Variable Definition

$Vin\_min := 85V$

$Vin\_max := 265V$

$Vout := 400V$

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

$fs := 92 \cdot 10^3 Hz$

$Pout := 5000W$ Maximum Output Power

$\eta := 0.92$ Maximum Output Effieceny at Low Line

$fline := 47Hz$ Minimum Line Frequency

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

$Tamb := 60$ Maximum Ambient Temperature Around Components

$Vholdup := 0.75 \cdot Vout$

$Dmax := 0.94$ Maximum Duty Cycle Clamp

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

$fdr := 6 \cdot 10^3 Hz$ 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

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

$Dpll = 0.699$ 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

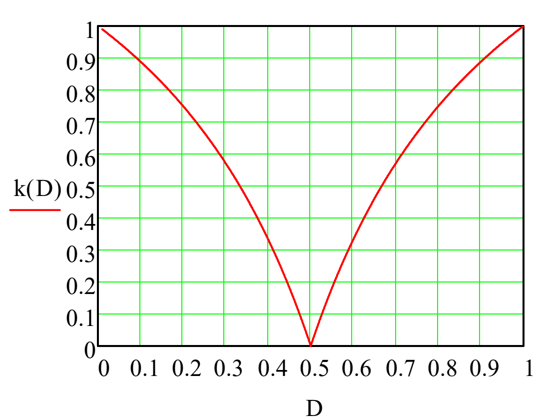
ΔIL is the inductor ripple current

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

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

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

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



$k(0.69) = 0.551$

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.

$Dpll = 0.699$

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

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

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

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

$$\Delta IL = 47.56\,A$$

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

$$Lboost = L1 = L2$$

$$Lboost = 1.922 \times 10^{-5}\,H$$

Choose a 140 uH inductor from Cooper Electronic Technologies

$Lboost\_min := 50 \cdot 10^{-6}\,H$ Enter minimum inductance

$Lboost\_max := 76 \cdot 10^{-6}\,H$ Enter Maximum inductance

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

$Lboost\_avg = 6.3 \times 10^{-5}\,H$ Average inductance value to be used for current loop compensation

4. Calculate Total Inductor RMS Current

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

$$IL1\_RMS = 32.216\,A$$

5. Size the boost capacitor

a. First Criteria is how much holdup capacitance you need

$$Vholdup = 300\,V$$

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

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

$$Cout = 3.04\times 10^{-3}\,F$$

$Cout := 3\cdot 10^{-3}F$ Choose a standar value

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

$$Vripple = 15.336\cdot V$$

b. Estimate Boost Capacitor RMS Current

$$ICOUT\_LF := \frac{Pout}{Vout \cdot \eta \cdot \sqrt{2}}$$ Total low frequency RMS current.

$$ICOUT\_LF = 9.607\,A$$

Calculate the high frequency component

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

$$ICOUT\_HF = 16.519\,A$$ Total low frequency RMS current.

6. Calculate Peak FET and Boost Dioded Current

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

$$Ipeak = 65.221\,A$$

7. Calculate Boost Switch RMS Current

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

$$Ids = 27.592\,A$$

8. Calculate Avarage Boost Diode Current

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

$$Id = 6.25\,A$$

$$Vf := 1.25V$$

9. Current Sense Resistor and Transformer Set up

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

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

$$\text{Irs} := 0.2\text{A}$$

$$\text{Nct} := \frac{\text{Ipeak}}{\text{Irs}} \qquad \text{Ipeak} = 65.221\ \text{A}$$

$$\text{Nct} = 326.105$$

$\text{Nct} := 300$ Select 50 turns for the transformer

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

$$a := \frac{1}{300} \qquad \text{Nct} = \frac{\text{Ns}}{\text{Np}} = \frac{\text{Vp}}{\text{Vs}} = \frac{\text{Ipeak}}{\text{Irs}}$$

Calculate Minimum Magnatizing Inductance

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

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

$$\text{Lmag} = 6.47 \times 10^{-3}\ \text{H}$$

Calculate Current Sense Resistor

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

$$\text{Rs} = 15.317\,\Omega$$

$\text{Rs} := 16\text{ohm}$ Select Standard Value

Select Reset Resistor

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

$$Rr = 250.667\ \Omega$$

$Rr := 1000ohm$ Select Standard Value

Calculate Maximum Voltage Across Rr

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

$$Vdmax = 217.404\ V$$

$$Rpk1 := 3.65 \cdot 10^{3} ohm$$

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

$$Ipeak = 65.221\ A$$

$$Rpk2 = 5.872 \times 10^{3}\ \Omega$$

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

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

$$Roa = 1.024 \times 10^{3}\ \Omega$$

$Roa := 2.00 \cdot 10^{3} ohm$ Select Standard Value

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

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

$$Rta = 1.264 \times 10^{3}\,\Omega$$

$Rta := 2.49 \cdot 10^{3}\,ohm$ Select Standard Value

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

$$Cta = 2.264 \times 10^{-7}\,F$$

$Cta := 47 \cdot 10^{-9}\,F$ Select Standard Value

11. Set up Peak Current Limit

$$Rpk1 := 3.65 \cdot 10^{3}\,ohm$$

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

$$Rpk2 = 5.872 \times 10^{3}\,\Omega$$

Select Standard Resistor

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

12. Set up Controller Timing

Setup Oscillator Timing

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

$$Rrt = 8.152 \times 10^{4}\,\Omega$$

$Rrt := 82 \cdot 10^{3}\,ohm$ Select Standard Value

Check Switching Frequency

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

$$fs = 9.146 \times 10^{4}\,\frac{1}{s}$$

Setup Duty Cycle Clamp

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

$$Rdmx = 7.216 \times 10^{4}\,\Omega$$

Select Standard Resistor

$$Rdmx := 72\cdot 10^{3}\,\text{ohm}$$

13. Voltage Loop Compensation

$Vripple = 15.336\,V$ $Vref = 3\,V$ $gm := 70\cdot 10^{-6}\,\frac{A}{V}$ $\Delta Vea := 3.2V$

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

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

$$RA := 960\cdot 10^{3}\,\text{ohm}$$

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

$$RB = 7.254 \times 10^{3}\,\Omega$$

$$RB := 7.3\cdot 10^{3}\,\text{ohm}$$

Calculate OVP Trip Point

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

$Vovp = 421.372\,V$

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

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

$Zo = 1.161 \times 10^{4}\,\Omega$

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

$Cpv = 1.458 \times 10^{-7}\,F$

$Cpv := 145 \cdot 10^{-9}\,F$

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

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

$fc = 11.429 \cdot Hz$ $\quad\quad$ $\Delta Vea = 3.2\,V$

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

$Rzv = 9.604 \times 10^{4}\,\Omega$

Select a standard resistor

$Rzv := 96 \cdot 10^{3}\,ohm$

$Rzv = 9.6 \times 10^{4}\,\Omega$

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

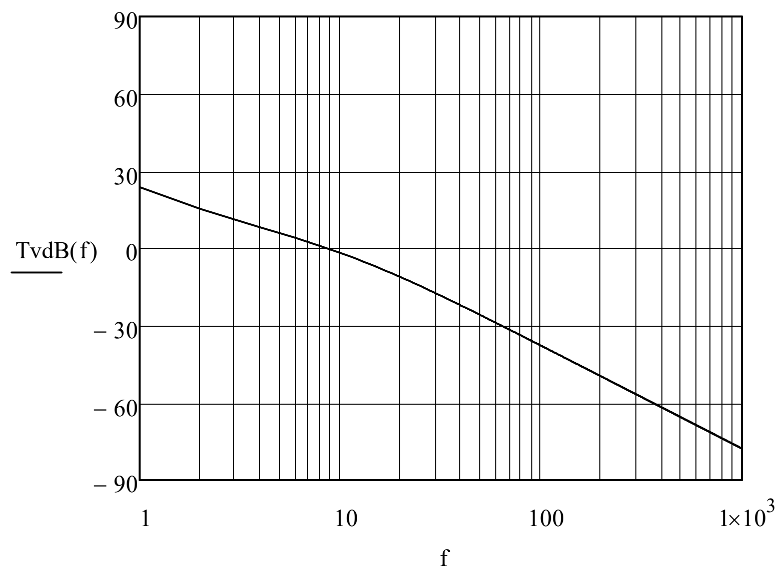
$$Czv = 1.451 \times 10^{-6} F$$

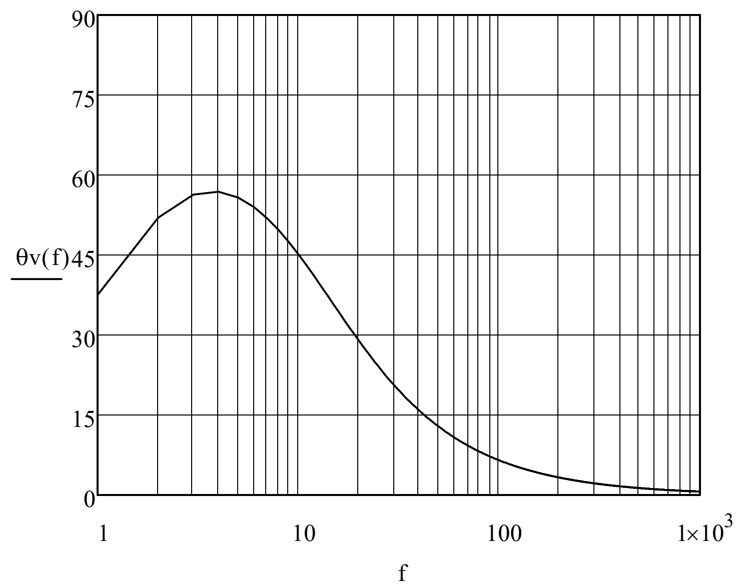
$$Czv := 1.5\cdot 10^{-6} F$$

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

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

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





$\theta v(9Hz) = 47.329$ $\qquad$ $TvdB(9Hz) = -0.47$

14. Setup Current Loop

$Lboost\_max = 7.6 \times 10^{-5} H$

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

$Rsyn = 1.075 \times 10^{5} \Omega$

Select Standard Value

$Rsyn := 100\ 10^{3} ohm$

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

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

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

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

$V1 = 71.209 V$

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

$Vs = 3.166 \cdot V$

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

$Rimo = 2.438 \times 10^{4} \Omega$

$Rimo := 25 \cdot 10^{3} ohm$

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.

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

$fc = 9.146 \times 10^{3} \cdot Hz$ $\qquad s(f) := 2j \cdot \pi \cdot f$

$Lboost\_avg = 6.3 \times 10^{-5}\,H$

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

$Gps = 1.473$

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.

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

$Rzc = 6.788 \times 10^{3}\,\Omega$

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

$Czc = 2.563 \times 10^{-9}\,F$

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

$Cpc = 5.127 \times 10^{-10}\,F$

Select Standard Values

$Rzc := 6.8 \cdot 10^{3}\,ohm$

$Czc := 2.5 \cdot 10^{-9}\,F$

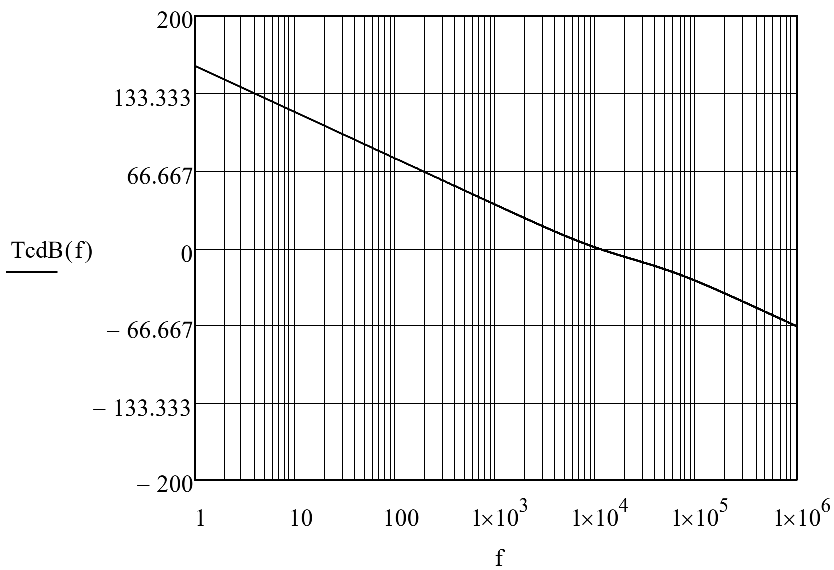
$Cpc := 512 \cdot 10^{-12}\,F$

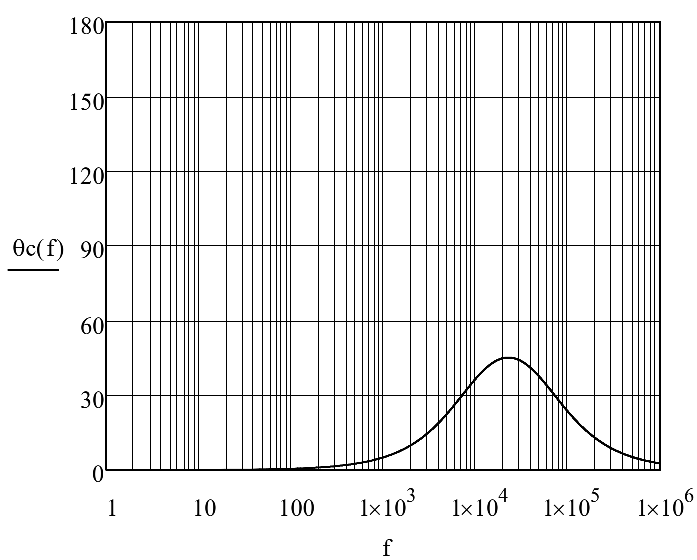
Plot Loop Gain

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

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

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





$TcdB\left(10\cdot10^{3}Hz\right) = 0.214 \qquad \theta c\left(10\cdot10^{3}Hz\right) = 36.596$

15. Soft Start

$$Css := \frac{10\cdot10^{-6}\cdot0.2}{2.25}$$

$$Css = 8.889\times10^{-7}$$

Capacitor needs to be greater than or equal to Czv

$$Czv = 1.5\times10^{-6}F$$

$$Css := 1.5\cdot10^{-6}F$$

16. Dither Programming

$$Rrdm := 937.5\cdot10^{6}\frac{ohm}{fdm} \qquad fdm = 1\times10^{4}\cdot Hz$$

$$Rrdm = 9.375\times10^{4}H$$

$Rrdm := 100\cdot10^{3}ohm$ Select Standard Value

$$Ccdr := 0.0667\cdot10^{-9}F\cdot\frac{Hz}{ohm}\cdot\frac{Rrdm}{fdr}$$

$$Ccdr = 1.112\times10^{-9}F$$

$Ccdr := 2.2\cdot10^{-9}F$ Select Standard Value