Design of a 3-Phase Line Impedance Stabilization Network For Conducted Emission Test

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***Abstract*—Conducted Emission (CE) tests are carried out to find out the amount of high frequency noise injected to the grid by the equipments. Line Impedance Stabilization Networks (LISN) are utilized in order to obtain noise measurements, under different grid conditions, which meet the CE standards. This paper presents how to make a 3-phase $10kVA$ LISN which costs about 5% of a commercialized ones. The procedure is explained for making the air core inductors. The simulation and experimental results are presented which shows the effectiveness of the design. The guidelines for selection of components are explained. The LISN is used to evaluate a SMPC and a 3-phase drive. The readings from the LISN is compared with common mode current measurement on the SMPS to validate the effectiveness of the LISN.**

***Index Terms*—Conducted Emissions (CEs), Electromagnetic Compatibility (EMC) Measurements, EMC Test Setup, Line Impedance Stabilization Networks (LISN).**

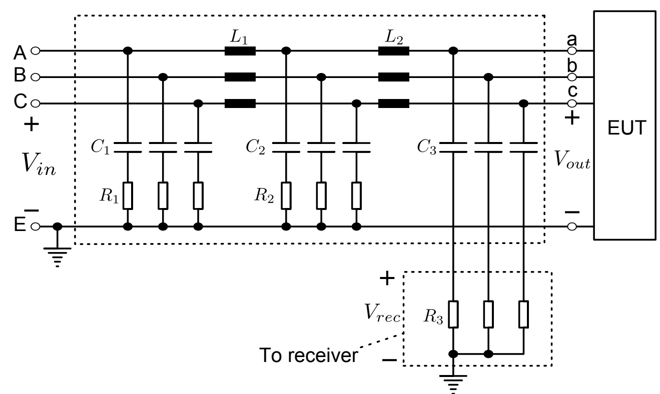

Fig. 1. Typical 3-phase CE compliant measurement set-up schematic to measure conducted EMI from a test equipment.

I. Introduction

One of the major challenges for designing power converter equipments is the Electromagnetic Compatibility concerns. If an equipment is meant to be commercialized, it has to pass all the standard electro magnetic emission tests. Conducted emission test is a standard test which identifies the amount of high frequency noise injected to the grid by the equipments. Standards like CISPER 16 [1] indicates the guidelines for the conducted noise measurement test. In CISPER 16 it is proposed to use a Line Impedance Stabilization Network (LISN) between the grid and the Equipment Under Test (EUT). According to this standard, the LISN should fulfil the following requirements [1], [2]:

1- To stabilize the mains impedance in order to standardize the measurement.
2- To filter out the high frequency noise coming from the grid and prevention of affecting the measurements.
3- To provide a path for high frequency noise coming from the EUT to the EMI receiver. Also, providing 50Ω match connectors for the receiver.

It is possible to measure the conducted electromagnetic emission without using LISN [3], but numerical treatment would be needed to be performed on the the data. In [4] a LISN is proposed where the number of components are doubled. However, any advantage of the circuit over the circuit proposed by the CISPER is not observed. In [5] two novel 3-phase common mode/differential mode noise separation networks, which are passive and active networks presented for measurement of conducted emission test. However, it is possible to observe conducted EMI performance even without such separation network. Commercially LISN's are available from a number of manufacturers [7].

In this paper steps involving the design procedure and building a low cost $10kVA$ 3-phase LISN is presented. The circuit topology used in this paper is shown in Fig. 1. The circuit is analysed and the output to input transfer functions are derived analytically. The frequency responses of the system are measured using network analyser. The LISN components are then analysed to identify the cause of derivation of the practical LISN from the analytical circuit model. The experimental and analytical results comparison shows the effectiveness of the design.

II. LISN Circuit Topology and Transfer Function Analysis

Fig. 1 shows a typical 3-phase LISN. The resistance, capacitance and inductance values are tabulated in Table I. There are three terminals available in the circuit, input to the LISN (V_{in}), output of the LISN (V_{out}) and the port for the measurement (V_{rec}). Three input-output transfer functions are considered and their relationships are derived. Bode magnitude

TABLE I
COMPONENT VALUES OF LISN SHOWN IN FIG. 1

SL.NO.	PARAMETER	VALUE
1	R_1	10Ω
2	R_2	5Ω
3	R_3	$50\Omega \vert\vert 1k\Omega$
4	C_1	$4\mu F$
5	C_2	$8\mu F$
6	C_3	$250nF$
7	L_1	$250\mu H$
8	L_2	$50\mu H$

plot of each transfer function is plotted in Fig. 2. First we consider the receiver to input transfer function ($\frac{V_{rec}}{V_{in}}$), it is given in (1). The bode plot of (1) is shown in Fig. 2(a). It can be seen that the high and low frequency noises, in the input, are well attenuated. The attenuation at $150kHz$ is about $-35dB$ and it is further more for higher frequencies. The gain at fundamental frequency (50Hz) is about $-50dB$, this indicates that the power losses in the resistor R_3 are very small.

$$\frac{V_{rec}}{V_{in}} = \frac{C_2C_3R_2R_3s^2 + C_3R_3s}{K_1s^4 + K_2s^3 + K_3s^2 + K_4s + 1} \tag{1}$$

where,

$$K_1 = C_2C_3L_1L_2$$
$$K_2 = C_2C_3L_1R_2 + C_2C_3L_1R_3 + C_2C_3L_2R_2$$
$$K_3 = C_2L_1 + C_3L_1 + C_3L_2 + C_2C_3R_2R_3$$
$$K_4 = C_2R_2 + C_3R_3$$

Second, we consider the transfer function $\frac{V_{out}}{V_{in}}$. It is given in (2) and plotted in Fig. 2(b). It can be seen that the gain is unity for low frequency and high frequencies are well attenuated. Fundamental drop across L_1 and L_2 at $10kVA$, $415V$ is about $1.3V$ which is 0.55% of the phase voltage and is negligible. CE frequency range of interest is frequencies higher than $150kHz$ to $30MHz$. In this frequency range the LISN should act as an open circuit. This can be seen from Fig. 2(a) and Fig. 2(b). For low voltage EUT up to the range of 100s of kW the frequency separation of the filter impedance of the converter and the impedance of the LISN are high. If the converter rating is 10s of MW then this separation would be small and the converter filter impedance would change the performance of the LISN. However, such high power converters do not undergo standard conducted EMI test.

$$\frac{V_{out}}{V_{in}} = \frac{C_2C_3R_2R_3s^2 + (C_2R_2 + C_3R_3)s + 1}{K_1s^4 + K_2s^3 + K_3s^2 + K_4s + 1} \tag{2}$$

Finally, the transfer function $\frac{V_{rec}}{V_{out}}$ is given in (3) and plotted in Fig. 2(c). This transfer function acts as a high pass filter and passes the higher frequencies noise, generated by the EUT, to the receiver.

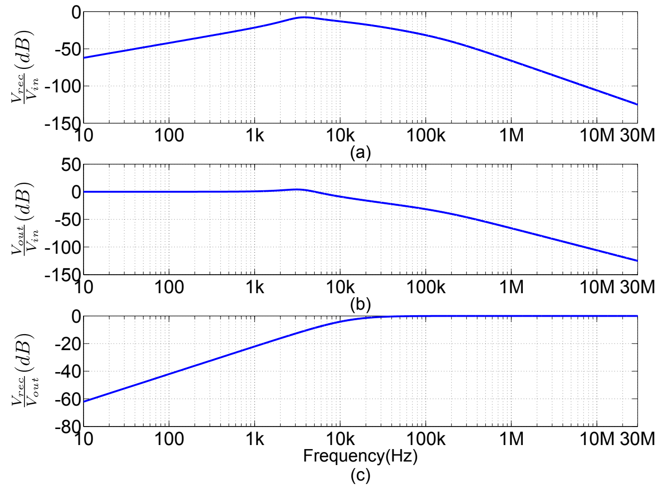

Fig. 2. Bode magnitude plots of LISN transfer functions. (a) Receiver to input $\frac{V_{rec}}{V_{in}}$, (b) output to input $\frac{V_{out}}{V_{in}}$, and (c) receiver to output $\frac{V_{rec}}{V_{out}}$.

$$\frac{V_{rec}}{V_{out}} = \frac{C_3R_3s}{C_3R_3s + 1} \tag{3}$$

Expected gain of unity above $10kHz$ satisfies the frequency range of $150kHz$ to $30MHz$ where the conducted EMI test is performed.

The LISN is specified with resistors R_1 and R_2, which provide sufficient damping. It can be seen from the Fig. 2(b) that the peak at 4kHz is less than 0dB and there would not be any resonance amplification. Additionally, the EMI frequencies of interest are between 150kHz to 30MHz. The typical switching frequencies are far below the EMI frequency range of interest and the LISN resonance will not affect the conducted emission test results.

III. LISN COMPONENT DESIGN

The circuit components of the LISN shown in Fig. 1 need attention to parameter selection and design for its construction.

A. *Resistor Selection*

There are three resistor per each phase. The losses of resistor R_i can be approximately calculated as given in (4) where, the inductors voltage drops are negligible. The resistors are carbon resistors which have good high frequency response.

$$P_{R_i} = \frac{(\frac{V_{in}R_i}{X_{c_i}+R_i})^2}{R_i} \tag{4}$$

The losses are calculated and found to be $P_{R_1} = 0.88W, P_{R_2} = 1.78W$, and $P_{R_3} = 0.018W$ at $50Hz$. The resistors used for R_1 and R_2 are parallel combination of $20\Omega, 1W$ resistors. So, for R_1 two parallel resistor and for R_2 four parallel resistor are needed. With this kind of arranging the resistor R_1 and R_2 a safety factor two for power dissipation is used. A normal 50Ω quarter watt resistor can be used as R_3. With these, the power dissipation of each resistor does not cross its limit and they would be in a safe

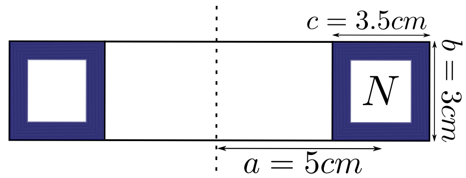

Fig. 3. The dimensions of coil L_1 shown in Fig.4 top.

region. The losses have been experimentally measured to be $P_{R_1} = 0.98W, P_{R_2} = 1.95W$, and $P_{R_3} = 0.017W$.

B. Inductor Design

In the LISN, the inductors play a vital role. The inter winding capacitance of inductors should be minimized specially L_2 which directly affects the measurement data if it is not well designed. For that matter, L_2 is wounded as a solenoid which has only one layer of winding. The inductor L_1 can be wounded as a multilayer air core inductor. The inductor L_1 design is based on Wheeler's formula [6] for a multi-layer air-core inductor, given in (5).

$$L = \frac{31.49a^2N^2}{6a + 9b + 10c} \tag{5}$$

Where, L is the inductance of the coil in micro-Henry, N is number of turns, a, b and c are the dimensions of the coil shown in Fig. 3 in meters. The bobbin of the L_1 is made of NYLON with the temperature range from -40^oC to approximately $+100^oC$.

The inductor L_2 is designed based on Wheeler's formula [6] for a single-layer air-core inductor, given in (6).

$$L = \frac{39.37N^2D^2}{18D + 40l} \tag{6}$$

Where, L is the inductance of the coil in micro-Henry, N is number of turns, D is the diameter of the coil and l is the length of the coil in meters. polyvinyl chloride (PVC) tube is used as a bobbin for the inductor L_2 with the temperature range from -25^oC to approximately $+70^oC$. The specification of the inductors are given in Table II. The actual inductors photo are shown in Fig.4.

C. Capacitor Selection

Capacitors used in the LISN are plastic film capacitor the considerations about the capacitors are that they have to have low Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL). Specially for C_3 which is the path for high frequency noise generated by the EUT to the receiver. From the transfer function $\frac{V_{rec}}{V_{out}}$ shown in Fig. 2(c) it can be seen that the high frequency gain of this transfer function is unity. However, if the ESL of the $C_3 - R_3$ branch is high the unity gain at high frequency can not be obtained.

The inductors are to be located such that the coupling between them are minimized. Mechanical layout of the LISN is given in Fig.5(a). The circle, rectangle and square show the places of the inductors L_1, inductors L_2 and the $R - C$

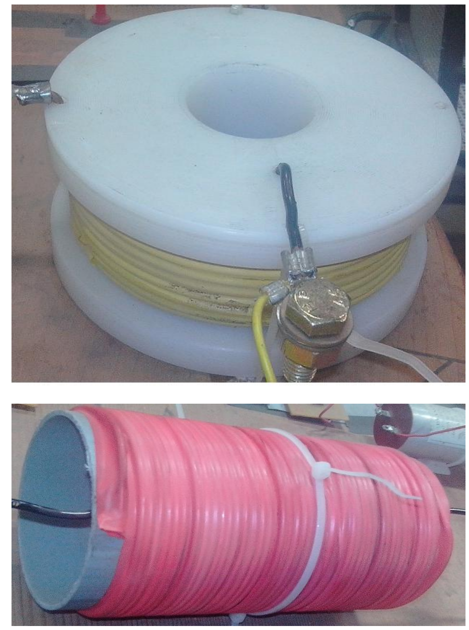

Fig. 4. Designed inductor L_1 (top), designed inductor L_2 (bottom).

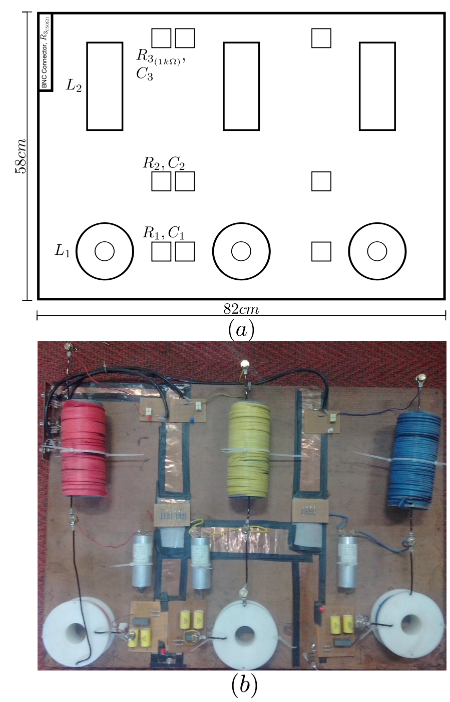

Fig. 5. Mechanical layout of the designed LISN.

branches respectively. The laboratory built LISN photo is shown in Fig.5(b).

IV. Experimental Result

The LISN based on circuit configuration given in Fig. 1 is built in the laboratory. The frequency response plot of the LISN has been obtain using an AP Instrument Inc. 200 Network Analyser. The results are shown in Fig. 6. Comparing Fig. 6 and the analytical response shown in Fig. 2 we can

TABLE II
SPECIFICATION OF INDUCTORS L_1 AND L_2.

Parameters	L_1	L_2
Coil Diameter	65mm	75mm
Coil Length	30mm	150mm
Wire Gauge	11SWG	11SWG
No. of Turns	54	41
No. of Layers	6	1

see that, the experimental results and analytical calculation are matching till around $2-3MHz$. Beyond $3MHz$ the experimental frequency response shows lower attenuation in $\frac{V_{rec}}{V_{in}}$ and $\frac{V_{out}}{V_{in}}$.

To investigate the reason of the deviation the frequency response of individual L_1 and L_2 are obtained and is shown in Fig. 7. Fiq. 7(a) shows the admittance plot of inductor L_1. it can be observed that at around $1MHz$ effects of parasitics capacitances are coming into the picture. Similarly in Fiq. 7(b) which shows the admittance plot of L_2. One possibility is that the inter winding capacitance can cause this kind of behaviour, the other possibility is the capacitances of the probes and the network analyser limitations. To investigate the reason, another inductor is built with the inductance of $50\mu H$ with $N = 30$ turns, $D = 14.5cm$ and $l = 30cm$ in the laboratory. The conductors are placed with a pitch of $10mm$ between each conductors. Capacitance between two conducting surfaces can be calculated by the well known equation of $C = \epsilon\frac{A}{d}$. where, ϵ is the permittivity of a homogeneous medium, A is the surface of the conductor and d is distance between two conductors. In the new inductor design the surface of the conductor is reduced by a factor of about 5, and the distance between two conductors is increased by a factor of about 15. So, the capacitance between two turns will be reduced by a factor of about 75. So the inter windings capacitances are reduced drastically. The admittance plot of this inductor is obtained and is shown in Fig. 7(c). It can be seen that the same pattern are captured with the new inductor. It was also observed that the network analyser had an input capacitance of $25pF$. This would resonate close to $4MHz$ with the LISN inductance. From this experiment we can draw the conclusion that this deviation is due to the limitation of the network analyser and not the inter winding capacitances of the inductors.

A. Conducted Emission Test

The LISN is used to evaluate a SMPC and a 3-phase motor drive. The results are shown in Fig. 8 and Fig. 9. Fig. 8(a) shows the CE test result of a 3-phase motor drive the background noise which is due to sampling of the high frequency oscilloscope is about $30dB$, this is shown in Fig. 8(b). If the background noise is taken into account, it would be expected that the measured noise level comes below the $60dB\mu V$ recommended by CISPER standard. A single phase SMPC is connected between two lines of the LISN. The CE test is

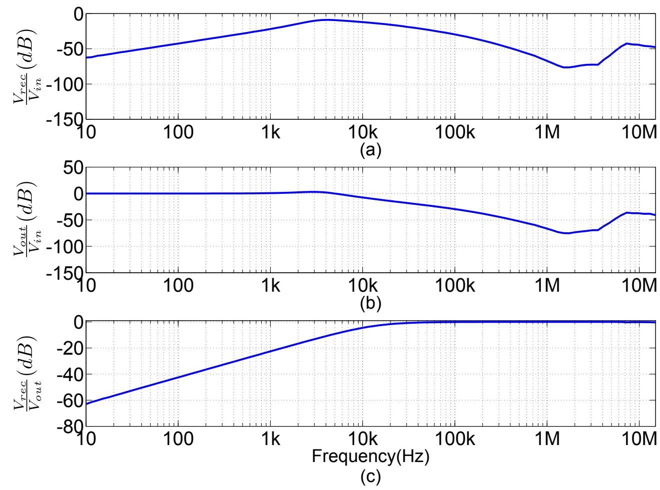

Fig. 6. Measured frequency response of (a) $\frac{V_{rec}}{V_{in}}$ (b) $\frac{V_{out}}{V_{in}}$ (c) $\frac{V_{out}}{V_{rec}}$.

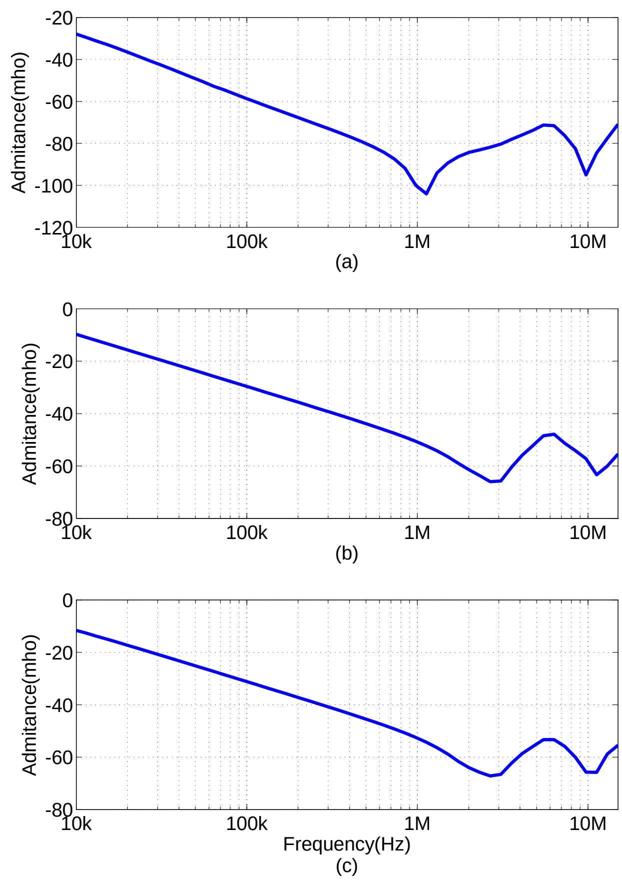

Fig. 7. Admittance plot of (a) inductor L_1, (b) inductor L_2 and (c) the new designed $50\mu H$ inductor with $N = 30$ turns, $D = 14.5cm$ and $l = 30cm$.

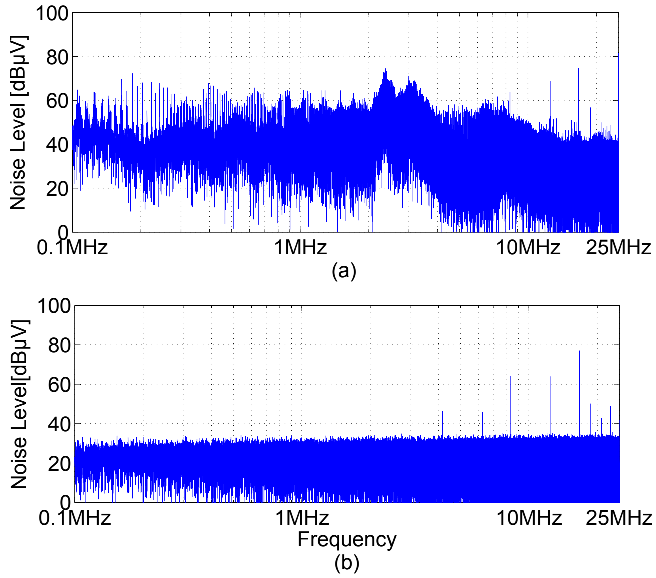

Fig. 8. CE test results of (a) 3-phase motor drive and (b)background noise of the high frequency oscilloscope.

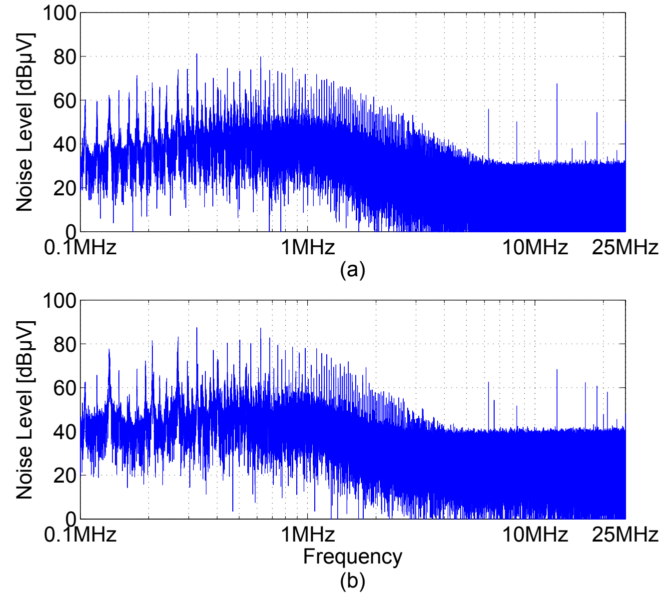

Fig. 9. CE test results of (a) single phase SMPC (b) common mode current of the SMPC scaled by LISN factor of 50.

performed and the results are shown in Fig. 9(a). This result can be validated with the help of common mode current which is the summation of the line and neutral current. The common mode current is measured by the help of a TCP300 Tektronix current probe with the bandwidth of $100MHz$. The common mode current is scaled by a factor of 50, this is due to 50Ω termination of the CE test. The scaled common mode current is shown in Fig 9(b). Comparing Fig 9(a) and Fig 9(b) it can be seen that they tally with each other. A high frequency oscilloscope $500MHz$ LeCroy 6050 is used as a receiver. The signal is sampled with the rate of $100M$ sample per second, the number of sample per cycle $(50Hz)$ is $2M$ sample. To obtained the spectra shown in Fig 8 and Fig 9 Fast Fourier Transform (FFT) on data are performed in Matlab, then the results are plotted in $dB\mu V$.

V. Conclusion

A low cost LISN is built using components that are easily available in the laboratory. The laboratory built 3-phase LISN bill of materials costs about Rs.8k. This is less than 5% of the case of commercial single phase certified LISN of similar voltage and current rating. Attention must be paid to the component parasitics for assembling in the laboratory LISN. The set-up is evaluated analytically and experimentally. The effectiveness of the LISN is checked with laboratory measurements on a SMPC and a 3-phase adjustable speed motor drive. The test provide a good assessment of the EMI characteristics of the power electronic equipments.

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