COMPARATIVE ANALYSIS OF THREE LINE COUPLING CIRCUITS FOR NARROW BAND POWER LINE COMMUNICATIONS APPLICATION

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ABSTRACT: *Power Line Communications (PLC) is an emerging technology that utilizes the power lines as the communications medium to transmit control signal or data from one device to another. This is made possible through the use of a PLC modem. The line coupling circuits are vital in the operation of a power line communication modem. The power line is found to have an impedance of 1 ohm to 20 ohms [1], [2] in low voltage networks particularly in-building wiring while most PLC modems have an impedance of about 50 ohms [3]. This impedance mismatch would require higher transmit power and could potentially produce damaging EMI or spurious radiation. The line coupling unit (LCU) must be designed to match the modem's impedance with the power line impedance while filtering the harmful 220V, 60 Hz power line voltage.*

This study focuses on developing and comparing three line coupling units (LCU) for Narrow Band PLC (NBPLC) applications in in-building wiring. The comparison is based on the frequency and phase responses as stand-alone circuits; attenuation when the LCUs are connected to the power line; and the SNR when the LCUs are connected to the NBPLC modem. The frequency and phase responses are acquired by applying the frequency of interest which is from 30 kHz to 500 kHz. The three LCUs are all capacitive couplers, one uses a capacitor and an inductor, while the other two use a capacitor and a transformer. One of the transformer-capacitor couplers employs an EF20 core while the other uses an EF30 core.

The attenuation is measured by applying signal at the modem side of the transmitting LCU and measuring the signal at the modem side of the receiving LCU. The first capacitive coupler exhibits attenuation from -11dB to -13dB, while the second coupler that uses EF20 core has an attenuation of -5 dB while the third that uses EE30 core showed 0 dB attenuation.

The SNR of the LCUs are also measured with the LCU integrated to the TMDSPLCKIT-V3 PLC modem by bypassing the modem's internal LCU. The first capacitive coupler gives an SNR from 2 dB to 5 dB, the second coupler achieves 12 to 14dB SNR while the third generates 14 dB to 16dB. The *two couplers that use transformers surpassed the 10 dB SNR of the modem's internal LCU given the same loading and wiring conditions. Based on the above measurements, it is concluded that the third coupler design that uses EE30 offers the best characteristics for use with narrowband PLC.*

Key Words*: Line Coupling Unit (LCU); Power Line Communications (PLC); TMDSPLCKIT-V3, NBPLC.*

1. INTRODUCTION

Power line communications (PLC) is the technique of sending data or control signal through the power lines. It operates in the frequency range from 30 kHz to 450kHz [4]. PLC is a similar technique with wireless communications. A carrier frequency is needed since the power line is intended to carry the 60 Hz 220V power. This carrier frequency is modulated so that it can ride along the 60 Hz power frequency. However, the modem cannot be directly connected to the high voltage power line. Hence, there is a need to isolate the modem from the power line. This is the purpose of the line coupling unit (LCU). It couples the modem to the line while attenuating the high voltage 60 Hz signal before it reaches the modem [5]. The design of the LCU is critical in the operation of the PLC modem. Aside from attenuating the 60Hz signal, it has to make sure that the modem's impedance matches that of the power line in order to transfer maximum power to the line. If there is significant mismatch, a significantly larger power is required at the transmitter which can dangerously produce EMI.

2. METHODOLOGY

2.1 PLC System Block

The basic block diagram of a PLC system is shown in Figure 1. The transmitter contains the encoder and modulator which are coupled to the power line channel through the coupling circuit. The process is reversed at the receiver by demodulating and decoding the original signal. The typical impedance of the transmitter's modem is about 25 ohms to 50 ohms [3] while that of the loaded power line also called access impedance is from 1 ohm to 20 ohms [1], [2]. The coupling circuit serves as the interface between the transmitter and the powerline channel. The next section discusses in-depth the function of the coupling circuit.

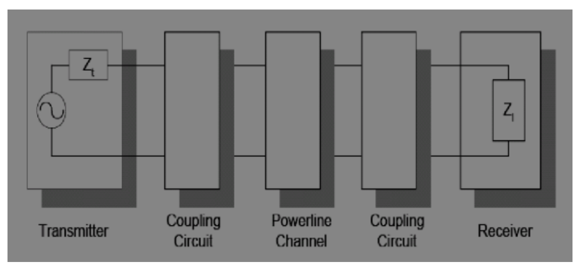

Figure 1. PLC Block Diagram

2.2 Line Coupling Unit (LCU)

The main function of the line coupling unit (LCU) is to isolate the high voltage electrical line from the low voltage digital signal transmitted by the modem. Incidentally, the high impedance mismatch between the modem and the power line prompted designers of the line coupling unit to design it not only to filter out the high voltage, but also to match the impedance of the line for maximum power transfer. Three coupling designs are developed and compared in this study.

2.2.1 Capacitive Coupling Circuit

The basic capacitive coupling circuit is shown below. The circuit is a basic bandpass filter with a resonant frequency given by

$$f_R = \frac{1}{2\pi\sqrt{LC}} \quad \text{Eqn. 1}$$

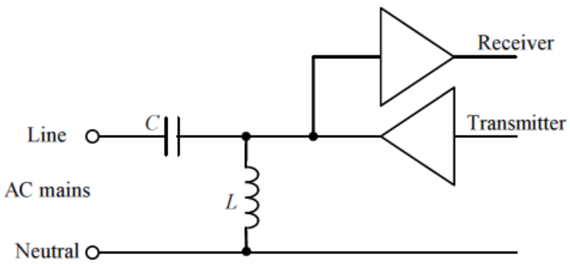

Figure 2. Basic Capacitive Coupling Circuit [4]

The low frequency cut-off is chosen such that the 60 Hz high voltage signal of the power line does not pass through the modem.

2.2.2 Transformer-Capacitive Coupling

The problem with the basic capacitor coupling circuit is that there is no galvanic isolation between the modem and the power line. Hence, even though protection devices like MOV and TVS are employed, there is still some probability that intermittent high voltage transients caused by disturbances in the line like lightning and switching on and off of motors can pass through and destroy the modem. Inserting a transformer between the modem and the power line provides this galvanic isolation.

The effective response is still that of a bandpass filter with the resonant frequency given by equation 1. The leakage inductance at the primary side (power line side) serves as the L in the equation.

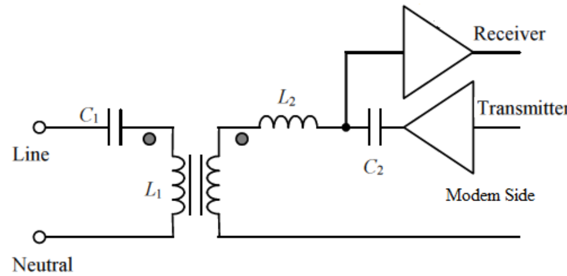

Figure 3.Transformer-capacitive coupling circuit and its connection to the MODEM

Aside from the galvanic isolation, the transformer also offers better impedance matching for the power line and the modem. Matching the impedance of the modem with the power line, which is typically in the range 1 ohm to 20 ohms, and 50 ohms respectively, maximizes power transfer.

3. LCU DESIGN

3.1 Design 1- Capacitive LCU

The components of the first design are shown in Figure 4. The basic capacitive coupling circuit given in Figure 2 is added with additional LC circuit and protection devices. Using equation 1, the indicated values produce a resonant frequency of 107 kHz.

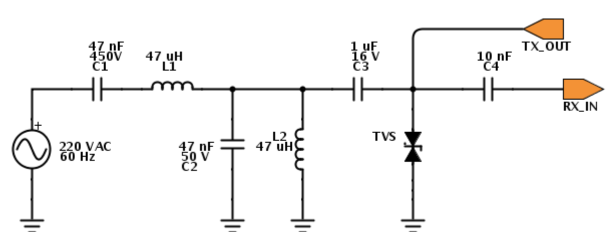

Figure 4. Capacitive Coupling circuit for PLC modem [7]

The Metal Oxide Varistors (MOV) limits the maximum voltage that will flow through the bandpass filter. Nonetheless, the series capacitors C1 is rated at 450V in order to handle the 311 V peak voltage generated by the 220V line. The TVS at the modem side further reduces any high voltage transients that may reach the modem.

3.2 Design 2- Transformer-capacitive coupler using EF20 Core (EF20 LCU)

The actual circuit for design 2 used in this study is given in Figure 5. It also employs a MOV at the power line side and a TVS at the modem side. The transformer utilized in this circuit is built by the proponents using the transformation equation given in equation 2. Based on the TMDSPLCKIT-V3 PLC modem specifications, its impedance is about 50 ohms. The impedance of the line is assumed to be 1 ohm based on the CENELEC standard. Given these values and plugging them in equation 2, the turns ratio of the transformer is found to be 7:1. The actual power line side winding (primary side) is 4, while the modem side winding (secondary side) is 28.

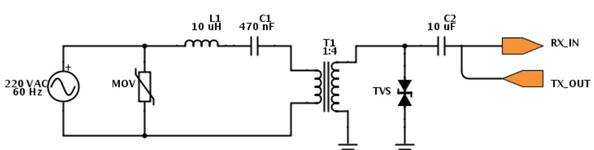

Figure 5. Transformer capacitive coupling circuit

$$\left(\frac{a}{b}\right)^2 \times z_m = z_p$$

Eqn. 2

The EF20 N87 core uses Mn-Zn ferrite material with a cross sectional area of 31.9 mm^2, a flux path length of 46.3 mm, and a flux density of Bsat = 18.08 mT.

The final circuit uses a 680 nF capacitor at the modem side. Considering that the modem has 50 ohms impedance, this gives a low cut-off frequency of about 5kHz..

3.3 Design 3- Transformer-Capacitive Coupler using EE30 Core

The circuit is basically the same as in Figure 5. The main difference lies in the core that is used. EE30 also uses Mn-Zn material but has a larger cross sectional area, Ae = 60 mm^2, and a longer flux path length. It has an inductance factor of 1900 nH

The transformation ratio is calculated to be 4:1. The resonant frequency is at about 6.8 kHz.

4. DATA AND RESULTS

There are three sets of tests done for each LCU, the single LCU attenuation test, the hot connection test, and the complete modem connection test. For the first two tests, a single frequency spanning the range from 300 Hz to 3MHz is applied to the modem side of the LCU. The Narrowband PLC range is from 30 kHz to 500 kHz. The test extends the range of the frequency below and above the NBPLC range in order to make a credible conclusion on the LCU characteristics.

4.1 Single LCU Attenuation Test

The purpose of this test is to measure the attenuation at the power line side of the LCU. Figure 6 shows the test set-up. A single frequency covering the range from 3kHz to 3MHz is injected to the modem side of the LCU. The oscilloscope measures both the input and output voltage waveforms. All designs exhibit bandpass behavior.

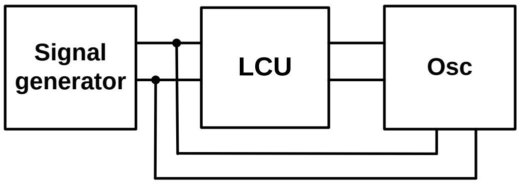

Figure 6. Attenuation Measurement for a single LCU

4.1.1 Magnitude and Phase Response for Design 1

The magnitude response of the capacitive coupler is shown in Figure 7. An attenuation of -10 dB for the frequency range 60kHz to 200 kHz is observed. This is well within the specifications of the designed circuit. However, some frequencies in the NBPLC band are severely attenuated.

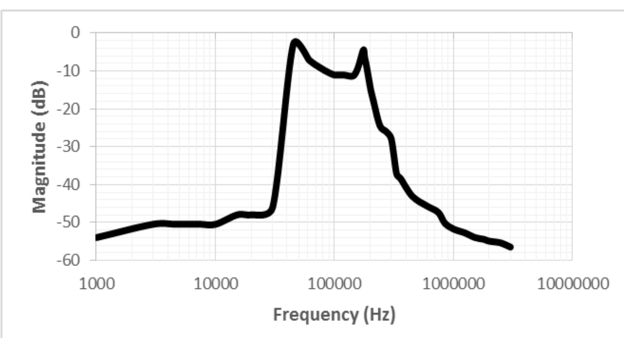

Figure 7. Magnitude Response of Capacitive Coupler for single LCU test

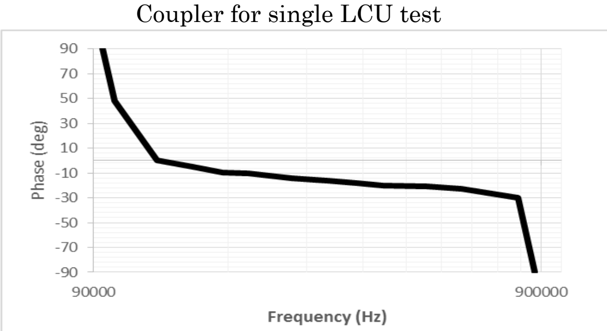

Figure 8. Phase Response of Capacitive Coupler for single LCU test

4.1.2 Magnitude Response for Design 2

The utilization of the transformer gave a big improvement on the frequency response as seen in Figure 9. A +10 dB is noted in the passband range of the PLC frequency of operations. This boost in the signal is expected since the transformer is a step-up transformer when referred from the modem side. The input is applied at the modem side and the output is measured across the power line side. The -3dB cut-off is at 25kHz instead of 5 kHz. Core losses and winding errors are the possible causes of the error. The theoretical response gives a passband gain of 33 dB.

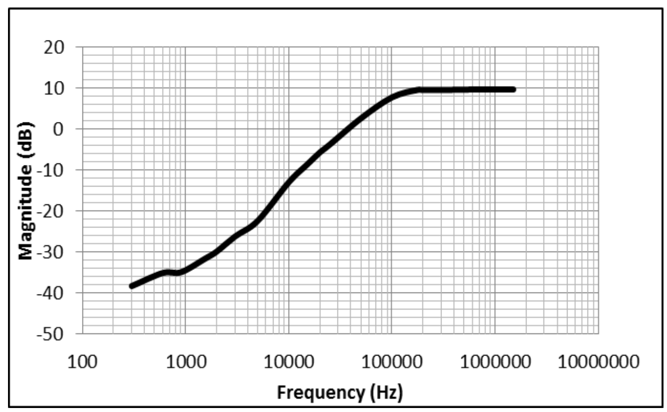

Figure 9. Magnitude Response of Transformer-capacitor Coupler using EF20 Core for single LCU test

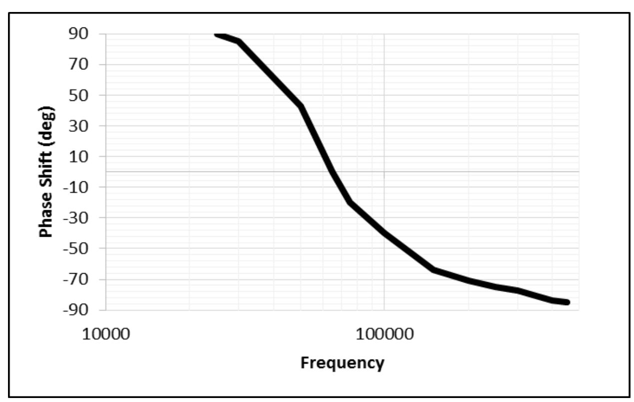

Figure 10. Phase Response of Transformer-Capacitive Coupler using EF20 Core for single LCU test

4.1.3 Magnitude Response for Design 3

The response curve for the EE30 coupler generates the same passband gain with that of the EF20. It's theoretical gain is 18 dB. Comparing this with the EF20, the EE30 has a smaller deviation. This can be attributed to core losses and winding errors. Both transformers are manually wound by the proponents. The -3dB cut-off is at about 10 kHz, just a little above the 6.8kHz design specifications.

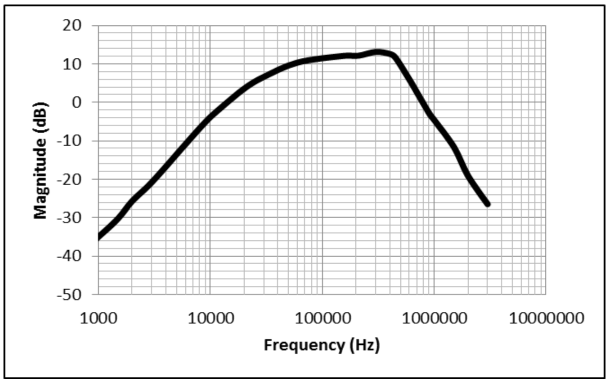

Figure 11. Magnitude Response of Transformer-capacitive Coupler using EE30 Core for single LCU test

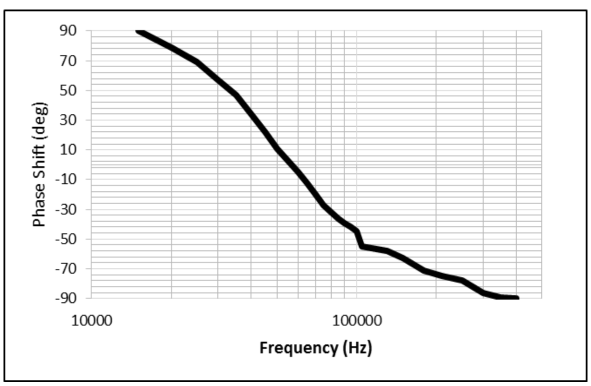

Figure 12. Magnitude Response of Transformer-capacitive Coupler using EF20 Core for single LCU test

4.2 Hot Connections Attenuation Test

In this test, a pair of LCUs is connected to the power line, one for the transmitter and the other for the transmitter. The process done in the Single LCU test is repeated here for each of the LCU. The oscilloscope measures both the input and output voltage waveforms.

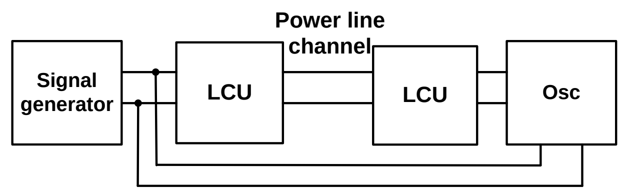

Figure 13. Test Set-up for hot connections

4.2.1 Attenuation Test for Design 1

The effect of connecting the LCUs directly to the power line is apparent in the response curve shown in Figure 14. It is observed that the signal is severely attenuated, -11dB to -13dB in the passband. This is due to the fact that the capacitive LCU is a passive device. Signals undergo attenuation twice, each LCU attenuates the signal. The graph here only shows up to 160 kHz but the bandpass characteristics have been noted in the entire PLC frequency range..

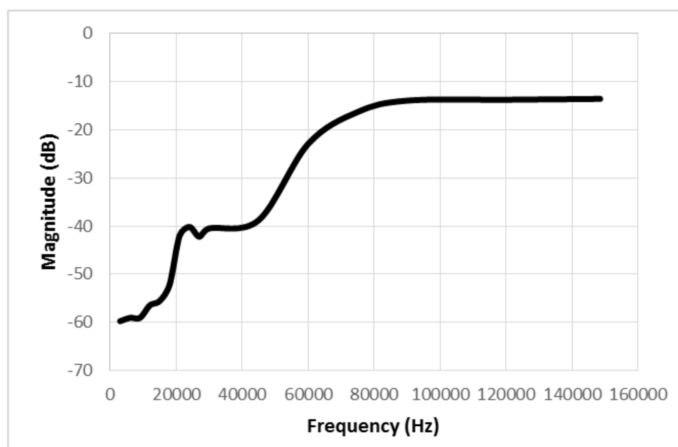

Figure 14. Magnitude Response of Capacitive Coupler for hot connection test

4.2.2 Attenuation Test for Design 2

Figure 15 shows the response curve for the EF20 coupler. As expected, the low impedance of the power line reduces the signal amplitude. From the +10 dB in the single LCU test, the passband now registers an attenuation of -5dB. Although unavoidable, the attenuation of Design 2 is considerably acceptable than that of Design 1.

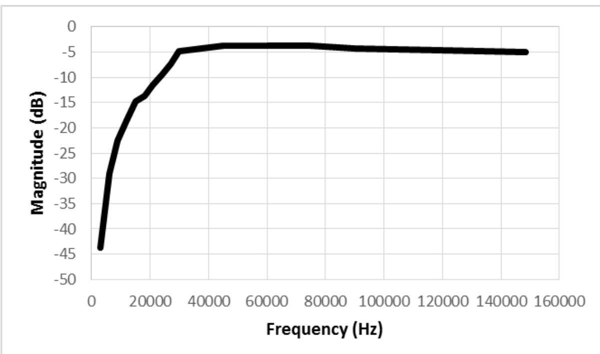

Figure 15. Magnitude Response of EF20 coupler for hot connection

4.2.3 Attenuation Test for Design 3

The magnitude response curve of the EE30 coupler shows great improvement in the attenuation profile (Figure 16). A 0 dB attenuation is noted for the whole range of NBPLC and this means that whatever is applied at the modem side of the transmitter, the same signal amplitude is realized at the modem side of the receiver. This is desirable since there are other factors that affect signal degradation which includes the length of the wire, the loads connected to the power line, and the number of branches or nodes that are connected to the line. The low cut-off frequencies, however, is shifted at frequency just below 20 kHz. It is notable however, that all of the LCUs -3dB cut-off moved to a higher value.

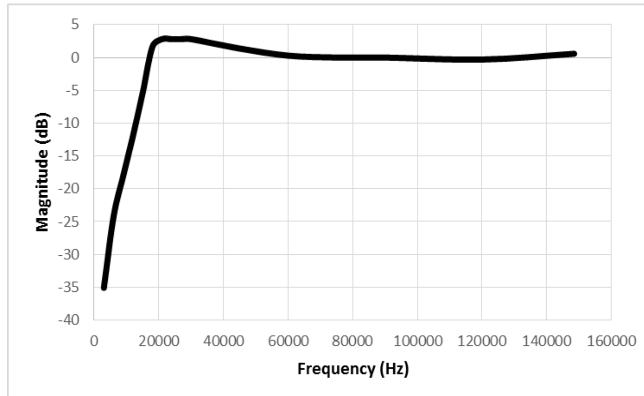

Figure 16. Magnitude Response of EE30 coupler for hot connections

4.3 Complete Modem Connections SNR Test

Since the first two tests show the EE30 to have a more desirable characteristic, it is the one used in the last test. In this test, an OFDM signal generated by the Modem is sent through the LCU. Through the modem's firmware, the signal to noise ratio (SNR) at the transmitter and receiver are measured. The SNR includes the effect of noise that are prevalent in the power line in the overall characterization of the LCU.

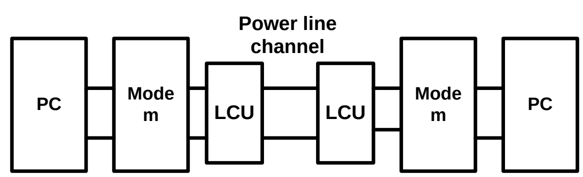

Figure 17. Test Set-up for the Complete test with LCU connected to an actual modem

The SNR measurements for both the transmitter and receiver are provided in Figures 18 and 19 respectively. The flat SNR measured at the transmitter side is obviously the expected result since the transmitter is noise-free. A 15 dB of SNR is noted. For the receiver, though, a varying SNR can be seen. This is caused by variation in electrical loads ranging from 500W to 1500W that the proponents deliberately varied.

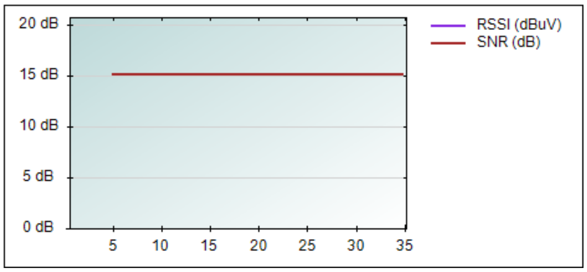

Figure 18. *SNR at TX of EE30 Coupler*

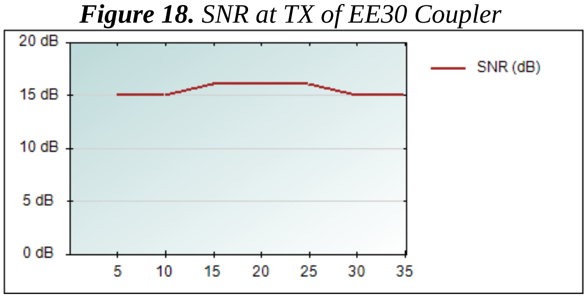

Figure 19. *SNR at RX of EE30 Coupler*

The effect of distance to the overall performance of the LCU is also done by separating the transmitter and receiver up to 30 meters. SNR drops to– 16dB across all trials.

5. CONCLUSION

The line coupling unit (LCU) plays a vital role in the optimum operation of a PLC modem. The low impedance of the power line as well as disturbances caused by switching on and off of electrical loads like appliances inherently requires a well-designed LCU. In this study, three LCUs were designed, namely, the capacitive LCU, the EF20 LCU, and the EE30 LCU. Of the three, the EE30 coupler promises less attenuation and robustness to effects of noise. The transformer in both the EF20 and EE30 couplers provided some gain and this helped a lot in reducing the attenuation once the LCUs are already connected to the power line. The two couplers also exceeded the 10 dB SNR of the internal LCU.

Based on the experimental results, the EE30, which has a larger cross sectional area than the EF20 provides the best LCU characteristics for PLC applications.

6. REFERENCES

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