Application of Narrow Band Power Line Communication in Volt/Var Optimization

by

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B.Eng., Islamic Azad University (Shahre Rey), 1997

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Abstract

Smart grid is an advanced and sophisticated electrical network that uses a combination of information and communication technology to gather required data from different nodes on the network through a reliable, robust and cost effective communication solution, and acts on them to improve the efficiency and reliability of production and distribution of electricity. Volt/Var optimization (VVO) is one of the most important smart grid applications that gives this capability to utility companies to have an efficient electricity distribution network by maintaining an acceptable voltage level along the distribution section under different loading situations. This project focused on characterizing and evaluating the performance of narrow band power line communication (NB-PLC) as a prevalent communication technology for smart grid applications such as VVO in North American power grid. This work was done by establishing and setting up a real test bed in the lab. In this work we tried to implement S-parameter measurements due to its simplicity for channel characterization at high frequency ranges, when we have cascades of different components over the channel. It should be mentioned that the main focus of our work was on analyzing the behavior of an energized 5KVA MV/LV transformer over our channel. Then, we have shown the relationship between S-parameters and ABCD parameters to derive the channel transfer function based on ABCD matrix. Additionally, we did some simple noise measurements over our channel when it was non-energized and energized.

Keywords: Narrow band power line communication (NB-PLC); Volt/Var optimization (VVO); smart grid; MV/LV transformer; Low voltage (LV); Medium voltage (MV)

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Chapter 1.

Introduction

Volt/Var Optimization (VVO) is a priority application for many utility companies. Real-time VVO requires real-time data such as voltage, current, active power and reactive power, to be captured from smart meters at customer site [1]. To do that, utility companies require a robust and cost effective communication channel to transfer such data from termination points to VVO engines inside substations. Both Radio Frequency (RF) and Power Line Communication (PLC) technologies could be used for this purpose. However, given public's negative perceptions towards RF technologies, PLC is the technology of choice for such applications. Two different PLC technologies could be considered [2]:

1) Broad band power line communication (BPL)
2) Narrow band power line communication (NB-PLC)

BPL uses the frequency range of 2- 32MHz which has been designed for application that need high bandwidth. However, given the typical North American distribution feeder topology, in which a pole-top transformer is placed in close proximity to customer termination points, BPL may not be a viable option. BPL signals, in MHz range, are not able to pass through such transformers, resulting in the need to bypass them and thus increasing the cost. NB-PLC, which uses the frequency range of 10-500 KHz, is designed to overcome this obstacle as their signals are expected to pass through a transformer [3]. The purpose of this project is to investigate the characteristics of the communication channel that includes a transformer. In this work we took channel measurements and evaluated the behavior of energized MV/LV distribution transformer in the frequency range of NB-PLC (10-500KHZ)In particular, our goal is to obtain the ABCD parameters of the transformer. We consider ABCD parameters as suitable characterization of the transformer as a communication channel because i) these

parameters provide characteristics invariant of the time varying loads on the power system, and ii) the ABCD parameters of serially concatenated channel components can be simply represented as matrix multiplication of the ABCD parameters of individual components. This measurement has been done based on S-parameter measurement technique and we will explain later why we have selected this approach. In addition, the noise measurement in the frequency range of NB-PLC on both the LV and MV channels was done to compare the background noise level while there is no communication signal travelling over these channels. For this work, a test bed was set up at the electrical training centre of the British Columbia Institute of Technology, a polytechnic institute, in Burnaby, BC, Canada. In the following sections we explain the two most common types of channel measurement methods, and then the test setup and procedure will be presented. It is important to mention again that the problem caused by pole-top transformer and its effect on the performance of power line communication technology is still an open problem, and further analysis and investigation is totally necessary. For example, beside significant signal attenuation caused by this transformer, we need to know why we see an asymmetric behavior on LV-MV and MV-LV channel when the communication signal travels across the transformer.

1.1. Channel measurement methods

1.1.1. ABCD-parameters

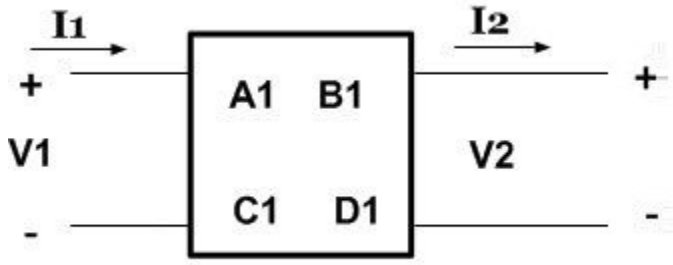

Figure 1.1. Diagram of a 2-port network

ABCD-parameters are well known parameters that are normally used for characterizing linear two-port networks. This can be defined as a matrix, presented in equation 1.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} . \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (1)$$

$$A_1 = \frac{V_1}{V_2}, \text{when } I_2 = 0 \quad (2)$$

$$B_1 = \frac{V_1}{I_2}, \text{when } V_2 = 0 \quad (3)$$

$$C_1 = \frac{I_1}{V_2}, \text{when } I_2 = 0 \quad (4)$$

$$D_1 = \frac{I_1}{I_2}, \text{when } V_2 = 0 \quad (5)$$

According to aforementioned equation, ABCD parameters are expressed based on voltage and current on a two-port network. We then need to measure voltage and current in a short and open circuit situation. This can be a risky job in an energized circuit especially in a high voltage environment such as power line channel, and it is also difficult to measure voltage and current at high frequencies, because regular multimeters cannot measure voltage and current accurately at high frequencies. Hence, based upon the literature review and further investigation, we found that the S-parameter analysis could be an easier method for this purpose. Therefore, S-parameters measurement was used to identify ABCD parameters for each energized network element such as the transmission line, the MV/LV transformers, and other electrical apparatus existing over power line channel. Once the S-parameters are obtained, they could be converted to ABCD parameters via a mathematical relationship (addressed later). Then, by concatenating these parameters, the entire channel's transfer function can be derived based on ABCD [4].

1.2. S-parameters

Scatter parameters, also known as S-parameters, are in the category of two port network parameters in two port network theory. They are generally frequency dependent complex values, expressed in dB. This tool can show the performance of a two port network that is called device under test (DUT), in terms of transmission or reflection of a signal. Please note that each network element such as MV/LV transformer can be

considered as a DUT in our test. These parameters are obtained by measuring the magnitude and phase of the incident, reflected, and transmitted signals when the output of a two port network is terminated at Z0 (50Ω) in order to have an impedance matching. As we know, this impedance matching is necessary to avoid reflection at output ports. [5]. Figure 1.2 shows a scattering matrix of a two port network.

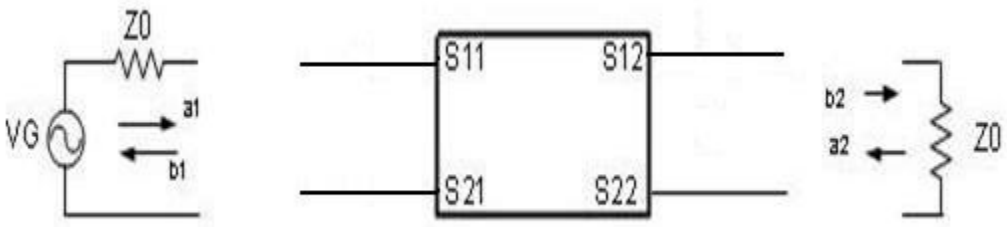

Figure 1.2. The Scattering matrix of a two port network

$$b_1 = S_{11}a_1 + S_{12}a_2 \tag{6}$$

$$b_2 = S_{21}a_1 + S_{22}a_2 \tag{7}$$

These equations could be written in the matrix format (b) = (S) (a) as shown below:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \tag{8}$$

Since the two port network is embedded in a characteristic impedance of Z0, the waves could be interpreted as a normal voltage or current amplitude as depicted here:

$$a_i = \frac{Voltage\ towards\ the\ two\ port}{\sqrt{Z0}} \tag{9}$$

$$b_i = \frac{Voltage\ away\ from\ the\ two\ port}{\sqrt{Z0}} \tag{10}$$

S11 is called the input reflection coefficient when incident wave on output port (a2) is set to zero. This shows how much of incident signal on port 1 does not reach at the output (port 2) of DUT and is reflected to the input port.

$$S_{11} = \frac{b_1}{a_1}, When\ a_2 = 0 \tag{11}$$

S12 is the forward transmission coefficient which shows a how much of the input incident wave can reach the output of the system.

$$S_{21} = \frac{b_2}{a_1}, When\ a_2 = 0 \quad (12)$$

S22 is the reflection coefficient at the output of the system when the input incident wave is equal to zero. This shows how much of incident signal on port 2 does not reach at port 1 and is reflected to port 2.

$$S_{22} = \frac{b_2}{a_2}, When\ a_1 = 0 \quad (13)$$

S12 is the reverse transmission coefficient which shows how much of the incident wave at the output could reach the system input.

$$S_{12} = \frac{b_1}{a_2}, When\ a_1 = 0 \quad (14)$$

After capturing the full S-parameters, we will be able to derive the transmission matrix of the desired channel based on ABCD parameters via the following equations. Please note that Z0 in these equations is the system characteristic impedance, which is usually considered 50Ω [6] [7].This impedance is based on characteristic impedance of transmission line which is normally considered 50Ω in industry. As we know, if a transmission line is terminated at its characteristic impedance, we will have no reflection due to impedance matching. Therefore, all transmitted power will be absorbed. The following formulas show the relationship between S and ABCD parameters.

$$A = \frac{[(1+S_{11})(1-S_{22})+S_{12}.S_{21}]}{2S_{21}} \quad (15)$$

$$B = Z_0.\frac{[(1+S_{11})(1+S_{22})-S_{12}.S_{21}]}{2S_{21}} \quad (16)$$

$$C = \frac{1}{Z_0}.\frac{[(1-S_{11})(1-S_{22})-S_{12}.S_{21}]}{2S_{21}} \quad (17)$$

$$D = \frac{[(1 - S_{11})(1 - S_{22}) + S_{12}.S_{21}]}{2S_{21}} \quad (18)$$

It is important to draw the reader's attention to this fact that the accuracy of the S-parameter test is completely dependent on obtaining a perfect termination as applied to the inactive port. This means that the device under test (DUT) connected to the network analyzer test ports should be terminated at 50Ω impedance which would result in perfect impedance matching with the network analyzer. This is accomplished by connecting the network analyzer to the 50Ω input of the Cipunet medium voltage (MV) coupler located on the medium voltage side. Another port of network analyzer will be hooked up to the LV coupler embedded on the EV-Kit on low voltage (LV) side.

Chapter 2. Test Setup Procedure

In this chapter we explain how our test bed was set up and the test procedure is explained in detail. First of all we introduce the real MV/LV transformer that was used during this test.

The MV/LV transformer used in this work has the following characteristics:

- Manufactured by Reliance.
- Serial No. K7726-3
- Single - phase. 5 KVA
- High voltage rated: 14400 volts
- Low voltage rated: 120/240 volts
- The percent Impedance: 4.0 %Z
- Frequency: 60 Hz
- Manual tap changer with taps at 86½%, 91%, 95½, & 100%-used at the 100% tap position.
- Rated temperature rise 55°C
- Oil-filled: ONAN
- 7.5 gallons [34.1L]
- 195 lbs. [88.45 kg]
- Subtractive polarity

Manufacturer-provided internal protection consists of a circuit breaker for the low voltage winding and a protective link for the high voltage winding.

The transformer was placed in the high voltage test vault due to the flammability of the oil and for personnel safety precautions. The low voltage windings were series connected to obtain the 240 volt rating with a center tap to allow for 120 volts, which was not used.

Typically this small distribution transformer would be pole-mounted to supply a 240/120 volt Edison three-wire, single-phase service supplied from a 14.4 kV, AC, and single-phase supply. For the communications tests the transformer was back-fed. The 240 volt low voltage winding was supplied from a 208 volt, AC, single-phase, two-wire circuit to the LV bushings while the centre-tap not was used. With the 60:1 step-down voltage ratio, the transformer would now step-up (1:60) the voltage to approximately 12.5 kV with no load on the high voltage winding; only excitation current on the low voltage winding. The transformer's H1 high voltage bushing was tied to the station ground as well as to the transformer's case. The transformer's case was also tied to the station ground. The two high voltage communications couplers were connected to the transformer's H2 high voltage bushing. The insulation shielding of the couplers and the cases of the couplers were also tied to the station ground as per the coupler manufacturer's requirements. Figure 2.1 shows the actual MV/LV transformer (5KVA) and the Cipunet MV couplers that we used in our test. Please note that Cipunet coupler was the only appropriate medium voltage coupler during our test which is designed for the frequency range of 10-500KHz. I need to remind that these kinds of couplers are difficult to be found in the market.

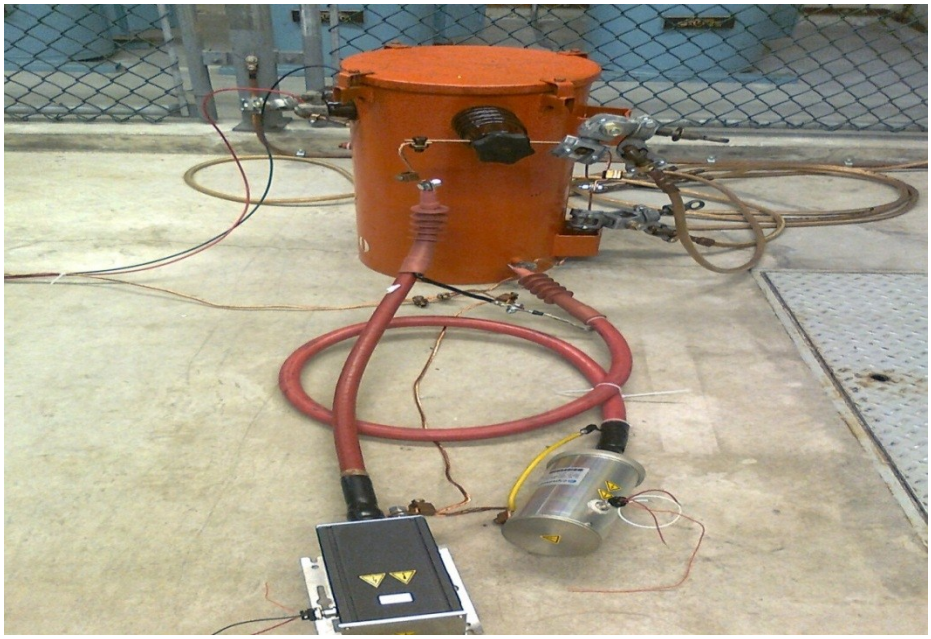

Figure 2.1. MV/LV transformer & Cipunet MV coupler

Since the transformer and the MV couplers were located in the high voltage electrical vault for safety, the network analyzer (located outside of the electrical vault) was connected via long cables to the MV couplers. LMR400 cables, which support the 50Ω characteristic impedance, were selected for this measurement to obtain the required impedance matching. The network analyzer was connected to 50Ω input of MV coupler via the LMR400 cable. The effect of this cable has been removed from the measurement results by using the calibration method. On the low voltage side, the network analyzer must also be connected to a coupler. An embedded LV coupler (MAX2991 AFE) on the MAX2992 NB-PLC modem (EV-Kit) was implemented in our test. Please note that this modem was provided by a company, called Maxim Integrated that is doing research actively in the field of narrow band power line communication and its usage for smart grid applications in North American power network. It is important to note that the main modulator and demodulator part of modem was not used during our test. This measurement was done under both energized and de-energized states for comparison and analysis. Figure 2.2 shows a portion of the MAX2992 NB-PLC modem's schematic diagram including the embedded LV coupler. In this diagram the signal injection points (TP34&TP43), are identified. These points are provided to allow the connection of the signal generator or the VNA (Vector Network Analyzer) to the LV coupler. This enables the injection of the NB-PLC signal via this coupler over the low voltage AC power line.

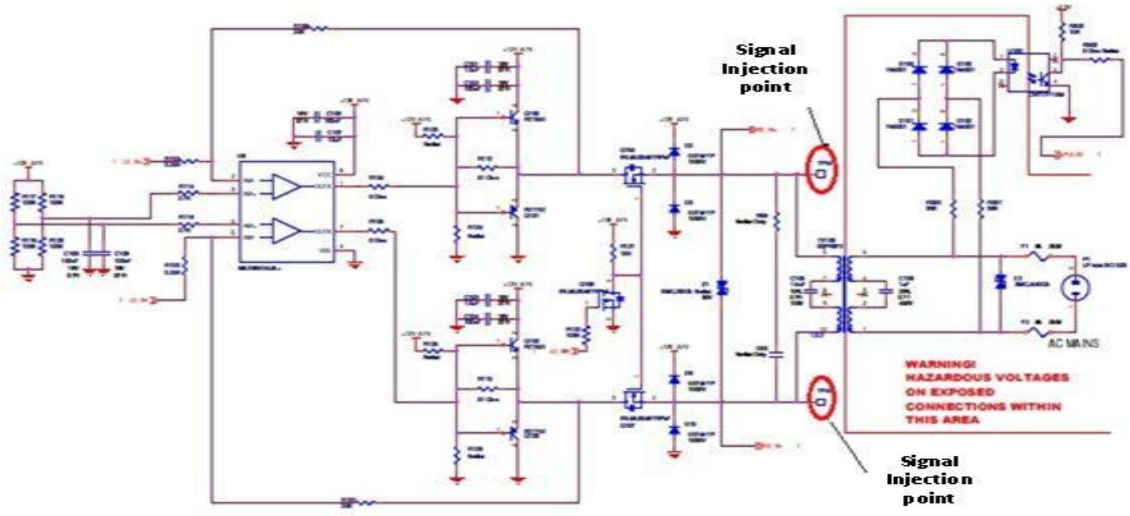

Figure 2.2. Maxim NB-PLC modem schematic

In the de-energized state, the VNA can be connected to these signal injection points directly. However in the energized case it is an absolute necessity to employ a power limiter between the VNA and LV coupler. A power limiter is a device which is used to protect the input circuitry of the measurement equipment, such as a spectrum analyzer or a network analyzer, against a high power input signal which could damage these instruments. A power limiter was not required on the medium voltage side. This is due to the high degree of isolation afforded by the MV coupler between the VNA and medium voltage line. If a power limiter is used during this measurement its effect should be removed by calibration as well. Figures 2.3, 2.4 and 2.5 present a test setup diagram for channel measurement between LV-MV, MV-LV, MV-MV and LV-LV respectively.

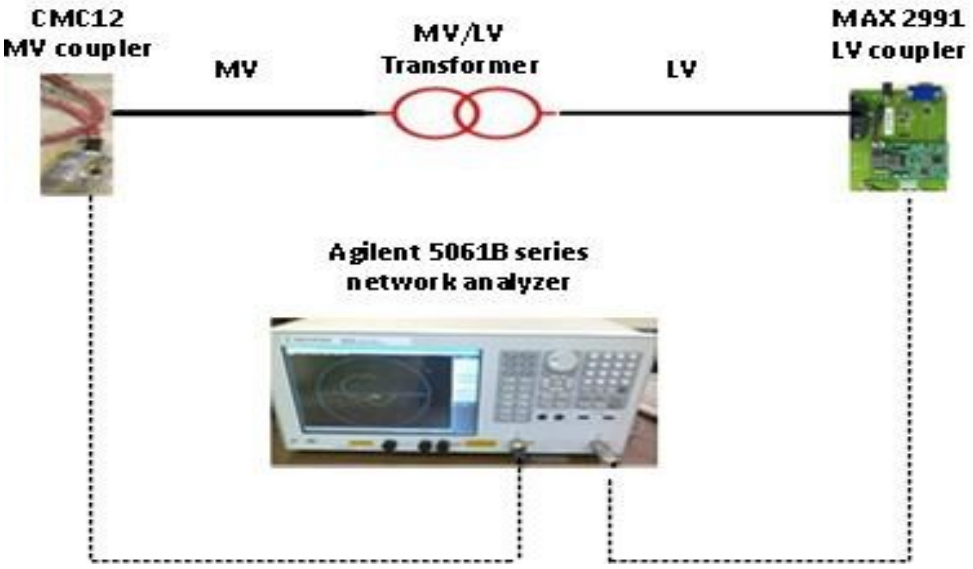

Figure 2.3. Test setup diagram for channel measurement between LV-MV and MV-LV

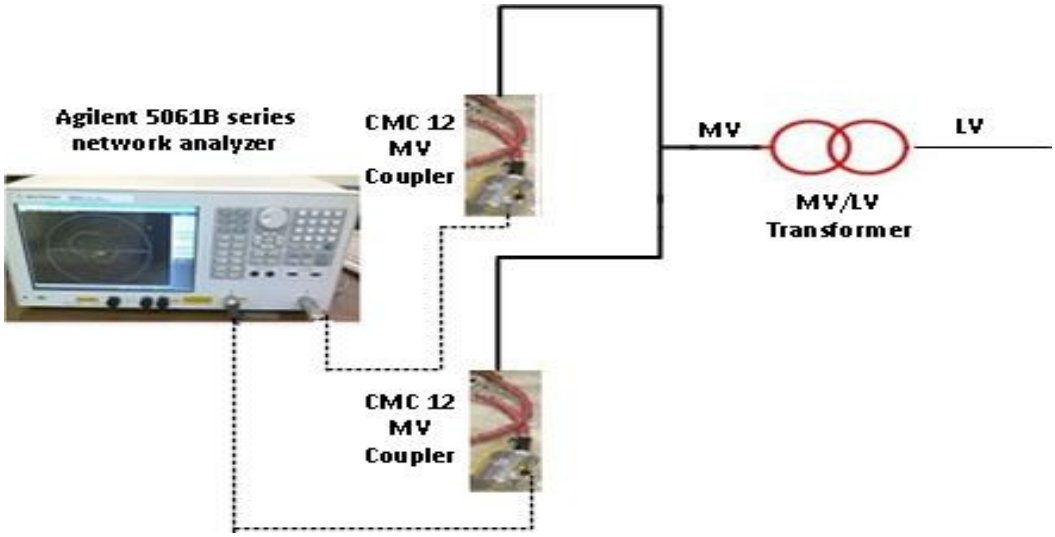

Figure 2.4. Test setup diagram for channel measurement between MV-MV

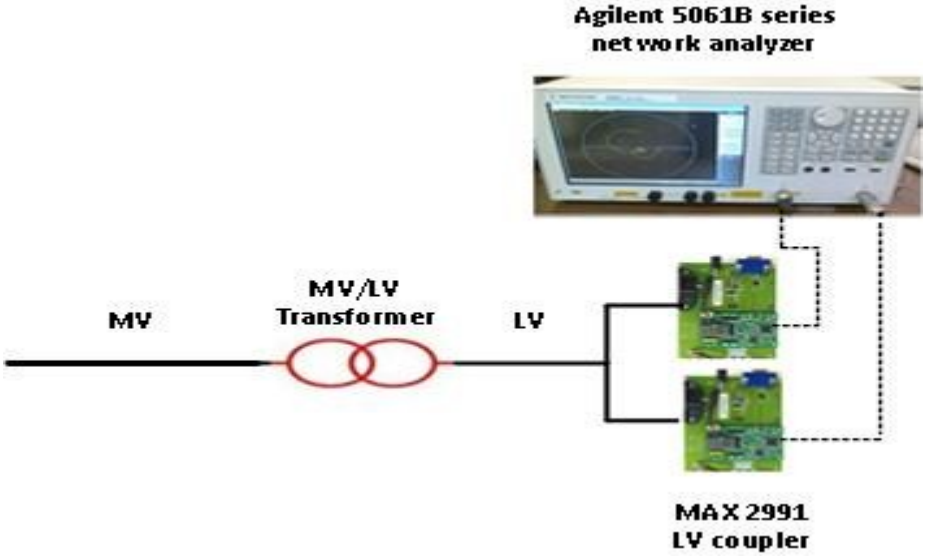

Figure 2.5. Test setup diagram for channel measurement between LV-LV

The first part of the test examines the channel measurement based on the S-parameter measurements. This test was done on LV-MV, MV-LV, and MV-MV sections through a full S-parameter measurements. After the calibration is completed, the main test is started. The VNA starts to measure a full S-parameter sweep in the frequency range of 10-500 KHz. The test results are acquired in raw data and plot formatted using MATLAB code from a laptop connected to the VNA via an RJ45 Ethernet cable.

2.1. Noise Measurement

This measurement was accomplished by using an Agilent 9000 series (90604) digital oscilloscope on the low voltage and medium voltage sides in both time and frequency domains. This measurement device is a type of data acquisition equipment (DAQ) that can listen to the power line via a coupler. When there is no signal transmitted it captures the background noise trace. We will present the noise measurement results later. Figure 2.6 shows the test setup for this part of measurement.

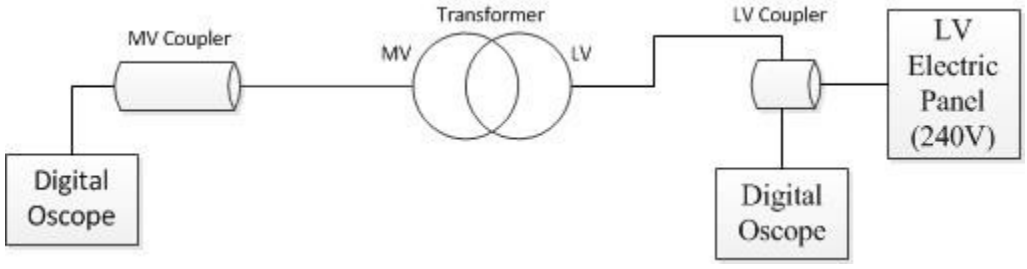

Figure 2.6. Noise measurement test setup diagram

Figure 2.7. Agilent 90604 digital oscilloscope

Chapter 3. Test Results

The first portion of this test result presentation covers the S-parameters which demonstrate the behaviour of time varying power line channel over the frequency range of 10 KHz to 500 KHz. These results contribute to a full understanding of the channel which will foster a more robust and reliable communications solution. It also shows that the characteristics of LV-MV and MV-LV channels are asymmetrical. This test was performed in steps with both de-energized and energized cases on these channels. The main focus and contribution of this work then follows, in which the behaviour of the 5 KVA pole-top MV/LV transformers is evaluated when de-energized and energized on this channel.

- Step 1: MV-MV
- Step 2: LV-MV, MV-LV
- Step 3: LV-LV

As mentioned in the test setup and procedure, port 1 of the network analyzer was connected to LV coupler and port 2 was connected to the MV coupler. The following results were captured according to this test setup. Please note that the devices under test (DUT) constitute the LV and MV couplers as well as the real 5 KVA MV/LV transformer in this test. The S-parameters measurements, which are considered to be complex numbers, are obtained by measuring the magnitude and phase of the signal created by the network analyzer. This measurement is done via embedded MATLAB code in the network analyzer and then is converted to decibels. This is accomplished with the following formulas, using S11 as an example.

$$S_{11} = a + jb$$

$$r = |S_{11}| = \sqrt{a^2 + b^2}$$

$$dB = 20\log_{10} r$$

3.1. Full S-parameters for MV-MV channel

In this portion of test we tried to characterize our medium voltage coupler at both energized and non-energized cases in the frequency range of NB-PLC. This part of test was done based on test setup diagram depicted in figure 2.4. This part of test is in the area of interest to the NB-PLC community. It is also important to note that due to certain lab limitations, it was not possible to add medium voltage loads on this channel. This could be considered in a future work in exploring the possible impact that medium voltage loads may have on NB-PLC communications. Please note that each experiment was repeated for 3-5 times over a period of 30 minutes, and all experiments of the same parameters are plotted in the same figures. Due to the short period of the experiments, all curves are very similar to each others. Fig.3.1 and Fig.3.2 presents the four S parameters for de-energized MV-MV channel. It can be seen that all curves are quite smooth which showing the behavior of Cipunet MV couplers in the frequency range of NB-PLC when the channel is de-energized. S11 and S22 have similar lowpass characteristics, whereas S12 and S21 have similar highpass features. Fig 3.3-3.4 show the S parameters when the channel is energized. As shown by the figures, although the general trends are similar to Fig.3.1 and Fig.3.2, all four S parameters curves show some ripples, which are caused by the AC power signal and its harmonics. In particular, S11 and S22 show more ripples than S12 and S22. More analyses will be given in Sec.3.5. Please note that the noise-like result at the beginning of some figures especially in energized cases are caused by some impulses which are existed over power line channel.

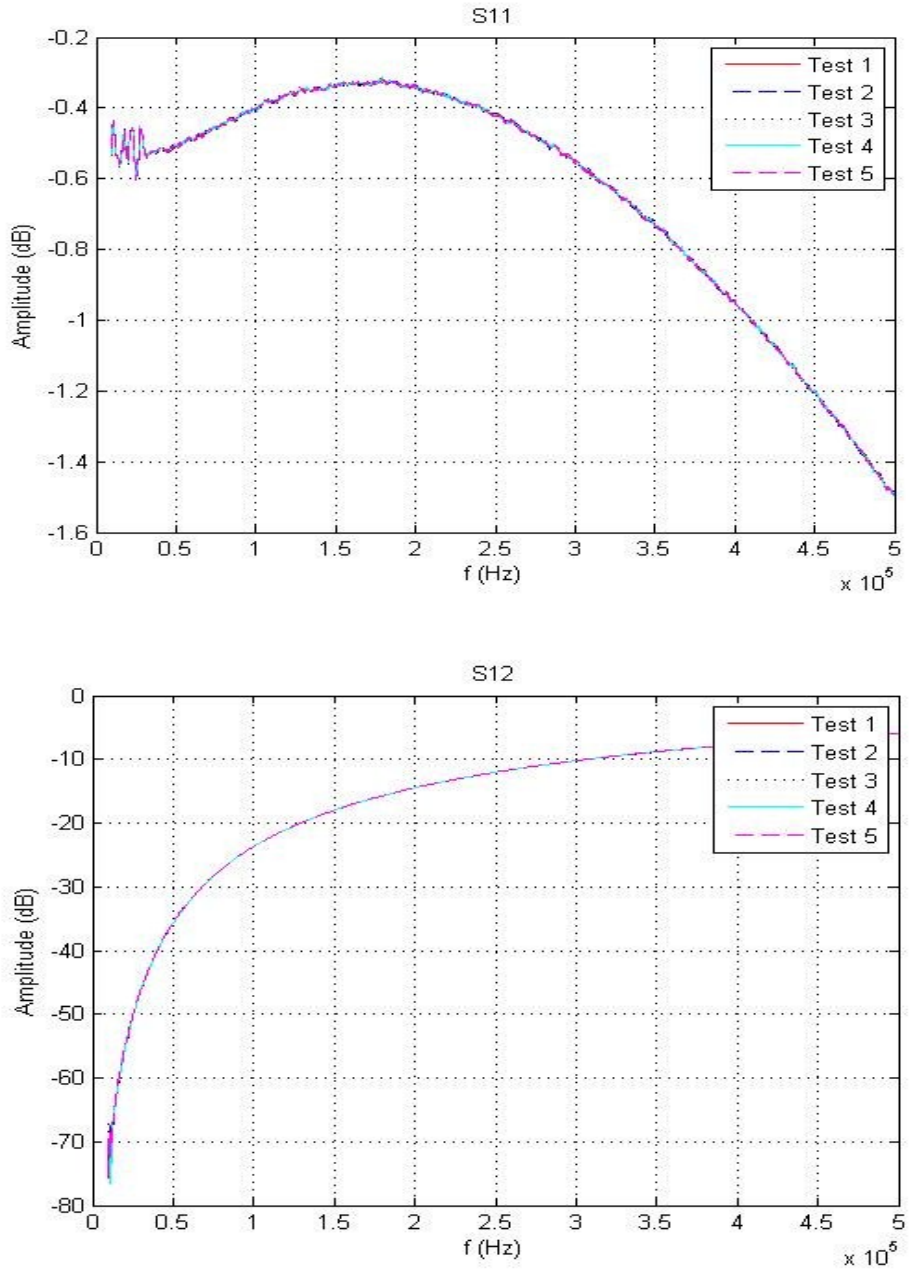

Figure 3.1. S-parameters for de- energized MV-MV channel

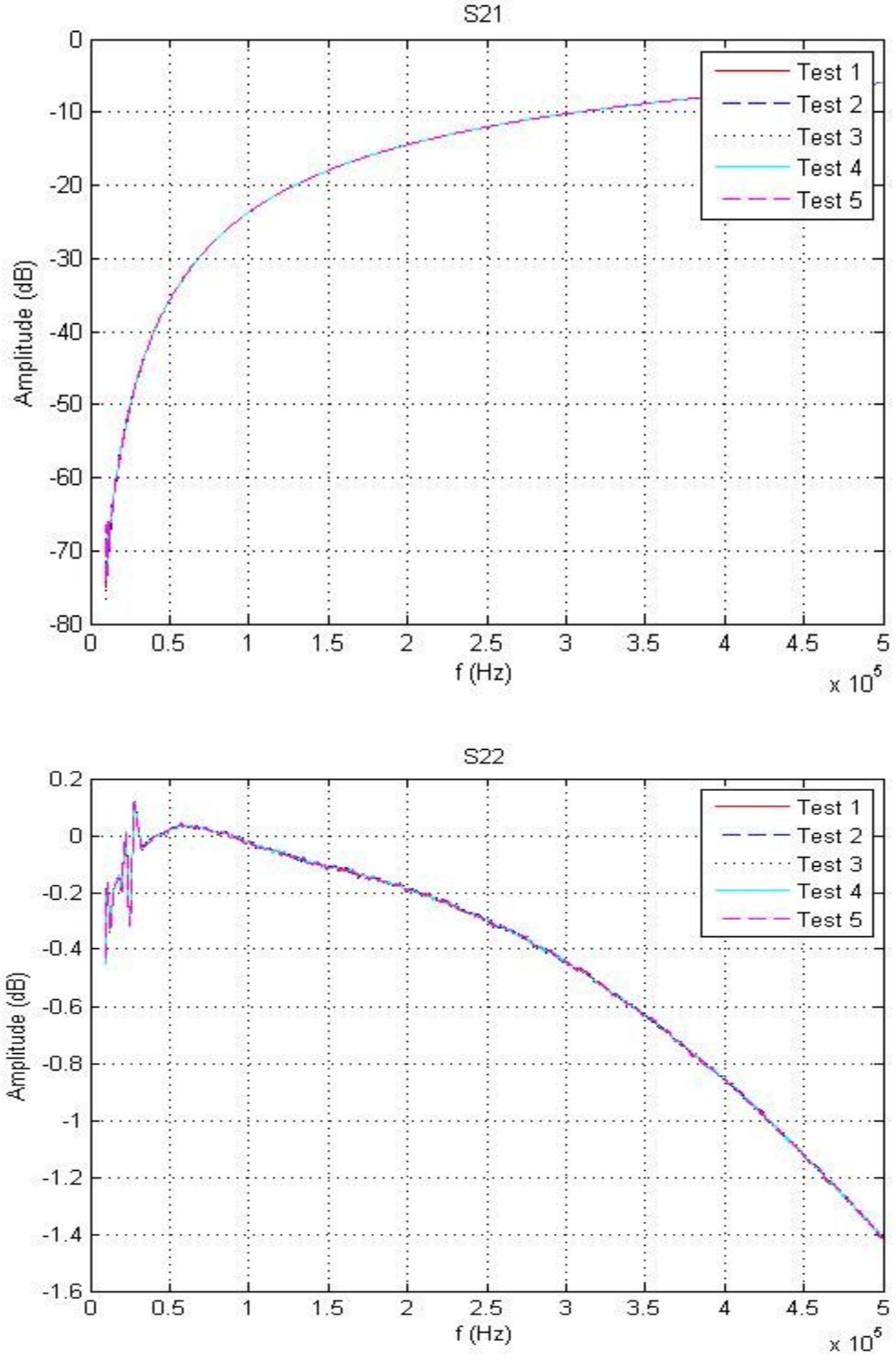

Figure 3.2. S-parameters for de-energized MV-MV channel

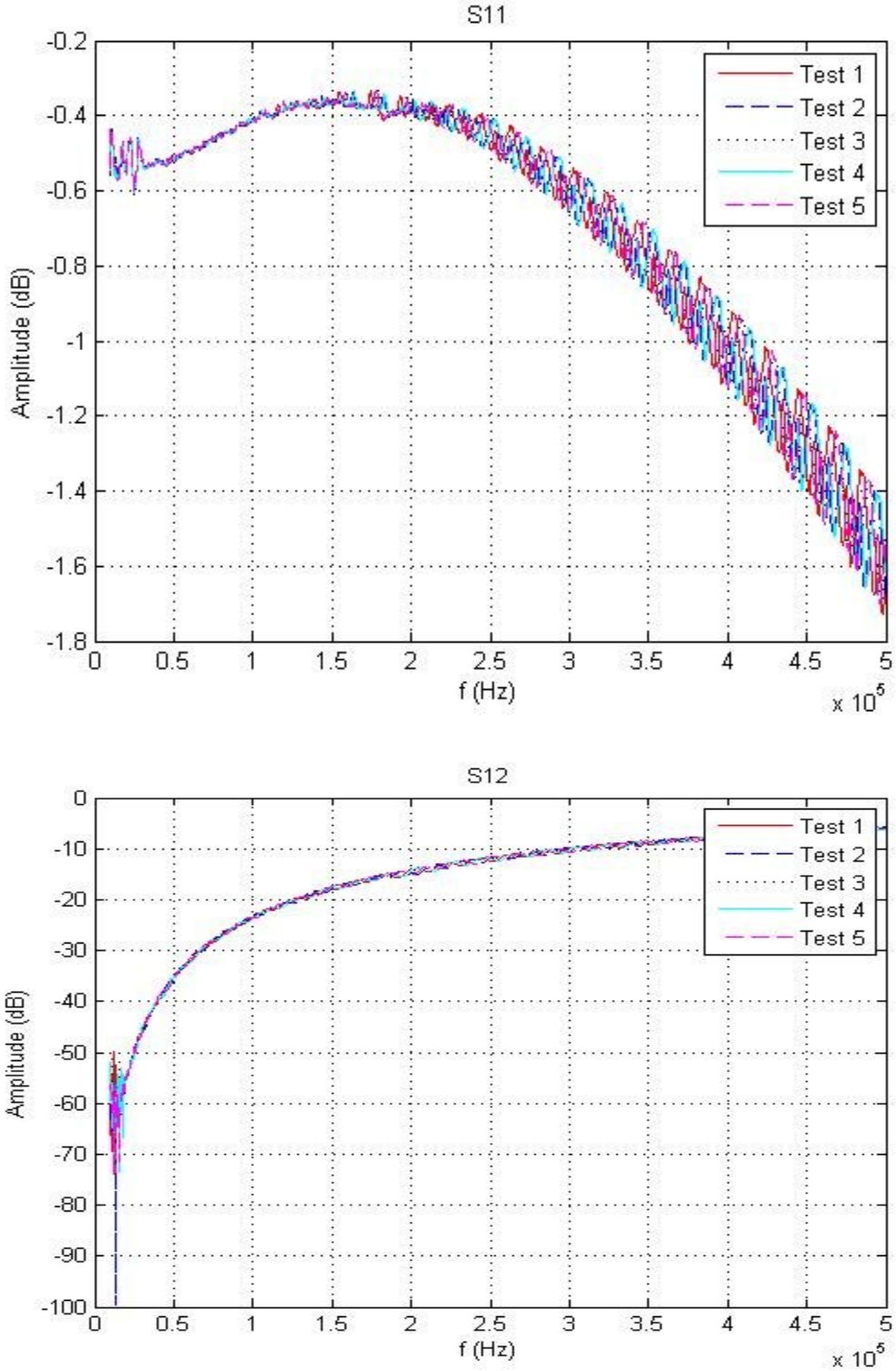

Figure 3.3. S-parameters for energized MV-MV channel

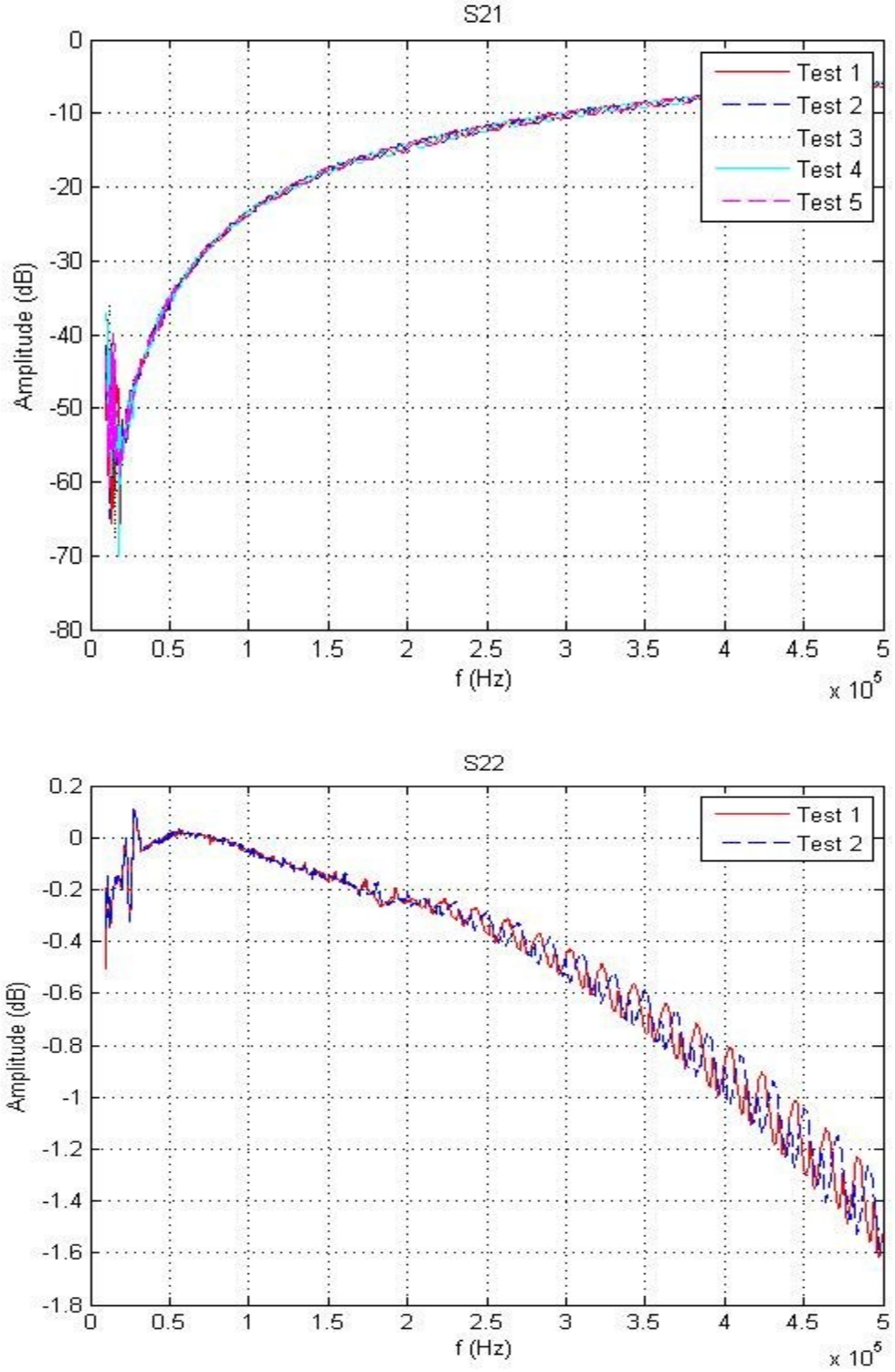

Figure 3.4. S-parameters for energized MV-MV channel

3.2. Full S-parameters for de-energized and energized LV-MV and MV- LV

In this portion of test, the full S-parameters for the de-energized and energized LV-MV and the de-energized and energized MV-LV channel are presented. This included an actual MV-LV transformer utilizing LV and MV couplers as shown in figure 2.3. Based upon the test setup and network analyzer connections, the full S-parameter for this channel means that S11 and S21 are related to the LV-MV section and that S22 and S12 are related to the consequent MV-LV section. Fig.3.5 and Fig.3.6 present the S parameters for the de-energized LV-MV channel. Fig. 3.7 presents the S parameters for energized LV-MV and Fig.3.8 shows the S parameters for energized MV-LV section. Please note that the analyses of these figures are given in Section 3.5. As we see there is significant signal attenuation observed at the frequency of 300KHz in S12 parameter on both de-energized and energized. I need to emphasize that this result caused by 5KVA transformer which is used in our test, and does not apply to the other common type of MV/LV transformers. Please note that further research is necessary to clarify that.

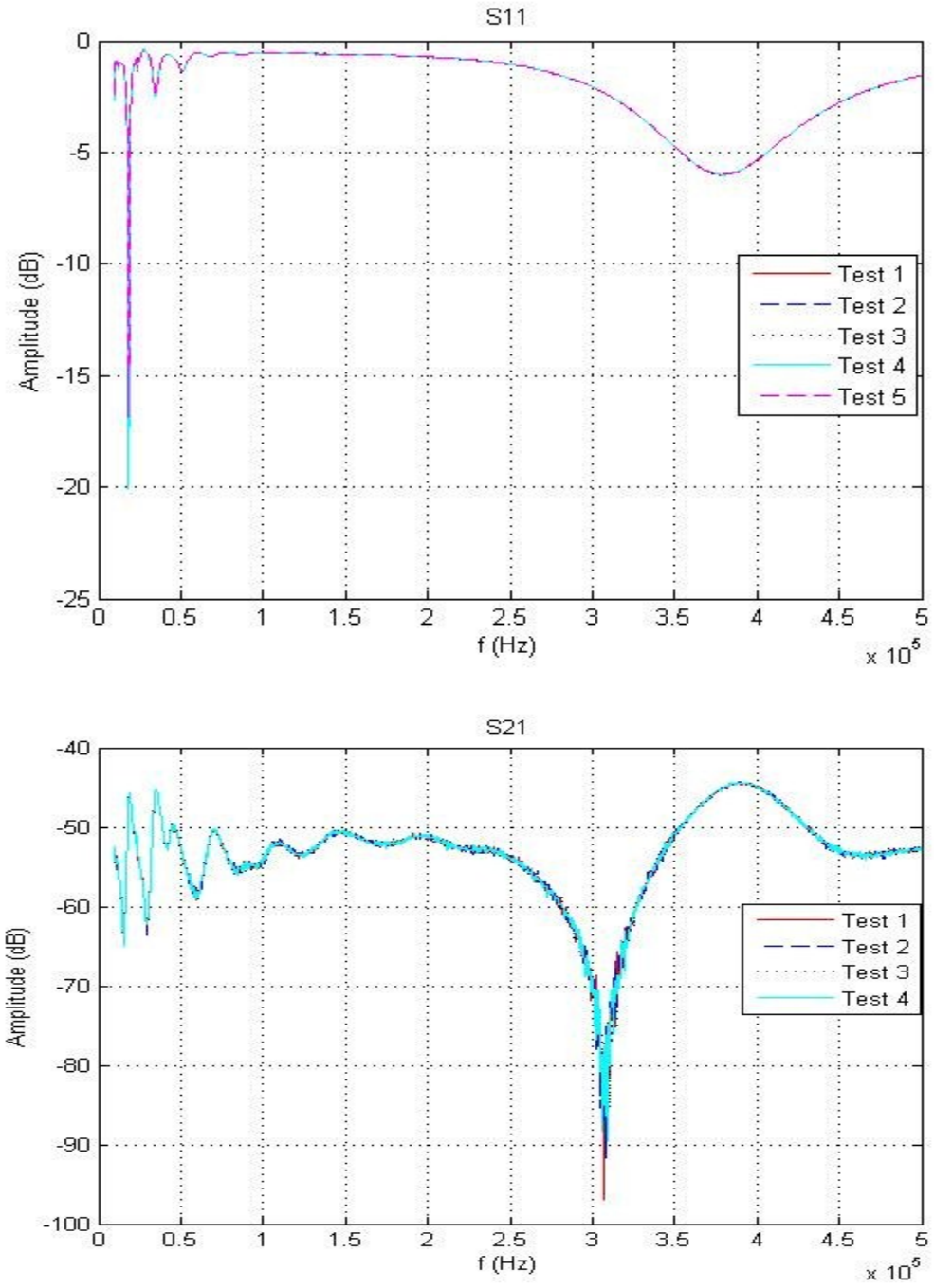

Figure 3.5. S-parameter for de- energized LV- MV

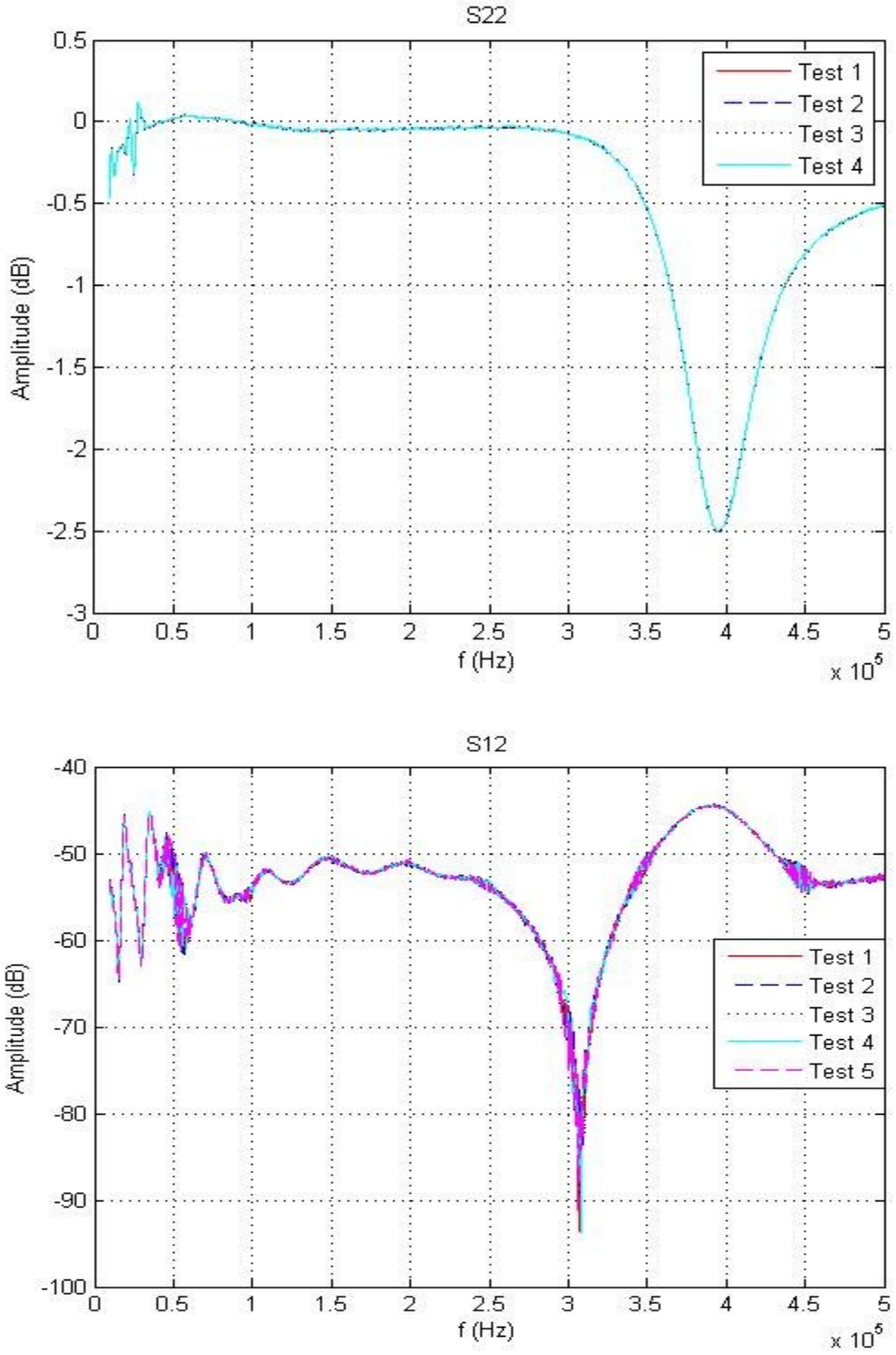

Figure 3.6. S-parameter for de- energized MV- LV

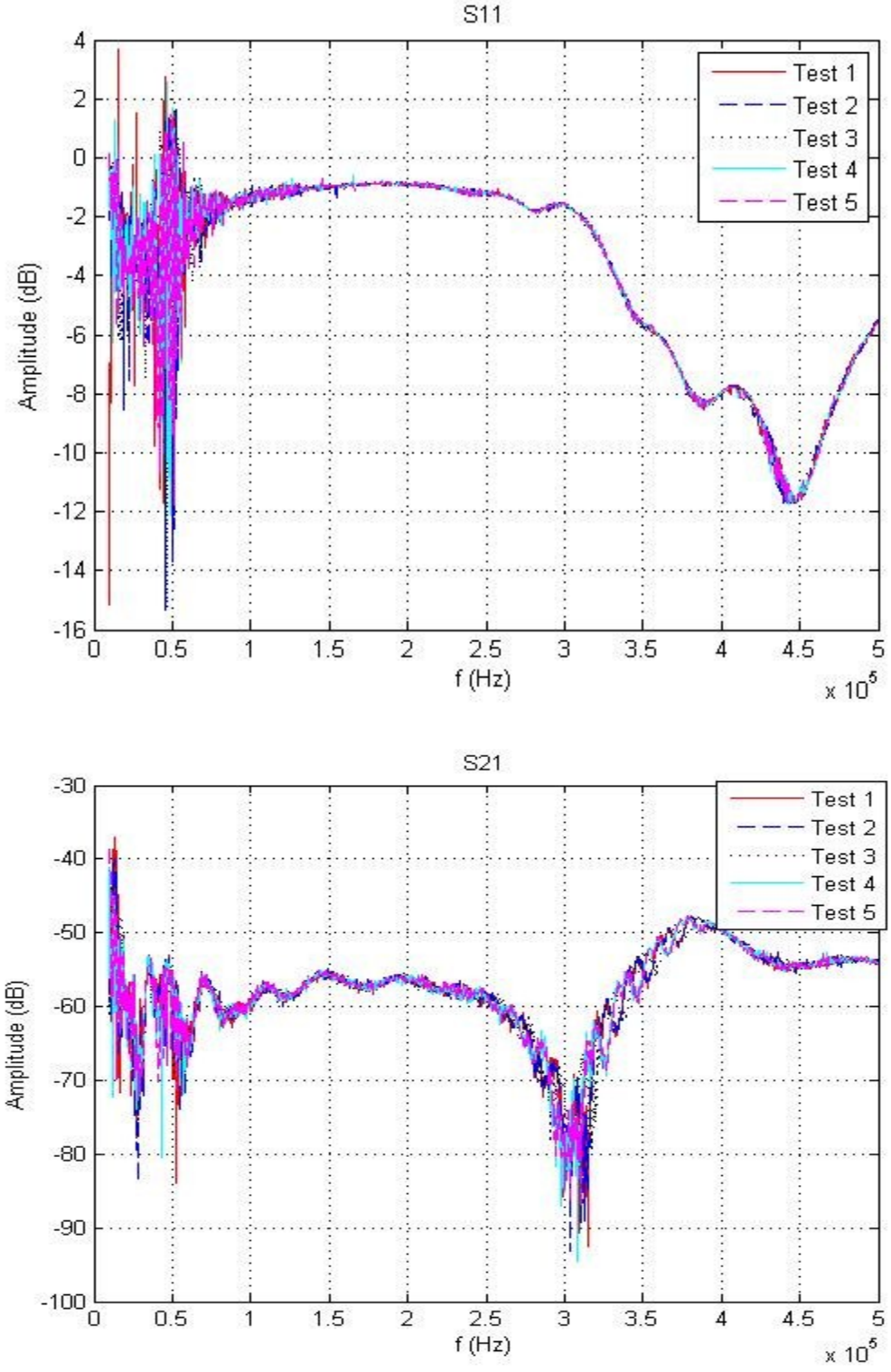

Figure 3.7. S-parameter for energized LV- MV

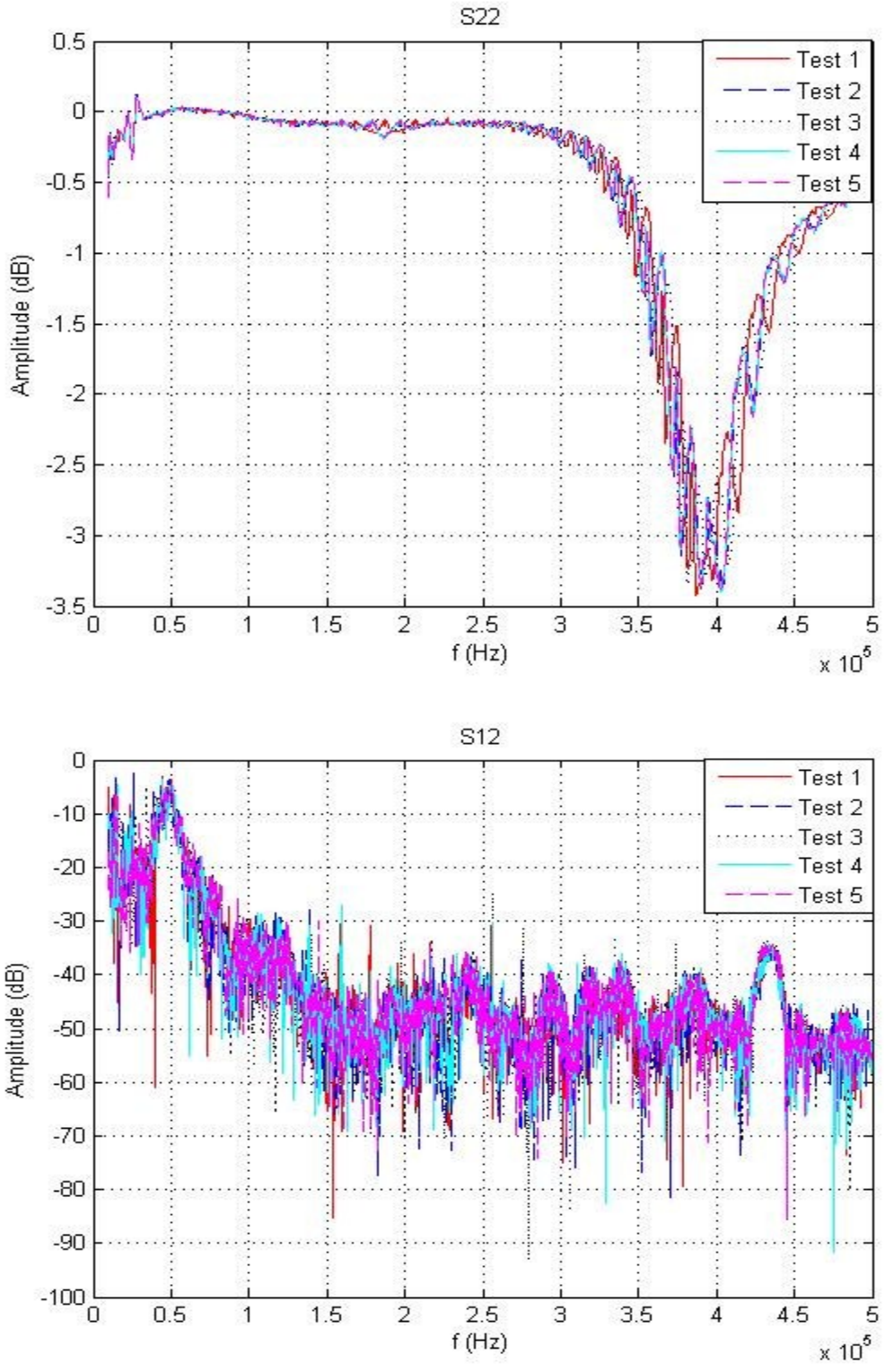

Figure 3.8. S-parameter for energized MV- LV

3.3. S-parameters for de-energized LV-LV

The main goal of this portion of the test was to characterize the embedded LV coupler used in the NB-PLC modem by studying the coupler's behaviour in the NB-PLC frequency range. Due to the constraints of the power limiter on the network analyzer and in order to avoid damaging this equipment, it was not possible to capture the S-parameter over an energized LV-LV channel. Fig.3.9 and 3.10 are presenting the behavior of LV-LV coupler, embedded on EV-KIT when the channel is de-energized.

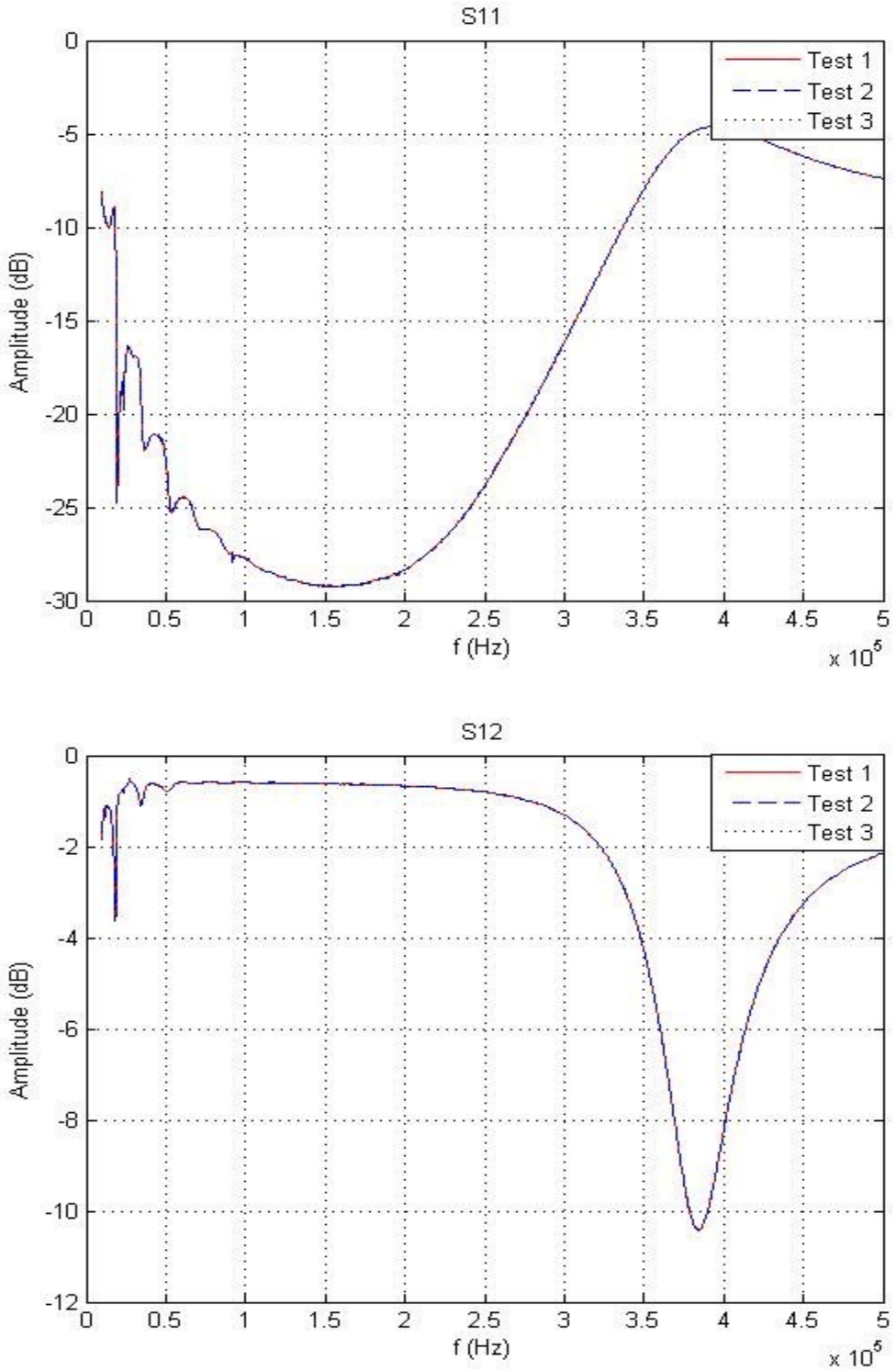

Figure 3.9. S-parameter for de- energized LV- LV

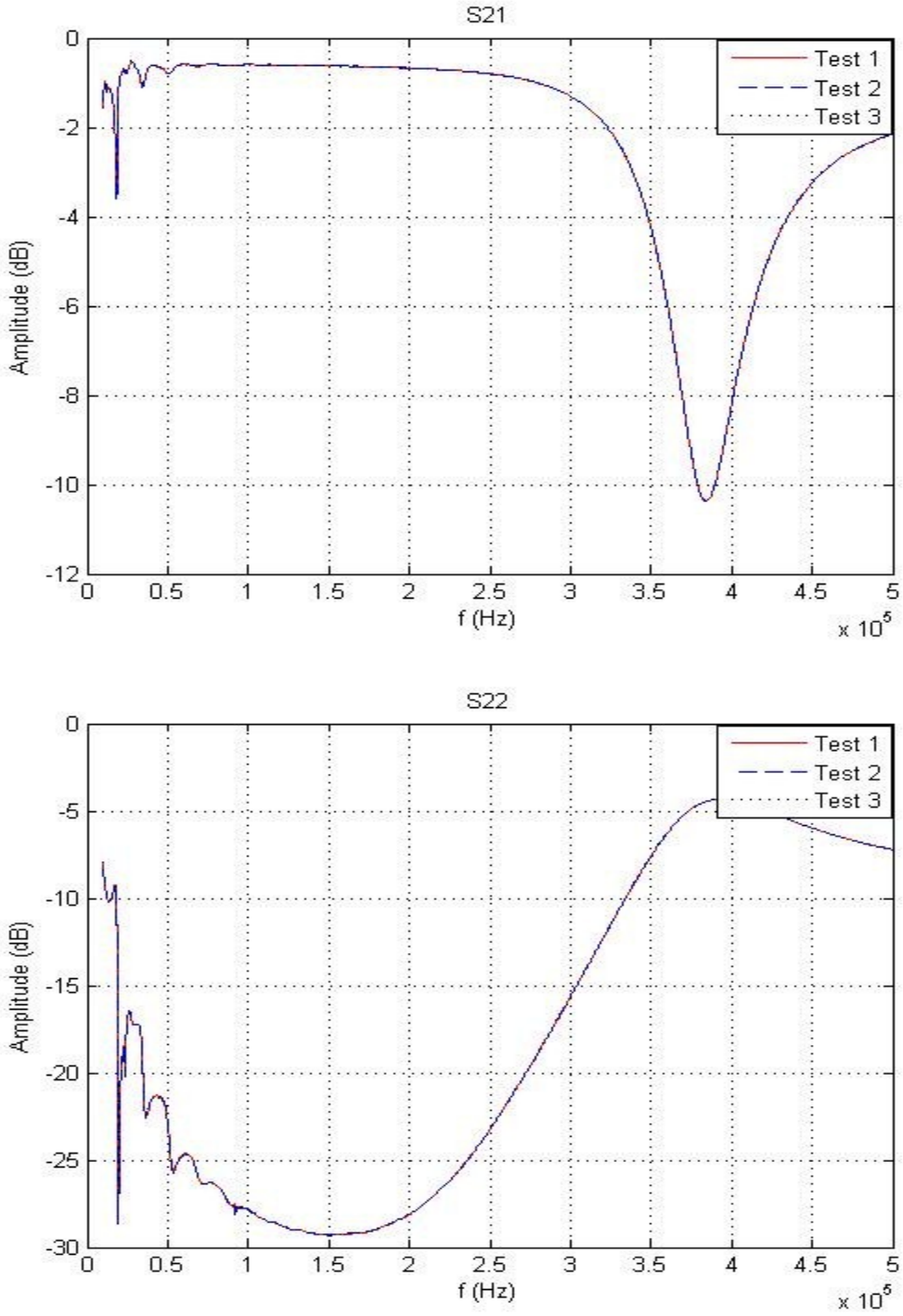

Figure 3.10. S-parameter for de- energized LV- LV

3.4. Noise measurement

The noise over the de-energized and the energized LV and MV channels was captured at both frequency and time domains via a digital oscilloscope, as was explained previously. These measurements show the magnitude of the noise signals on both the de-energized and energized LV and MV channels in the test setup. These measurements can be useful in noise modeling to anticipate required filtering or possible signal cancellation upon the NB-PLC which are beyond the scope of this work. The results are depicted below. As we show here, the noise level is below -55dBm when the channel including MV/LV transformer is de-energized, and becomes as high as -10dBm when it is energized.

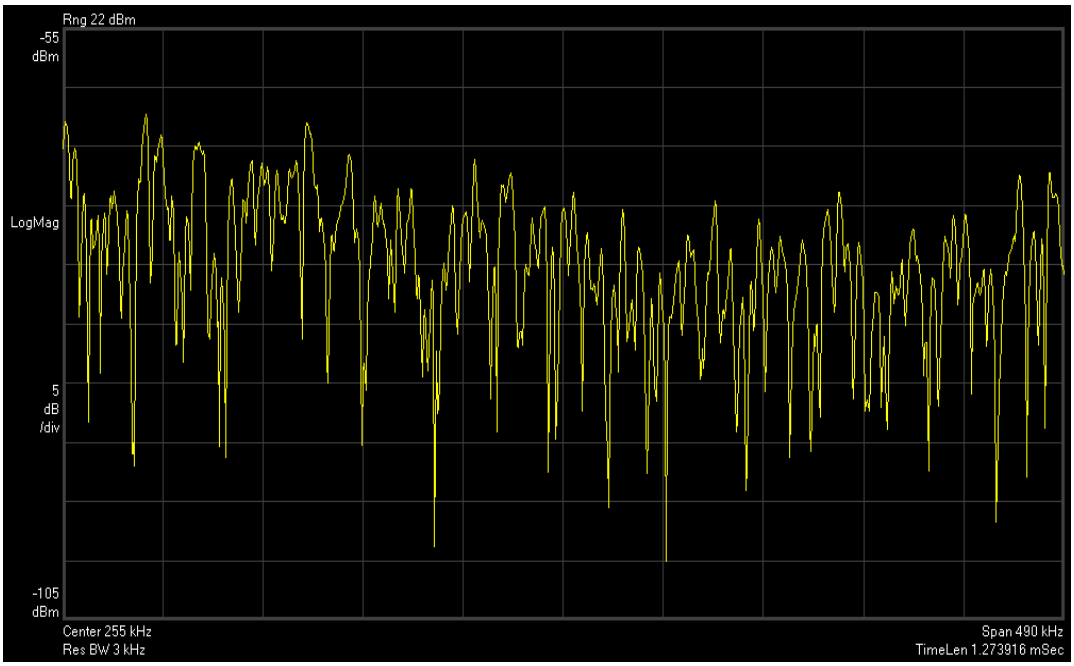

Figure 3.11. Noise measured over the de-energized LV side vs. frequency domain

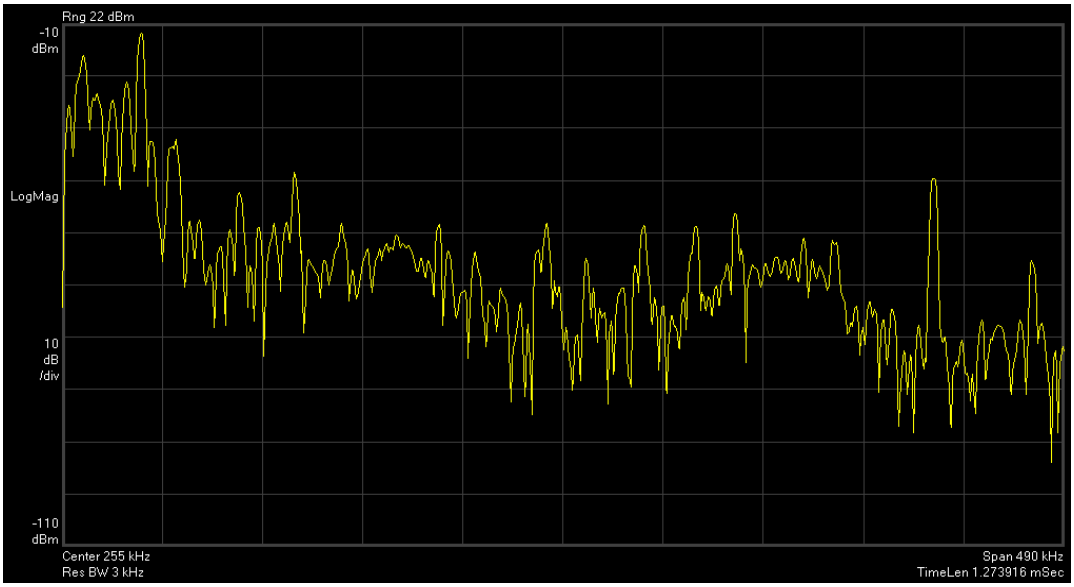

Figure 3.12. Noise measured over the energized LV side vs. frequency domain

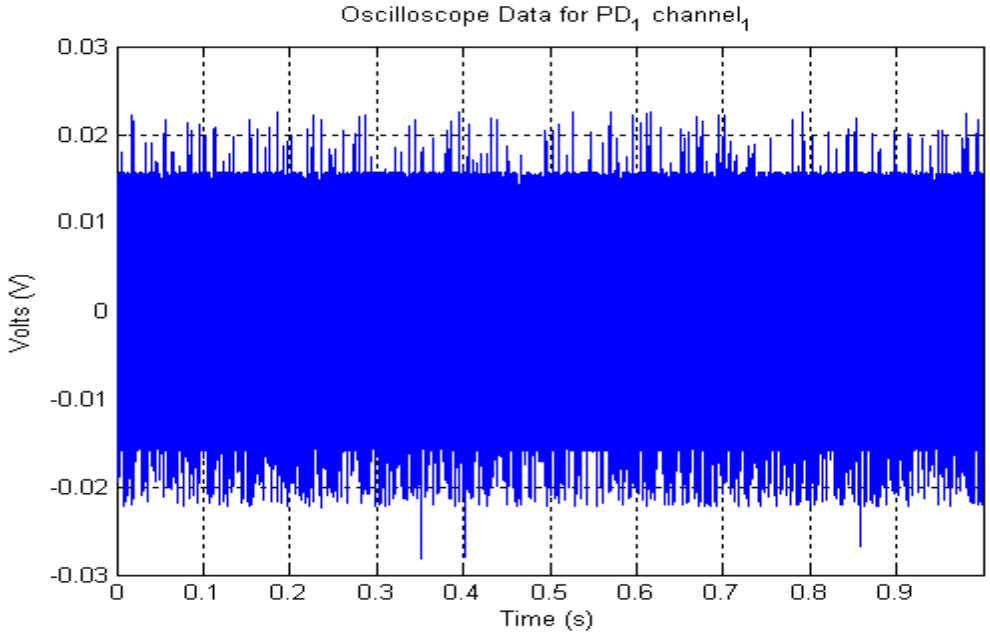

Figure 3.13. Noise measured over the de-energized LV side vs. the time domain

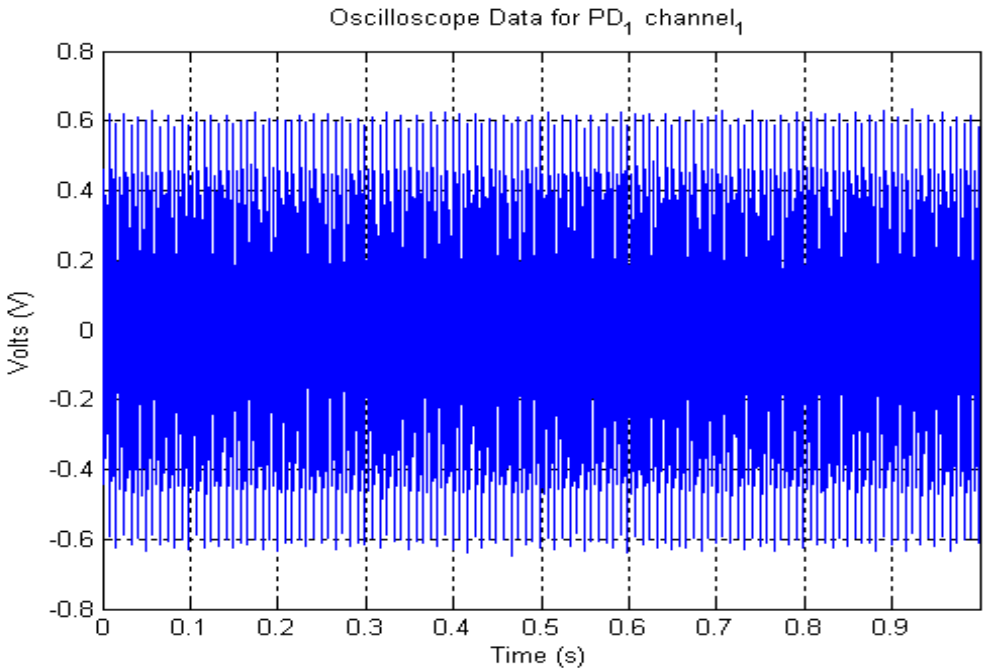

Figure 3.14. Noise measured over the energized LV side vs. the time domain

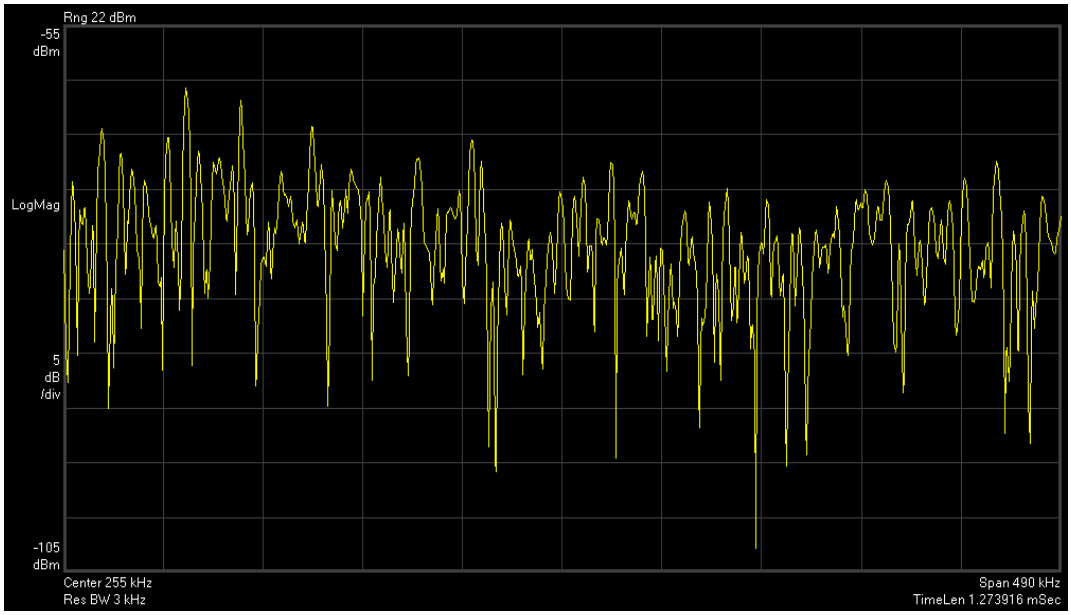

Figure 3.15. Noise measured over the de-energized MV side vs. the frequency domain

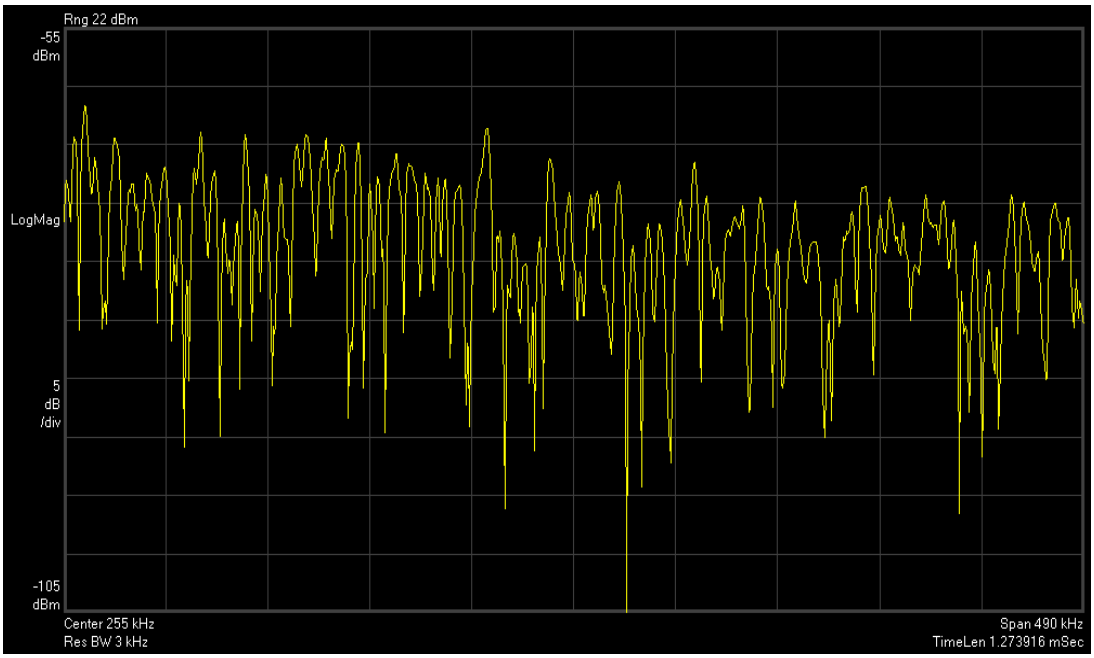

Figure 3.16. Noise measured over the energized MV side vs. the time domain

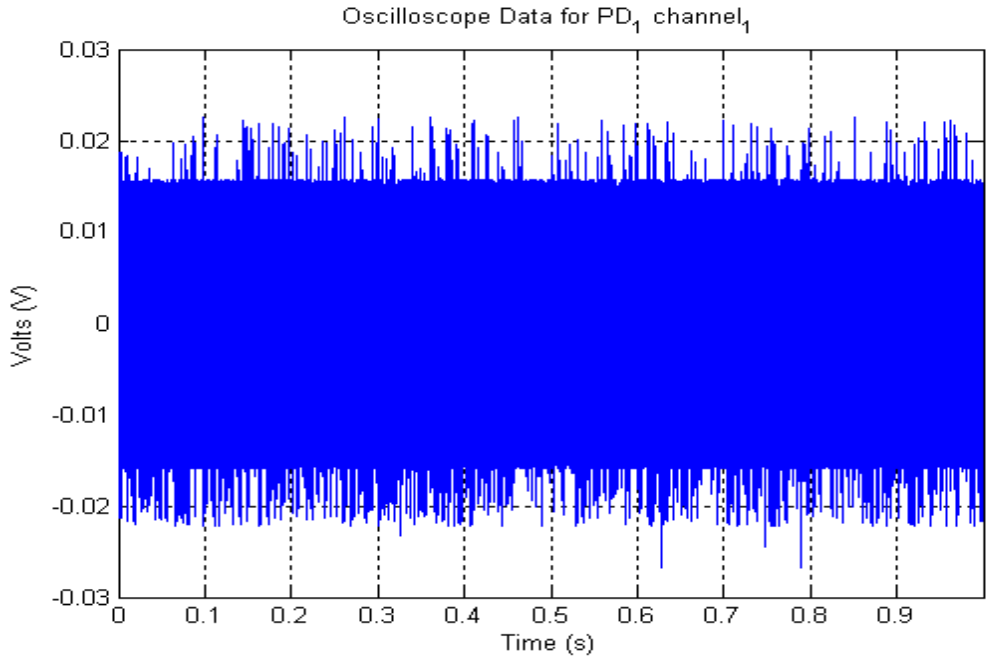

Figure 3.17. Noise measured over the de-energized MV side vs. the time domain

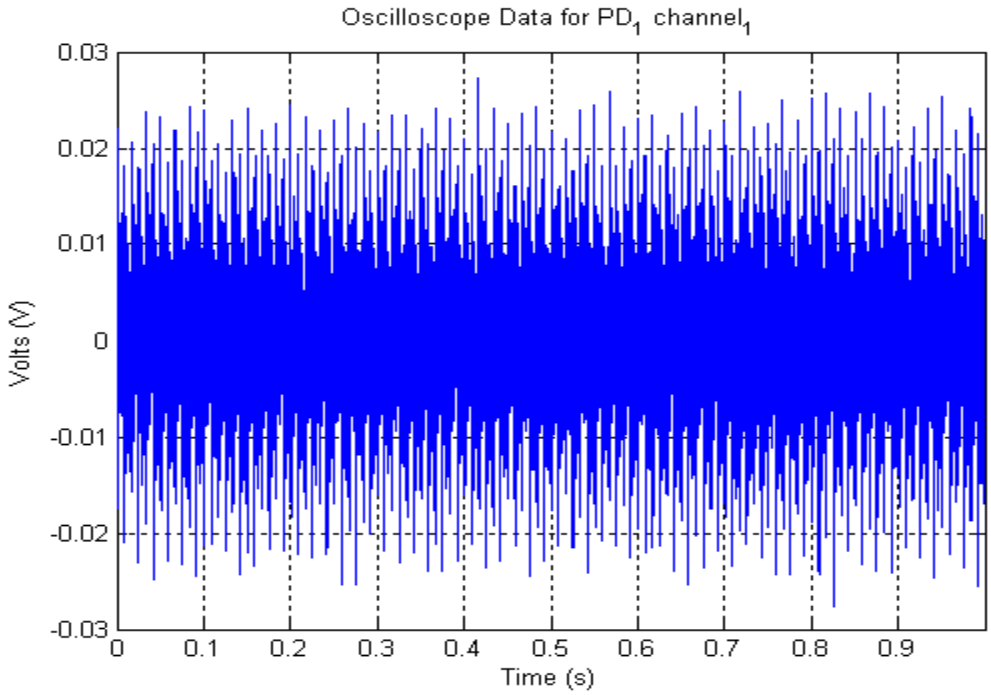

Figure 3.18. Noise measured over the energized MV side vs. the time domain

3.5. Results analysis

From the S-parameters and the noise measurements, it is essential to identify which parameters and factors caused these test results and to use these in arriving at a reasonable conclusion. It is also necessary to suggest some possible research opportunities for future works. The first part of the analysis focuses on the noise measurements by addressing the most important noise sources. As shown from the noise measurement data, the noise level on the energized LV side is higher than in the non-energized case. This can be seen obviously in figures 3.11 and 3.12. It was further found to be even higher than that measured on the energized MV side which is presented in figure 3.16. This was attributed to time varying loads on LV side. We need to recall that due to lack of medium voltage loads on our medium channel, noise measurement and analysis on MV channel need to be achieved as a future work. It is important to remind that the MV/LV transformer physically isolates the LV and MV sides

electrically from each other. Therefore the LV side's noise has no influence on the MV side. The most important noise types could be categorized as follows:

- Impulse noise (at twice AC main frequency)
- Tonal noise
- High frequency impulse noise

A possible source of impulse noise could be the commonly used light dimmer. These components generate noise while they connect the lamp to the AC line through each half AC cycle.

The tonal noise is divided into two sub-categories: intended and unintended. The unintended tonal noise could be generated by the power supplies existed within different electronic devices, such as PCs or fluorescent fixtures. The frequency of these noise sources might be anywhere within the range of 20 KHz to greater than 1MHz. Intended tonal noise could result from certain devices such as power line intercoms or baby monitors. In North America these components work in the frequency range of 150-400 KHz. Commercial radio broadcasts are another source of intended tonal noise as well. High frequency impulse noise is generated by various house hold electric devices, such as vacuum cleaners, electric shavers, and various common types of kitchen appliances. The commutator in these devices could make impulses in the several KHz range. These characteristics could be evaluated more via captured S-parameters measurement.

As mentioned earlier, the power line channel has a non-linearity and time variant behaviour. For example, the impedance of a point on a power line network at the LV side changes with time when appliances on the network are drawing and not drawing power from the line at twice the AC line frequency. Additionally, some loads such as capacitors used inside computers and TVs or heating elements inside ovens show a lower impedance in comparison to the characteristic impedance of the power line. This causes severe impedance mismatching, which results in high attenuation. In addition MV/LV transformer behaviour at high frequencies should be taken into account for this analysis. In the following we will try to analyse our measured S-parameters further.

As we mentioned before, the S-parameters presented in figures 3.1 and 3.2 show the behavior of Cipunet medium voltage coupler designed for NB-PLC frequency range (10-500KHz) on both de-energized and energized channel. Based on these pictures, we can figure out that this coupler doesn't attenuate the communication signal during injection over the power line channel, and can be used efficiently for this purpose. This situation applies to embedded low voltage coupler on EV-KIT as well. The behavior of LV coupler is presented in figures 3.9 and 3.10.

S12 and S21, captured on both de-energized and energized LV-MV path, shown in figures 3.6 and 3.7 present that MV/LV transformer attenuates the communication signal significantly, and can be considered as an important obstacle in power line communication. Hence, further measurement and analysis is totally necessary in future to be familiar more with the behavior of this transformer over power line channel.

By looking at the S-parameters measurement based on figure 3.8, an excessive attenuation and ripple was observed over the energized MV-LV path that shows an asymmetrical behavior in compare to S-parameters measurement on energized LV-MV side, depicted in figure 3.7. One of the most likely parameters to cause this problem is the signal crossing from a high impedance environment to a lower one introducing attenuation. For example, the characteristic impedance of the medium voltage line is usually around 320Ω which is much higher than on the LV side. In addition the surge impedance of the transformer (also known as wave impedance) is greater on the MV side than on the LV side due to higher inductance (L) on the MV side of the transformer. This impedance is shown in the following formula:

$$Z = \sqrt{L/C}$$

It is necessary to mention that any internal problems within a transformer could impact the frequency response and would be reflected in the S-parameters as well. For example some empirical measurements show that frequencies in the range of 10-500 kHz are sensitive to winding movements, primarily in bulk transformers. Partial discharge (PD) in old transformers should be taken into account as well. A complete discussion on frequency response analysis (FRA) and PD is beyond the scope of this work.

Chapter 4. Conclusions and Future Work

S-parameters measurement can reveal conclusively that the power line channel has a time-varying behaviour. This was especially noted when a MV/LV transformer existed on the channel. Therefore, this case study requires more research and investigation on the behavior of these types of transformers in order to construct a characterized model in the future. For example, due to some limitations in this work the following items need to be considered as future research opportunities:

Developing an accurate analytical model of the most common types of MV/LV pole-top transformers in the North American power network at a frequency range of 10-500 KHz could be considered a research opportunity for better analysis and evaluation. The behaviour of these transformers in the above frequency range has had very little study. This followup should experiment with short/open circuit testing to find out the exact values of the transformer's reactive components. Then, the objective is to model R,L, and C accurately to the actual transformers that are used in the field.

Like all power transformers, each MV/LV transformer has a different characteristics and structure. The most common types of real MV/LV transformers connected in the North American power grid (e.g. 25KVA, 50KVA, and 75KVA) should be characterized and tested in a future work. Some criteria to be evaluated would include the 4 layer and 8 layer windings. A 5KVA transformer is an example of 4 layer transformer.

The work presented was on a 5kVA transformer while it was unloaded. The behaviour of the transformer needs to be further evaluated while under both loaded and unloaded conditions. For example, when there is no load connected to the secondary side (MV), the current in the primary only produces magnetic flux needed for transformer action, to cause hysteresis and eddy-current losses in the iron. This current is called excitation current. Additionally, when a transformer's primary winding is overloaded from

excessive voltage being applied, the core flux may reach saturation level during peak moments of the AC cycle. That voltage induced in the secondary winding will no longer match the wave-shape of the voltage powering the primary coil. This results in the over-loaded transformer distorting the wave shape from the primary to the secondary windings, creating harmonics in the secondary winding's output. As was mentioned throughout, these harmonics are a main source of noise over the power line channel.

Different network topologies should be evaluated as well. From network component and structural points of view, there are different power network topologies present in the urban areas as compared to rural areas. Subsequently, the performance of NB-PLC should be tested and compared under in these different topologies.

Another factor, which should be considered in a future work, is the effect of insulating/cooling materials such as oil (mineral and synthetic) or air within the transformer. For example, when the insulating oil is removed from the transformer, the capacitance of the transformer is reduced. This is a result of changing the dielectric from oil to air. For a better understanding of how this change in capacitance may affect frequency response (FR), the changes in the position of resonance and their amplitudes should be studied. A future study may include the analysis of the frequency response of an oil-filled and a gas-filled transformer [8].

Figure 4.1 shows the effect of oil and no oil on the frequency response of an actual 30 MVA transformer.

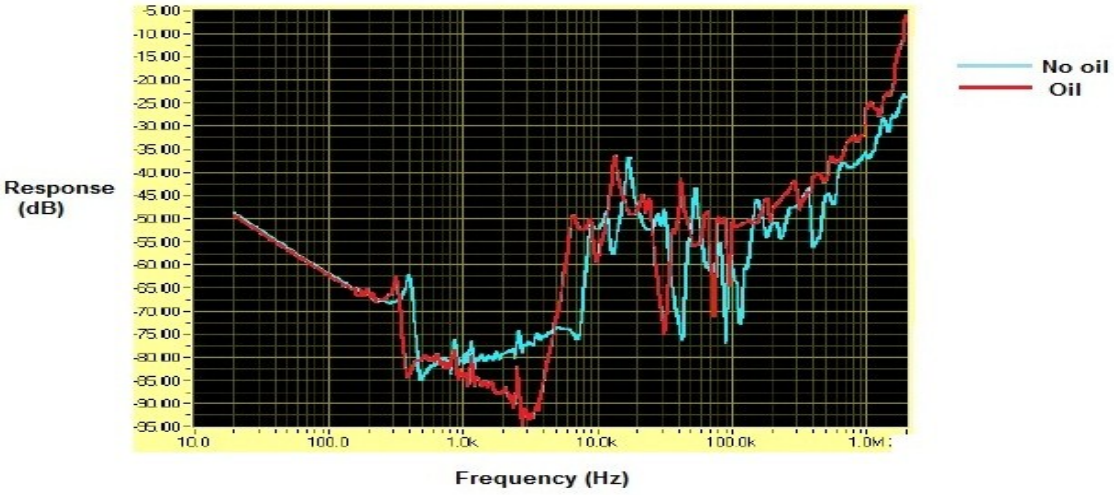

Figure 4.1. The effect of insulating material on the FR of a power transformer [8]

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