TEXAS INSTRUMENTS

Variable Definition

$Vin\_min := 85V$

$Vin\_max := 265V$

$Vout := 390V$

$Vripple := 30V$ Peak to Peak Output Ripple

$fs := 50 \cdot 10^{3} Hz$

$Pout := 1000W$ Maximum Output Power

$\eta := 0.90$ Maximum Output Effieceny at Low Line

$fline := 47Hz$ Minimum Line Frequency

$thold\_up := \frac{1}{fline}$

$Tamb := 60$ Maximum Ambient Temperature Around Components

$Vholdup := 0.75 \cdot Vout$

$Dmax := 0.97$ Maximum Duty Cycle Clamp

$fdm := 30 \cdot 10^{3} Hz$ Dither Magnitude

$fdr := 10 \cdot 10^{3} Hz$ Dither Rate

Fixed Variables

$Vref := 3.0V$ $VINAC := 3V$ $VIMO := 3.3V$ $PKL := 3.3V$

I. Power Stage Design

1. Calculate min and maximum duty cycle

$$\frac{Vout}{Vin} = \frac{1}{1 - D}$$

Minimum duty cycle at peak inductor ripple current at low line

$$Dpll := \frac{Vout - Vin\_min \cdot \sqrt{2}}{Vout}$$

$Dpll = 0.692$ Minimum D at Low Line

At crossover the duty cycle will be 100%

2. Estimate Interleaved Boost Input Ripple Current Cancellation with Changes in Duty Cycle

Inductor ripple current cancellation is similar to the output of a synchronous buck converter.

ΔIcin is the input capacitor ripple current

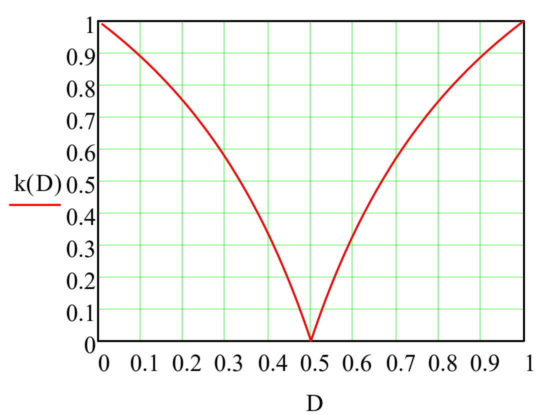
ΔIL is the inductor ripple current

$$k(D) = \frac{\Delta ICin}{\Delta IL}$$

$$D := 0.01, 0.011 .. 1$$

$$k(D) := \begin{cases} \frac{1 - 2D}{1 - D} & \text{if } D \le 0.5 \\ \frac{2 \cdot D - 1}{D} & \text{if } D > 0.5 \end{cases}$$

$$K(D) = \frac{\Delta Iin}{\Delta IL1}$$



$k(0.69) = 0.551$

a. The duty cycle of the converter will vary from 2.7% to 100%
b. At peak inductor ripple current the duty cycle will be 0.69 which will have a 55% reduction in inductor ripple current seen at the input.

$Dpll = 0.692$

3. Size the boost Inductor at the peak of line for a converter input ripple current of 30%.

$$\Delta Iin = \Delta IL \cdot K(D)$$

$$\Delta IL = \frac{\Delta Iin}{K(D)}$$

$$\Delta IL := \frac{Pout \cdot \sqrt{2} \cdot 0.3}{Vin\_min \cdot \eta \cdot k(Dpll)}$$

$$\Delta IL = 10.003\ A$$

$$Lboost := \frac{Vin\_min \cdot \sqrt{2} \cdot Dpll}{\Delta IL \cdot fs}$$

$$Lboost = L1 = L2$$

$$Lboost = 1.663 \times 10^{-4}\ H$$

Choose a 140 uH inductor from Cooper Electronic Technologies

$Lboost\_min := 166.3 \cdot 10^{-6} H$ Enter minimum inductance

$Lboost\_max := 166.3 \cdot 10^{-6} H$ Enter Maximum inductance

$$Lboost\_avg := \frac{Lboost\_max + Lboost\_min}{2}$$

$Lboost\_avg = 1.663 \times 10^{-4} H$ Average inductance value to be used for current loop compensation

4. Calculate Total Inductor RMS Current

$$IL1\_RMS := \sqrt{\left(\frac{Pout}{2Vin\_min \cdot \eta}\right)^2 + \frac{1}{\pi} \cdot \int_0^{\pi} \left(\frac{\frac{Vin\_min \cdot \sqrt{2}\,\sin(\theta)}{Lboost \cdot fs} \cdot \frac{Vout - Vin\_min \cdot \sqrt{2}\,\sin(\theta)}{Vout}}{\sqrt{12}}\right)^2 d\theta}$$

$$IL1\_RMS = 6.891\ A$$

5. Size the boost capacitor

a. First Criteria is how much holdup capacitance you need

$$Vholdup = 292.5\ V$$

$$Pout \cdot thold\_up = \frac{Cout \cdot Vout^2}{2} - \frac{Cout \cdot Vholdup^2}{2}$$

$$Cout := 2 \cdot Pout \cdot \frac{thold\_up}{Vout^2 - Vholdup^2}$$

$$Cout = 6.395 \times 10^{-4} F$$

$Cout := 3 \cdot 330 \cdot 10^{-6} F = 9.9 \times 10^{-4} F$ Choose a standar value

$$Vripple := \frac{2Pout}{Vout \cdot \eta} \cdot \frac{1}{2 \cdot \pi \cdot 2 \cdot fline \cdot Cout}$$

$$Vripple = 9.745 \cdot V$$

b. Estimate Boost Capacitor RMS Current

$$ICOUT\_LF := \frac{Pout}{Vout \cdot \eta \cdot \sqrt{2}}$$

Total low frequency RMS current.

$$ICOUT\_LF = 2.015\ A$$

Calculate the high frequency component

$$ICOUT\_HF := \sqrt{\left(\frac{Pout}{\eta \cdot Vout} \cdot \sqrt{\frac{16 \cdot Vout}{6 \cdot \pi \cdot Vin\_min \cdot \sqrt{2}} - \eta^2}\right)^2 - ICOUT\_LF^2}$$

$$ICOUT\_HF = 3.423\ A$$

Total low frequency RMS current.

6. Calculate Peak FET and Boost Dioded Current

$$Ipeak := \left(\frac{\frac{Pout \cdot \sqrt{2}}{Vin\_min \cdot \eta}}{2} + \frac{1}{2} \cdot \frac{Vin\_min \cdot \sqrt{2} \cdot Dpll}{Lboost \cdot fs}\right) \cdot 1.2$$

Peak Fet and Diode Current

$$Ipeak = 17.094\ A$$

7. Calculate Boost Switch RMS Current

$$Ids := \frac{\frac{Pout}{\eta}}{2Vin\_min \cdot \sqrt{2}} \cdot \sqrt{2 - \frac{16 \cdot Vin\_min \cdot \sqrt{2}}{3 \cdot \pi \cdot Vout}}$$

$$Ids = 5.616\ A$$

8. Calculate Avarage Boost Diode Current

$$Id := \frac{Pout}{2Vout}$$

$$Id = 1.282\ A$$

$$Vf := 1.25V$$

9. Current Sense Resistor and Transformer Set up

Calcuate turns ratio based on peak FET current and peak current sense current

$$\text{Nct} = \frac{\text{Ns}}{\text{Np}} = \frac{\text{Vs}}{\text{Vp}} = \frac{\text{Ipeak}}{\text{Irs}}$$

$\text{Irs} := 0.1\text{A}$

$$\text{Nct} := \frac{\text{Ipeak}}{\text{Irs}} \qquad \text{Ipeak} = 17.094\ \text{A}$$

$\text{Nct} = 170.935$

$\text{Nct} := 200$ Select 200 turns for the transformer(PCS040)

$$a = \frac{1}{\frac{\text{Np}}{\text{Ns}}}$$

$$a := \frac{1}{200} = 5 \times 10^{-3} \qquad \text{Nct} = \frac{\text{Ns}}{\text{Np}} = \frac{\text{Vp}}{\text{Vs}} = \frac{\text{Ipeak}}{\text{Irs}}$$

Calculate Minimum Magnatizing Inductance

$\text{Vs} := 3.7\text{V}$

$$\text{Lmag} := \frac{\text{Vs}\cdot\text{Dpll}}{\frac{\text{Ipeak}}{\text{Nct}}\cdot 0.02\cdot \text{fs}}$$

$\text{Lmag} = 0.03\ \text{H}$

Calculate Current Sense Resistor

$$\text{Rs} := \frac{\text{Vs}\cdot 0.9}{\frac{\text{Ipeak}}{\text{Nct}}}$$

$\text{Rs} = 38.962\ \Omega$

$\text{Rs} := 39\text{ohm}$ Select Standard Value

Select Reset Resistor

$$Rr := \frac{Rs \cdot Dmax}{1 - Dmax}$$

$$Rr = 1.261 \times 10^{3}\ \Omega$$

$Rr := 1300ohm$ Select Standard Value

Calculate Maximum Voltage Across Rr

$$Vdmax := \frac{Ipeak}{Nct} \cdot Rr$$

$$Vdmax = 111.108\ V$$

$$Rpk1 := 3.6 \cdot 10^{3} ohm$$

$$Ipeak = 17.094\ A$$

$$Rpk2 := \frac{Vs \cdot Rpk1}{6V - Vs}$$

$$Rpk2 = 5.791 \times 10^{3}\ \Omega$$

$Rpk2 := 5.9 \cdot 10^{3} ohm$ Select Standard Value

10. Set up PWM Ramp to be added to current sense signal.

$$VCC := 13V$$

$Voff := 0.200V$ Discontinues current sense signal offsetmdurring discontinues opperation when the gate drive turns on.

$$Roa := \frac{Rs \cdot (VCC - Voff)}{Voff}$$

$$Roa = 2.496 \times 10^{3}\ \Omega$$

$Roa := 2.40 \cdot 10^{3} ohm$ Select Standard Value

$$\frac{VCC - (Vs \cdot 0.1 - Voff)}{RTA} = \frac{Vs \cdot 0.1 - Voff}{Rs}$$

$$Rta := \frac{[VCC - (Vs \cdot 0.1 - Voff) + 0.6V] \cdot Rs}{Vs \cdot 0.1 - Voff}$$

$$Rta = 3.081 \times 10^{3}\,\Omega$$

$$Rta := 3.0 \cdot 10^{3}\,ohm$$ Select Standard Value

$$Cta := \frac{\frac{1}{fs \cdot 3}}{Rs}$$

$$Cta = 1.709 \times 10^{-7}\,F$$

$$Cta := 220 \cdot 10^{-9}\,F$$ Select Standard Value

11. Set up Peak Current Limit

$$Rpk1 := 3.6 \cdot 10^{3}\,ohm$$

$$Rpk2 := \frac{Vs \cdot Rpk1}{6V - Vs}$$

$$Rpk2 = 5.791 \times 10^{3}\,\Omega$$

Select Standard Resistor

$$Rpk2 := 5.9 \cdot 10^{3}\,ohm$$

12. Set up Controller Timing

Setup Oscillator Timing

$$Rrt := \frac{7.5 \times 10^{9}\,ohm \cdot Hz}{fs}$$

$$Rrt = 1.5 \times 10^{5}\,\Omega$$

$$Rrt := 150 \cdot 10^{3}\,ohm$$ Select Standard Value

Check Switching Frequency

$$fs := \frac{7.5 \times 10^{9} ohm \cdot Hz}{Rrt}$$

$$fs = 5 \times 10^{4} \frac{1}{s}$$

Setup Duty Cycle Clamp

$$Dmax := 0.97$$

$$Rdmx := Rrt \cdot (2 \cdot Dmax - 1)$$

$$Rdmx = 1.41 \times 10^{5} \Omega$$

Select Standard Resistor

$$Rdmx := 140 \cdot 10^{3} ohm$$

13. Voltage Loop Compensation

$Vripple = 9.745\ V$ $\quad$ $Vref = 3\ V$ $\quad$ $gm := 70 \cdot 10^{-6} \frac{A}{V}$ $\quad$ $\Delta Vea := 3.2V$

$$f := 1Hz, 2Hz .. 1 \cdot 10^{3} Hz$$

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

$$RA := 3 \cdot 10^{6} ohm$$

$$RB := \frac{Vref \cdot RA}{Vout - Vref}$$

$$RB = 2.326 \times 10^{4} \Omega$$

$$RB := 24 \cdot 10^{3} ohm$$

Calculate OVP Trip Point

$$Vovp := 3.18V \cdot \frac{RA + RB}{RB}$$

$Vovp = 400.68\,V$

$\Delta Vea \cdot 0.03 = \frac{Vripple \cdot RB}{RA + RB} \cdot gm \cdot Zf$

$Zo := \Delta Vea \cdot 0.03 \frac{1}{Vripple \cdot 0.0077 \cdot gm}$

$Zo = 1.828 \times 10^{4}\,\Omega$

$Cpv := \frac{1}{2 \cdot \pi \cdot 2fline \cdot Zo}$

$Cpv = 9.264 \times 10^{-8}\,F$

$Cpv := 100 \cdot 10^{-9}\,F$

$T(f) = 1 = \frac{R2}{R1 + R2} \cdot gm \cdot \left(\frac{\frac{Pout}{\eta}}{\Delta Vea} \cdot \frac{\frac{1}{f \cdot Cout}}{Vout} \right) \cdot \frac{1}{2 \cdot \pi\, f \cdot Cpv}$

$fc := \sqrt{\frac{RB}{RA + RB} \cdot gm \cdot \left(\frac{\frac{Pout}{\eta}}{\Delta Vea} \cdot \frac{\frac{1}{2 \cdot \pi\, Cout}}{Vout} \right) \cdot \frac{1}{2 \cdot \pi \cdot Cpv}}$

$fc = 11.25 \cdot Hz$ $\Delta Vea = 3.2\,V$

$Rzv := \frac{1}{2 \cdot \pi \cdot fc \cdot Cpv}$

$Rzv = 1.415 \times 10^{5}\,\Omega$

Select a standard resistor

$Rzv := 150 \cdot 10^{3}\,ohm$

$Rzv = 1.5 \times 10^{5}\,\Omega$

$$Czv := \frac{1}{2\cdot\pi\cdot\frac{fc}{10}\cdot Rzv}$$

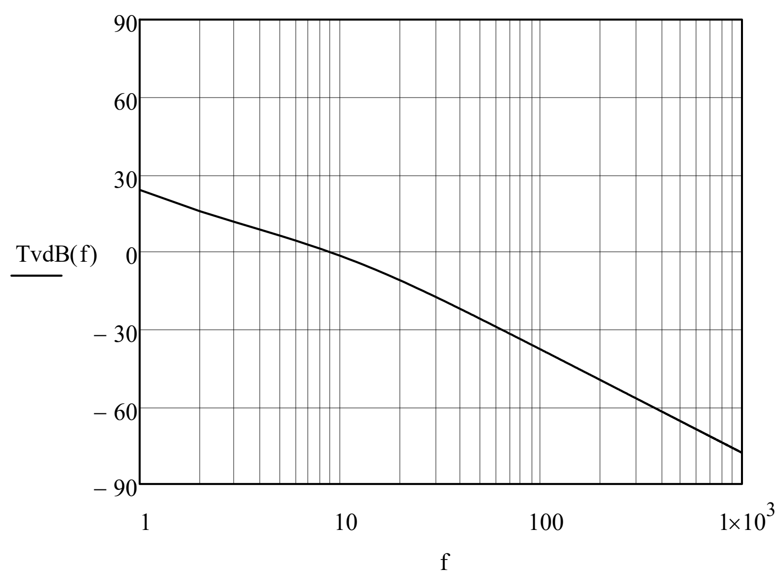
$$Czv = 9.432\times10^{-7}F$$

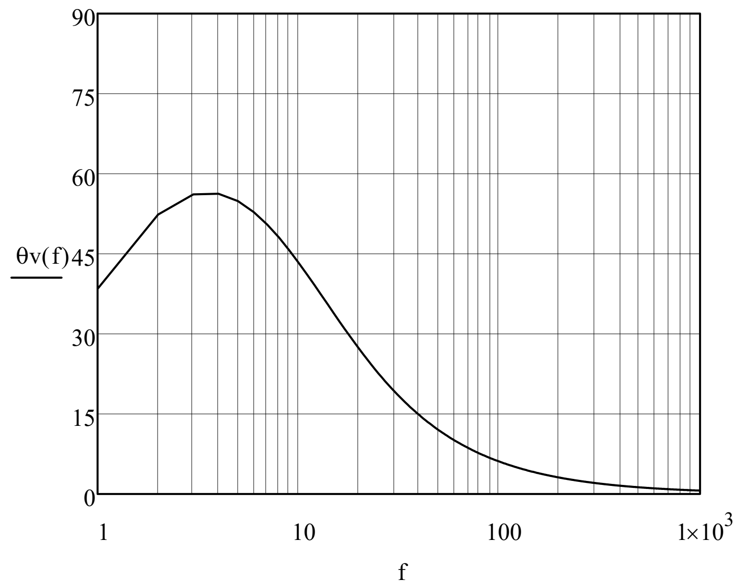
$$Czv := 1\cdot10^{-6}F$$

$$T(f) := \frac{RB}{RA+RB}\cdot gm\cdot\left(\frac{\frac{Pout}{\eta}}{\Delta Vea}\cdot\frac{\frac{1}{s(f)\cdot Cout}}{Vout}\right)\cdot\frac{s(f)\cdot Rzv\cdot Czv+1}{s(f)\cdot(Czv+Cpv)\cdot\left(\frac{s(f)\cdot Rzv\cdot Czv\cdot Cpv}{Czv+Cpv}+1\right)}$$

$$\theta v(f) := \arg(T(f))\cdot\frac{180}{\pi}+180$$

$$TvdB(f) := 20\cdot\log(|T(f)|)$$





$\theta v(9Hz) = 45.64$ $TvdB(9Hz) = -0.348$

14. Setup Current Loop

$Lboost\_max = 1.663 \times 10^{-4} H$

$$Rsyn := \frac{Lboost\_max \cdot \frac{RB}{RA + RB}}{a \cdot Rs \cdot 0.1 \cdot 10^{-9} F}$$

$Rsyn = 6.768 \times 10^{4} \Omega$

Select Standard Value

$Rsyn := 68\,10^{3} ohm$

$KVFF := 0.398V^{2}$ $VAO\_MAX := 5V$

$$Imo := \frac{0.76V \cdot 17 \cdot 10^{-6} A \cdot (VAO\_MAX - 1V)}{KVFF}$$

$Imo = 1.298 \times 10^{-4} A$

$$V1 := 0.76V \cdot \frac{RA + RB}{RB \cdot \sqrt{2}}$$

$V1 = 67.713\ V$

$$Vs := \frac{1.1Pout}{2 \cdot \eta \cdot V1} \cdot \sqrt{2} \cdot a \cdot Rs$$

$Vs = 2.489 \cdot V$

$$Rimo := \frac{Vs}{Imo}$$

$Rimo = 1.917 \times 10^{4} \Omega$

$Rimo := 20 \cdot 10^{3} ohm$

Compensate Current Amplifier Compensation

$$gm := 100 \cdot 10^{-6} \frac{A}{V}$$

Gain of the PFC Power Stage is:

$Vramp := 4.0V$

$$Gps(s) = \frac{Vout \cdot \frac{Rs}{Nct}}{s \cdot Lboost \cdot Vramp}$$

Solving for the power stage gain at the desired crossover frequency at 10th of the switching frequency.

$$fc := \frac{fs}{10} \qquad f := 1Hz, 10Hz .. 1 \cdot 10^{6} Hz$$

$fc = 5 \times 10^{3} \cdot Hz \qquad s(f) := 2j \cdot \pi \cdot f$

$Lboost\_avg = 1.663 \times 10^{-4} H$

$$Gps := \frac{Vout \cdot \frac{Rs}{Nct}}{2 \cdot \pi \cdot fc \cdot Lboost\_avg \cdot Vramp}$$

$Gps = 3.639$

In order to have a gain of 1 at the crossover frequency the current amp must have a gain of 1/Gps at the crossover frequency.

$$Rzc := \frac{1}{gm \cdot Gps}$$

$Rzc = 2.748 \times 10^{3} \Omega$

$$Czc := \frac{1}{2 \cdot \pi \cdot fc \cdot Rzc}$$

$Czc = 1.158 \times 10^{-8} F$

$$Cpc := \frac{1}{2\pi \cdot \frac{fs}{2} \cdot Rzc}$$

$Cpc = 2.317 \times 10^{-9} F$

Select Standard Values

$Rzc := 2.7 \cdot 10^{3} ohm$

$Czc := 12 \cdot 10^{-9} F$

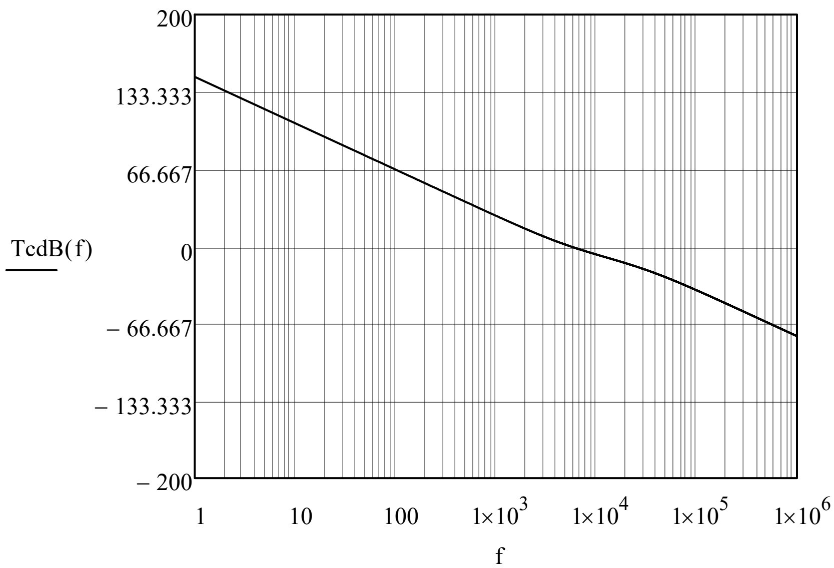
$Cpc := 2.2 \cdot 10^{-9} F$

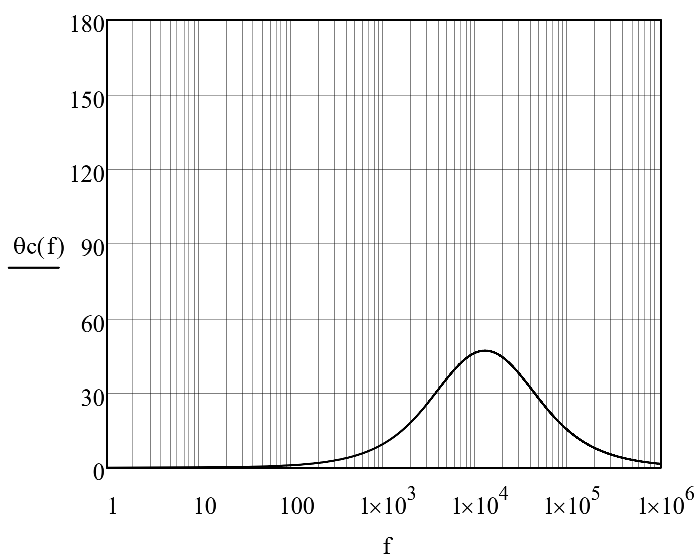
Plot Loop Gain

$$T(f) := \frac{Vout \cdot Rs \cdot a}{s(f) \cdot Lboost\_avg \cdot Vramp} \cdot \left[gm \cdot \frac{s(f) \cdot Rzc \cdot Czc + 1}{s(f) \cdot (Czc + Cpc) \cdot \left(\frac{s(f) \cdot Rzc \cdot Czc \cdot Cpc}{Czc + Cpc} + 1 \right)} \right]$$

$$\theta c(f) := \arg(T(f)) \cdot \frac{180}{\pi} + 180$$

$$TcdB(f) := 20 \cdot \log(|T(f)|)$$





$$TcdB\left(20\cdot 10^{3}Hz\right) = -14.857 \quad \theta c\left(20\cdot 10^{3}Hz\right) = 43.957$$

15. Soft Start

$$Css := \frac{10\cdot 10^{-6}\cdot 0.2}{2.25}$$

$$Css = 8.889 \times 10^{-7}$$

Capacitor needs to be greater than or equal to Czv

$$Czv = 1 \times 10^{-6}F$$

$$Css := 1\cdot 10^{-6}F$$

16. Dither Programming

$$Rrdm := 937.5\cdot 10^{6}\frac{ohm}{fdm} \qquad fdm = 3 \times 10^{4}\cdot Hz$$

$$Rrdm = 3.125 \times 10^{4}H$$

$Rrdm := 47\cdot 10^{3}ohm$ Select Standard Value

$$Ccdr := 0.0667\cdot 10^{-9}F\cdot\frac{Hz}{ohm}\cdot\frac{Rrdm}{fdr}$$

$$Ccdr = 3.135 \times 10^{-10}F$$

$Ccdr := 330\cdot 10^{-12}F$ Select Standard Value