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Design Procedure for Conducted EMI Filter by Using Butterworth Function for SMPS

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Abstract: *A conventional design Butterworth filter is used in this paper for power line using high power passive components. A low order low pass double π -filter is taken into account of different cut-off for differential as well as common mode. This paper study the effects of poles and zeros .It accurately predicts the changes are being made in the design . As an EMI filter the overall circuit resonates at particular frequency. The parasitic effects are also taken into account .The overall filter prototype is tested as per standard procedure CISPR-16-2.*

***Keywords**: Conducted Emission, Emi Filter, Butterworth Filter, Passive Lumped Elements, Parasitic Components*

I. Introduction

Conducted emission regulations are intended to control the radiation from the public alternating current (ac) power supply system, which results from noise currents conducted back onto the power line. The noise which travels from phase to neutral is differential mode noise .The noise also travels from phase to ground as well as neutral to ground which is known as common mode noise .SMPS provides power at high frequency using high speed switching technique . Since the impedance of a power supply is not constant we use LISN (Line Impedance Stabilizing Network) to provide a constant 50Ω impedance. The noise from ground in LISN causes conducted emission which transfer to SMPS. The paper uses standard procedure as per CISPR-16-2 for the measurement in noise level of the overall filter .The filter provides an overall insertion loss of 64dB in the prototype. Also this paper considers the non-linear behaviour of the passive components.

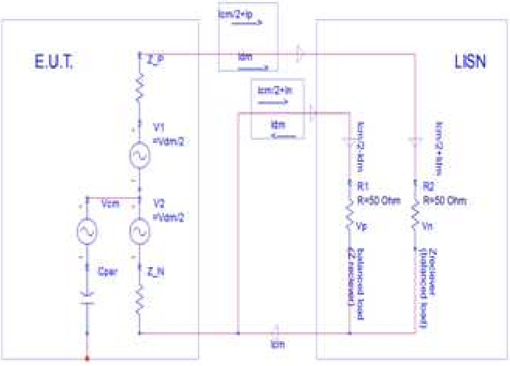
II. Characterization Of Filter And Measurement

The overall DM and CM characterization can be done on the basis of current flow through overall circuit In order to separate DM an CM filter it should should satisfy 3 requirements [1]
1.input impedance always real 50 Ω and are independent from noise source impedance
2. Output is$|(V_1-V_2)/2|$ for DM noise measurement and $|(V_1+V_2)/2|$for CM noise measurement
3.Leakage between CM and DM at output should be small

$$|V_{DM}|=|\frac{Vp-V_n}{2}|=50|i_{DM}| \quad = 2.5\Omega\frac{i_p-i_n}{2}\ 100\Omega i_{dm} \tag{1}$$

$$|V_{CM}|=|\frac{Vp+Vn}{2}|= 50|i_{CM}| =25\Omega i_{cm} \tag{2}$$

Impedance of the input port is not constant so we use LISN which gives the output of a constant 50 Ω impedance .When the current moves from phase to neutral the voltage is out of phase. When the current moves from phase to ground as well as neutral to ground the voltage is half since the impedance gets doubled. The EUT is supplied by power source through an artificial mains network (AMN). For measurement we use the arrangement in fig:2[3].For measuring DM filter the overall filter (fig:9) input port is connected between input of phase –neutral and output port is connected between phase-neutral spectrum analyzer .CM measurement is taken by shorting DM phase and neutral and one port of is 50 Ω terminated and other phase is measured with spectrum analyzer.



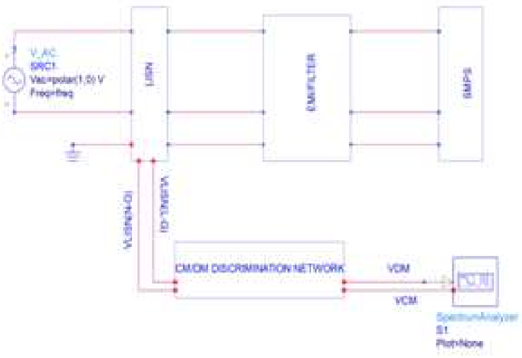


Fig:1 current flow from testing equipment to LISN Fig:2arrangement of measurement of Conducted EMI filter

III. Butterworth Function

3.1.Design Pattern

For a filter to satisfy it must satisfy the Pale. A Butterworth filter satisfies this criterion because it is a rational function. Since the zeros are considered generally at infinity the magnitude function takes the general form

$$M(w) = K_0/ [1+f(w^2)] \quad (3)$$

Where K_0 is the dc gain constant and f (w^2) is monotonically decreasing. The 3-db point down of the amplitude vs. Frequency curve gives the point of half- power point .This is the frequency which is known as cut-off frequency. Rather than having a sharp role-over its better to provide a descending roll of using low-order filter. The order of filter is described by

$$N = \frac{\log\left(\frac{10^{-0.1*\alpha\mathrm{stop}}-1}{10^{-0.1*\alpha\mathrm{pass}}-1}\right)}{2*\log\left(\frac{\mathrm{fstop}}{\mathrm{fpass}}\right)} \quad (4)$$

Stop band attenuation is given by

$$\alpha_{\mathrm{stop(dB)}} = 10\log\left(1 + \left(\frac{f_{\mathrm{stop}}}{f_c}\right)^{2N}\right) \quad (5)$$

For any Butterworth function magnitude of amplitude response is equal to the magnitude function of complex system function.

$$M^2(w) = h(-w)^2 \quad (6)$$

As our designing from a rational function it its roots can be divided into even and the odd part where Even part is $f(-x) = f(x)$ so its polynomial is given by $f(x) = \sum_{i=0}^{m} a_{2i}x^{2i}$ and odd part $f(-x) = -f(-x)$ given by $f(x) = \sum_{i=0}^{m} a_{2i+1}x^{2i+1}$. After getting the polynomials the synthesis of ladder filter is given by open circuit and short circuit parameters[2]

$$Z_{21} = \frac{z_{21}}{1+z_{22}} \text{ and } Y_{21} = \frac{y_{21}}{1+y_{22}} \quad (7)$$

A Hurwitz polynomial is one that has all of its poles in the left hand plane in 2nd quadrant of the *s* plane. That is, poles can occur in positions for which $\sigma = 0 \text{ or } \sigma < 0$. A strictly Hurwitz polynomial is one for which all of the poles are in the left hand plane, those with$\sigma < 0$. The transfer function :

$$T(s) = \frac{N_e(s)+N_o(s)}{D_e(s)+D_o(s)} \quad (8)$$

Where, N(s) is even function and D(s) is strictly Hurwitz polynomial separating the polynomial into odd and even parts $T(s) = \frac{N_e(s)}{D_e(s)+D_o(s)}$ since for being strictly Hurwitz polynomial the order of numerator should be less than that of denominator so that the poles roots cannot reach the right hand side of jw axis.

3.2. Analysis And Synthesis

From the above transfer function we can get the Butterworth response. For Butterworth response we get the poles of H(-s)H(s) which are the roots of equations

$$(-1)^n s^{2n} = -1 = e^{j[2k-1]\pi} \quad k = 0,1,2 \ldots 2n-1\,, \quad (9)$$

we have poles given by

$$s_K = e^{j\left[2k-\frac{1}{2n}\right]\pi} \text{ which is given for } n = \text{ even and } s_k = e^{j(k/n)\pi} \text{ when } n \text{ is odd} \quad (10)$$

The s_k is a sum of real (σ_k) and imaginary parts w_k are:

$$s_k = \sigma_k + j\, w_k = \sin\left(\frac{2K-1}{n}\right)\frac{\pi}{2} + \cos\left(\frac{2K-1}{n}\right) \qquad (11)$$

The overall transfer function is synthesized given by h(s) =1/s+s^K .The value of the elements are obtained by using Caur form II realization.

3.3.Simulated Filter Design

A differential mode Butterworth filter is connected between phase and neutral. From the above method the Butterworth filter if defined for cut off frequency F_c of 17 KHz and infinite attenuation pole at F_∞ = 1Mhz.Schematic of DM filter is as follows

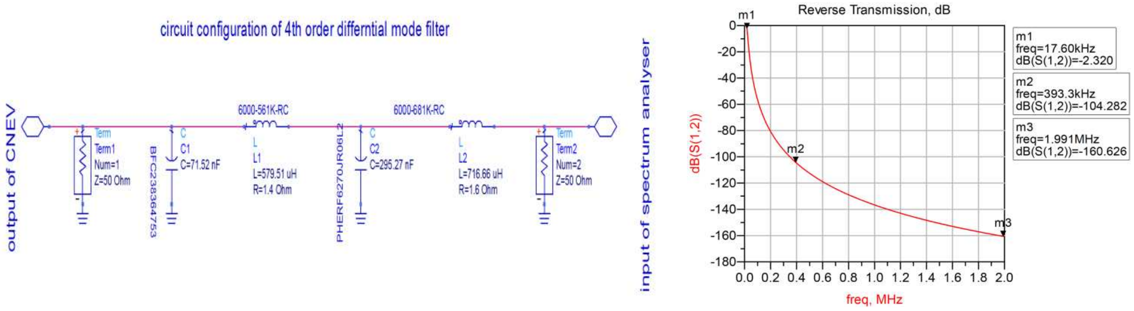


Fig:3circuit configuration of differential mode filter with simulation results

The CM filter has a cut off frequency of F_c=330 KHz and an attenuation of F_∞ = 10MHz.The schematic of CM filter is

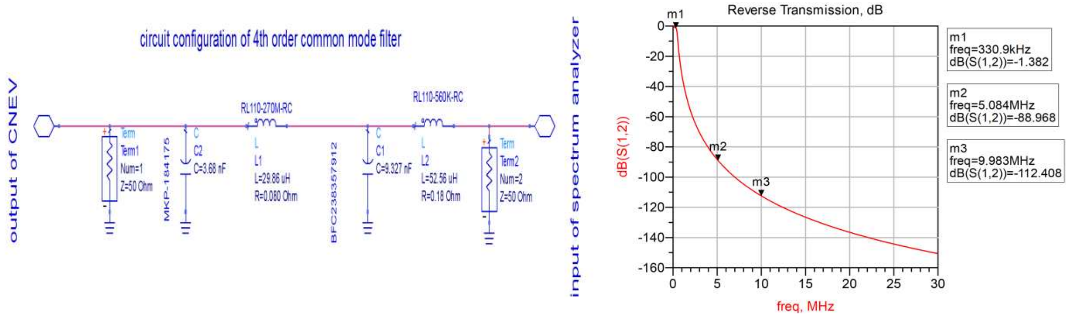


Fig: 4circuit configuration of common mode filter with simulation results

IV. Parasitic Effects Of Passive Elements

Passive components behaves non-linearly at HF .Capacitors have leads which behaves as parallel lines .At DC circuit capacitors appears to be open circuit and inductors as short circuit .As the frequency increases impedance of capacitor increases at 20dB/decade but after a certain frequency its impedance starts decreasing The frequency at which this occurs is known as self resonating frequency F_{SRF} =$1/2\pi\sqrt{L_{par} * C}$. This happens because inductive effect of the leads become dominant. The equivalent impedance of the capacitor at HF is given by

$$Z_C = R_{par} + jwL_{par} + \frac{1}{jwC} \qquad (12)$$

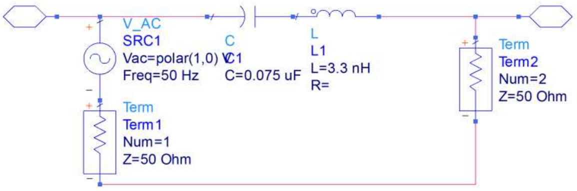


Fig:5 measuring capacitor parasitics

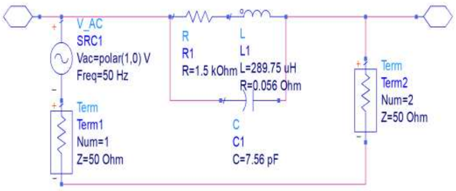


Fig 6: measuring inductor parascitics

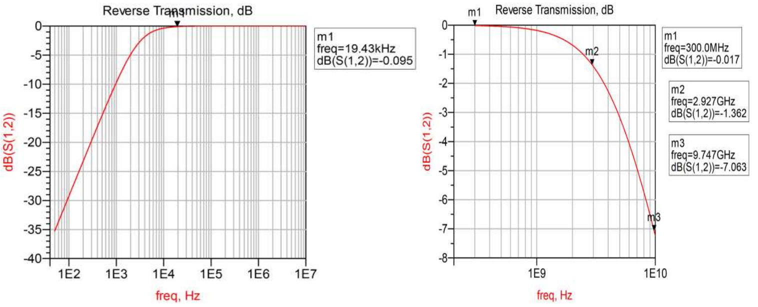


Fig:7 capacitor parasitic results

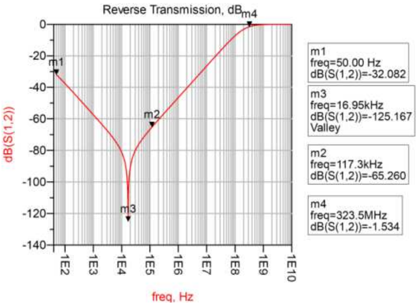


fig:8 inductor parasitic results

Inductor have resistance of the wire. Each turn produces resistance which gets added .So when then the inductor is modelled this resistance is connected in series R_{par} The dielectric between each coil and air together acts as parallel-plates.This produces parasitic capacitance C_{par} .Similarly the frequency at which the capacitive effect becomes dominant is known as F_{SRF} =1/2π$\sqrt{L * C_{par}}$ .The impedance of inductor at HF is equal to

$$Z_L = \frac{R_{par}+jwL}{1-w^2\, jwLC+jwR_{par}C} \qquad (13)$$

The parasitic values are being referred from the datasheet by simulating them to approximate condition required in ads schematic design A simulation for practical inductor 289.5uHis shown in fig: 6 and of practical 0.075uH capacitor is shown in fig:5

V. Equivalent Balanced Filter Simulation Results

The overall circuit will be a combination of DM and CM filter. When current travels from phase to neutral it gets divided into $I_{phase}/2$ and $I_{neutral}/2$ .Since the current travelling from phase with respect to ground is not same as that from neutral to ground so the overall circuit becomes unbalanced .whereas the capacitor in shunt is open circuited at MF and short at HF . so the inductance is taken half the value in phase and neutral to balance the circuit. In CM the voltage is $2V_{cm}$ .so we use a torroid inductor is taken so the voltage is divided. So the equivalent balanced circuit is given by:

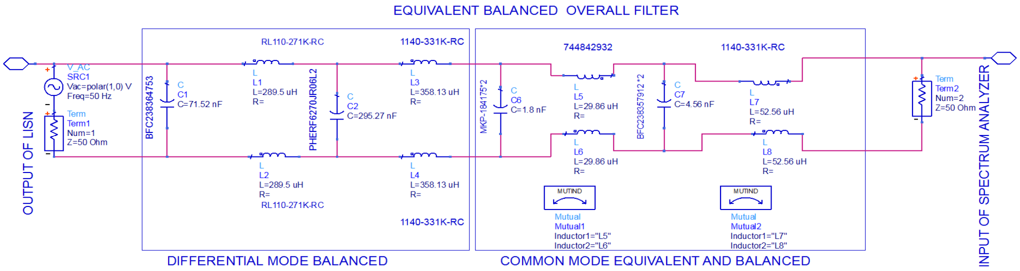


Fig:9 Equivalent balanced overall filter with differential mode and common mode

The parasitic effect is not included in the above simulation .If we include the parasitic effects the overall filter will be different for DM and CM filter. The insertion loss is defined by

$$IL=-20\log\,[V_{2\ output}/V_{1input}] = S_{21}(dB) \qquad (14)$$

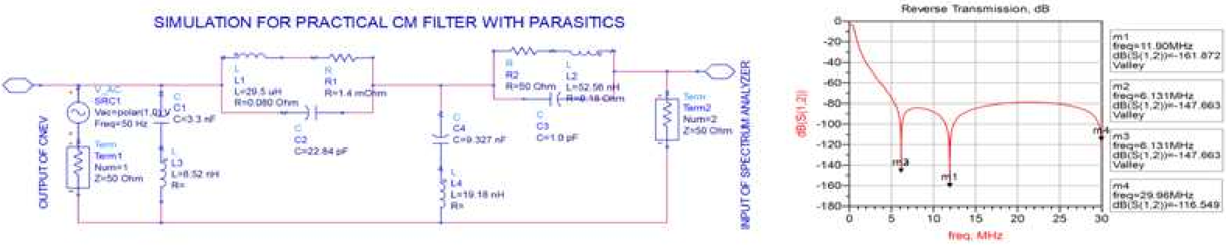


Fig:10DM filter with parasitic and results

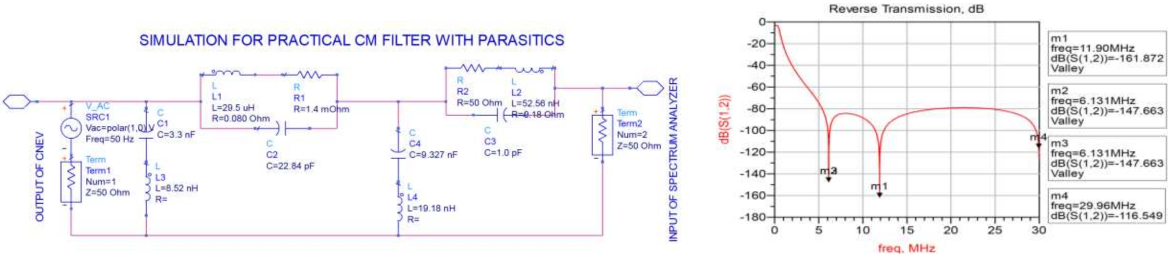


Fig:11:CM filter with parasitic and results

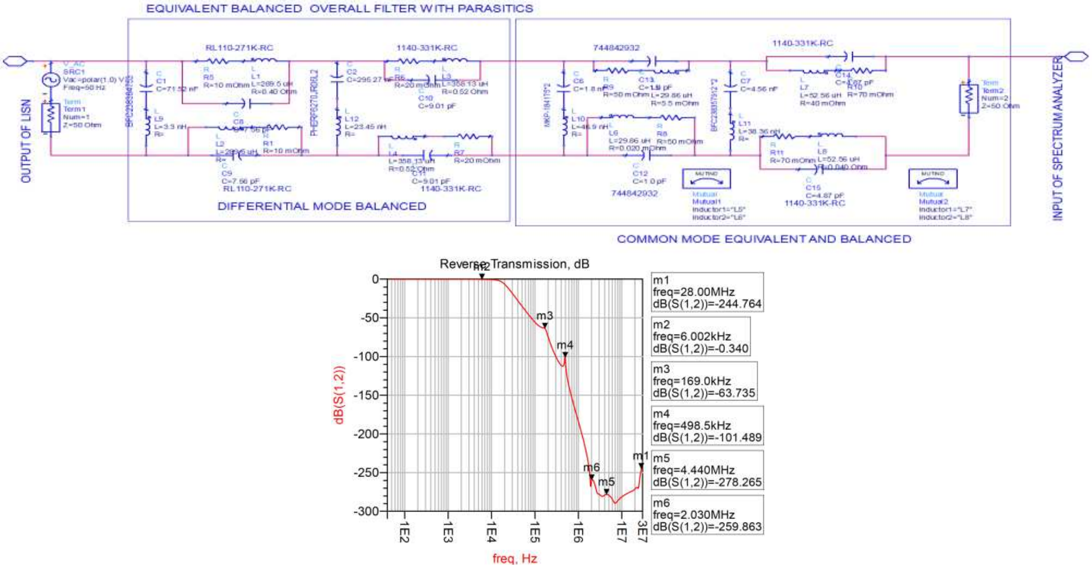


Fig:12 overall equivalent filter with parasitic and results

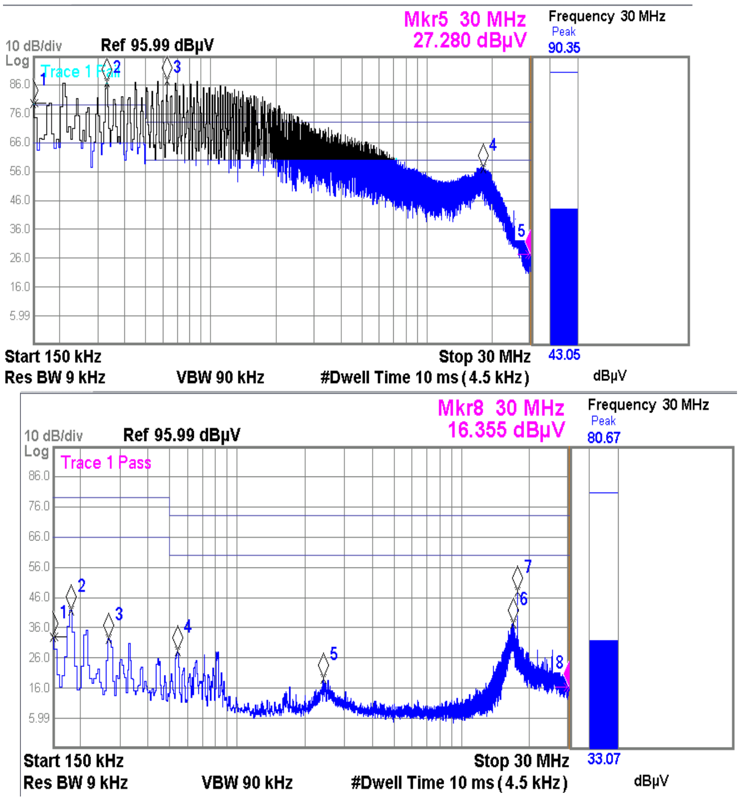


Fig:13 Practical filter showing the effect of SMPS with line and SMPS with filter line measurement

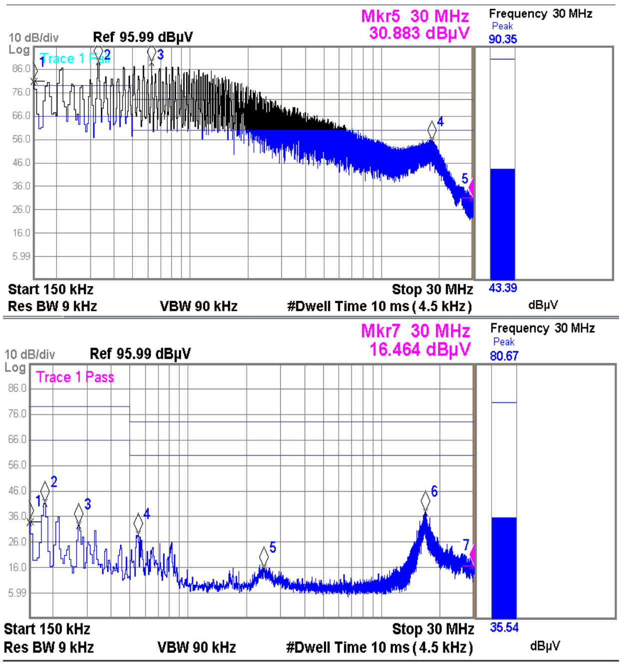


Fig:14 Practical filter showing the effect of SMPS with neutral and SMPS with filter Neutral measurement

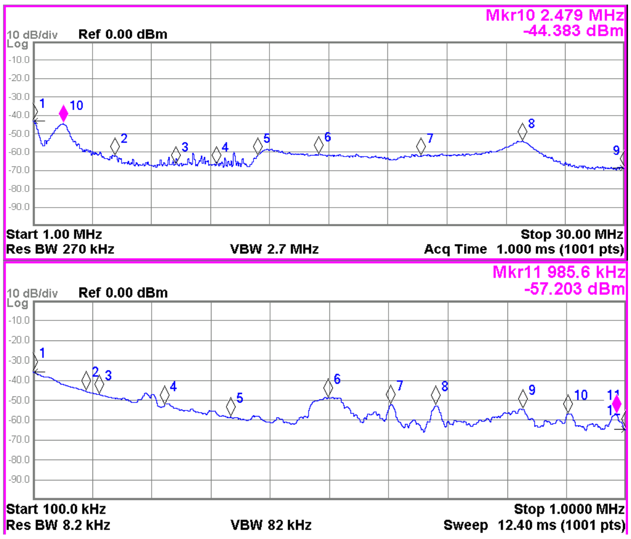


fig15 : neutral to ground measurement

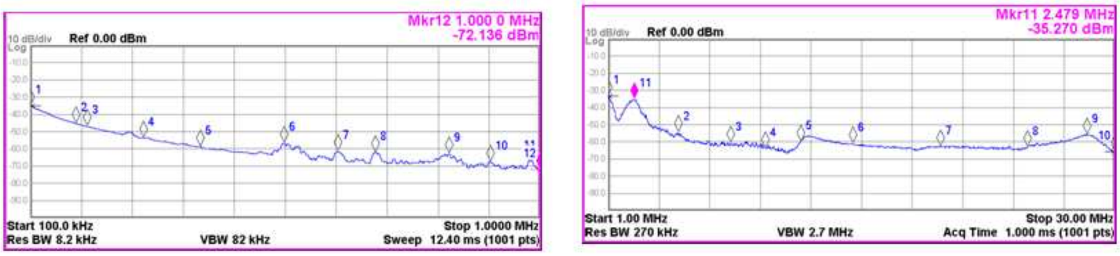


Fig 16:phase to ground measurement

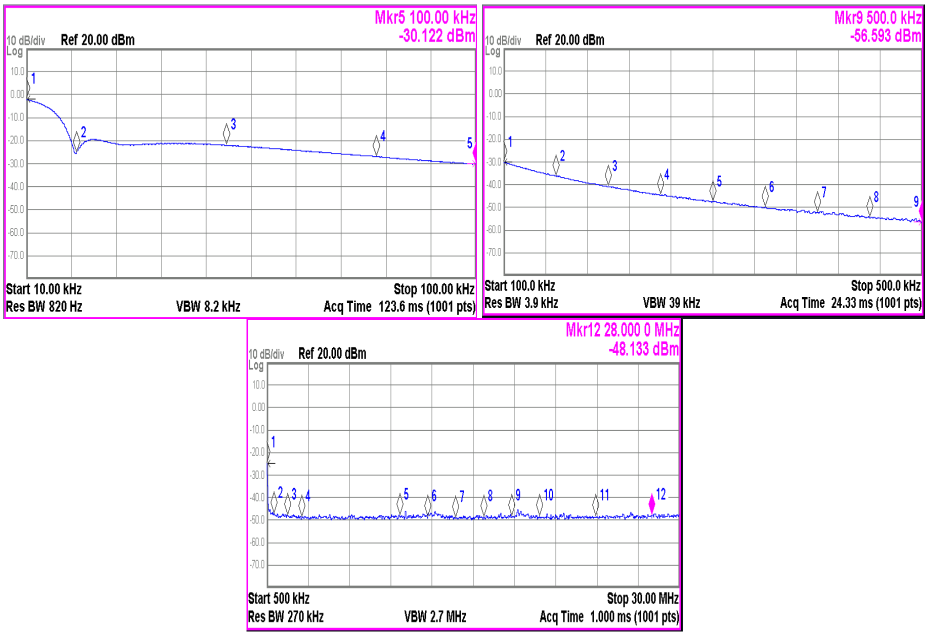


Fig17:phase and neutral measurement

VI. Conclusion

The above filter arrangement shows both CM and DM arrangement for Butterworth filter of 4th order and gives an attenuation of 64db which can be used in SMPS. And further work can be done on this filter for removal of mutual inductances between the inductors and the torroid which will enhance the attenuation and decrease the parasitic noise

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