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Master Thesis

EMI Filter Design and Verification using RF Simulation Tools and Measurements

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Abstract

Modern technologies are depended on efficiency that includes size reduction, cost reduction, supply power reduction of a system. All these efficiencies come with the obvious generation of noise. The more a device is noise-free the more it becomes efficient. All the electronic devices are produced considering the effect of electromagnetic interference. This interference is defined as the noise that travels through the electronic components like resistors, inductors, capacitors, wires, printed circuit boards, or through the overall design. This form of electromagnetic interference (EMI) has a serious impact on malfunctioning. To reduce this interference a filter is used named electromagnetic interference (EMI) filter.

Ideally, an EMI filter is a low pass filter that blocks the high frequencies as well as the noise flow while passing through the input. It will also reduce the amplitude of high-frequency signals (which are greater than the cutoff frequency). This filter is constructed with two lumped elements inductors and capacitors. There are several orders of this filter depending on the component's alignment and value.

This thesis work will deal with an EMI filter constructed with basic components. We will measure the unintended radiated electromagnetic wave from the test kit and the disturbance, also how much radiation actually produced. We will apply different valued inductors, capacitors, and chocks to measure the filter effect first and then we will synthesize the disturbances. Microwave Office software (AWR) will be used to calculate S-parameters to simulate the actual device. We are going to perform linear and nonlinear measurements to observe the filter performance as well. The simulation of this filter circuit will also be done both in frequency and time domain and at the end we will compare the performance analysis between the manufacturers' circuit board and simulated filter.

Before starting the lab work, several filters will be designed and tested in the AWR platform to identify the least disturbance circuit. Hardware simulation will be performed after designing the proper filter schematic, and the printed circuit board accordingly.

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Chapter One: Introduction

1.1 Literature review

Electromagnetic Interference filter is an essential part of electronic study that estimates the device efficiency. In electronic system or device, noise is very common factor that cannot be avoided, and can be generated in many ways. Different device deals with different type of noise according to their use or purpose. These noise can be supressed by two very common and useful methods. One of them is filtering and another one is shielding. Although these two methods is meant to use for different noise level in different frequency range. Filtering is a process that is used to remove the unwanted signal appears while connecting to a signal generator. Filter is a device in electronic study that is designed for bypassing unwanted frequencies or band of frequencies. In addition, simulation of a filter response can be done both in frequency domain and time domain. In practice there are a number of filters are available in electronics. They are differentiated according to input and output demand. Electromagnetic interference filter is a filter that is only use to supresses the noise whatever it is conducted or radiated. The only difference is for reducing radiated noise it is marketed in a metal shield. But in case of conducted it is a very useful one as it is designed with a compensated choke. Generally, EMI filter is used in between the source and the load so that, no noise can harm the other components attached to it. There are a number of electronic circuitry where EMI filter is used like in laboratory equipment, Computer equipment, radio equipment, medical equipment, military equipment and so on.

1.2 Motivation

It is very important to set a goal before starting designing and implementing a device especially if it is an efficiency regulator. Before designing an EMI filter it is very important to understand the behaviour of that filter and what does this filter will do, how to build this filter, how this filter will work, where this filter can be used, and how much efficient this filter will be in terms of cost and size.

What does an EMI filter do in Electronic circuitry?

EMI filter is called electromagnetic interference suppression filters that is an effective media to protect against the harmful electromagnetic interference impacts. When this filter is attached to devices or circuits it can suppress electromagnetic noise transmitted through conduction. These filters is capable to extract unwanted current conducted through wiring or cables and allow the desirable currents to flow towards the output terminal of it. In a certain situation it delivers extra currents to the ground so that the rest of the connectivity remains secure from harming.

How this filter can be designed?

An EMI filter is a type of low pass filter that will allow only the low frequency signal to pass through the filter and block the other frequencies or frequency band. That is why it is can also be designed following the design method of a low pass filter. In practical it is generally a LC filter where instead of using the inductor, coupled inductor is used. Coupled inductor are planned to use as it can increase or decrease the voltage or current transferring the impedance through the circuit and isolate the other devices electrically. But now a days, it is experimented that a common mode choke is mode flexible to use instead of coupled inductor. A common mode choke is used as a filter itself that actually neutralize the common mode noise from the circuitry. The capacitor plays an important role to design this filter. Two set of capacitors are used to minimize two different noise. One set of capacitor is used in series with the choke and another set is used in shunt with the choke to control common mode noise and differential mode noise respectively. Although the purpose is different, the value of these capacitors can effect opposite noise.

How this filter will work?

Most of the electromagnetic noise are in a higher frequency range. That is why EMI filters are designed as low-pass filters that blocks or sift out high frequencies and let the lower frequencies to pass through. There are different type of EMI filter that are designed to suppress specific noise frequencies, while allowing others to flow without hampering. After completing the filtering process, unwanted noise gets diverted away from the device and it is send to the ground. Some of the EMI filter may route that unwanted currents back to the noise source or some of them may absorb that current.

Where we can place or install this filter?

Electromagnetic interferences can be generated inside the electrical device by impendence mismatch of interconnected wiring. Interferences can also be generated by voltage variance in conductors. That is why proper setup of this filter is needed into the device. Installation of this filter is different for individual device it is used into. If the installation in not get perfect then it won’t be able to perform correctly. Proper installation of components and wiring will minimize the propagation and susceptibility. Generally, filter should not be installed very close to the source and the load or too long to power line. When the installation is closed then the filter will not be able to complete the filtering process properly and the signal will escape without suppression of the filter and directly coupled to the other end with interference. It is better if the connection cable is twisted pair because twisted pair cable can eliminate high frequency interference signal.

EMI filter remarks a vital role for recent electronic and electrical signal process. This thesis will emphasise the overall performance of an EMI filter having both linear and nonlinear properties and response both in frequency and time domain.

Chapter two: Theory

2.1 EMI in details

2.1.1 EMC compliance

In a system, electronic or electrical devices emit a large amount of electromagnetic interference known as radiated and conducted emissions and electromagnetic immunity known as conducted and radiated immunity. These emissions and immunity innate the entire performance of the system and may cause unwanted effects such as physical damage to the equipment. Electromagnetic compatibility (EMC) is the measurement ability of an equipment in an electromagnetic environment without introducing intolerable electromagnetic disturbance to function satisfactorily. The main purpose of EMC is to limit the generation of unintentional signals and those signals propagation as well as reception of electromagnetic energy as output [1] [2] [3].

EMC can be classified into two main categories. Each of these two categories also can be classified into two. EMC may be defined by understanding and identifying any or all of these issues.

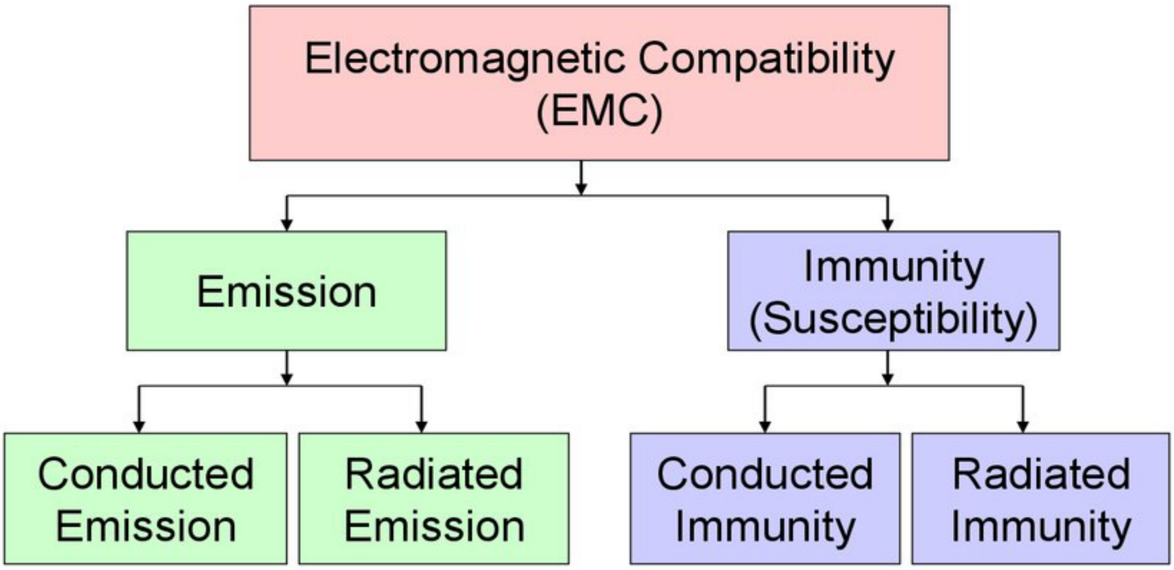


Figure 01: Classes and subclasses of Electromagnetic compatibility [4].

Emission is the production of electromagnetic energy by some source in a deliberate or accidental way, that release into the environment. EMC takes these unwanted emissions into consideration and countermeasures which mostly reduce unwanted emissions.
Electrical equipment that becomes malfunctioned or breaks down in the presence of unwanted emissions, is referred as **Susceptibility** or Radio frequency interference (RFI). In case of **Immunity,** when a radio frequency is present in a system or equipment it functions correctly. Hardening equipment is also known as susceptibility or immunity.

A third issue which is a very common content of EMC is **coupling** by which emitted interference reaches the victim [1] [3] [5].

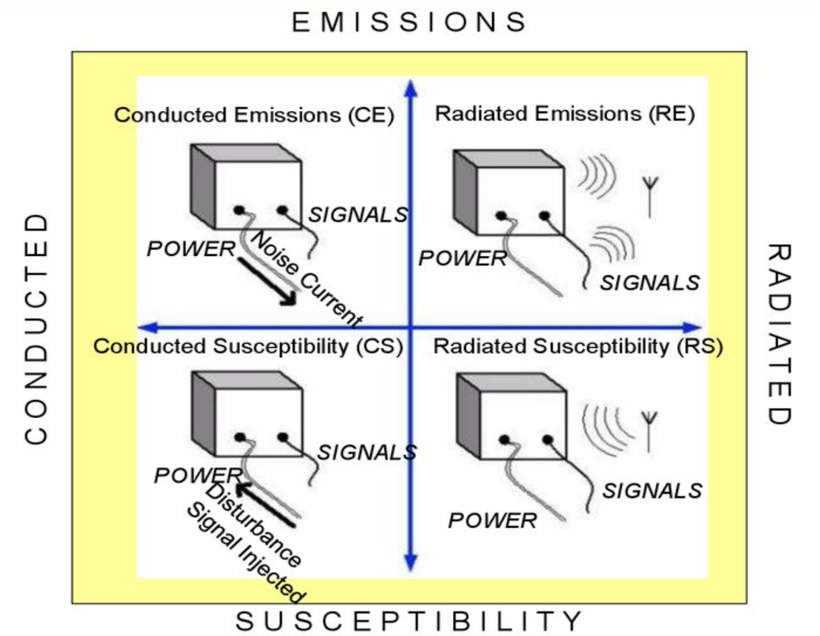


Figure 02: Measurement relationship between EMC classes.

2.1.2 EMI Definition

Electromagnetic Interference is referred to as an electromagnetic disturbance that may degrade the performance of a device, equipment, system, or subsystem and create malfunction to the equipment generating electromagnetic induction or emitting electromagnetic radiation.

Generally, when an electric field comes in contact with a magnetic field, electromagnetic (EM) waves are generated. EM waves can travel at a very high speed like the speed of light in vacuum and can travel over anything whatever it is air or solid material or wave. It occurs when an electronic device is unshielded to an electromagnetic field and any device that has electronic circuitry and is connected with power supply, can be responsive to EMI.

EMI is the combination of two or more waves that can result in greater, lesser, or equal measured waves than the original one. Hence, the resulting wave may be potentially different from the original waves and may also be potentially unsuitable for its purpose [3] [4] [6].

2.1.3 Electromagnetic Interference Classification

i. EMI can be generated from different sources. The way of classifying the EMI types is done by the way it was generated:

Human-made EMI: This type of EMI is generally generated from the electronic circuit or electrical device. Examples as power lines, auto ignition, fluorescent lights, and so on [7].

Naturally induced EMI: This type of EMI can be generated from many sources like extra-terrestrial sources including radiation from the sun and galactic sources including radio stars, galaxies, and other cosmic sources, atmospheric charge or discharge like lightning [7].

ii. Second method of classifying the EMI types is done by its duration:

Continuous interference: When a circuit is connected to a source and emits a continuous signal then this type of EMI generally arises from that source. However, background continuous noise may be created in a number of ways either it is human-made or naturally induced [7].

Impulse interference: Including lightning, ESD, and switching systems all those which contribute to impulse noise, is a form of EMI. This type of EMI may be generated by human-made or naturally [7].

iii. EMI can also be classified according by their bandwidth.

Narrowband: This EMI is likely a single carrier source. The signal that is generated by intermodulation and other forms of distortion, also a form of narrowband EMI. It may appear at different points in the spectrum. It may be responsible for inducing interference to another user [8].

Broadband: Broadband EMI can be generated from different sources. Man-made broadband interference can be generated from sources spark is continuously generated. Naturally occurring broadband noise can be generated from the Sun. Actually when the Sun appears behind the satellite and noise can mask the wanted satellite signal [7].

2.2 EMI Filter Design

In this paper, EMI filter is designed considering the basic components a low pass (LC) filter need. Instead of inductors I have used a current compensate choke (coupled inductor) and ceramic capacitors.

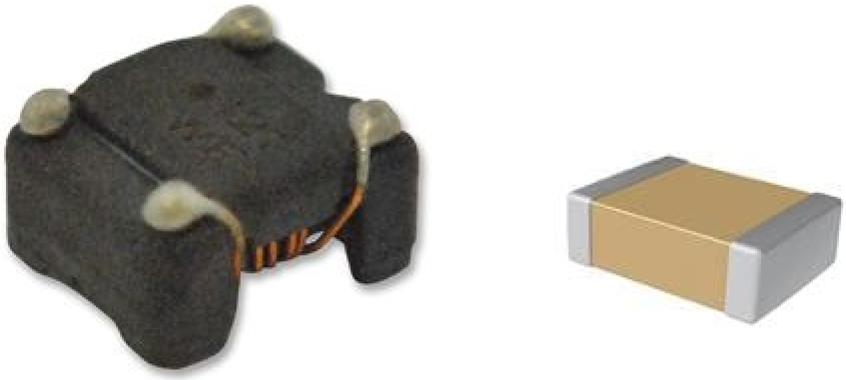


Figure 03: Passive components for building EMI filter

2.2.1 Schematic Design

There are two types of noise can be generated in a device named common mode noise and differential mode noise. In an EMI filter, different components are used, among them the CX capacitors are used to attenuate differential mode noise. Generally, differential mode noise are created from line to neutral by rapid changes in current within the loop of the converter and also the generation due to the leakage inductance. Coupled inductor L is a common-mode or current compensated choke that is responsible for generating leakage inductance also. On the other hand, common mode noise is generated by rapid voltage change within the converter, and current flows from the line and neutral to ground. The choke has a high impedance and each CY capacitor is diverting noise current to the ground [9] [10].

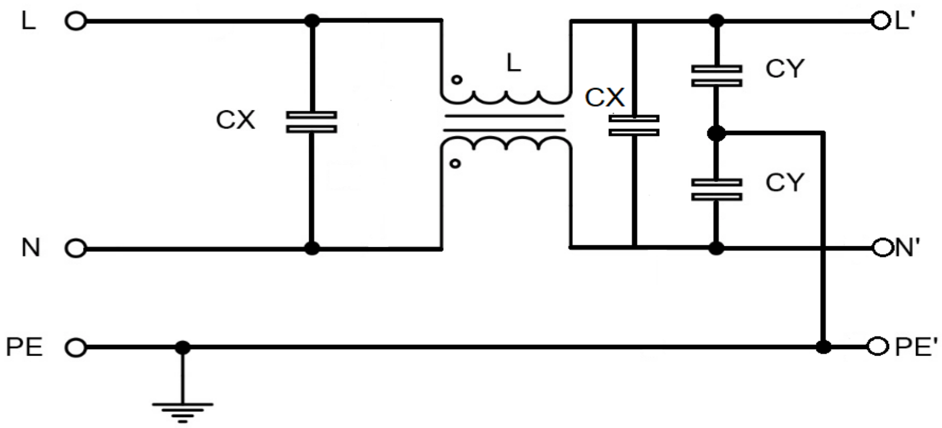


Figure 04: Standard schematic design of EMI filter [9]

Considering the mode noise the EMI filter is constructed with two unlike filter named according to the noise generated. One of them is Common mode filter which is patterned to reduce the conducted mode noise only and Differential mode filter which is designed to reduce differential mode noise. In each of the filter as we are using passive elements, very small amount of common mode noise or differential mode noise can be fluctuate due to the capacitors which are planned to use for minimising opposite mode noise [9] [10].

2.2.2 Common mode filter

In an EMI filter, a common mode filter is meant by the passive element common mode choke. It is used because the common mode current generates a magnetic flux in the opposite direction and produces almost zero inductance. In the following, a common mode filter is shown that is designed for our purpose.

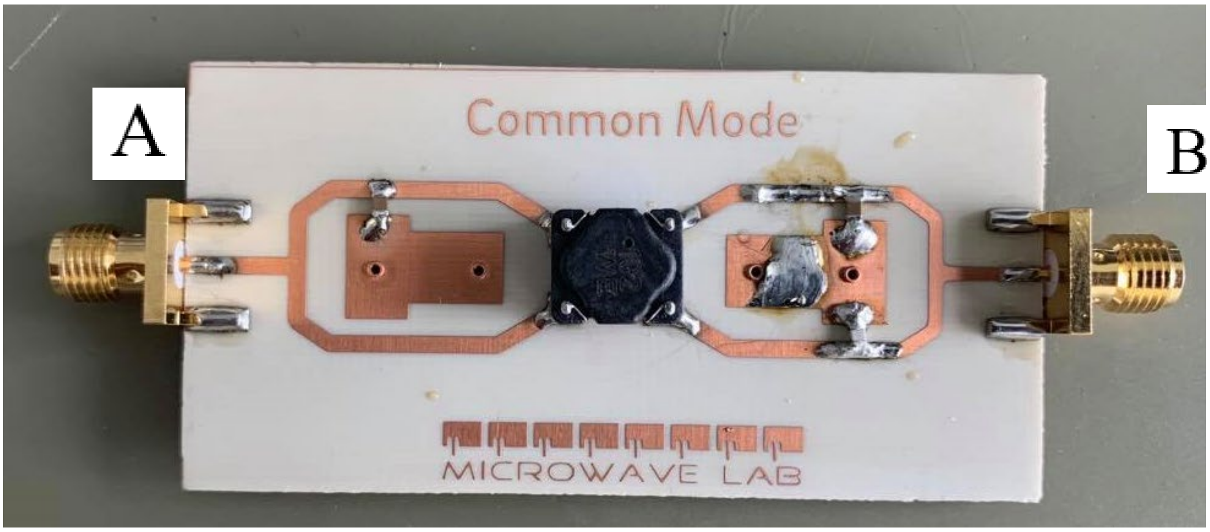


Figure 05: Hardware design of Common mode filter

In the Figure 05, input signal is provided where noise is also passing with the main signal through the port A. The main signal should have filtered the common mode noise generated in the input and at the output the noise will be filtered. The amplitude will be lower than the main signal as with the current as the noise current will pass through the capacitor used as Y capacitor. The input and the output signal should have the following pattern [11] [12] [13].

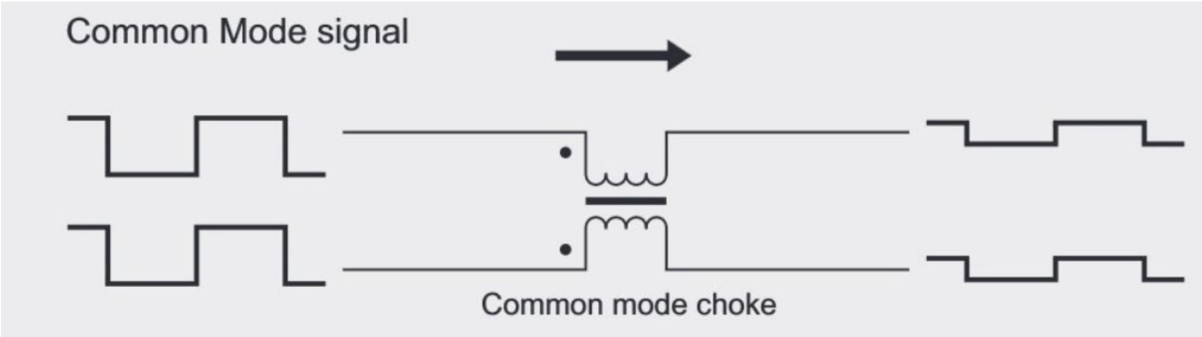


Figure 06: Expected input and output signal amplitude of a common mode filter [14].

In our experiment we have got the input output signal in the common mode but the output signal is not as expected due to the transient properties or harmonic imbalance and loss due to the component I have used [11].

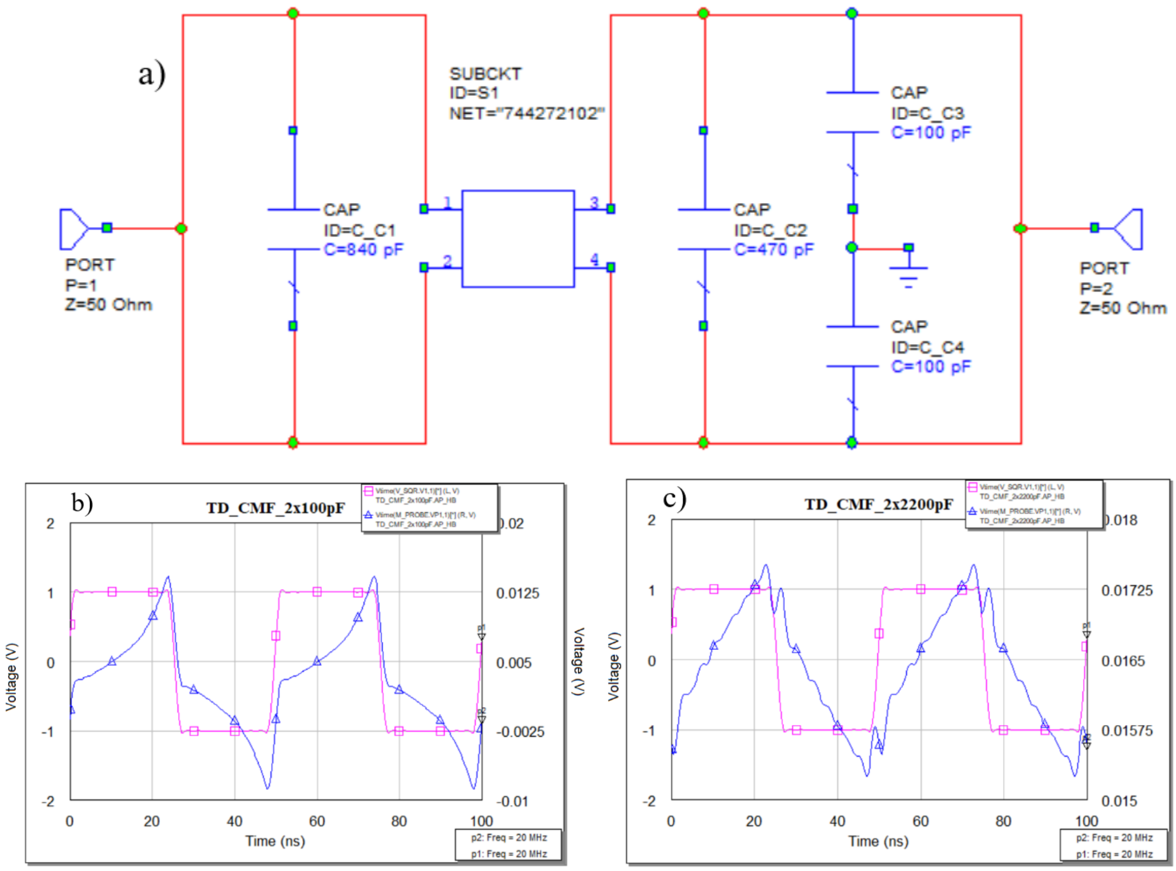


Figure 07: a) Common mode filter circuit diagram for software implementation, b) Input, output magnitude using 100pF cap, c) Input, output magnitude using 2200pF cap

2.2.3 Differential mode filter

In an EMI filter, differential noise is a major issue in case of generated conducted emissions. Differential mode noise is generated from the source in an ordinary way, that is why it is called general noise. There is another source from where differential mode noise can be generated. The leakage inductance induced due to magnetic flux of the common mode choke is the secondary differential mode noise. That is why there are two X capacitors are used at the two terminals of the common mode choke. One will reduce the differential mode noise generated due to general current flow from the source and another one will reduce the induced current due to leakage inductance. In the following, we can understand the hardware design.

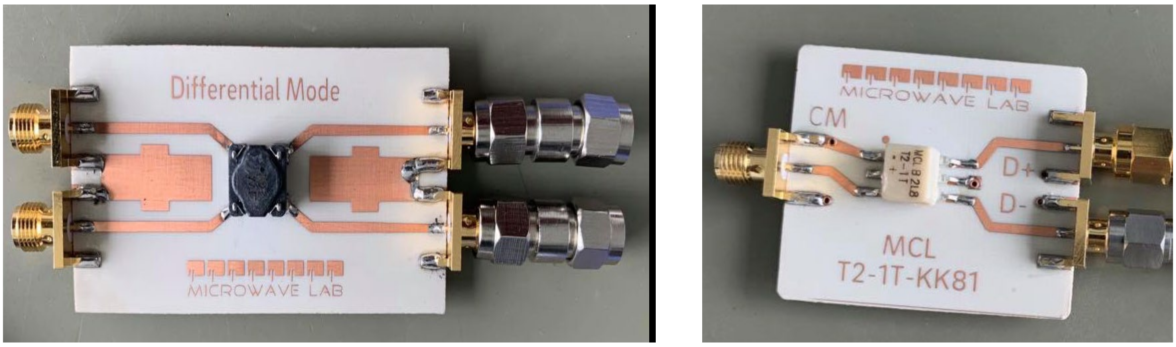


Figure 08: Hardware design of a differential mode filter.

Figure 08 shows a differential mode filter that will have two X capacitors. Two transformers will be installed in the both in and out terminal of the differential mode filter to observe the noise and identify the magnitude as the generaded value supposed to be very small. The input and output signal in a differential mode filter should be like figure 09 [12] [13].

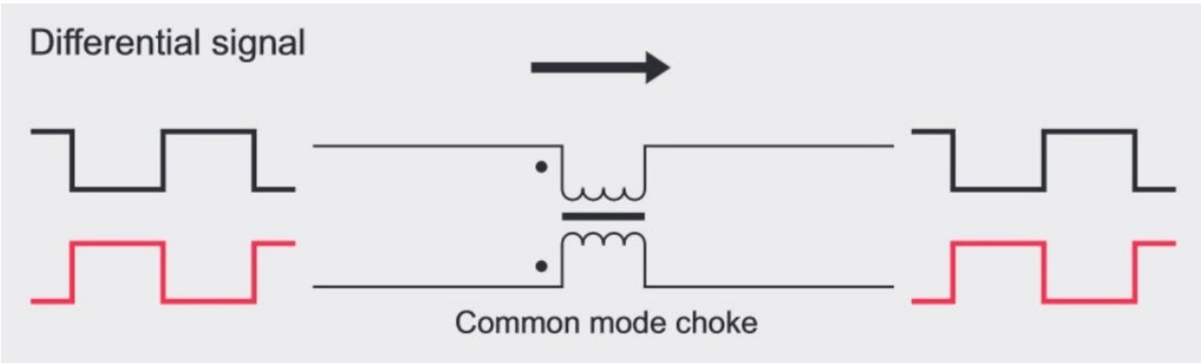


Figure 09: Expected input and output signal amplitude of a differential mode filter [14].

The software implementation provides a different result for the square wave in the output side. Since we can get almost close results.

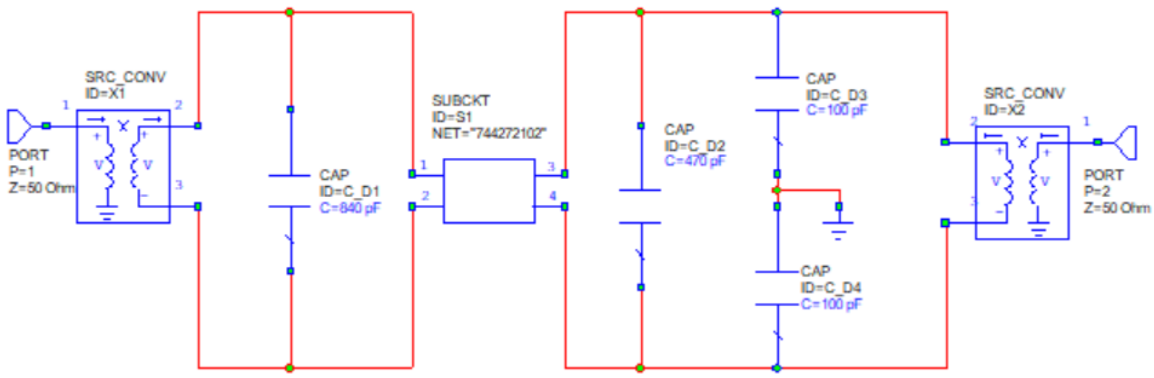


Figure 10: Differential mode filter circuit diagram for software implementation

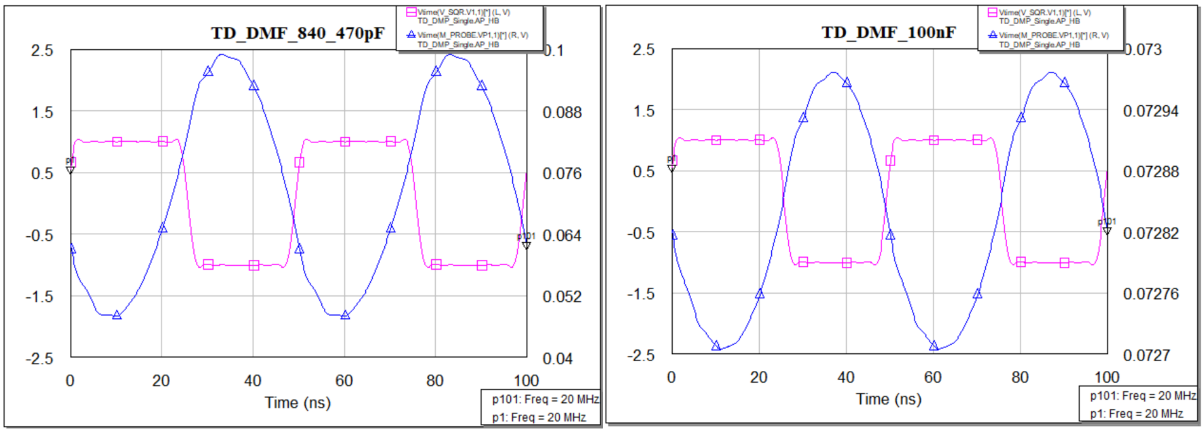
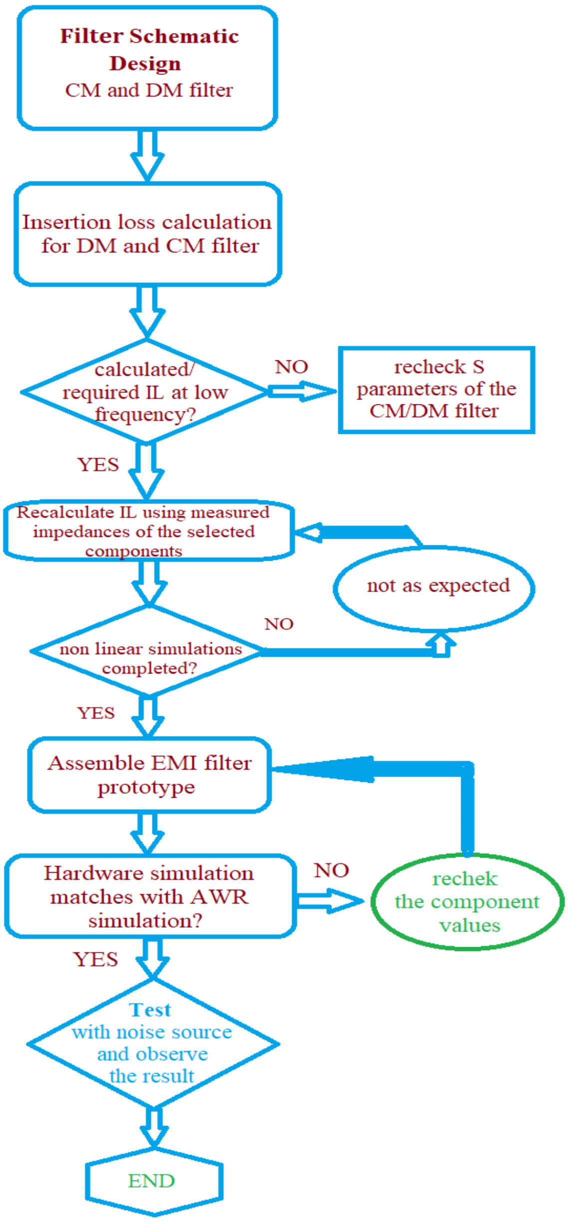


Figure 11: Input, output magnitude using 840pF &470pF cap (left), and Input, output magnitude using 2x100nF cap.

2.2.4 Design Flow diagram



2.3 EMI Emissions Analysis

When an electromagnetic energy is generated by any source whether accidentally or deliberately and is released into the environment then the existence of Emission is establish. EMC studies allows to identify these unwanted emissions and the countermeasures which may be taken in count to reduce this unwanted emissions.

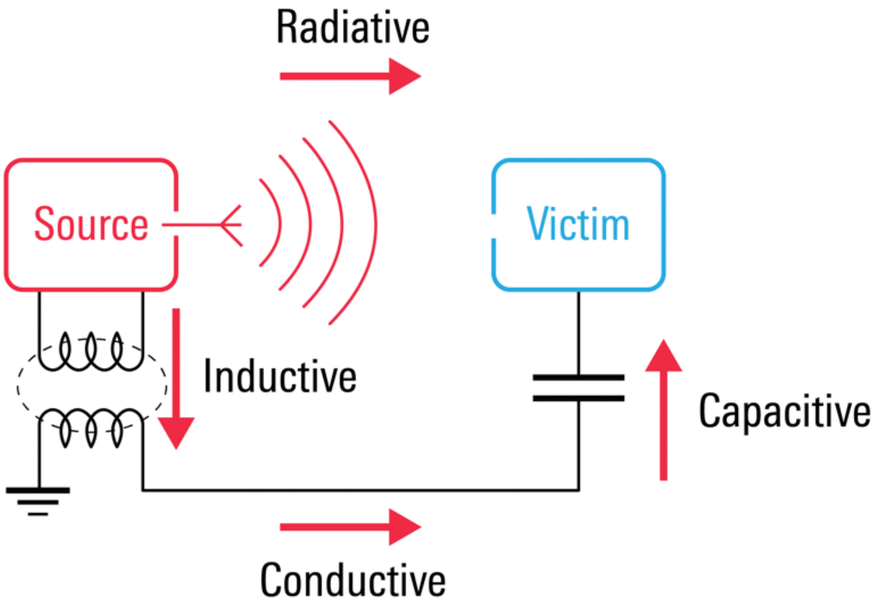


Figure 12: Induced emissions in an EMI filter

2.3.1 Conducted Emission

Conducted Emission is the mechanism where electromagnetic energy is created in an electronic device or sub-circuit and is transferred to another device or sub-circuit via cabling, PCB traces, power or ground planes, or capacitance. This emission is capable to travels through a conductive path. This emission can be continuous or discontinuous. Continuous emissions are emitted at a given frequency but discontinuous emissions are non-constant and occur sporadically [2] [15].

The frequency range for the conducted emissions standards is 150 kHz to 30 MHz. But this range may go higher or lower for a specific standards. There are some standards that use different frequency ranges. Different value of impedances is also a concern for the manufacturers [2] [15] [16].

The three most common standards CISPR 11, CISPR 14–1, and CISPR 22 and corresponding EN standards specify measurement in this frequency range. CISPR 13 (for broadcast receivers) and CISPR 15 (for lighting equipment) also require a similar range. CISPR 15 calls for measurement from 9 kHz to 30 MHz. Conducted EMI at below 9 kHz frequencies is usually categorized as low frequency while that between 9 kHz to 30 MHz is categorized as high frequency [2].

2.3.2 Radiated emissions

Electromagnetic energy that is generated from an electronic device intentionally or unintentionally is called radiated Emissions. Radiated emissions spread through the air from the device’s chassis. It can also radiate from interconnected cables. HDMI ports are a good example that radiate emissions. Typical magnetic field loop antennas such as the Van Veen Loop antenna measures the magnetic field emissions of a product in three-axis [2].

Circuits are filled with time-varying signals that propagate electromagnetic radiation into space. In that sense, every conductor that carries electrical currents behaves like an antenna that source energy into the surrounding and simultaneously transmits and receives radiated EMI [2] [15].

The standard frequency range given by CISPR22 and EN55022 standards was 30 MHz–1 GHz intended for computers and communications-related equipment. The emission levels for Class B components are 30 dBμV/m in the frequency range 30–200 MHz but emission levels increase up to 37 dBμV/m as the frequency increases up to 1 GHz from 200 MHz [2].

Chapter Three: Filter mode

3.1 Conducted Emission Analysis

Conducted emission is the electromagnetic interference (EMI), or noise that originates from frequencies of an electronic or electrical device. These interference are then spread out along with interconnecting cables. Cables may be signal ports, wired ports such as telecommunication ports, or power conductors.

Conducted emissions are typically divided into two types: Common mode and Differential mode.

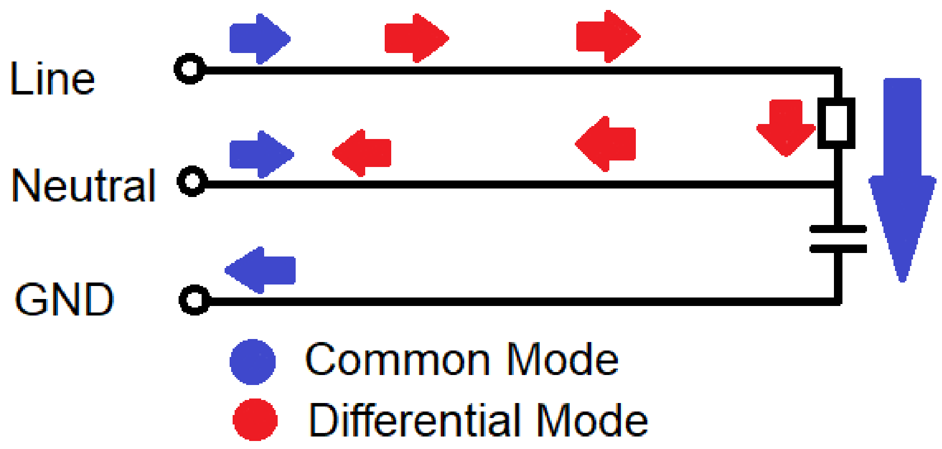


Figure 13: Conducted Emissions path in a designed device.

3.1.1 Common Mode Interference

Common mode noise is referred as the line to ground noise that is generated both sides of the ac input and in phase with its ground. It is an asymmetric noise. The common mode noise current flows in the same direction on both power conductor line and neutral and returns via the ground conductor. Common mode noise can be suppressed by the common mode choke and the Y capacitors used in the EMI filter [16].

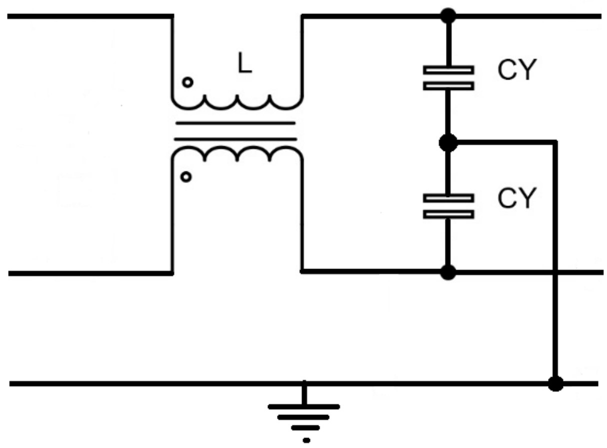


Figure 14: Common mode part in an EMI filter

3.1.1.1 Common mode voltage

Common mode voltage is an asymmetrical and unbalanced voltage. It is defined as the voltage between the conductor line and the ground, or as the mean of the phasor voltages appearing between each conductor and a specified reference, usually earth or frame. If V_1 and V_2 are voltages on phase and neutral respectively, then the following expression gives the common mode voltage. The voltages induced by external electric fields are generally common mode voltage 'V_{CM}' given by:

$$V_{CM} = (V_1+V_2) / 2 \quad \text{...} \quad \text{(equation: 1)}$$

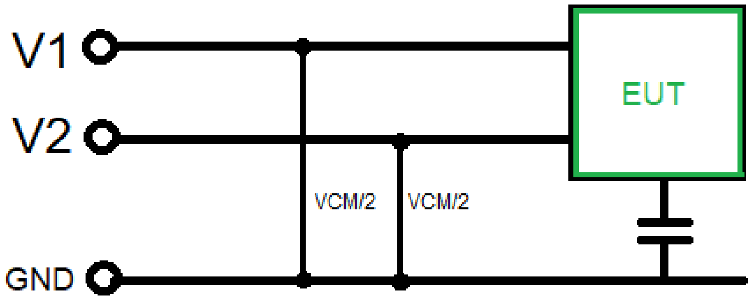


Figure 15: Voltage measurement of a Common mode filter

3.1.1.2 Common mode current

Common mode currents are those currents that flow in the same direction on line and neutral and return via ground. If I_1 and I_2 are currents on line and neutral, then the common mode current I_{CM} is given by the vector sum of those two currents [17].

$$I_{CM} = I_1 + I_2 \quad \text{...} \quad \text{(equation: 2)}$$

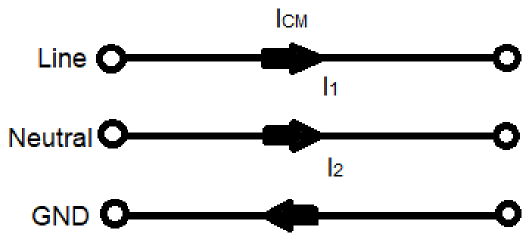


Figure 16: Current flow path in a Common mode filter

3.1.1.3 Radiation due to Common mode noise

When in a system, the electric field intensity radiates due to the common mode noise and current flow from transmitter to receiver having a specific distance then that field can be expressed by the equation (3). Cable length L is an important factor to solve the equation. The distance from the observation point to the channel is denoted by r. So it is seen that the electric field id depended on the cable length proportionally [18].

$$E_{CM} \propto \frac{I_c \times f \times L}{r} \quad \text{...} \quad \text{(equation: 3)}$$

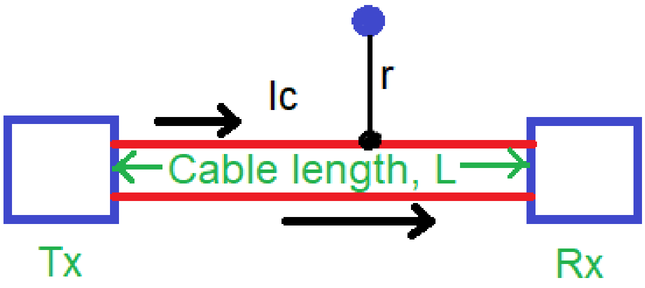


Figure 17: Common mode radiation overview.

3.1.2 Differential Mode Interference

Differential mode interference is referred as the signal that is generated in between line and neutral and because of the leakage inductance of the common mode choke which is generated due to short of two-port of the choke.

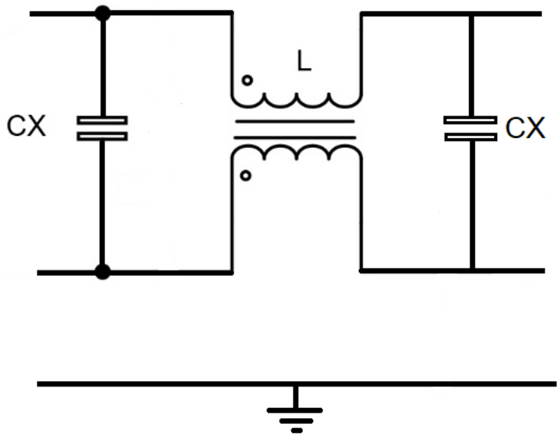


Figure 18: Differential mode part in EMI filter

3.1.2.1 Differential mode voltage

Differential mode is said to be a normal mode or symmetrical mode and has a balanced voltage. It is defined as the voltage between two wires of a two conductor lines. Voltage V_{DM} is the differential mode voltage and is the vector difference of the voltages on phase and neutral is given by:

$$V_{DM} = V_1 - V_2 \text{ .... (equation: 4)}$$

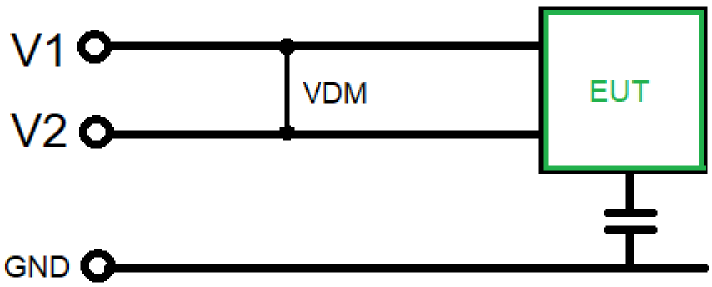


Figure 19: Voltage measurement of a Differential mode filter

3.1.2.2 Differential mode current

Differential mode currents are defined as half the vector sum of current flowing in any two of a specified set of active conductors at a specified cross-section area. In simpler terms, differential mode currents flow in opposite directions on phase and neutral [17]. The differential mode current is given by:

$$I_{DM} = (I_1 - I_2) / 2 \text{ .... (equation: 5)}$$

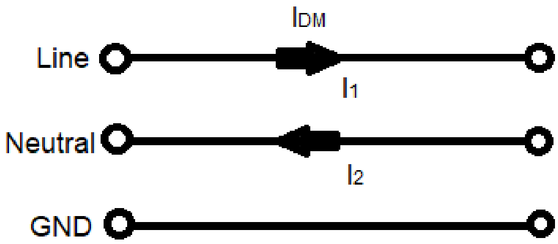


Figure 20: Current flow path in a Differential mode filter

3.1.2.3 Radiation due to differential mode noise

The electric field intensity of the differential mode noise can be presented using equation 6 where, the noise current is flowing in differential mode is I_d. The distance to the observation point and the noise frequency are 'r' and 'f'. Differential mode noise creates a current loop which is generally the noise current. We have considered that loop area S. From equation 6 it can be estimated that if the loop area becomes larger the electric field intensity gets higher and vice versa while keeping the rest of the elements constant [18].

$$E_{DM} \propto \frac{I_d \times f^2 \times S}{r} \text{ .... (equation: 6)}$$

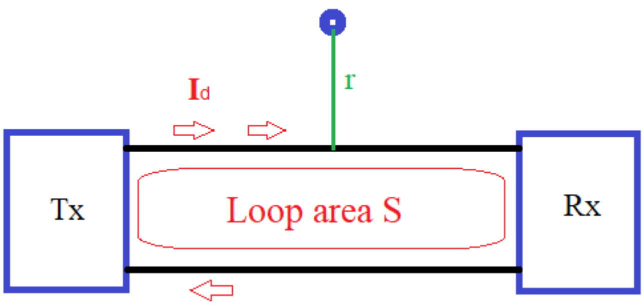


Figure 21: Differential mode radiation overview

3.2 Material Selection for Hardware Design

3.2.1 Common mode Choke

In electronic circuitry a common mode choke is use to suppress the common mode noise and recognized as an electrical filter. It blocks the high frequency noise and let the low frequency signal to pass. Common mode (CM) noise current radiates from sources and this noise arise interference problems in electronics circuits.

Chokes are basically two types. Single choke is used for differential mode suppression, and a common mode choke (current compensated) is used for common mode suppression. In our thesis, we have used a common mode choke. In a common mode choke, there are two windings or multiple windings, which means three line winding, or more can be possible. Here, we used two identical windings or coils around a common core in different direction. The basic property is that whatever the number of winding is made, all are on a common core.

Figure 22: A Common mode choke

Windings are coupled together around this common core. Common mode choke has common mode impedance that suppresses the unwanted common mode noise. Common mode choke also has some differential mode impedance that is known as leakage inductance. Most importantly, the overall distortion of the overall signal due to this leakage inductance is very low as the suppression does not occur at the transmitted signal frequency [19].

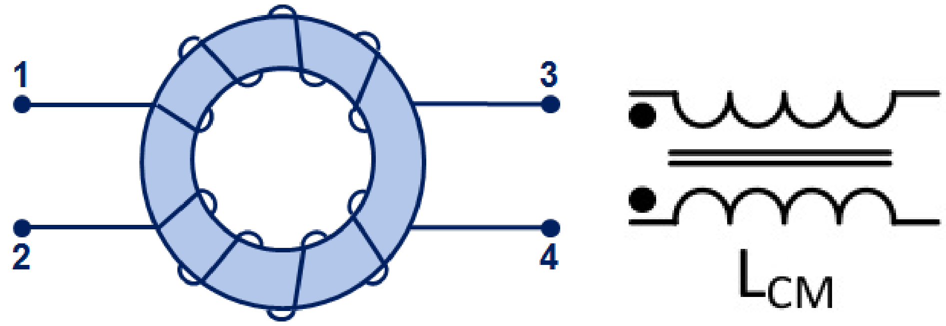


Figure 23: Physical layout and circuit schematic of a common mode choke

When a current enters in the CMC in the same direction, the two magnetic fields originated due to these directional coils are added together to provide a large inductance or impedance, which plays an important role in suppressing common mode noise [18][19].

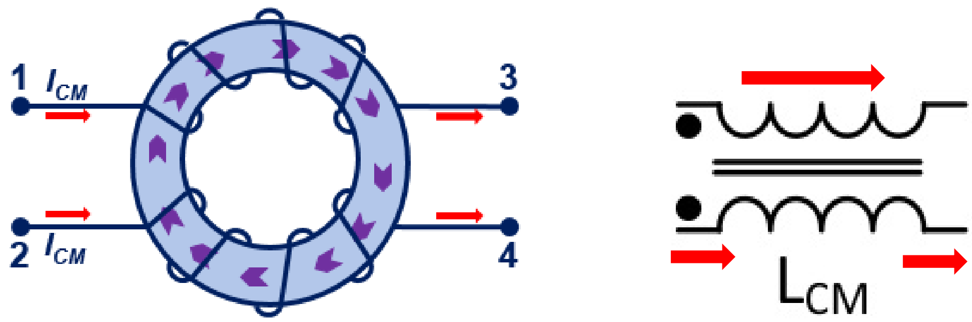


Figure 24: Common mode current flow through common mode choke

When the currents enter in the opposite direction of the CMC, they produce two magnetic fields in opposite direction of the windings and cancel each other. Then into the choke, a very little inductance or impedance generates which is called leakage inductance but the core does not saturate even with large input currents [18] [17].

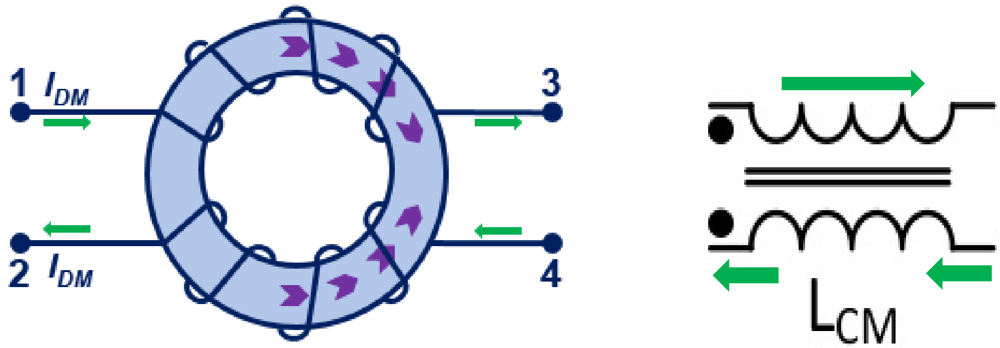


Figure 25: Differential mode current flow through common mode choke

When a CMC is designed for the filter purpose in the circuit, it attenuates the energy down to a given frequency, which reduces the unwanted noise going to the load. On that time choke produce a large inductance and common mode noise are filtered out only. But the differential mode signal induced from the choke leakage inductance also pass through the filter [17] [18].

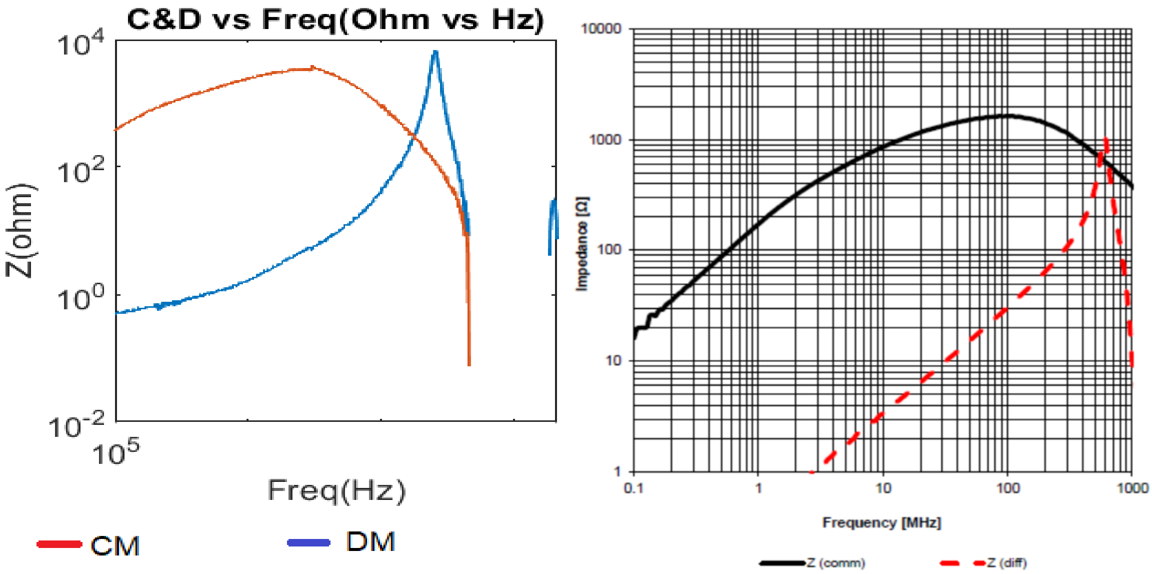


Figure 26: Impedance of a Common Mode Choke a. Measured b. Theory.

3.2.2 Lumped elements

EMI filter is designed with two capacitors connecting between the line and the neutral wires (called X capacitor), and two capacitors connecting between the line to the ground and the neutral to the ground wires (called Y capacitor), and a common mode choke. Due to the CM and the DM noise current directions, CM choke and the Y-caps (C_{Y1} and C_{Y2}) affect both CM and the DM emissions while the X-caps (C_{X1} and C_{X2}) affect the DM noise. When the CM noise propagates through the EMI filter, CM noise is suppresses by the equivalent CM filter. At the same time, the DM noise is eliminated by the equivalent DM filter, which is a π-configuration filter. The equivalent CM filter comprises the CM inductance (L_{CM}) of the CM choke at the load side and the parallel of C_{Y1} and C_{Y2} at the power supply side. The equivalent

DM filter resulted from the total leakage inductance of two windings of the CM choke (L_{DM}), the C_{X2} at the load and the C_{X1} at the supply side.

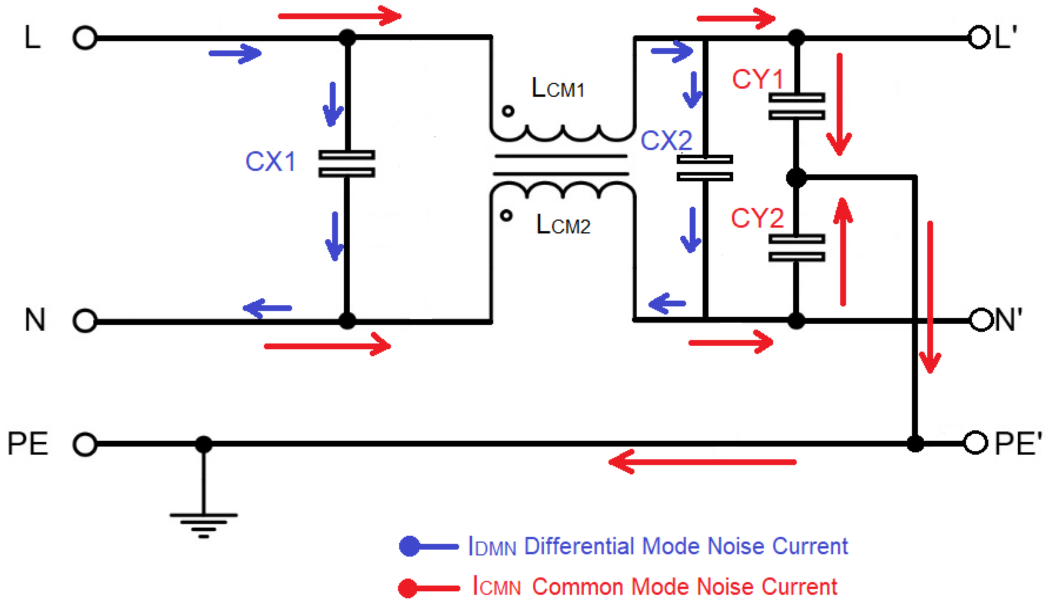


Figure 27: Lumped elements and current directions through them

3.3 Noise Source Design

In an electrical system, noise is an unwanted signal that may generate during signal transmission, processing, receiving, storage, or conversion. In an electromagnetic system, noise generates harmonies that distort the main signal to pass.

In our thesis work, we have considered a loss pass signal generator which is called Comb Generator. A comb is a signal generator that produces multiple harmonics having similar amplitudes in the input side. But as in the output, the spectrum analyser displays the signal like a comb that is why it is named Comb Generator [20]. We have used a comb generator that can generate signal frequency up to 1 GHz at an interval of 12MHz. That means we will get response at 12 MHz, 36 MHz, 60 MHz, 84 MHz, 108 MHz, 132 MHz, 156 MHz, 180 MHz, 204 MHz, and so on. As we are getting the signal response, we will get harmonics at exactly 24 MHz, 48 MHz, and so on.

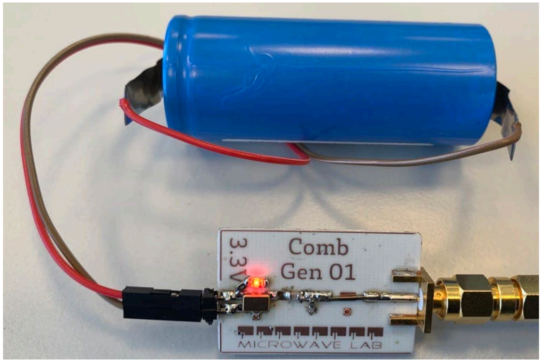


Figure 28: Noise signal generator (Comb generator), physical and circuit layout.

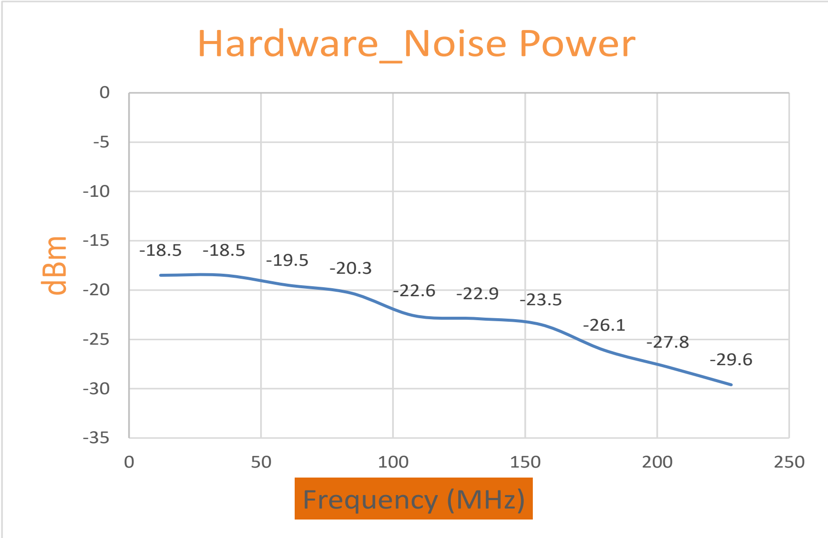


Figure 29: Hardware design of a Comb generator and the input power with frequency

3.4 Line Impedance Stabilization Network (LISN)

LISN is used to measure how strong radio transmitter is when the RF emissions enter via the power supply wires. LISN lets the equipment under test to get its power supply uninterrupted and directs all emissions to the resistive load. Spectrum analyser takes the measurement that load gets.

LISN is designed to provide a constant line impedance of over a frequency range required. Moreover, it minimizes the measured noise that is generated by EUT.
If we want to measure LISN performance, it is important to know how much external RF emissions are attenuated by the LISN from the power supply. As well as how much the RF emission is attenuated from EUT to the measuring equipment [21].

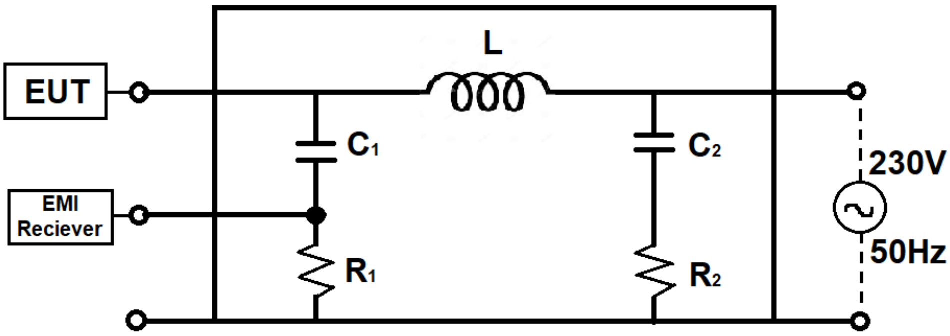


Figure 30: Circuit diagram of LISN

Chapter Four: Filter Behaviour Prediction

4.1 Linear Simulation

4.1.1 S-parameter measurement

S-parameters consists of two fundamental topics:

- Two-port networks,
- Reflections on transmission lines.

4.1.1.1 Two-port network

It is the most commonly used circuit analyzing technique that obtains an equivalent circuit model concerning the specified terminal pairs of the network. The fundamental principle of two-port network analysis is to calculate only the terminal variables (input voltage, input current, and output voltage, output current) instead of calculating voltages and currents of all points inside the circuit. In EMC the two-port network analysis calculate the voltages and currents in sinusoids at each frequency, described by their amplitudes and phases [22].

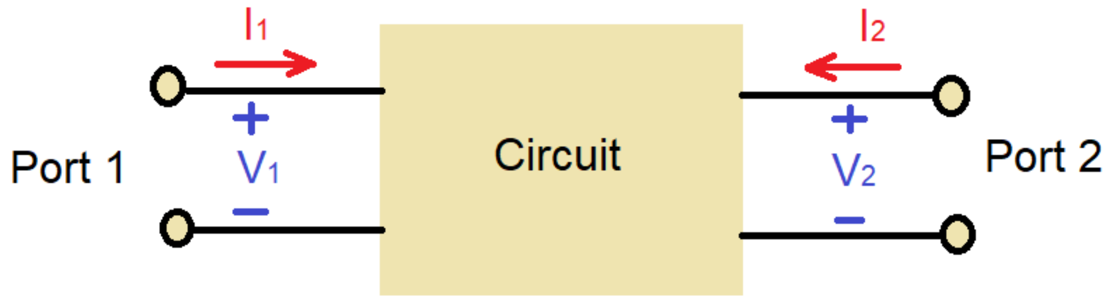


Figure 31: Two port network diagram

In a two-port S-parameters we can get four individual parameters which are:

S_{11} is the input voltage reflection coefficient
S_{12} is the reverse voltage gain
S_{21} is the forward voltage gain
S_{22} is the output voltage reflection coefficient.

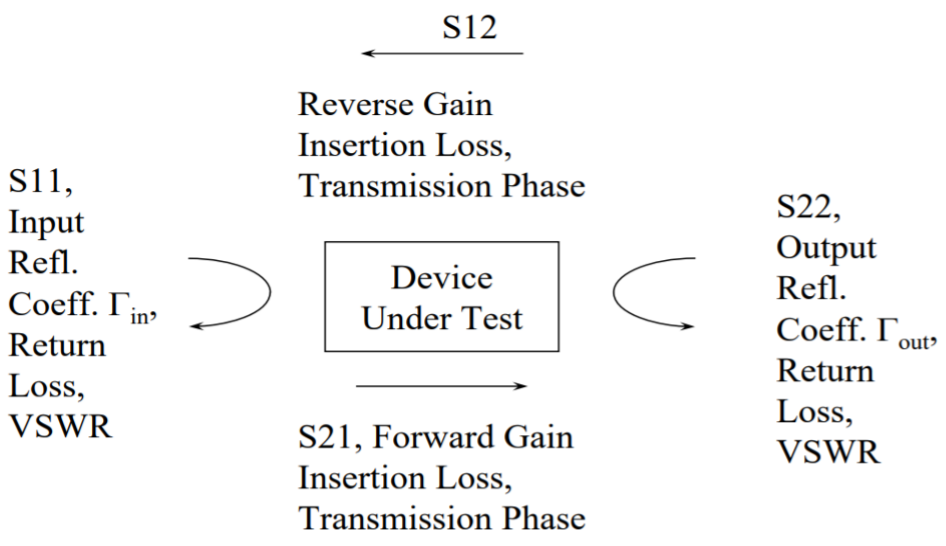


Figure 32: Definitions of four individual S-parameters.

To design an EMI filter and to simulate this filter attach with a noise generator, we did some linear simulation. This linear simulation includes identifying S-parameters of the Common mode choke, and capacitors. We had to measure the S-parameters of the common mode filter and Differential mode filter also. We have used Vector network analyzer to measure all these parameters [23] [24].

The measured S-parameters of the designed common mode filter and differential mode filter are given in Figure 33 and Figure 34.

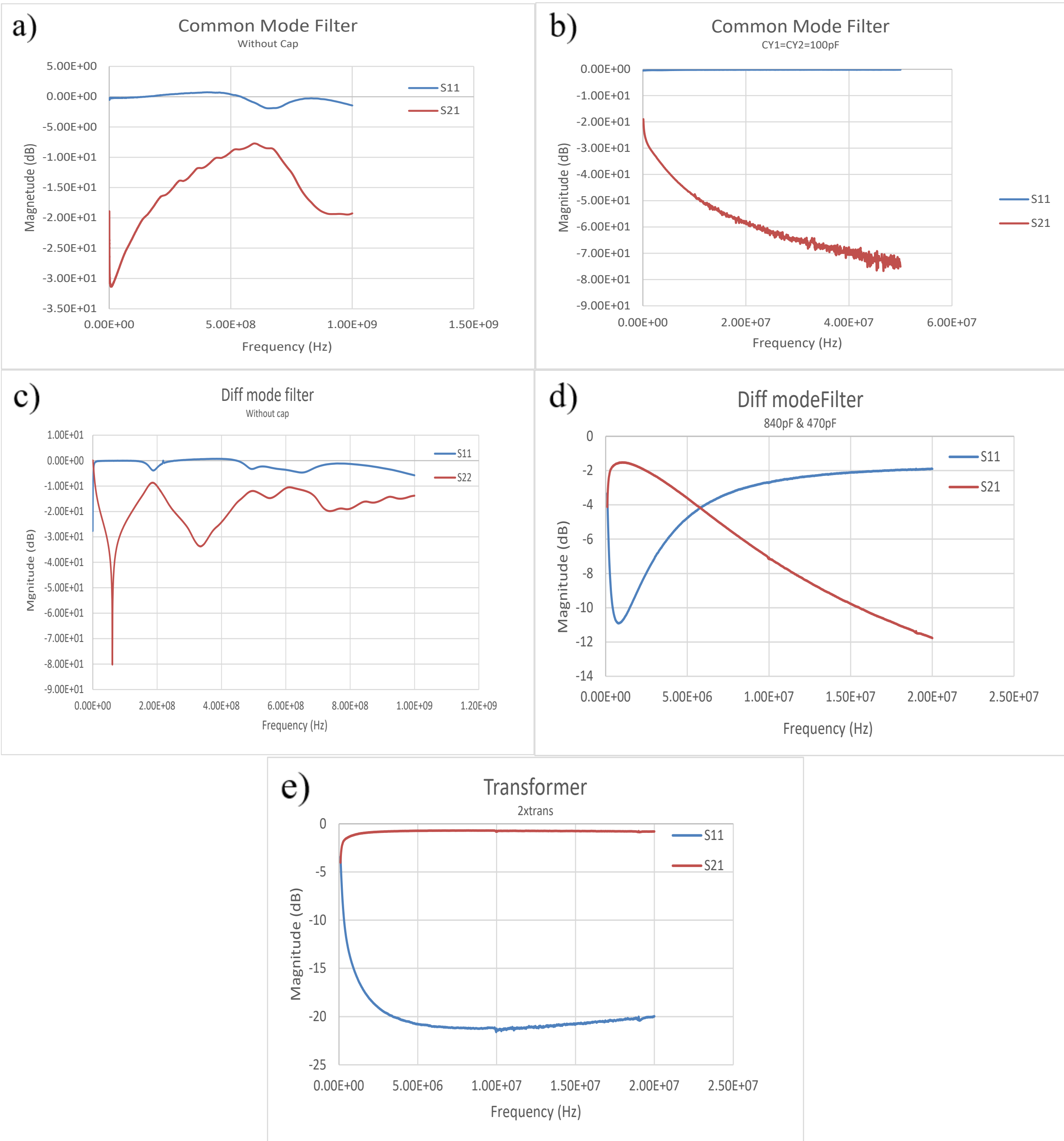


Figure 33: Hardware Measurement of S-parameters of a) Common mode filter with no capacitor; b) Common mode filter with $C_{Y1}=C_{Y2}=100pF$; c) Differential mode filter with no capacitor; d) Differential mode filter with $C_{X1}=840pF$, $C_{X2}=470pF$; d) 2 Transformer.

Comparison between Common Mode Filter and differential mode filter in software and Hardware simulation are countable. Two consideration is taken for this measurement test.

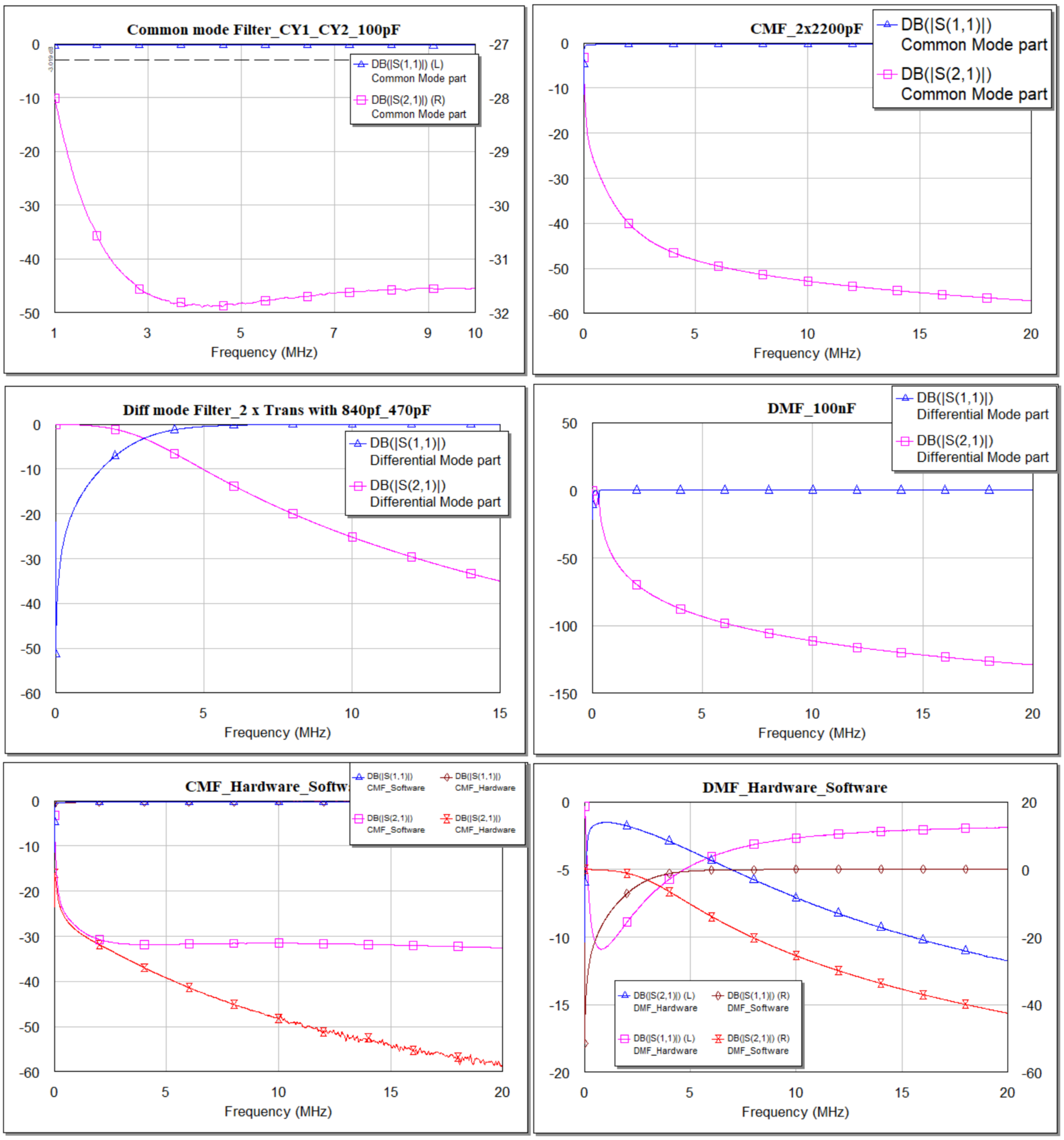


Figure 34: S-parameters measurements of CMF and DMF for 2 set of capacitors and comparison between Hardware and software measured values in dB.

4.1.2 Transfer function analysis

The transfer function is the easiest way to summarize the behavior of the filter. It determines how an output signal is related to the input signal at a specific frequency. A low-pass EMI filter allows low-frequency AC signals to pass a current through the filter circuit. The output coming from the filter will be attenuated, depending on the frequency of the input signal provided. A number of lumped elements are used to construct filter circuit having various characteristics. The transfer function can easily determine from a graph of the output signal at various frequencies and can easily be calculated using Kirchhoff's laws [25] [26].

$$H(f) = \frac{V_{out}(f)}{V_{in}(f)};\ |H(f)| = \left|\frac{V_{out}(f)}{V_{in}(f)}\right|;\ \theta = \arg H(f) \text{ .... (equation: 07)}$$

The input, output voltage and current can be measured using the S-parameters. But for doing this another parameter analysis is used and this parameter analysis is called ABCD parameter matrix. During a signal transmission, many losses can be occurred in the transmission line that decreases the efficiency of the line. All of these parameters are used to minimize the losses. The conversion from S-parameters to ABCD parameters can be followed by the equations 8, equations 9, equations 10, and equations 11.

$$A = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}} \text{ .... (equation: 8)}$$

$$B = Z_0\,\frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}} \text{ .... (equation: 9)}$$

$$C = \frac{1}{Z_0}\,\frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}} \text{ .... (equation: 10)}$$

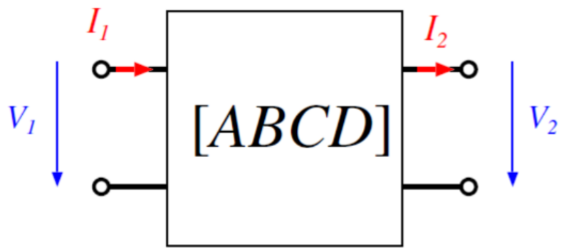
$$D = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}} \text{ .... (equation: 11)}$$

As all the S-parameters are set of data in phasor form, so ultimately we will obtain ABCD matrix in phasor form also. Here Z_0 is called the line impedance which is considered as 50Ω. The voltage and current can be calculated using the following formulas:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \text{ .... (equation: 12)}$$

So, $V_1 = AV_2 + BI_2$ .... (equation: 13)

$I_1 = CV_2 + DI_2$ .... (equation: 14)



When a signal passes through the filter, the filter applies some phase shift to the output signal with respect to the input signal. That means a transfer function is a complex function of frequency, and it contains all the information to determine the magnitude of the output signal and its phase [25] [26].

We can calculate transfer function using ABCD parameter more easily. Where ABCD matrix can be calculated using S-parameter. So, to get the transfer function from the ABCD parameters, we can use the equation 15 where the source impedance and the load impedance both are 50 Ω.

$$H(f) = \frac{V_{out}(f)}{V_{in}(f)} = \frac{Z_L}{AZ_L+B+CZ_SZ_L+DZ_S} \text{ .... (equation: 15)}$$

As ABCD parameters are complex quantities and frequency dependent, the transfer function will also have a complex phase and magnitude as a function of frequency. Putting the value of Z_L and Z_S we can find the value of ABCD parameter and then we can find transfer function as well. As S-parameters are in complex, so we have used MATLAB to solve these solutions and output graphs.

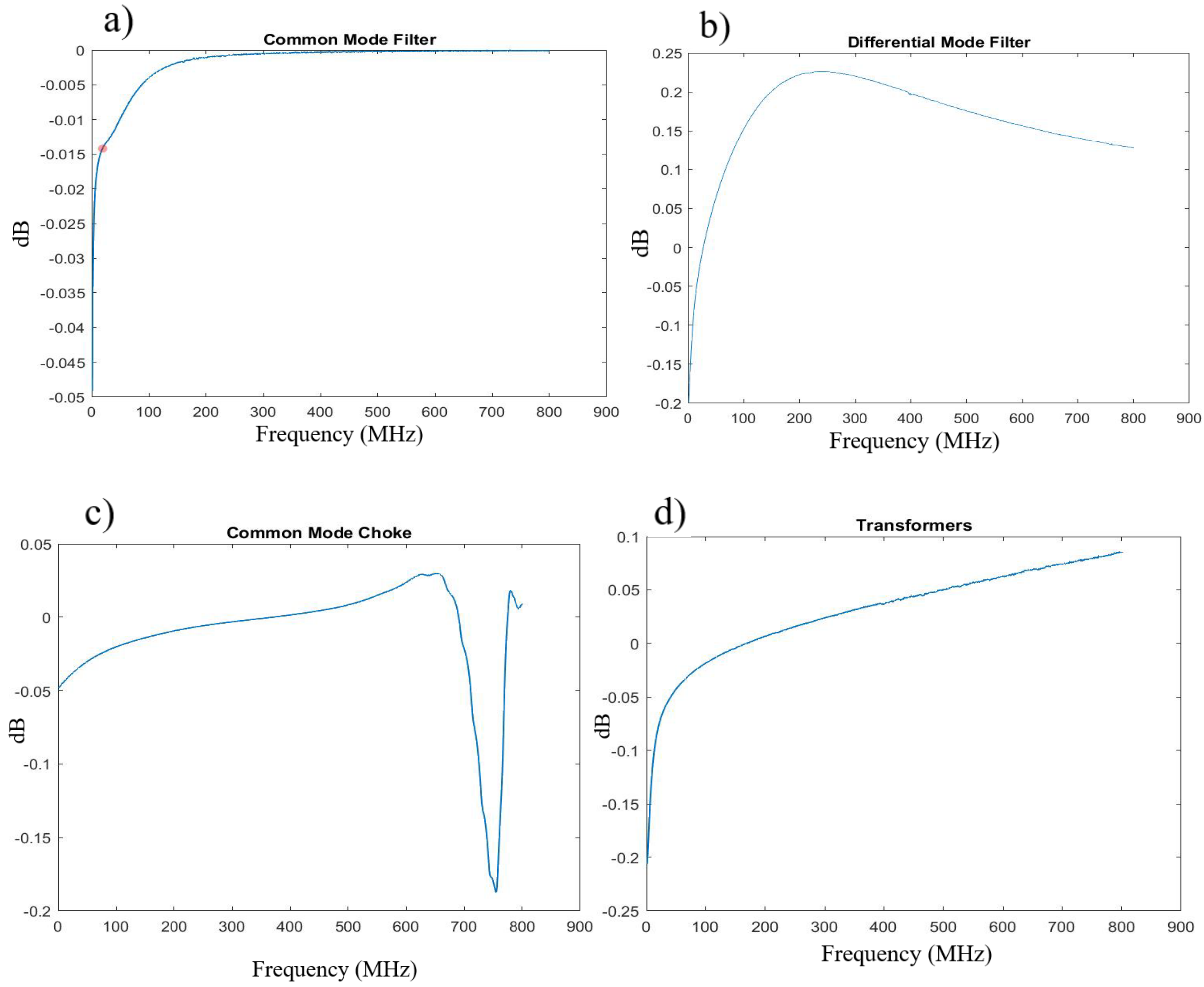


Figure 35: Transfer functions of a) common mode filter, b) differential mode filter, c) common mode choke, d) transformers.

4.1.3 Reflections on transmission lines

A two-port network is referred to as a system network that has two input and two output terminals. Two input terminals are connected with the source and the other two are connected with a load of the circuit. These ports are symmetrical, that is why interchanging these ports does not change the overall properties of transmission. The transmission line is dependent on the dimensions, thickness, spacing of the components that must be very precise and the impedance matching also just because, to minimize the transmitted and reflection power loss. In an RF system, transmission line is indicated by calculating the S-parameters of the entire network. S-parameters are mainly influenced by the characteristic impedance Z_C of the network and also the propagation constant γ [22].

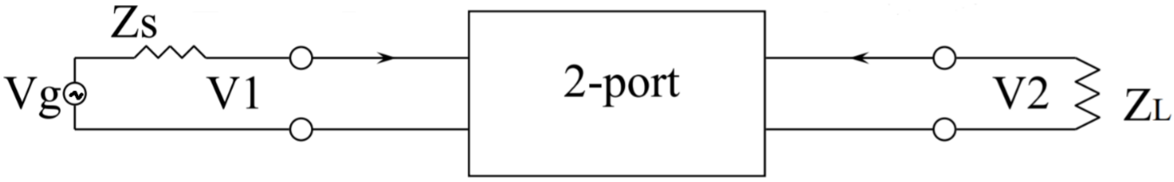


Figure 36: Transmission line of a two-port network

The interchanging of these two-port cannot change the transmission line S-parameters except these three factors:

- Frequency
- Characteristic impedance
- Line geometry

The characteristic impedance Z_C and the propagation constant γ can be calculate by equation 16 and equation 17.

$$Z_C = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \quad \text{(equation: 16)}$$

$$\gamma = \sqrt{(R+j\omega L)(G+j\omega C)} \quad \text{(equation: 17)}$$

Here, R, L, G, and C all are the distributed elements of the transmission line [27].

4.1.3.1 Insertion Loss Measurement

Generally, when a signal is generated and travels through a transmission line to a component or circuit, then the signal losses some power due to the noise or component limitations. While transmitting the RF signal from one port to another port, total amount of loss power is called insertion loss [28].

Insertion loss is the ratio of the output power and the input power. It is measured in decibels (dB) scale. The formula to identify the insertion loss is given bellow:

$$\text{Insertion Loss} = 10\, log_{10}\left[\frac{P_{out}}{P_{in}}\right]\, dB \quad \text{(equation: 18)}$$

Insertion loss can be measured using the S-parameter. It is denoted by S_{21}. So equation 18 can also be written in terms of S-parameter as:

$$\text{Insertion Loss} = -20\, log_{10}|S_{21}|\, dB \quad \text{(equation: 19)}$$

The DM and CM without EMI filter are measured; the required insertion losses (IL_{DM} and IL_{CM}) can be determined by subtracting the emission limit from the measured DM and CM noise levels without filter [29].

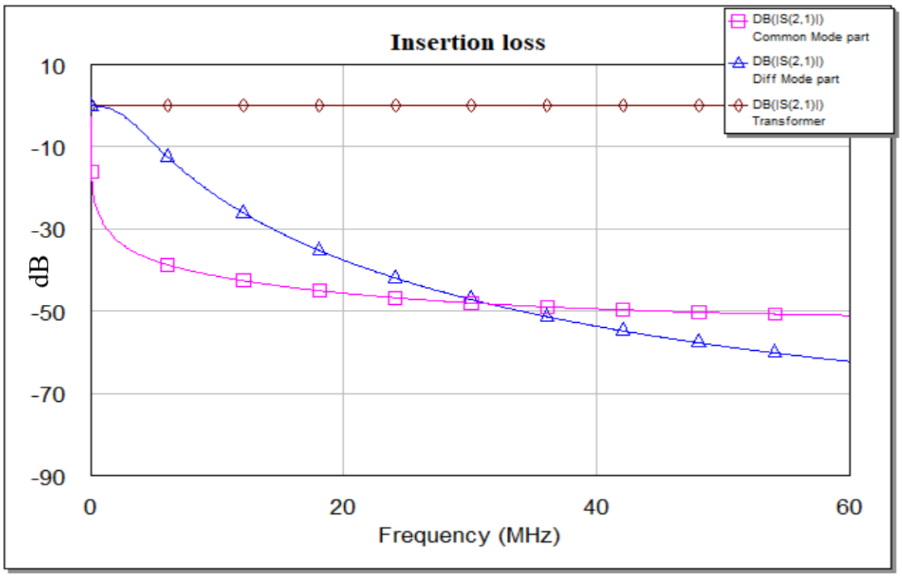


Figure 37: Insertion loss of CM and DM filter in Hardware and Software simulation

4.1.3.1.1 Common Mode Insertion Loss

Common mode insertion loss is the attenuation of a signal applied between the ground and the shorted input terminals. This attenuated signal induces in between the shorted output terminals and the ground.

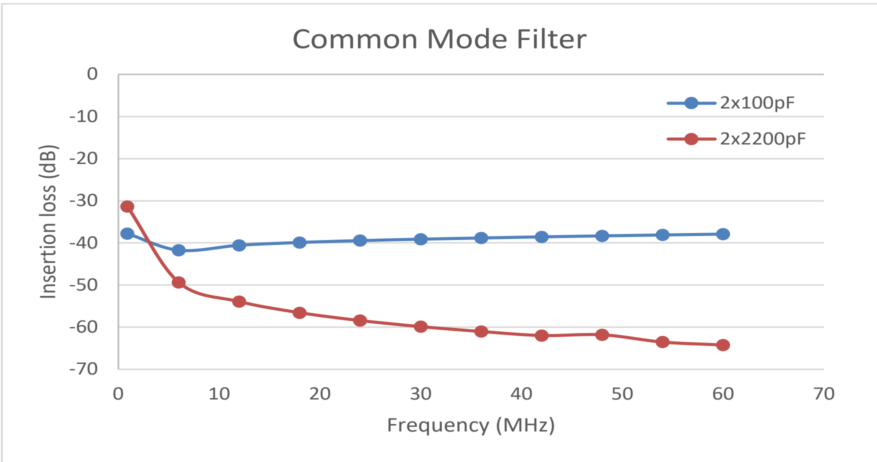


Figure 38: Common mode filter Insertion loss for 2 set of capacitor.

4.1.3.1.2 Differential Mode Insertion Loss

DM insertion loss is also the attenuation of the provided signal to the filter input terminals. The attenuated signal appears across the output terminals.

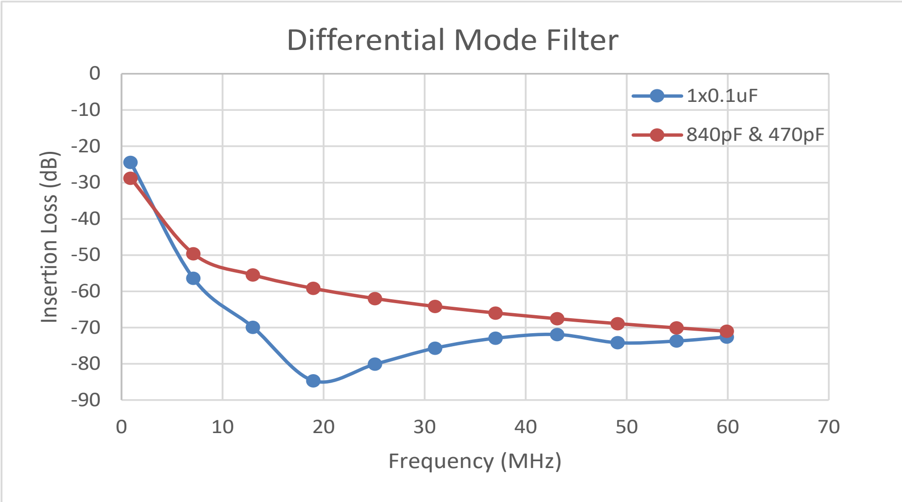


Figure 39: Differential mode filter Insertion loss for 2 set of capacitors

4.1.3.2 Reflection Loss Measurement

When a generated signal is intended to pass through a transmission line, then some of the energy is reflected back to the source. This lost energy is called reflection loss. Reflection loss can be occurred due to the impedance mismatch of the input signal and output signal. This mismatch happens between the cable and the load. Sometimes it happens only for the cables if it becomes damaged or spliced. If this loss becomes higher, then a very low amount of energy is transmitted. A large amount of reflection loss sometimes damages internal components.

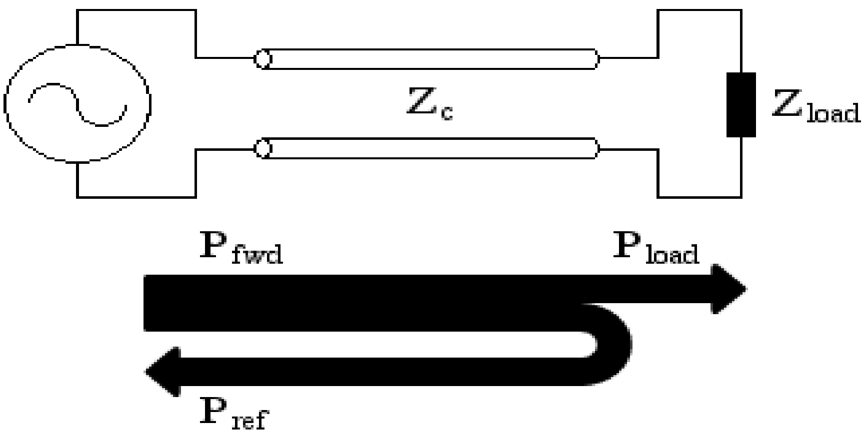


Figure 40: Power is reflecting to the source

We can measure the reflection loss in terms of signal power if we know the forwarding power and the reflected power.

Reflection Loss = $10\ log_{10}\left[\frac{P_{reflected}}{P_{incident}}\right] dB$ .... (equation: 20)

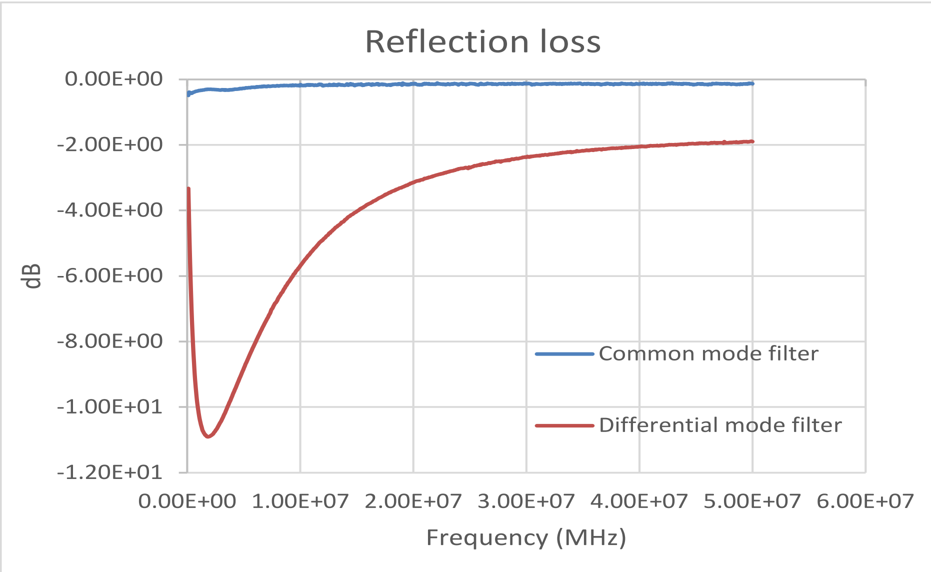
From the S-parameters of the transmission line we can easily calculate reflection loss by the equation below

$$\text{Reflection Loss} = |S_{11}|$$

There is a difference between return loss (RL) and the reflection coefficient S_{11} which is very minor. RL in dB is $10log_{10}\left[\frac{P_{incident}}{P_{reflected}}\right]$. So the relation between return loss and reflection loss is,

$$\text{Reflection Loss (dB)} = - \text{Return loss (dB)}$$

In our EMI filter design work we have measured reflection loss both of the common mode filter and differential mode filter in hardware and software platforms on dB scale [30].



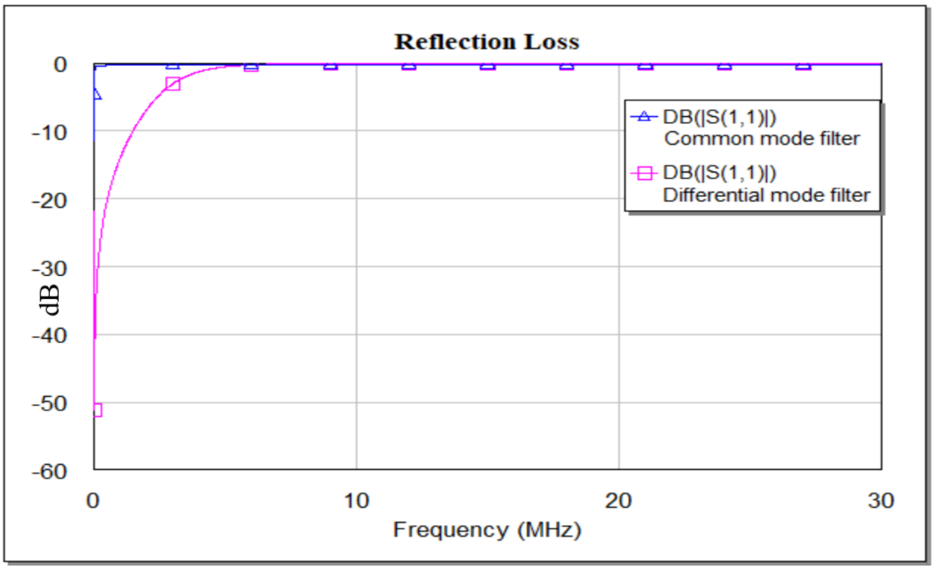


Figure 41: Reflection loss of common mode filter and differential mode filter.

4.2 Nonlinear Behaviour

A periodic signal can be represented both in the time or frequency domain. When such a signal drives a device into its nonlinear region, the shape of the waveform is distorted in such a way that it cannot be described simply by applying a scaling factor to the input signal. In the frequency domain, this behavior can be represented by changes to the harmonic and intermodulation spectral components as functions of the changing boosts and terminal impedances. The harmonic distortion model is fundamentally dependent on frequency-domain measurements. It is identified from the responses of Equipment under test (EUT). This EUT is inspired by a set of discrete tones, where these tones are relatively small. For this reason, the principle of harmonic superposition may be applied correctly.

4.2.1 Harmonic Balance Techniques

Now a day's harmonic balance (HB) algorithm is very common to solve nonlinear networks. The HB algorithm splits the main circuit into two sub-circuits, a linear sub-circuit and a nonlinear sub-circuit. It is also called frequency domain method for identifying the steady state. A sinusoidal signal is applied to a nonlinear component in the system. That signal will generate harmonics of the fundamental frequency in a certain range. With the fundamental simulation frequency (known as input tone), number of harmonic tones required for accurate representation of the nonlinear distortion. For a single tone HB solver only single frequency analyses such as Vin/Vout, Pin/Pout, are performed. With multi tone, the analyses can include the inter-modulation distortion. With the number of tones defined the HB solver splits the circuit into two sub-groups, linear and nonlinear, and proposes a set of voltages at the interface of these subgroups. These set of voltages are defined in the frequency domain. The voltages are firstly transmitted to the time domain and applied across the nonlinear models and then converted to the frequency domain again. If the simulation is to be conducted over a frequency range, then the sources should be appropriately updated and the algorithm should be repeated until the frequency set is covered.

4.2.2 Time-Domain Analysis

The best way to find out how a filter will perform is through simulation is time-domain simulation. It is a recently proposed technique that represents the response and simulates in time-domain waveforms. This technique is essential for finding signal distortion due to device nonlinearity. The time-domain solution is converted into the frequency-domain via fast Fourier transform (FFT).

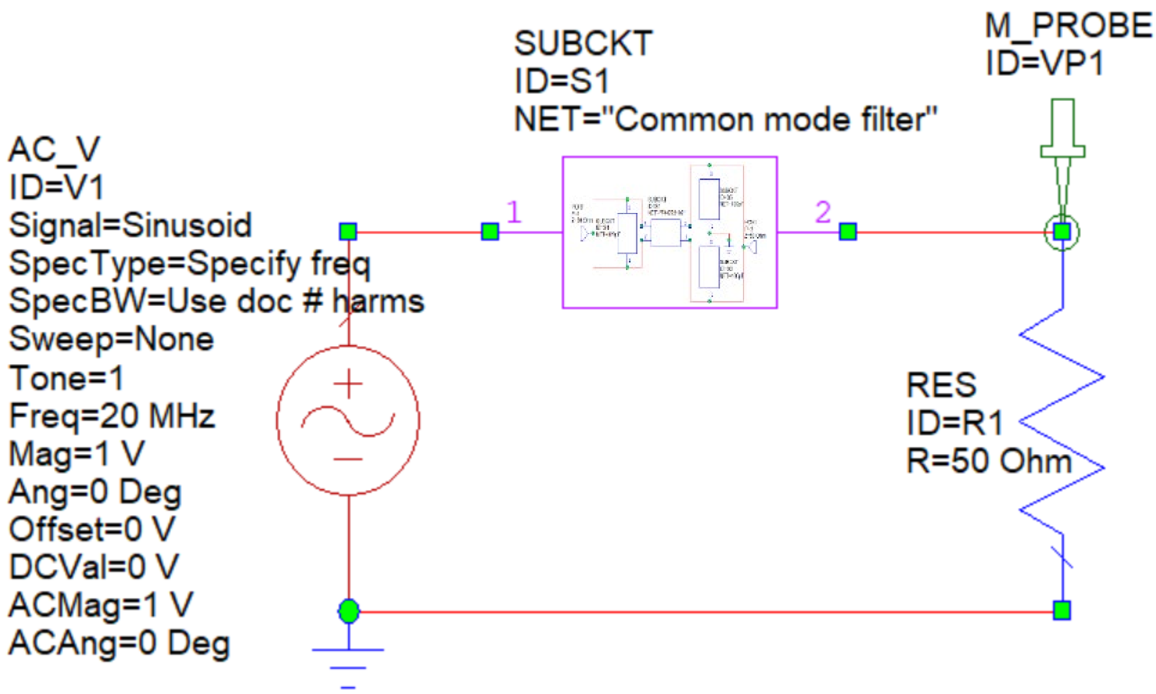
According to the continuity equation, the nonlinear currents are equal to the linear currents. The repeatedly done process of misbalancing the currents between the linear and nonlinear network nodes can make the simulation time lengthy and sometimes it may fail to converge [31].

4.2.2.1 Voltage analysis

The best way to find out how a filter will perform is through simulation is time-domain simulation. It is a recently proposed technique that represents the response and simulates in time-domain waveforms. This technique is essential for finding signal distortion due to device nonlinearity. The time-domain solution is converted into the frequency-domain via fast Fourier transform (FFT). According to the continuity equation, the nonlinear currents are equal to the linear currents. The repeatedly done process of misbalancing the currents between the linear and nonlinear network nodes can make the simulation time lengthy and sometimes it may fail to converge

As the entire filter is divided into two part according to the level of noise induced so every measurement divided systematically.

4.2.2.1.1 Common Mode measurement



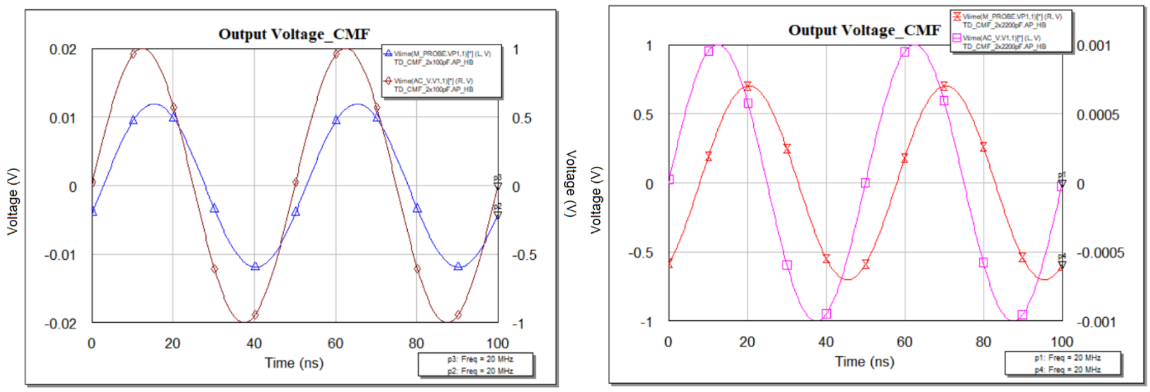


Figure 42: Common mode voltage measurement in time domain using different capacitor.

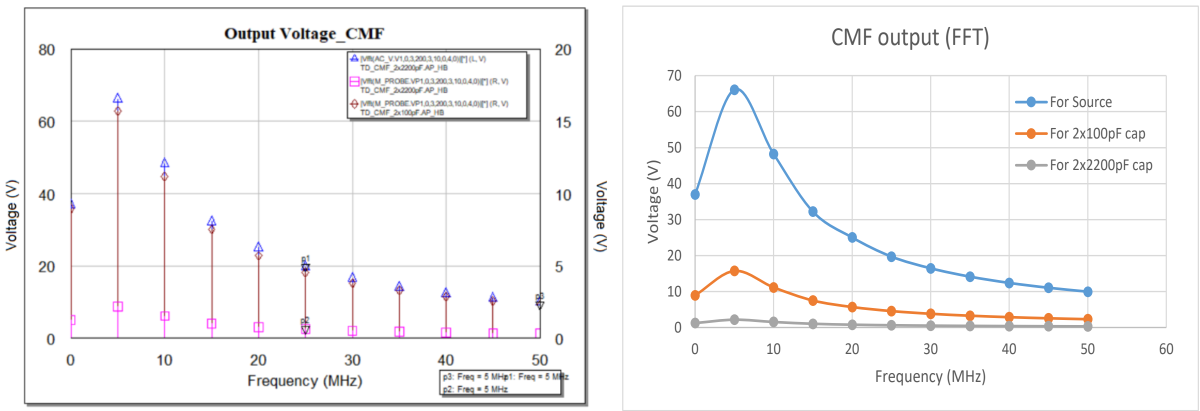


Figure 43: CM voltage measurement in Frequency domain using different capacitor

Observation

Looking deeper into this circuit, however, it has a single sinusoidal source. According to the basic structure of a common mode, the signal is passing through both line and neutral. Due to the common mode choke the voltage is decreasing and at the output, we are getting low voltage. In the Figure 43, two sets of capacitors were being used as the Y cap. Where for the set of 100pF cap the voltage drop across the load is lower than the set of 2200pF. We can easily observe the result in FFT domain simulation.

4.2.2.1.2 Differential mode measurement

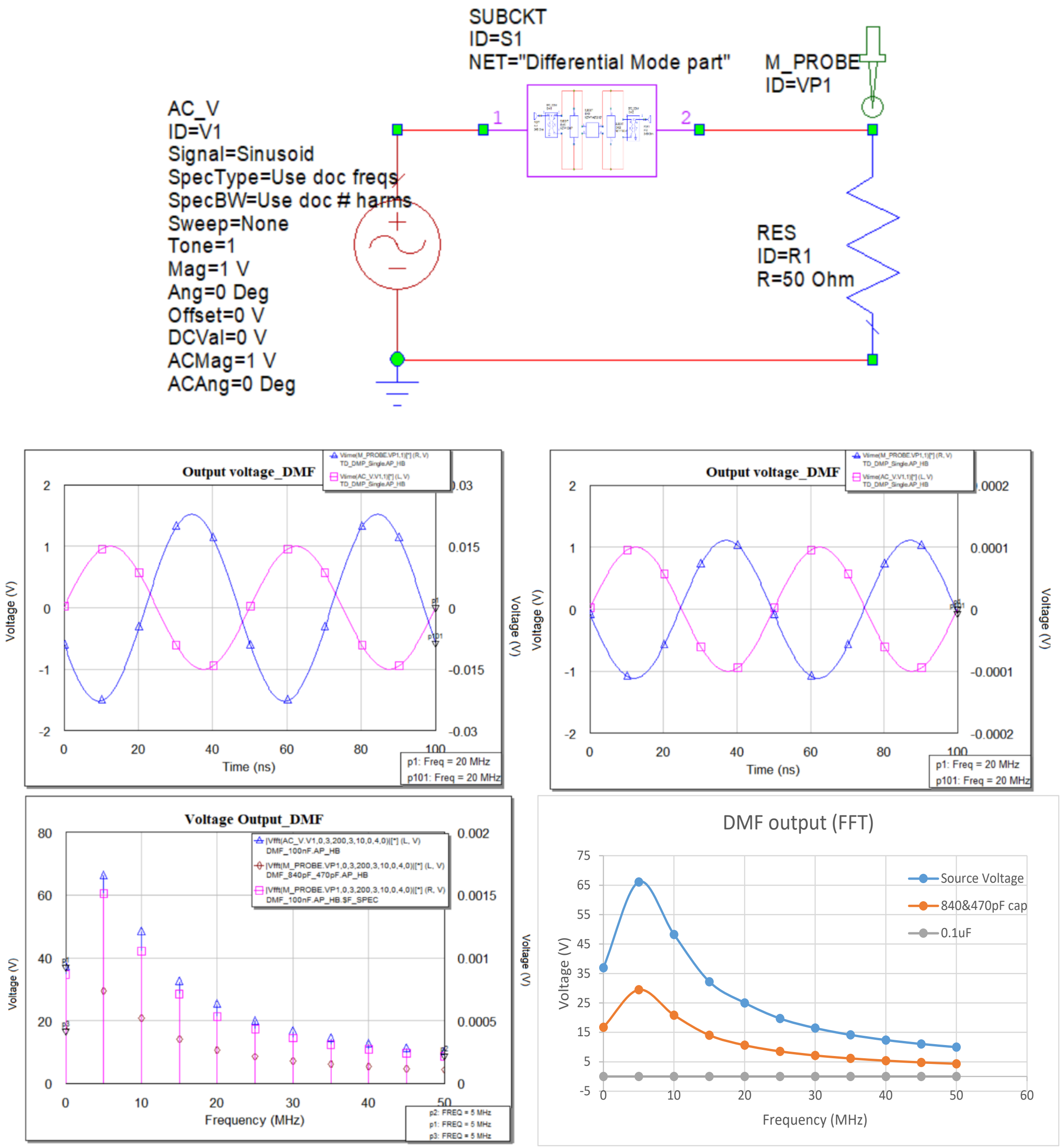


Figure 44: Differential mode voltage measurement in time and frequency domain using different capacitor

Observation

Differential mode noise is generated due to the source and common mode leakage inductance. We have use two set of capacitor where the maximum voltage drop can easily observe for set of 0.1uF in the load.

4.2.2.2 Multi-tone Analysis

Now as an advanced technique multi-tone analysis is commonly used for testing electronic devices whether it can be passive devices like filters or active devices like amplifiers. This test is done for nonlinear behavior devices, in this report we have applied this test to a linear device like an Electromagnetic interference filter (EMI). Multi-tone testing uses a number of tones to test equipment under test (EUT) and this technique is more efficient compared to single tone and two-tone testing. This test stands for an operation of generating multi-tone signals consisting of a summation of sine waves. These sine wares are other than input signal waves, connected to the EUT. Spectrum analyzer obtains the frequency response of EUT by analyzing. Only devices are accepted that satisfy the determined specification by calculating a crest factor (CF) which is the ratio of the peak amplitude of the waveform and the RMS value. [32].

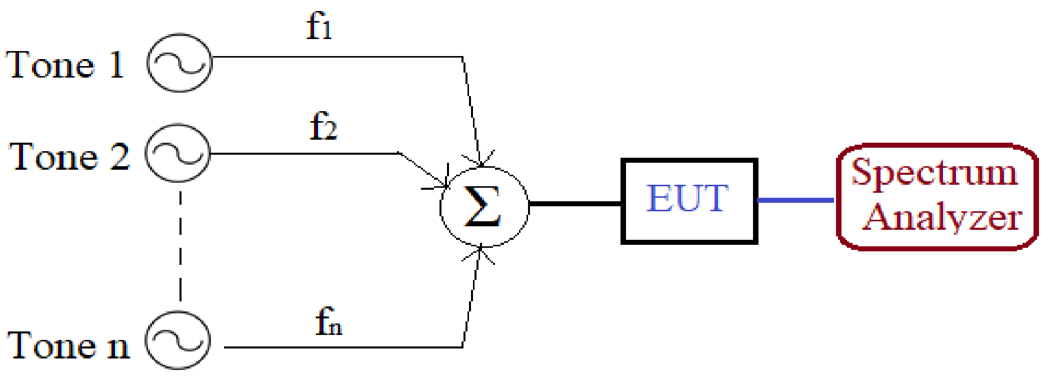
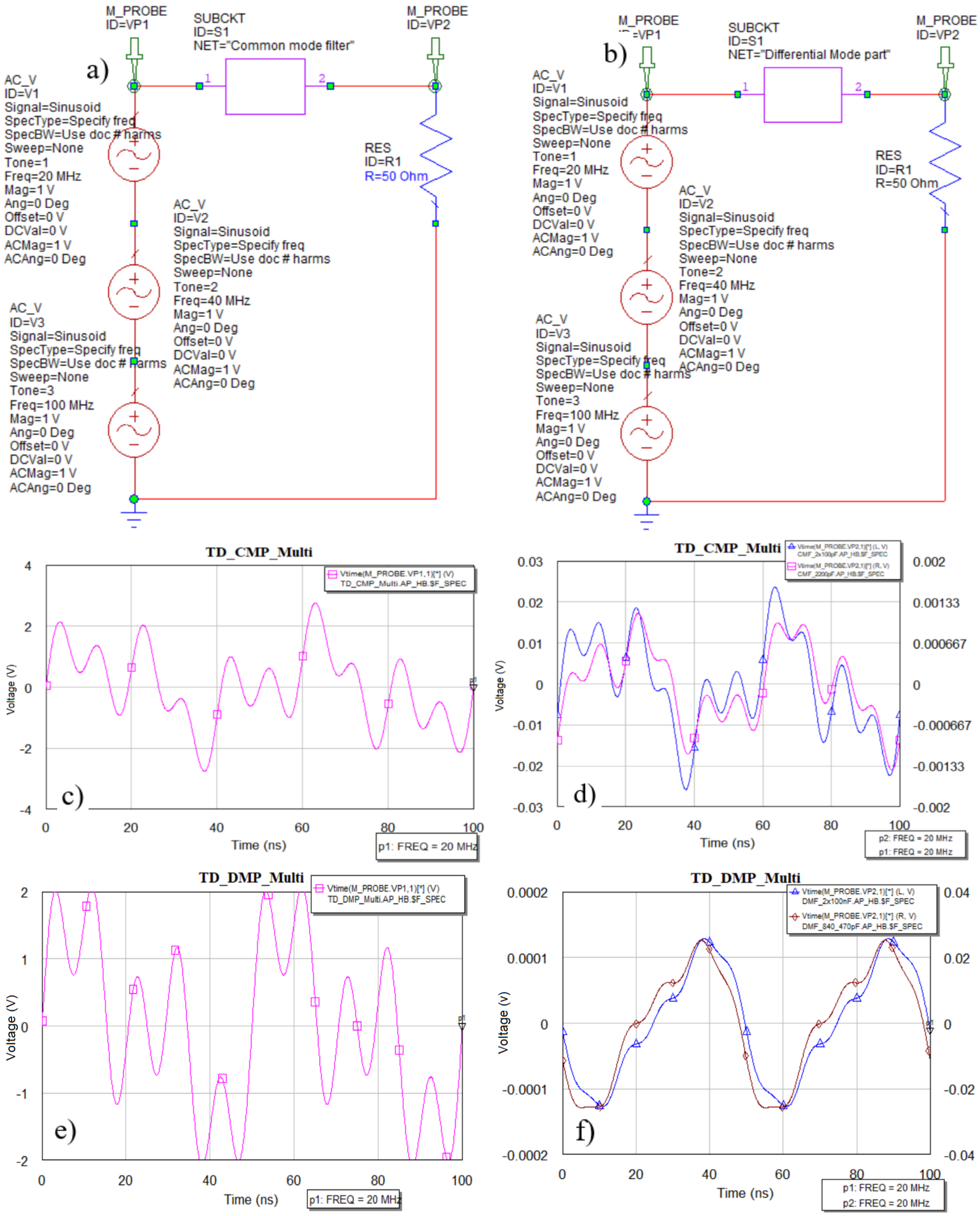


Figure 45: Multi tone measurement process

Sinusoid signal’s amplitude and phase changes will not be considered as distortion. However, complex, time-varying signal can change the amplitude and phase shifts dramatically that distorts the time domain waveform. In a nonlinear device, input signal can be shifted in frequency domain and create new output signal in the form of harmonics. For doing the test we have used three sinusoidal signals in the input and easily it can be seen that the output signal is generated in the form of harmonics with different order [33].



a)
M_PROBE
ID=VP1
SUBCKT
ID=S1
NET="Common mode filter"
M_PROBE
ID=VP2
AC_V
ID=V1
Signal=Sinusoid
SpecType=Specify freq
SpecBW=Use doc # harms
Sweep=None
Tone=1
Freq=20 MHz
Mag=1 V
Ang=0 Deg
Offset=0 V
DCVal=0 V
ACMag=1 V
ACAng=0 Deg
RES
ID=R1
R=50 Ohm
AC_V
ID=V2
Signal=Sinusoid
SpecType=Specify freq
SpecBW=Use doc # harms
Sweep=None
Tone=2
Freq=40 MHz
Mag=1 V
Ang=0 Deg
Offset=0 V
DCVal=0 V
ACMag=1 V
ACAng=0 Deg
AC_V
ID=V3
Signal=Sinusoid
SpecType=Specify freq
SpecBW=Use doc # harms
Sweep=None
Tone=3
Freq=100 MHz
Mag=1 V
Ang=0 Deg
Offset=0 V
DCVal=0 V
ACMag=1 V
ACAng=0 Deg
b)
SUBCKT
ID=S1
NET="Differential Mode part"
RES
ID=R1
R=50 Ohm
TD_CMP_Multi
Voltage (V)
Time (ns)
c)
p1: FREQ = 20 MHz
d)
p2: FREQ = 20 MHz
p1: FREQ = 20 MHz
TD_DMP_Multi
e)
f)
Voltage (v)

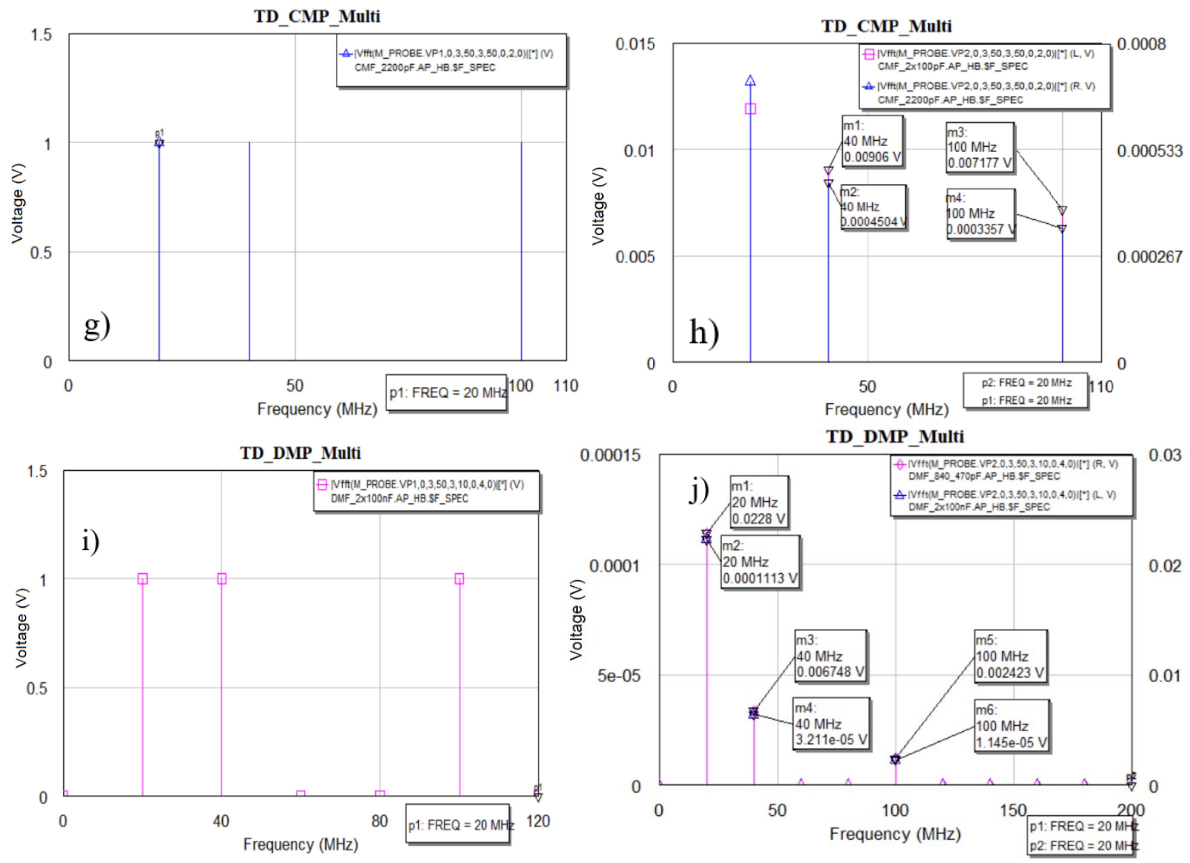


Figure 46: Multi tone a) CM filter schematic, b) DM filter schematic, c)CM input signal TD response, d) CM output signal TD response using 2x100 and 2x200pf cap DM input signal TD response, f) DM output signal TD response of 100nF and 840,470pf cap, g) CM input signal FD response h) CM output signal FD response using 2x100 and 2x200pf cap, i) DM input signal FD response, j) DM output signal FD response of 100nF and 840,470pf cap

4.2.2.3 Power analysis

Frequency (MHz)	Noise power (dBm)	Output power (no cap) dBm	Output power (2X100pF) dBm	Output power (2X2200pF) dBm
12	-18.50	-48.6	-52.7	-75.2
36	-18.50	-50.3	-52.1	-78.1
60	-19.5	-42.8	-60.6	-86.4
84	-20.3	-48.3	-58.1	-85.2
108	-22.6	-44	-65.3	-90.5
132	-22.9	-53.7	-70.8	-92.8
156	-23.5	-51.1	-67.5	-84.3
180	-26.1	-46.3	-69.6	-83.0
204	-27.8	-47.3	-67.7	-78.1
228	-29.6		-74.0	-81.2

Table 01: Hardware measurement of CMF with 2 set of capacitors

Frequency (MHz)	Noise power (dBm)	Output power (no cap) dBm	Output power (1X100nF) dBm	Output power (820pF &470pF) dBm
12	-18.50	-24.6	-49.1	-29.5
36	-18.50	-35.6	-51	-47.6
60	-19.5	-33.8	-44.9	-59.6
84	-20.3	-38.6	-47.3	-48.1
108	-22.6	-33.7	-41.3	-48.2
132	-22.9	-41.1	-47.9	-45.2
156	-23.5	-31.3	-37.3	-37.9
180	-26.1	-30.4	-34	-31.1
204	-27.8	-30.8	-34.4	-33.9
228	-29.6			

Table 02: Hardware measurement of DMF with 2 set of capacitors

Figure 47: a) Hardware simulation for CM filter, b) Hardware simulation for DM filter

Frequency (MHz)	Noise power (dBm)	Output power (no cap) dBm	Output power (2X100pF) dBm		Output power (2X2200pF) dBm	
			Sym com	real com	Sym com	real com
12	-18.46	-54.03	-56.02	-65.36	-78.37	-78.32
36	-18.46	-51.08	-59.02	-63.58	-85.31	-85.79
60	-19.46	-49.77	-61.67	-63.56	-88.58	-93.14
84	-20.24	-48.44	-63.13	-63.7	-92.7	-97.99
108	-21.1	-47.32	-64.12	-64.31	-96.25	-112.1
132	-22.85	-47.52	-66.05	-66.38	-103.1	-97.47
156	-23.47	-46.74	-66.74	-67.25	-113.7	-91.5

180	-26.08	-48.14	-69.57	-70.34	-105.8	-89.75

Table 03: Software measurement of CMF with 2 set of capacitors

Frequency (MHz)	Noise power (dBm)	Output power (no cap) dBm	Output power (1X100nF) dBm		Output power (820pF &470pF) dBm	
			sym com	real com	sym com	real com
12	-18.46	-37.53	-33.59	-39.71	-43.07	-42.61
36	-18.46	-45.77	-62.45	-65.51	-59.07	-57.65
60	-19.46	-49.01	-69.25	-70.41	-63.94	-61-94
84	-20.24	-49.82	-71.29	-73.2	-61.14	-57.63
108	-21.1	-49.33	-71.37	-74.71	-54.47	-61.0
132	-22.85	-49.01	-71.36	-73.88	-70	-73.52
156	-23.47	-46.61	-69.17	-71.25	-74.39	-78.23
180	-26.08	-45.16	-67.87	-69.77	-77.35	-81.99

Table 04: Software measurement of DMF with 2 set of capacitors

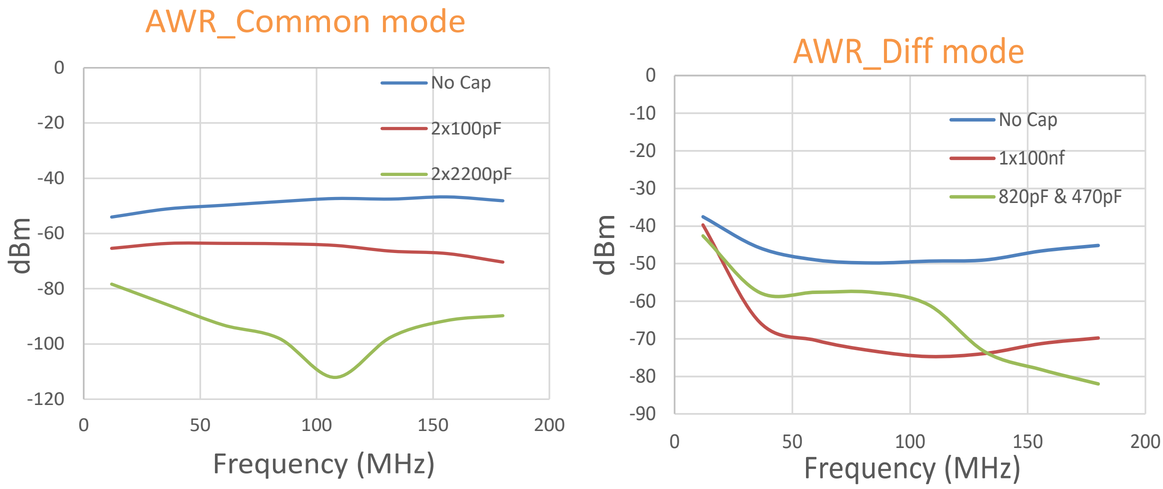


Figure 48: a) Software simulation for CM filter, b) Software simulation for DM filter

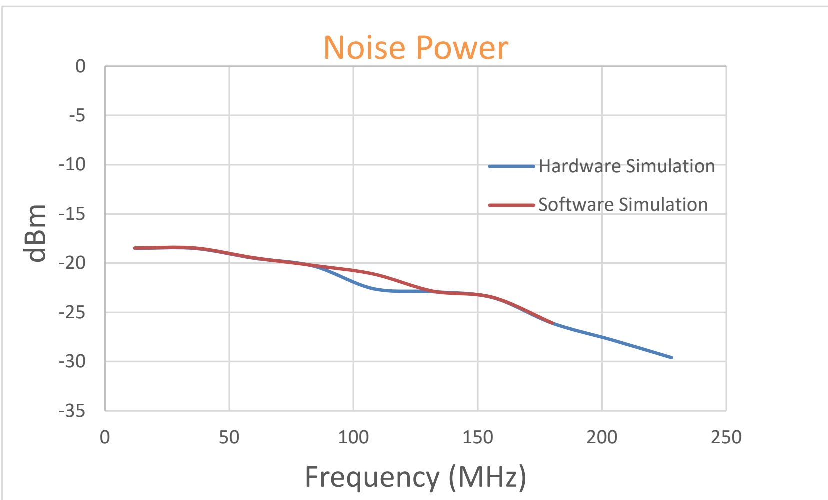
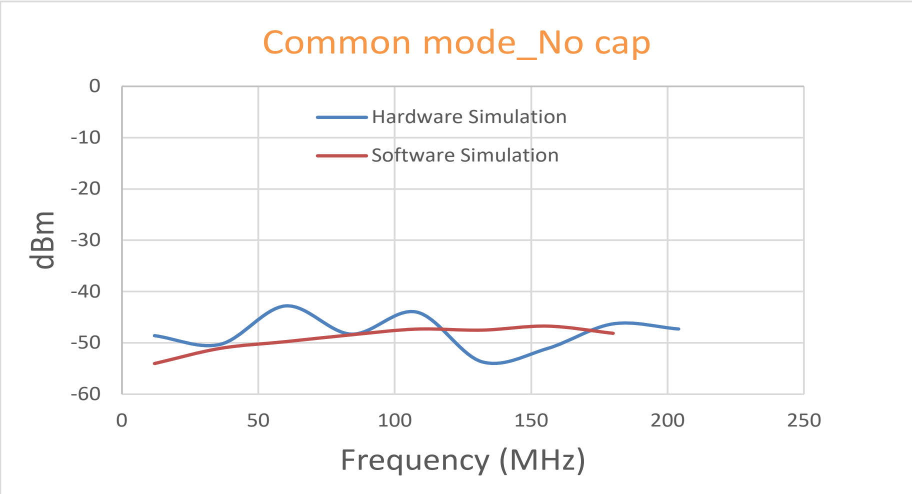
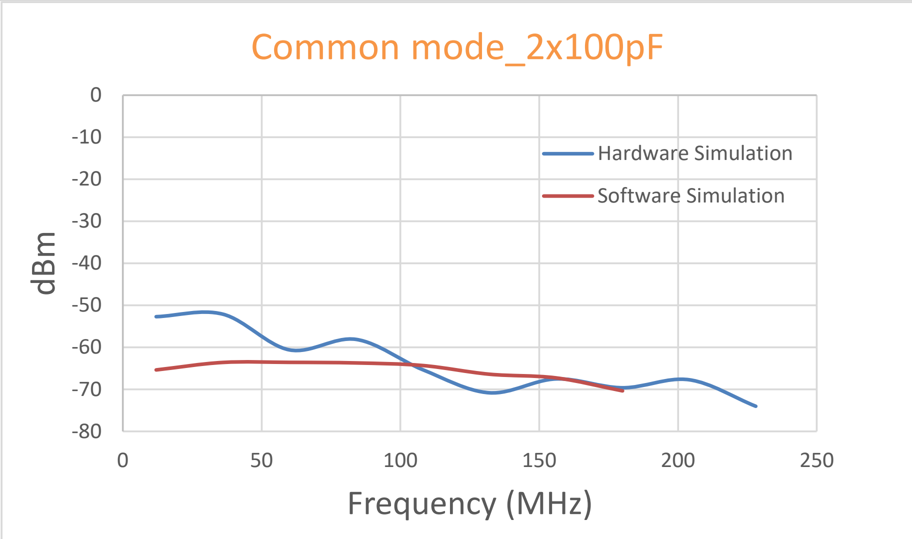


Figure 49: Noise power for both filter both in Software and Hardware platform

4.2.2.4 Measurement Comparison

4.2.2.4.1 Common Mode Filter





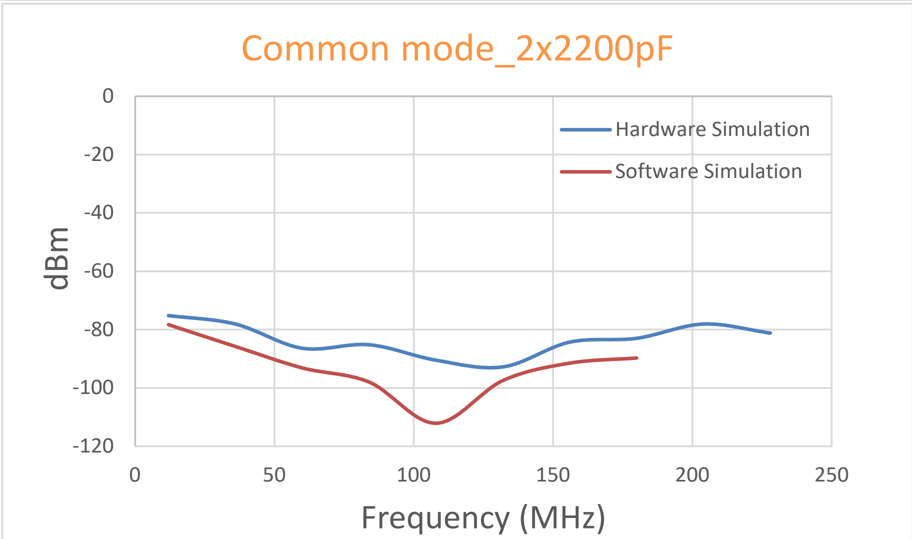
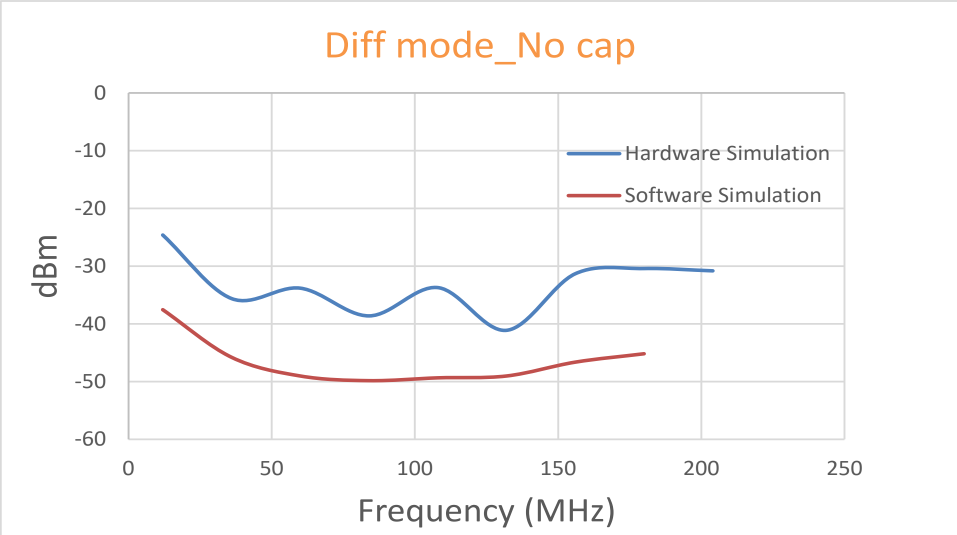
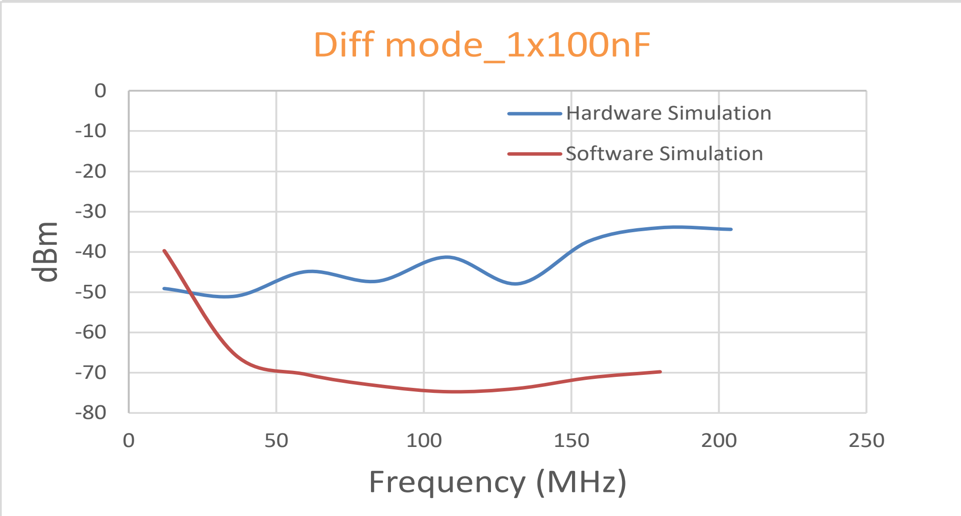


Figure 50: Comparison between Hardware and Software simulation with different components.

4.2.2.4.2 Differential Mode Filter





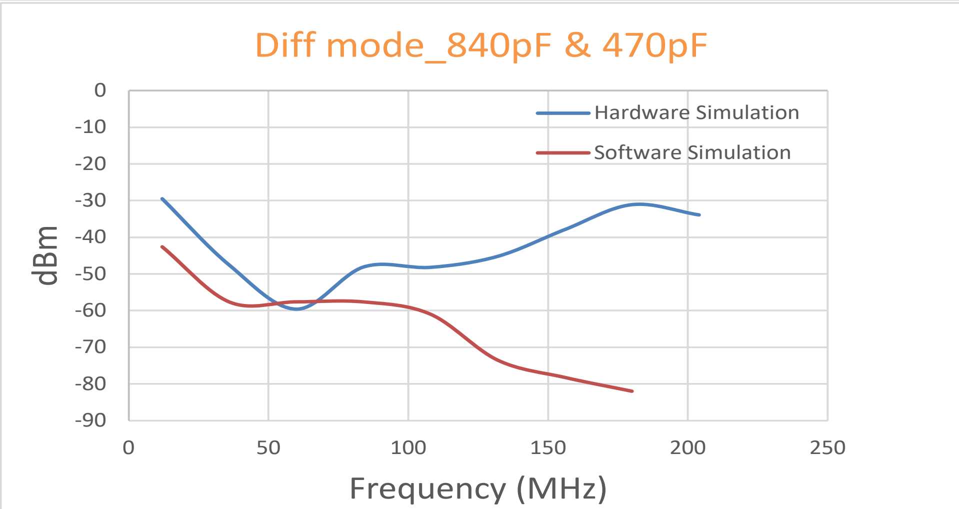


Figure 51: Comparison between Hardware and Software simulation with different components.

Discussion

An Electromagnetic Interference (EMI) filter is consist of two basic part which are the Common mode part and the Differential Mode part. These two-part can be implemented individually considering all the parameters and simulation process in an equal manner. In this thesis work, we have implemented these two basic parts of an EMI filter and tested the variation in frequency domain replacing the parasitic components (capacitors). For a common mode part, the hardware and software testing has been considered following three criteria.

- Considering the common mode choke as a common mode filter
- Considering the parasitic components value as they are being used in the market
- Considering the parasitic components value focusing only on the trigger point.

Chapter Five. Result Estimation and Discussion

5.1 Case Study 1: 230V 50Hz line

A common mode power line choke will be used to perform this case study where the inductance value is 2.2 mH and the rated voltage is 250V at 50Hz. We are going to take the linear and nonlinear measurements using the same EMI filter standard design we have previously used. The same X and Y capacitor set will be used to observe the variety of responses both in frequency and time domain. A different common mode choke is used to complete the case.

5.1.1 Linear operation

In the linear operation the insertion loss will be measured both in common mode filter and differential mode filter using 2 set of capacitors. The results will be compared for both cases.

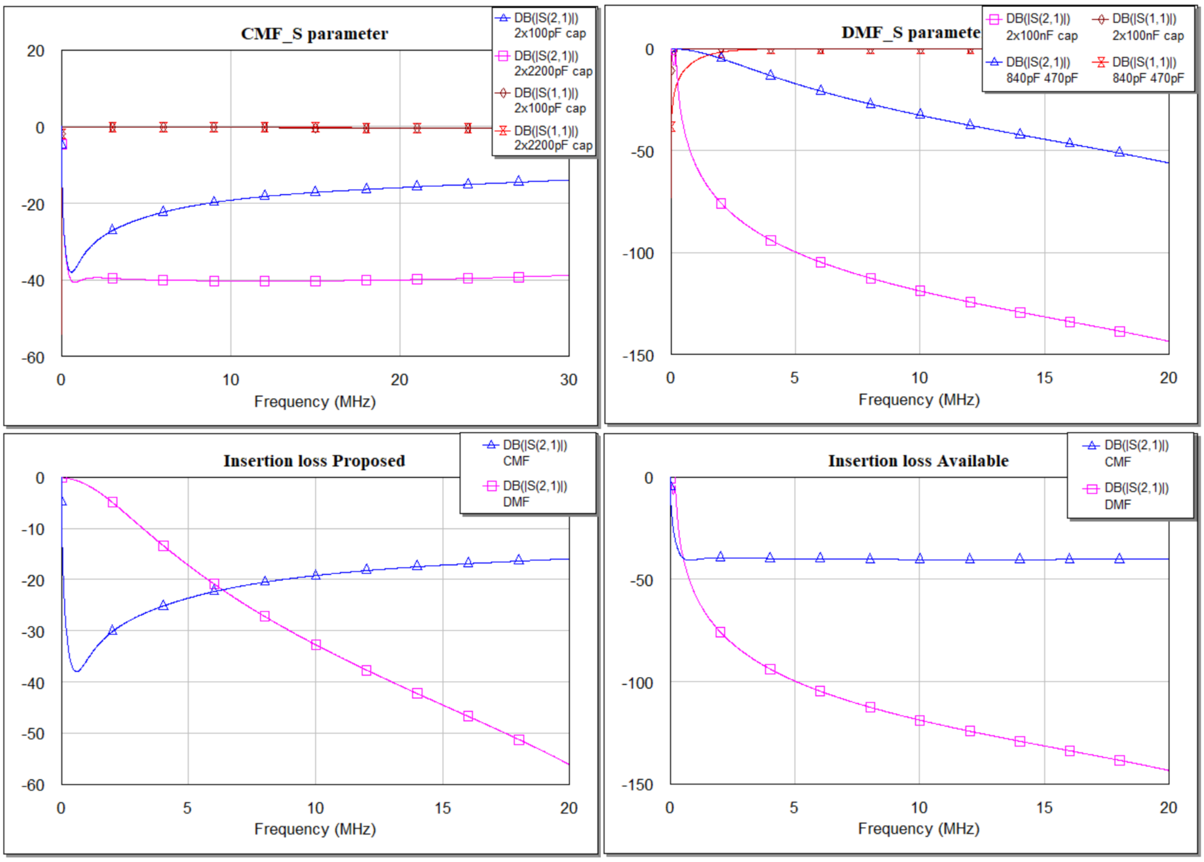


Figure 52: a) CMF s-parameters (s11, s21) for both 2x100pF cap and 2x2200pF cap
b) DMF s-parameters (s11, s21) for both 2x100nF cap and 840pF & 470pF cap
c) Comparison between CMF & DMF insertion loss (proprsed-2x100pF & 840,470pF)
d) Comparison between CMF & DMF insertion loss (available-2x2200pF & 2x100nF)

5.1.2 Nonlinear operation

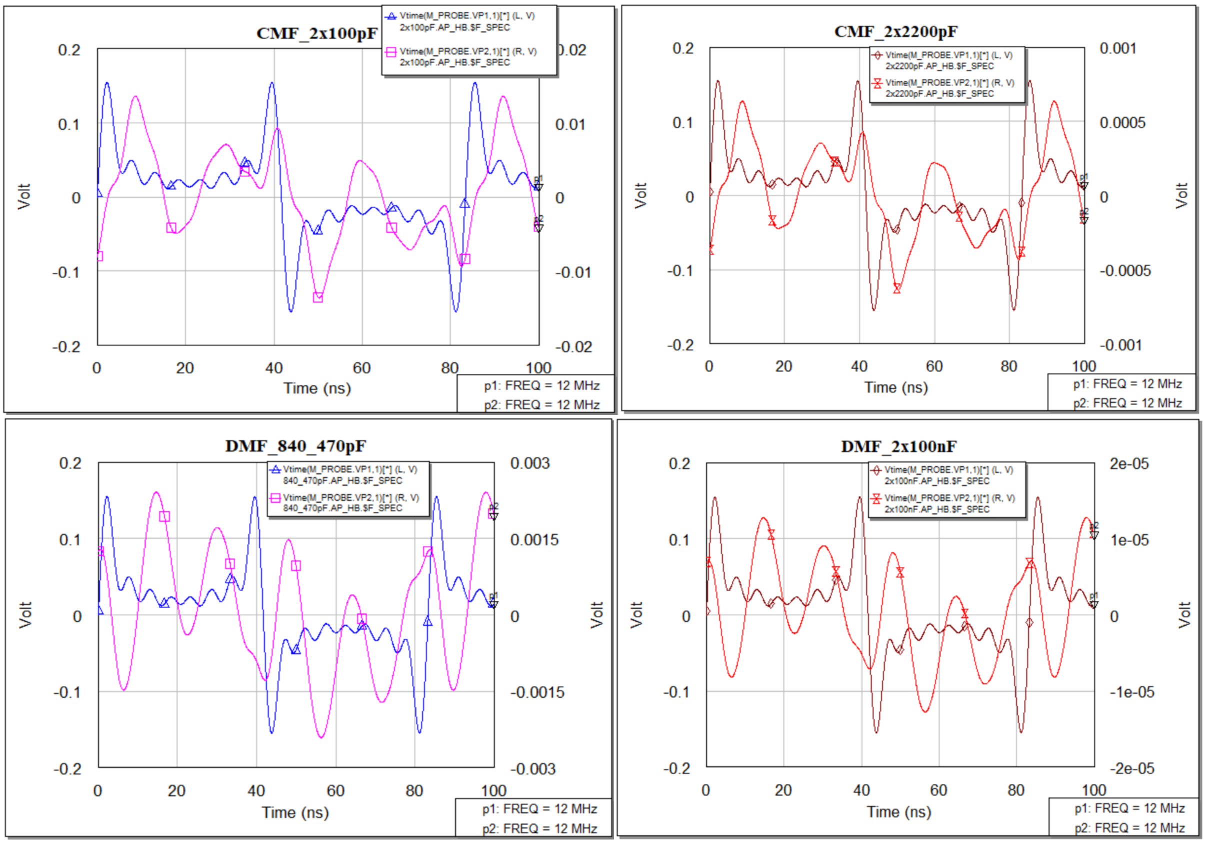
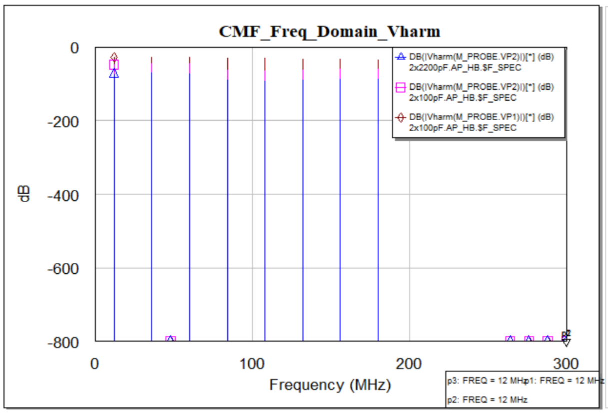
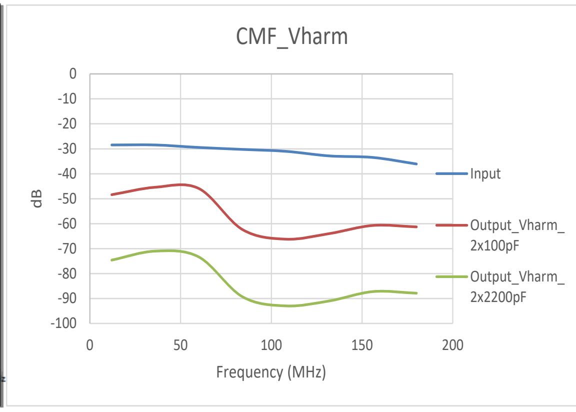


Figure 53: Time domain response of input and output CMF & DMF for 2 set of capacitor





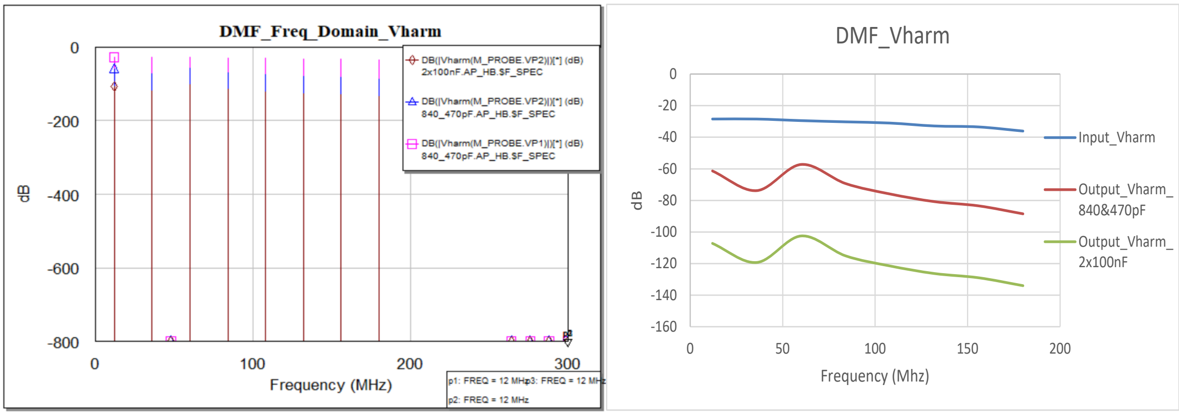


Figure 54: Frequency domain response of input and output harmonic voltage of CMF & DMF for 2 set of capacitors.

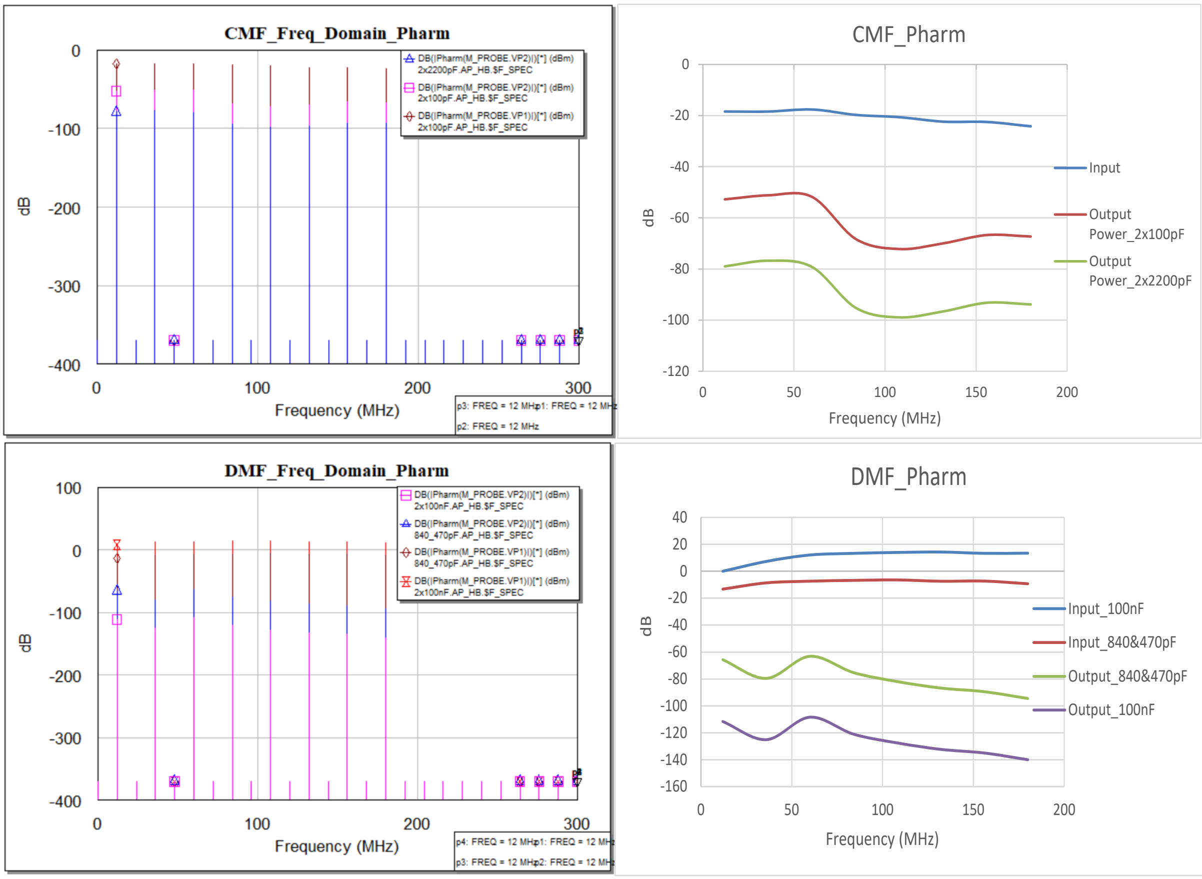


Figure 55: Frequency domain response of input and output harmonic power of CMF & DMF for 2 set of capacitors.

5.2 Case Study 2: Experimental Examples

5.2.1 USB cables

Universal Serial Bus is the standard that is invented for the purpose of interfacing with computers and some other electronic devices. The latest version of this standard is USB 3.0. The transfer speed is very high and that is why this cable is very common at present.

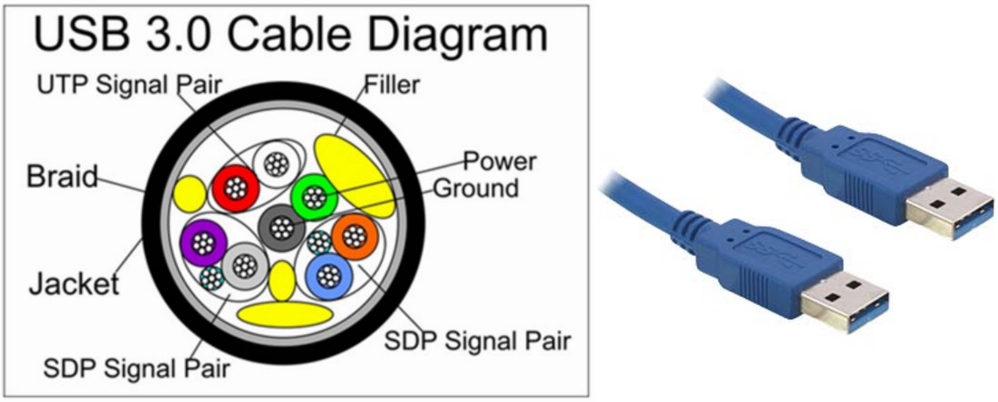
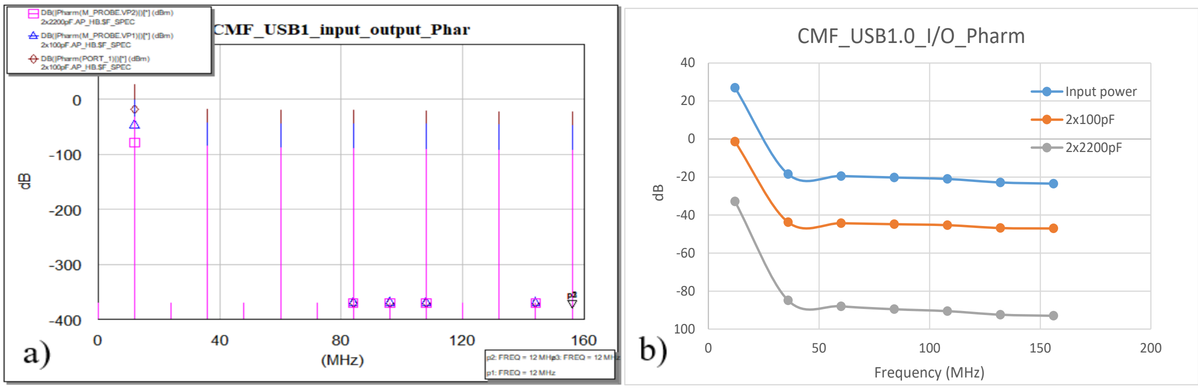


Figure 56: USB 3.0 cable and its core layout

All the USB cables deliver 5 volts of electricity only when it is connected with a high-performance device it can deliver a maximum of 12 Volts. The frequency range of the USB standard is 480MHz to 960MHz. But as USB 1.0 operate at a maximum of 12 MHz frequency and the voltage range is 5 volts so we will approach the nonlinear measurement of USB 1.0.

5.2.1.1 Components selection

Since the power supply can produce both common mode and differential mode noise in a wide range of frequencies so to minimize the conducted emissions the EMI filter characteristics must be analyzed. For that reason, some of the experiments need to execute to observe the voltage and power variation. As we have already measured the EMI filter output (both power and voltage) providing harmonic noise, we will measure and observe what the voltage and power variation happens if we connect another source having 5volt rms with 12 MHz frequency. In that case, we will use the same filter without changing its standard structure, common mode choke, and the X, Y capacitors. We are not going to change the values as well.



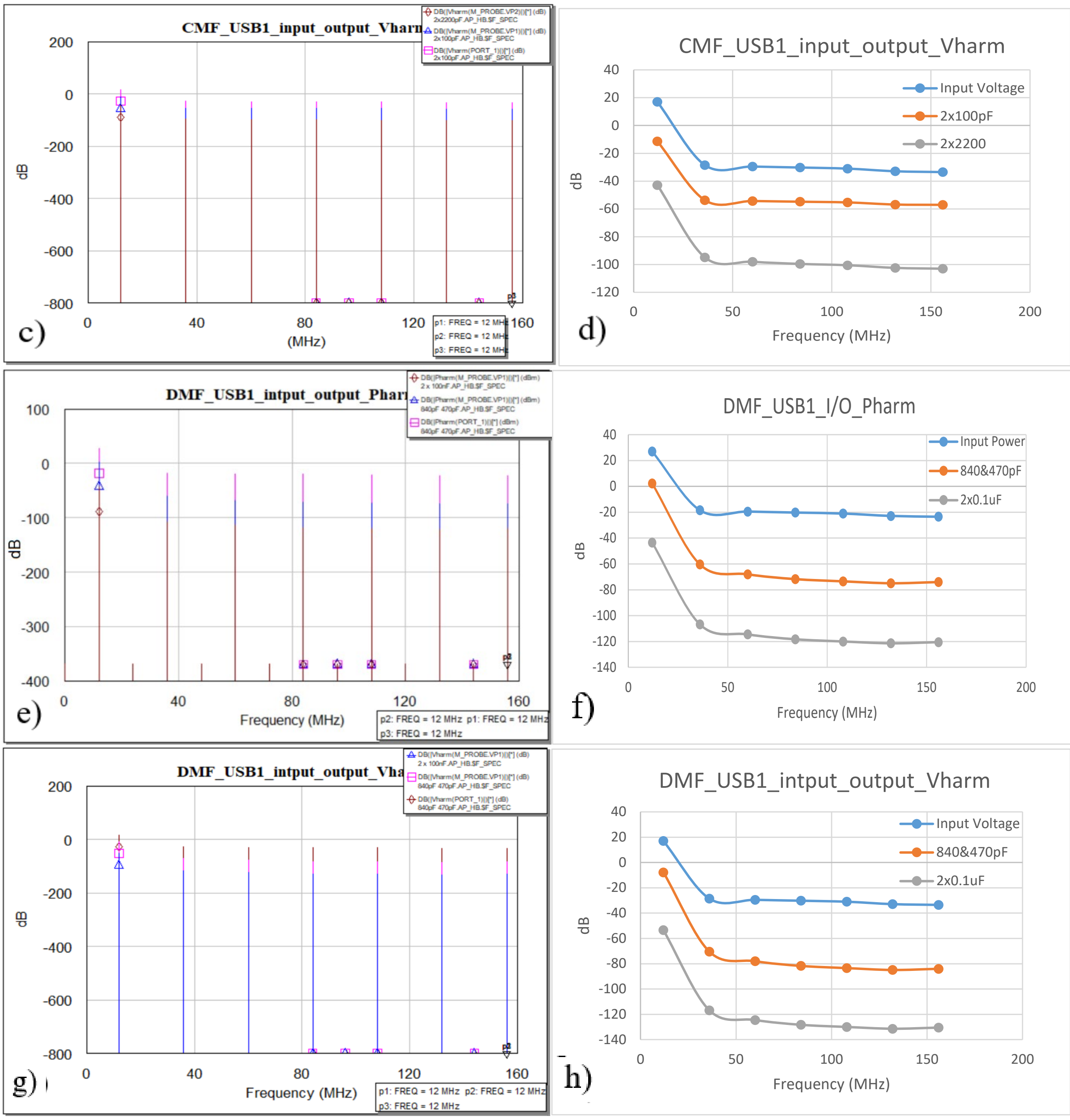


Figure 57: Common mode filter & Differential mode filter measurement for USB 1.0 cable towards the load a) CMF Power input and output in time domain (Pharm). b) CMF Input & Output harmonic power comparison. c) CMF voltage input and output in time domain (Vharm). d) CMF Input & Output harmonic voltage comparison. e) DMF Power input and output in time domain (Pharm). f) DMF Input & Output harmonic power comparison. g) DMF voltage input and output in time domain (Vharm). h) DMF Input & Output harmonic voltage comparison.

5.2.2 Ethernet cables

Ethernet cables carry broadband signals to the devices which are internet-capable. There is a number of versions of this cable and only use for the speed facility. The most commonly used Ethernet cables are unshielded twisted pairs. There is a total of four copper wires and each wire are consists of two twisted wires. Each copper wire is wrapped in an insulator plastic layer.

In an Ethernet physical layer, the electrical and optical properties are maintained by the physical layer complemented with the data link layer. The voltage on the line is nearly 2.5 V (peak). But the handling bandwidth varies according to cable type. As for cat5, the operating bandwidth is 100 MHz, where it is 250MHz for cat6 Ethernet cable. Again this bandwidth is quite higher for cat6a which is 500MHz. we will pick one of the cables and test the input-output response including the noise signal.

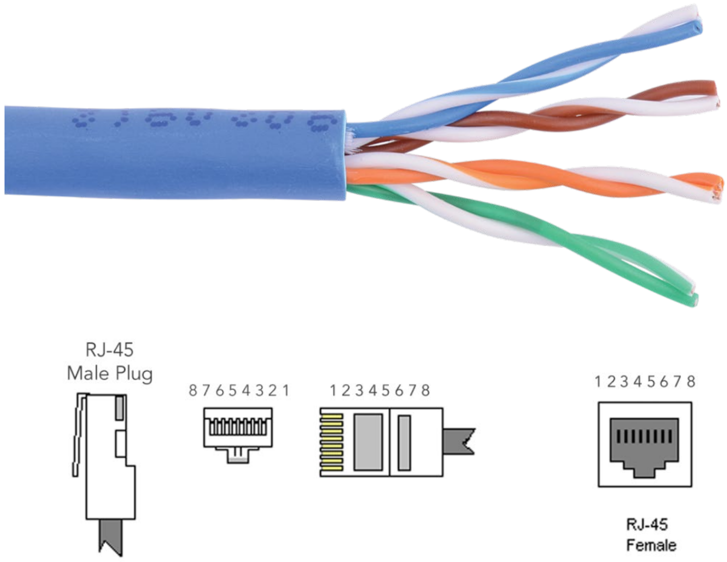


Figure 58: Ethernet cable and port having male and female port

5.2.2.1 Common mode measurement

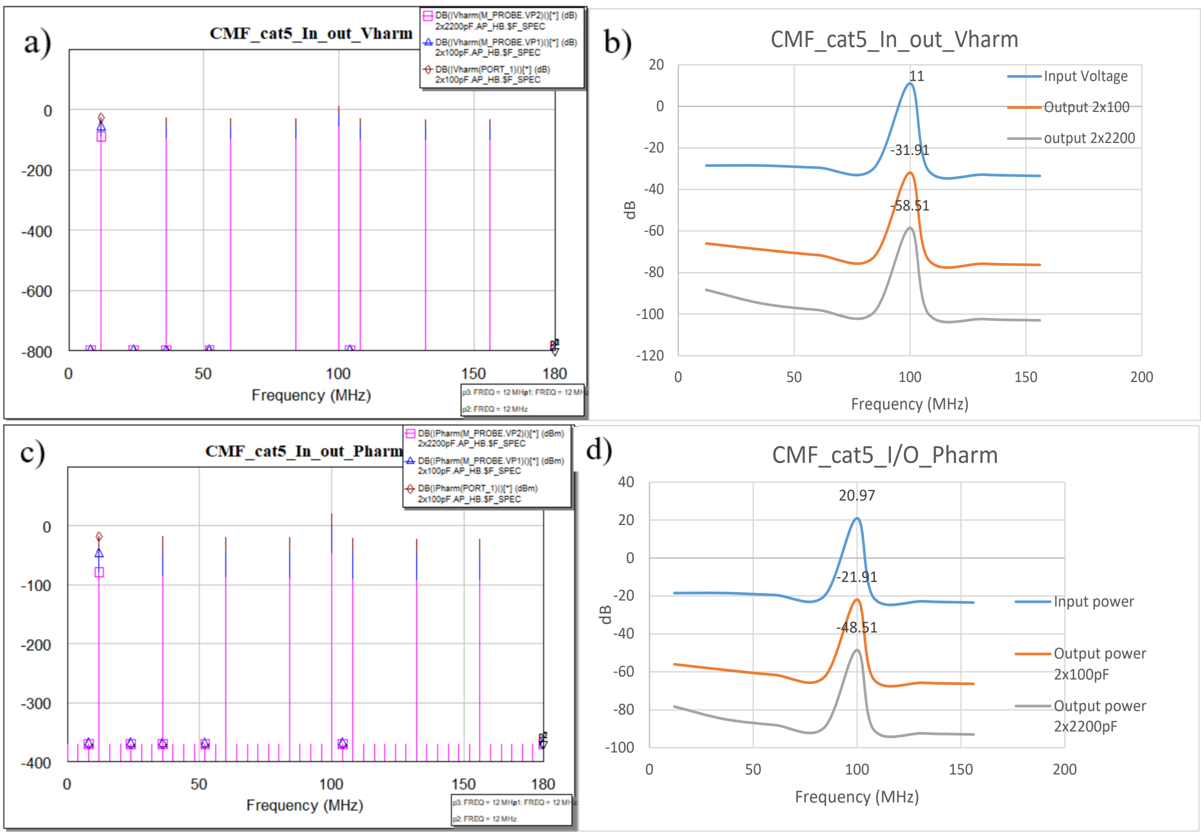


Figure 59: Common mode filter for cat5 Ethernet cable towards the load in frequency domain a) Voltage input AWR (Vharm) b) Voltage output Measured (Vharm) c) Power input AWR (Pharm) d) Power output Measured (Pharm)

5.2.2.2 Differential mode measurement

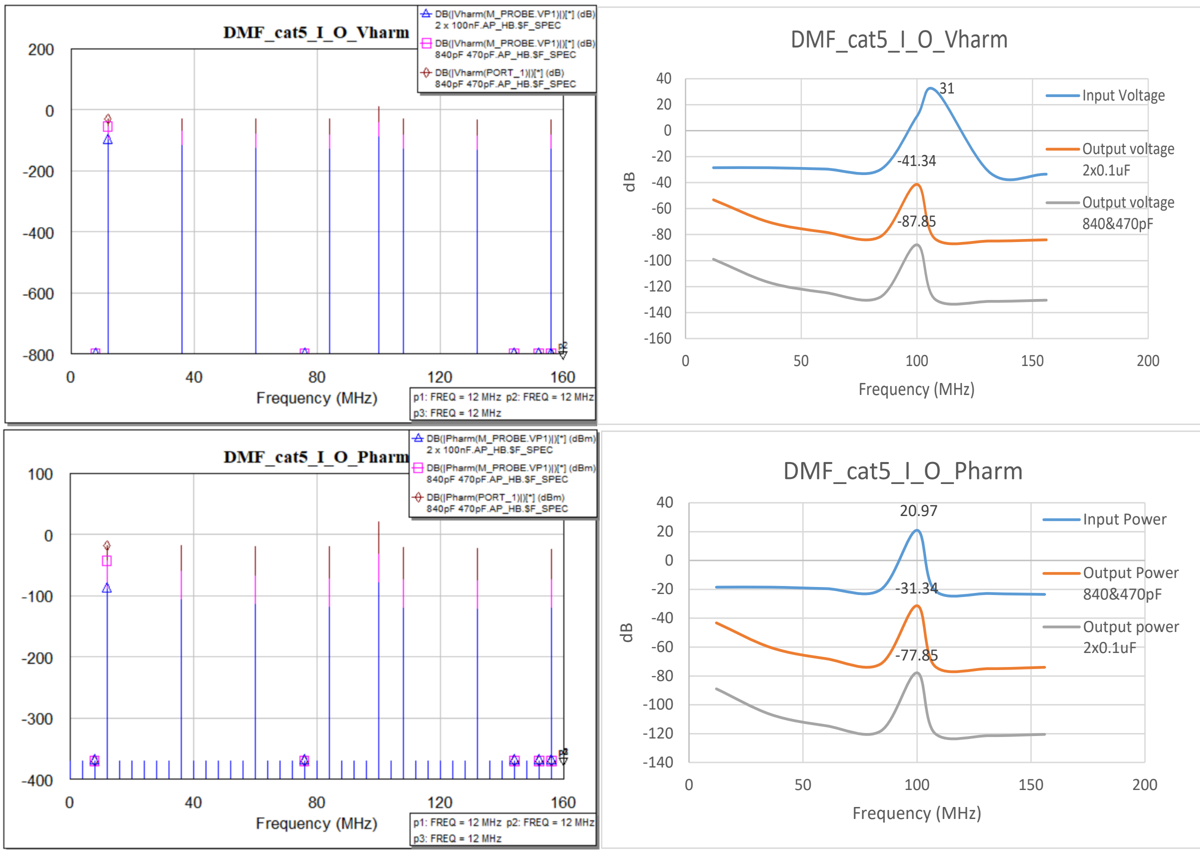


Figure 60: Differential mode filter for cat5 Ethernet cable towards the load in frequency domain a) Voltage input AWR (Vharm) b) Voltage output Measured (Vharm) c) Power input AWR (Pharm) d) Power output Measured (Pharm)

Conclusion

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