

$$Zlc(Fx) := j \cdot 2 \cdot \pi \cdot Fx \cdot L1 + \frac{1}{j \cdot 2 \cdot \pi \cdot Fx \cdot C}$$

$$Z(Fx) := Zrl(Fx) + Zlc(Fx)$$

Resonant Current:

$$I(Fx) := \frac{Vin}{Z(Fx)}$$

Transfer Function Vout/Vin:

$$M(Fx) := \frac{j \cdot 2 \cdot \pi \cdot Fx \cdot L2 \cdot \frac{R}{j \cdot 2 \cdot \pi \cdot Fx \cdot L2 + R}}{j \cdot 2 \cdot \pi \cdot Fx \cdot L2 \cdot \frac{R}{j \cdot 2 \cdot \pi \cdot Fx \cdot L2 + R} + j \cdot 2 \cdot \pi \cdot Fx \cdot L1 + \frac{1}{j \cdot 2 \cdot \pi \cdot Fx \cdot C}}$$

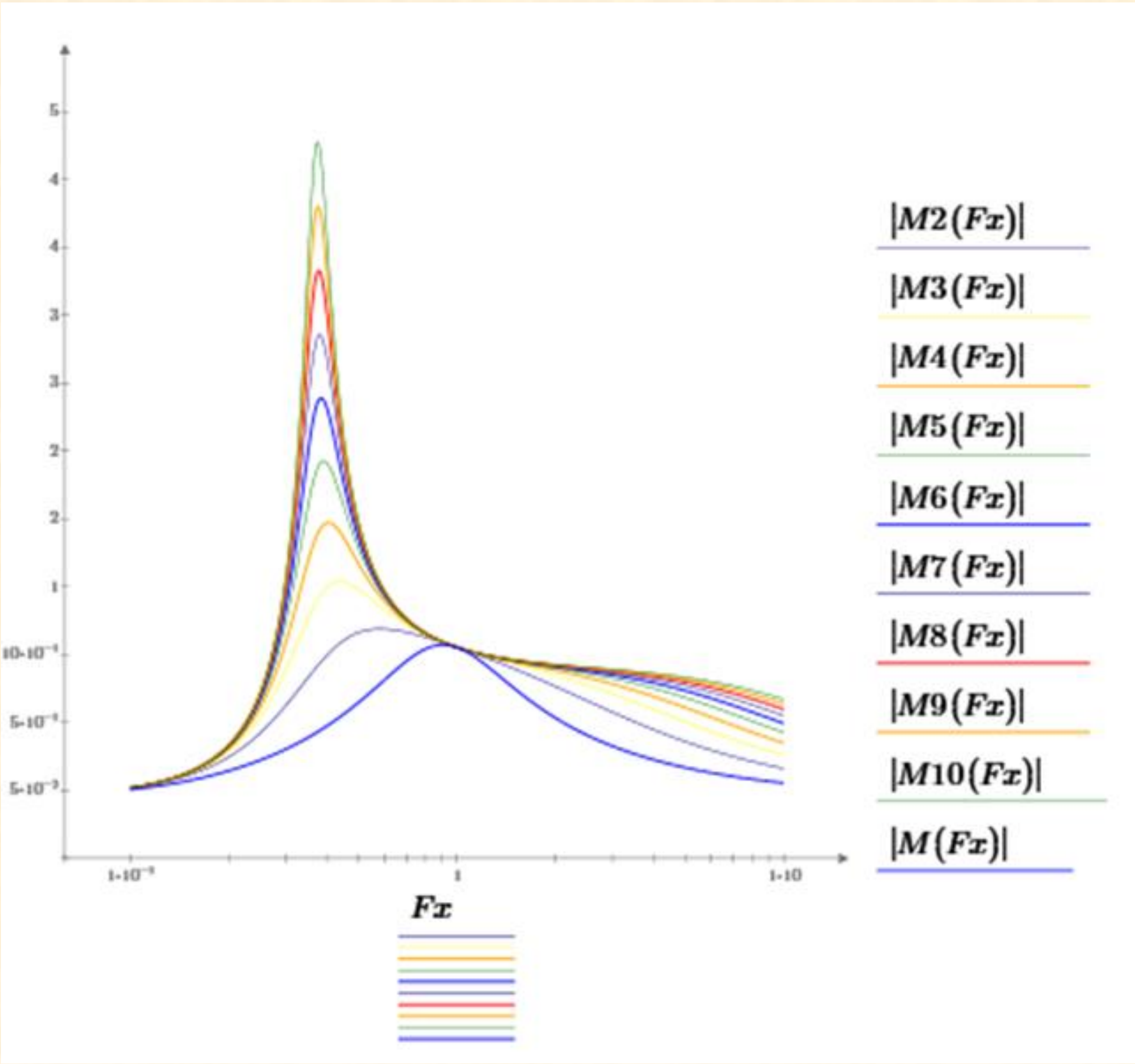


Figure 1. Transfer Function Plot

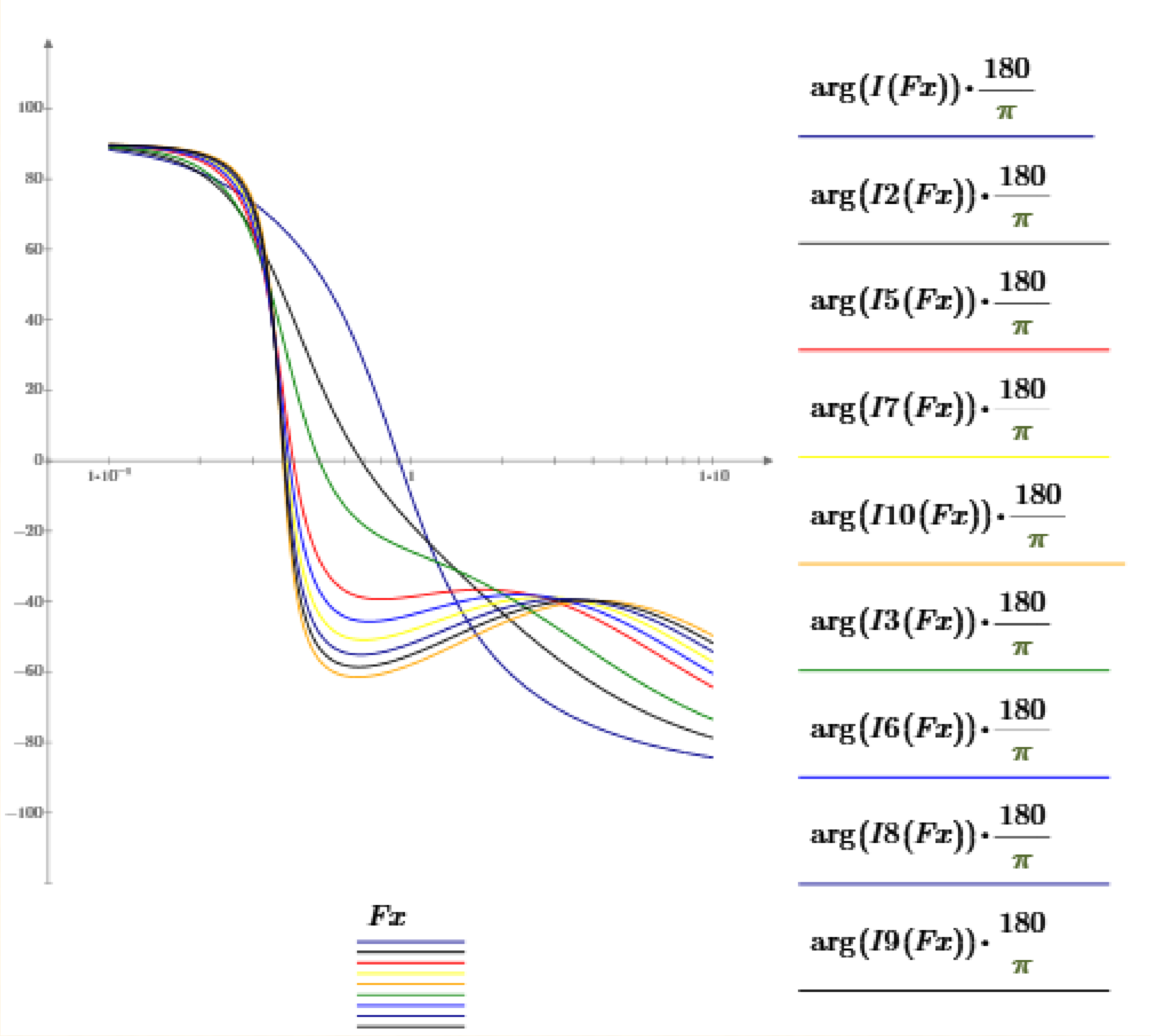


Figure 2. Resonant Current Plot

4. PSPICE SIMULATION

Next, I decided to check if the results I got in Mathcad are correct.

In order to do that I simulated the same circuit in Pspice:

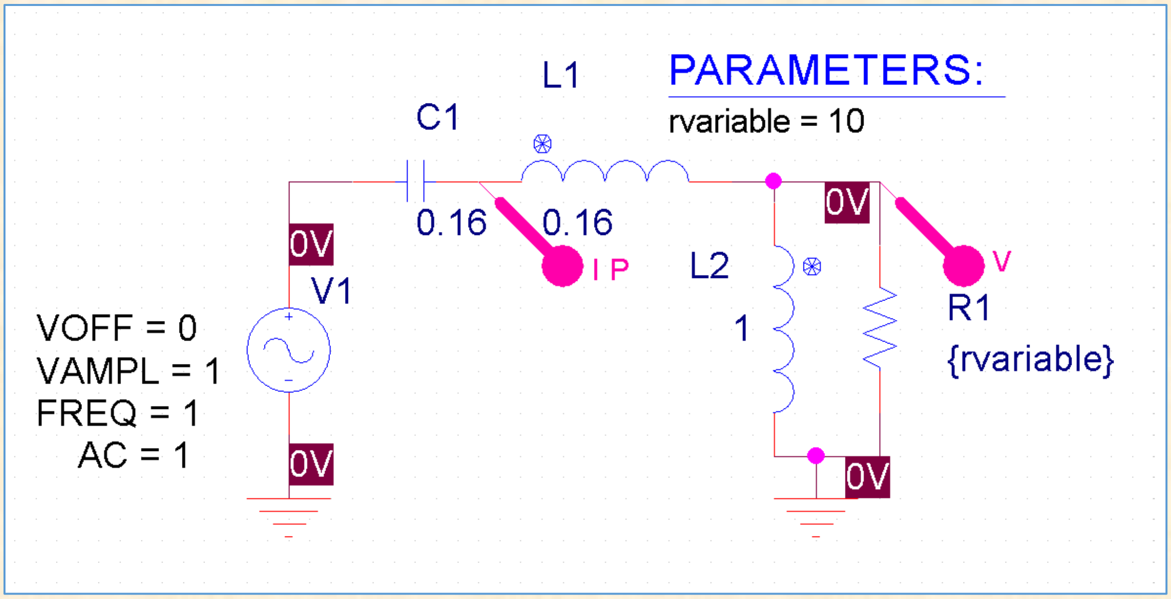


Figure 3. Pspice LLC Converter Model Schematic

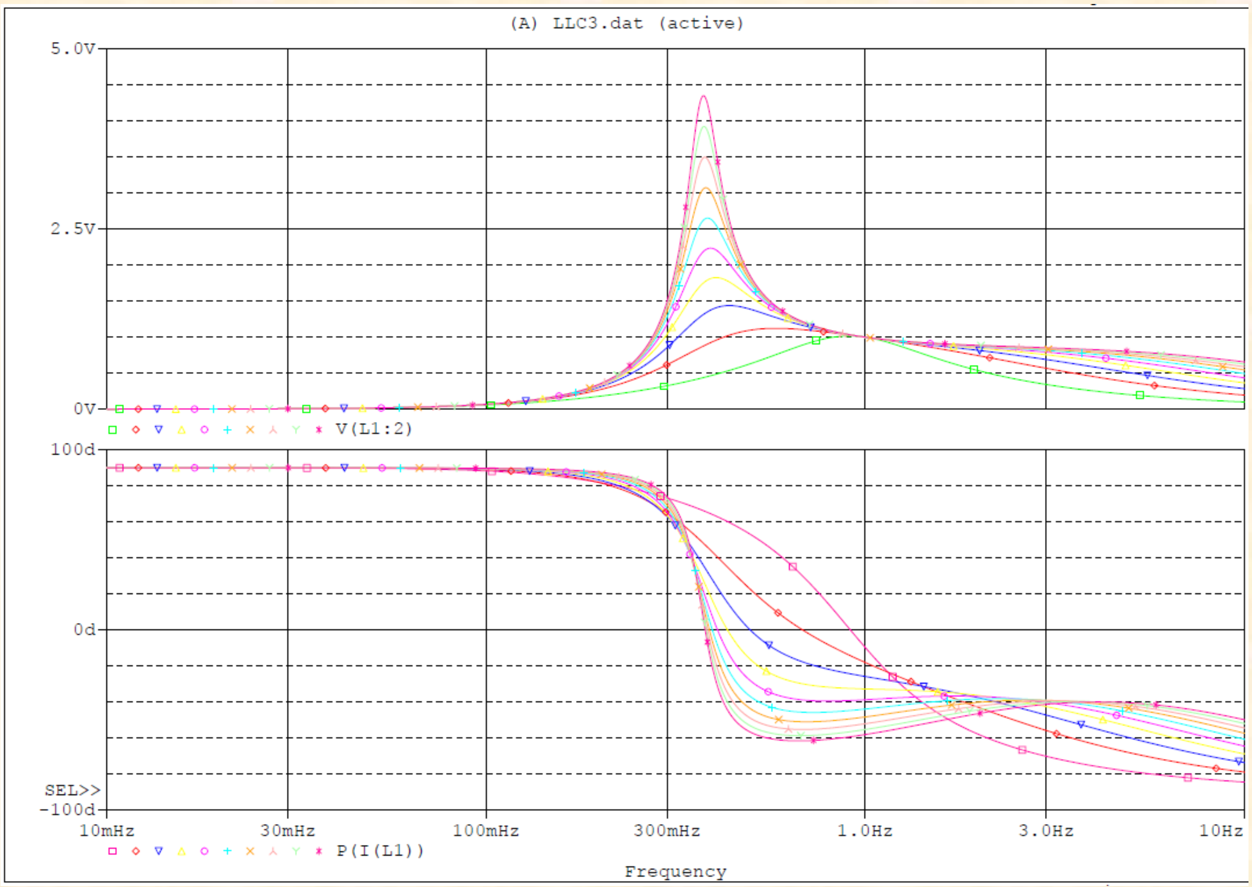


Figure 4. Pspice Simulation Transfer Function and Resonant Current Plots

5. DESIGN FORMULAS

AC Voltage Vac equivalent to square wave voltage Vin (for half bridge)	$Vac\ pk = \frac{2 * Vin}{\pi}$	y
	$Vac\ rms = \frac{\sqrt{2} * Vin}{\pi}$	y
Rac equivalent to load resistance Rl:	$Rac = \frac{8 * Rl}{\pi^2}$	y
Rac equivalent to load resistance Rl incl. transformer turns ratio n	$Rac = n^2 * \frac{8 * Rl}{\pi^2}$	
AC Voltage Voac equivalent to output voltage Vodc	$Voac = \frac{2 * \sqrt{2} * Vodc}{\pi}$	y
AC Voltage Voac equivalent to output voltage Vodc approximation	$Voac = 0.9 * Vodc$	y
AC Voltage Voac equivalent to output voltage Vodc incl. transformer turns ratio n	$Voac = n * \frac{2 * \sqrt{2} * Vodc}{\pi}$	y
Resonant frequency, Hz	$Fr = \frac{1}{2 * \pi * \sqrt{Lr * Cr}}$	y
Quality Factor	$Q = \frac{\omega r * Lr}{Rac}$	y
	$Q = \frac{\sqrt{\frac{Lr}{Cr}}}{Rac}$	y
Operational range, Maximum and Minimum gains Gmax. Gmin	$\frac{Gmax}{Gmin} = \frac{Vin\ max}{Vin\ min} = \frac{Vac\ max}{Vac\ min}$	

$Vout = Gmax * Vac\ min$	$Vac\ min = \frac{\sqrt{2} * Vin\ min}{\pi}$	$Pmax = \frac{Vout^2}{Rac\ min}$	$Rac\ min = \frac{(\frac{Gmax * Vin\ min * \sqrt{2}}{\pi})^2}{Pmax}$
$Qmax = \frac{\omega r * Lr}{Rac\ min}$	$Lr = \frac{Qmax * Rac\ min}{\omega r}$	$Cr = \frac{1}{Lr * 4 * \pi^2 * Fr^2}$	$Lm = M * Lr$
$Rdc\ min = \frac{Vout^2}{Pmax}$	$Rac\ min = n^2 * \frac{8 * Vout^2}{\pi^2 * Pmax}$		$n = \sqrt{\frac{Rac\ min * \pi^2 * Pmax}{8 * Vout^2}}$

6. SIMPLIFIED DESIGN EXAMPLE:

Given:		Determine:
Half Bridge topology		Lr Lm Cr n1/n2
Vin min	330vdc	
Vin max	410vdc	
Pout max	200w	
Fs at Fres	135kHz	
Vdc out	12vdc	

6.1 CHOOSE M = LM/LR.

Small M gives us high resonant gain and high reactive energy which could lead to increased conduction losses and increased size of resonant components.

Large M means low gain and low reactive energy. Switching frequency span could be prohibitively large and gain could be to low to satisfy our design requirements. M from 6 to 10 is somewhere in the middle.

Let's choose M = 6

M = 6

6.2 SELECT OPERATIONAL RANGE MAXIMUM AND MINIMUM GAIN G MAX AND G MIN

G max*Vin min = Vdc (Vout)

G min*Vin max = Vdc

$$\frac{Gmax}{Gmin} = \frac{Vin\ max}{Vin\ min} = \frac{Vac\ max}{Vac\ min} = \frac{410}{330} = 1.25$$

Let's count for 90% efficiency and 10% overload capability 1.25*1.2 = 1.5

Let's choose G min tentatively a bit smaller than 1 so that its corresponding frequency is higher than Fr.

G min = 0.98

G max = 1.47

6.3 SET Q MAXIMUM (SMALLEST RAC) USING TRANSFER FUNCTION CURVES PLOT ABOVE.

With the transfer function we derived before, we can use Mathcad and plot curves for any values. We can put actual values by calculating Rac, Vac min and Vac max using formulas from the formulas table.

I tentatively has chosen curve 4 on the plot with Q = 0.25

Qmax = 0.25

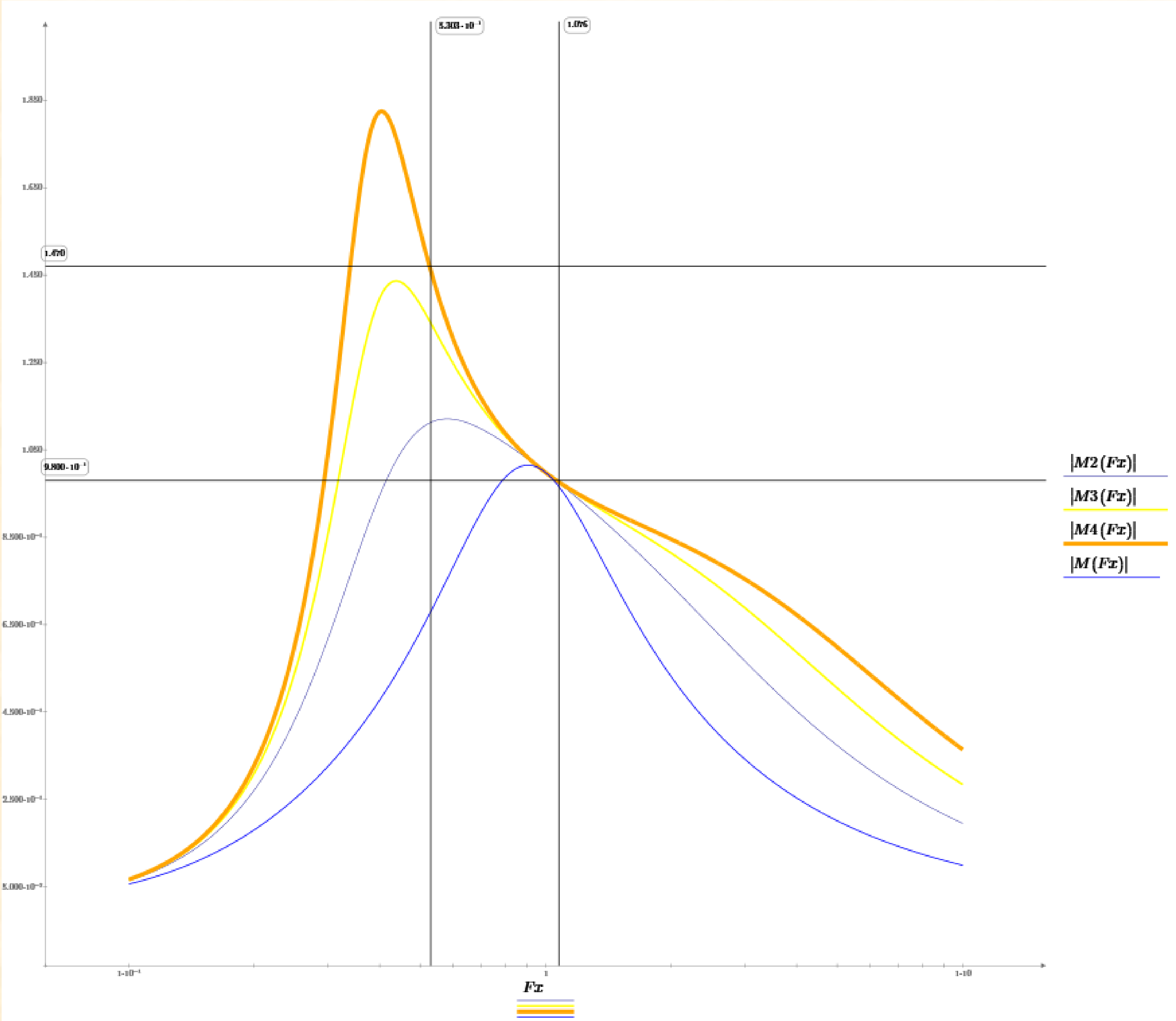


Figure 5. Choosing Qmax

Minimum frequency (see vertical markers) F min = 0.53*Fres = 72 kHz

Maximum frequency (see vertical markers) F max = 1.076*Fres = 145 kHz

Fmin = 72 kHz

Fmax = 145kHz

6.4 CALCULATE RAC MIN:

$$Vout = Gmax * Vac\ min \qquad Vac\ min = \frac{\sqrt{2} * Vin\ min}{\pi} \qquad Pmax = \frac{Vout^2}{Rac\ min} \qquad Rac\ min = \frac{(\frac{Gmax * Vin\ min * \sqrt{2}}{\pi})^2}{Pmax}$$

Rac min = 238

6.5 CALCULATE LR, CR, LM:

$$Lr = \frac{Qmax * Rac\ min}{2 * \pi * Fr}$$

Lr = 70 uH

$$Cr = \frac{1}{Lr * 4 * \pi^2 * Fr^2}$$

Cr = 20 nF

Lm = Lr*M = 70*6 =420 uH

6.6 CALCULATE TRANSFORMER TURNS RATIO:

$$Rac\ min = n^2 * \frac{8 * Vout^2}{\pi^2 * Pmax} \qquad n = \sqrt{\frac{Rac\ min * \pi^2 * Pmax}{8 * Vout^2}}$$

n = 20 turns