Evaluation of Low Frequency Communication Techniques
for Load Phase Identification

by

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Abstract

This is a discussion on the process of implementing a system for power line communication (PLC). A PLC system is desired as it will allow for phase identification of the load and the transmission of data from the load to a central receiver. There are two main processes in a PLC system: a communications protocol and signal coupling. The communications protocol involves the methodology employed for successful communication between the load and the receiver. Signal coupling involves coupling the communication signal onto the power line at the load and off of the power line at the receiver. A successful implementation of these two processes will establish a system for PLC. The methodology employed for communication between devices is frequency shift keying (FSK). FSK will allow for low frequency operation with minimal attenuation. There are various coupling strategies that are presented for discussion. It is found that magnetically coupling a communication signal should be avoided and that a directly coupled signal generator should be implemented.

Acknowledgments

"For by him all things were created, in heaven and on earth, visible and invisible, whether thrones or dominions or rulers or authorities—all things were created through him and for him."

Colossians 1:16 - ESV

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List of Abbreviations

CT   Current Transformer

DAQ   Data Acquisition

EMC   Electromagnetic Compatibility

FFT   Fast Fourier Transform

FSK   Frequency Shift Keying

HV   High Voltage

LSB   Least Significant Bit

LV   Low Voltage

MV   Medium Voltage

PLC   Power Line Communication

Chapter 1: Introduction

Weather is unavoidable and often a very destructive force of nature. High winds can knock trees over onto the ground. The weight of ice and snow on tree limbs can cause them to snap. These are a couple of the many weather conditions that can be detrimental to the distribution power grid. It is the power company's responsibility to keep the power line right of way clear of possible hazards. However, storms do occur which sometimes result in down power lines and poles. When this happens it is the job of the power company to restore the lost power to their customers as quickly as possible. As loads are reconnected there exists a chance that a particular load could be reconnected to a different phase from which it was originally connected. This results in an unbalanced power system (assuming the power system was previously balanced). Knowledge of how loads are connected to the power grid is one of the ways the power company maintains a balanced power system. Currently this knowledge is obtained by hiring people to "walk the power lines" and make a table of the phase to which each load is connected. This procedure is long, tedious, and most of all expensive, thus it is advantageous to implement a method that automates the process of load phase identification.

There are several companies that produce devices that can communicate with each other and ultimately send their information to some master device. The primary communication protocol implemented by these devices is wireless communication. This can be accomplished by using the existing cell phone infrastructure. In the event a device

is out of range of a cell tower it is able to transmit its data to any available device that is within range. If the second device is within range of a cell tower, then it will transmit its data and the data from the first device. However, if it is also out of range of a cell tower, then it will transmit its data and the data of the first device to another available device. This process is called a mesh network [1].

The wireless mesh network devices are primarily implemented when the desired data is meter data (e.g. power consumption, load voltage). Due to the wireless nature of the device it does not automatically keep track of the phase to which the load is connected. It is possible to program the phase information into the device and have it included in the transmitted information packet. However, the load could be swapped to a different phase at which point the device would have to be reprogrammed with the new phase data. This still requires an individual to find the phase information and is not an automated process.

An alternative approach is to use the power lines as the communication medium. This is referred to as power line communication (PLC). The PLC scheme will allow for communication from a master device to several slave devices via the existing power lines and vice versa. The master device will exist at a central location (e.g. a substation) and the slave devices will exist at the loads (e.g. meter boxes). The slave will be assigned a unique identifier which will be communicated to the master. A log will be developed by the master device as it receives an identifier from each slave device. This log will have three sections that are based on the phases of the power system. The master device will store the received identifier in the section of the log that corresponds to the phase that was used by the slave device as the communication medium. An example of how the master device and slave devices are connected is provided in Fig. 1. Each individual ID number

in Fig. 1 represents a slave device. An example log developed by the master device that utilizes the information in Fig. 1 is provided in Table 1.
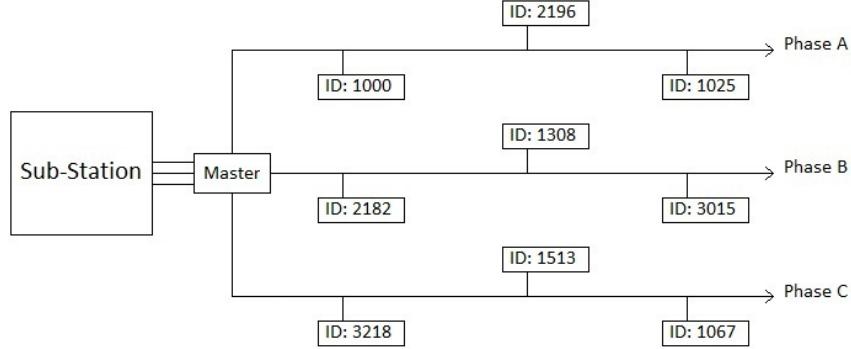
Figure 1: Load Phase Connection Diagram

Phase	A	B	C
	1000	2182	3218
ID #	2196	1308	1513
	1025	3015	1067

Table 1: Example Data Log Based on Figure 1

The PLC scheme is also self healing. If a load is disconnected from one phase and reconnected to another, then the slave device will transmit its identifier on the new phase to which it is connected. The master device will receive the identifier on the new phase and update its log accordingly. There is no longer a need for an individual to manually log how loads are connected as the PLC scheme has automated the process. Balancing the power system is still a huge task but obtaining information regarding how loads are connected to the power system will make up a much smaller percentage of the work at hand.

Chapter 2: Communications

A PLC scheme has two main activities that need to be resolved: a communications protocol and a signal coupling and decoupling technique to the power grid. There are two primary communication strategies to consider as a communications protocol. The first strategy involves the slave device verifying that the communication channel is open and then transmitting its data to the master device. The second strategy requires the master device to send a request signal to the slave device. The slave device will begin transmitting its data upon receiving the request signal from the master device.

It is advantageous to transmit data using a frequency between 6-130 Hz [2]. The reason why this is the case is because of the system line impedance. A power line's impedance is a function of frequency. The impedance has resistive, inductive, and capacitive elements. As the communication signal's frequency increases the impedance changes. The inductive reactance increases because it is a function of frequency. The resistive element increases because of the skin effect. Current density moves to the edges of the wire as the frequency increases. This reduces the area that the current is flowing through, which results in an increased resistance [4]. Capacitive reactance decreases because it is a function of the inverse of frequency. High frequency operation changes the impedance which is likely to result in attenuation of the communication signal.

The attenuation of the high frequency communication signal can be illustrated by utilizing an equivalent circuit model for the power line. The power line model that is

typically employed is the positive sequence line pi model. Unfortunately, this is a low frequency model and will not accurately describe high frequency operation because of errors associated with lumped-parameter models. This is not necessarily an issue because the present model is sufficient to illustrate problems associated with high frequency communication with the power line as the communication medium.

It is possible to develop a transfer function for this model. The transfer function will provide information on how the power line impedance affects signals of various frequencies. The line pi model is provided in Fig. 2.
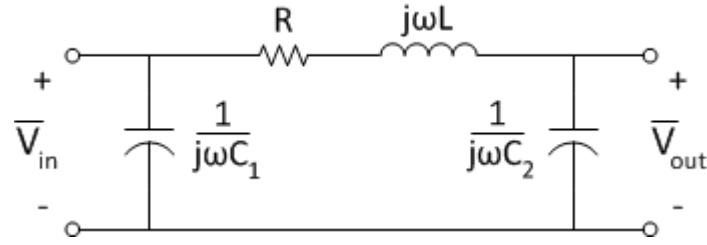
Figure 2: Positive Sequence Power Line PI Model

The transfer function that describes the ratio of the output voltage versus the input voltage as a function of frequency is described by $H(\omega)$.

$$H(\omega) = \frac{1}{j\omega RC_2 + 1 - \omega^2 C_2 L}. \tag{1}$$

If the type of power line conductor and spacing information is known then the line parameter elements for (1) can be found. As an example, assume the power line is a 477 MCM 24/7 ACSR conductor that is 5 miles long with 3 feet of equilateral spacing [9]. The resulting pi circuit model elements are a resistance R of 1.064 Ω, an inductance L of 10.91 mH, and capacitance's C_1 and C_2 of 34.05 nF. A frequency response plot of (1) that uses the calculated component values for the chosen type of power line conductor is provided in Fig. 3. It is difficult to see how the transfer function responds as the

frequency increases. The y-axis limits of Fig. 3 are adjusted in Fig. 4 to aid in the analysis of the frequency response as the frequency increases. The transfer function magnitude approaches zero, indicating attenuation, as the frequency increases.
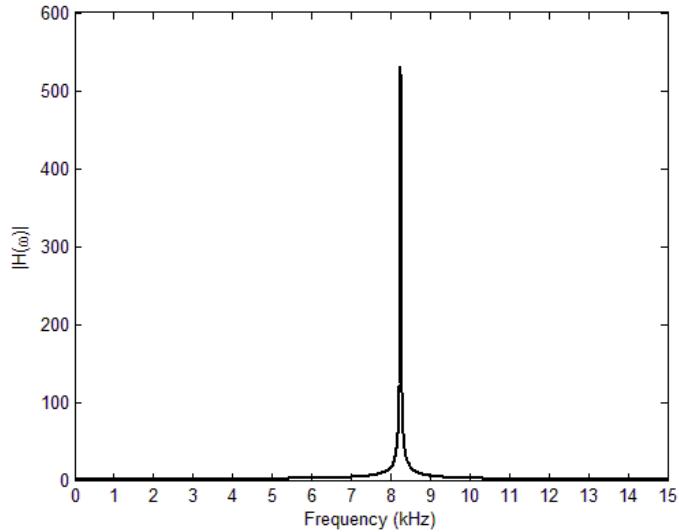
Figure 3: Frequency Response of the Power Line PI Model
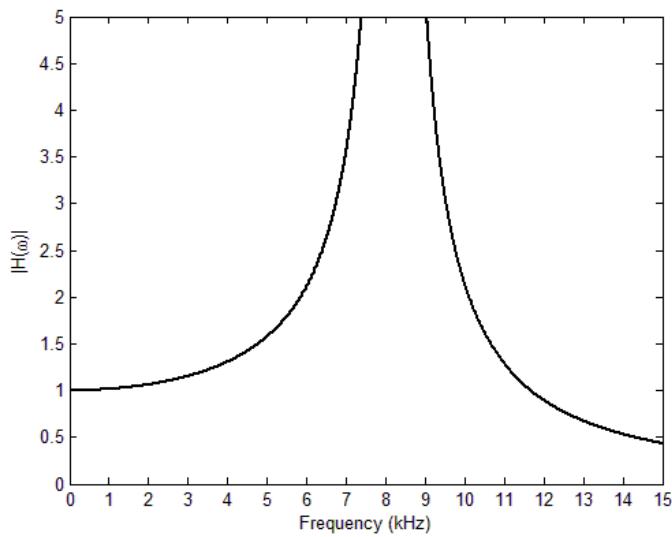
Figure 4: Frequency Response of the Power Line PI Model with Adjusted Y-Axis Limit

This response is expected because of the skin effect, the increasing inductive reactance, and the decreasing capacitive reactance. Notice the frequency range between 1-2 kHz in Fig. 4. This model of the power system is amplifying the signal for this frequency range. This suggests that the communication signal's frequency should be within this range as there is no attenuation. However, the chosen power line model ignores several factors that exist in the real power system which prevent the communication frequency from being in the 1-2 kHz range. An example is that a distributed line model and large power factor correction capacitor banks located at industrial facilities or on distribution feeders will introduce additional resonant points that would need to be addressed. These power factor correction banks can introduce resonant points in the 180-200 Hz range and will certainly have resonant points by 300-420 Hz. It is almost unheard of for there to be resonant points on the power line in the 6-100 Hz range. A communication frequency in the range of 6-130 Hz is desirable because it avoids the issues that are associated with resonant points in the power system. It is important to note again that the line pi model discussed here is not a good high frequency model. Therefore, a low frequency communication signal is desired to keep attenuation of the communication signal at a minimum while avoiding network resonance conditions.

2.1: Slave Device Wait and then Transmit

The first communication strategy involves the slave device waiting for the transmit line to become open and then transmitting the unique identifier to the master device. The data that will be transmitted is the slave's unique identifier, which is a binary number. Line and transformer impedances make transmitting digital ones and zeros, based on 5 V logic, impossible. It would be difficult for the master device to know when a zero is being transmitted and almost impossible to recognize a one. The one would be transmitted as a 5 V pulse. The pulse has infinite spectral content which would be filtered by the line and transformer impedances [5]. A suggested alternative would be to use sinusoids of a desired frequency to represent either a one or a zero. The slave device would transmit a carrier frequency that would let the master know that it is about to transmit data. After transmitting the carrier frequency, it would then shift the carrier frequency to a predetermined frequency that corresponds to a one or zero. The slave will transmit the carrier frequency and then the frequency that corresponds to each bit until completion. Once it has finished transmitting the data, it will resend the carrier frequency to let the master know it is complete. The slave will transmit the carrier frequency and the frequency that represents each bit of data for a predetermined length of time, τ. This process of using different frequencies for communication is called frequency shift keying (FSK) [3]. The master device would receive the frequency shifted sinusoid and calculate the frequency components of the signal to recover the transmitted data. The other slave devices would need to check the channel for communication frequencies before transmitting. If none are detected then transmission may begin. This will ensure that the channel is open and will avoid communication errors due to multiple slave devices trying

to communicate at the same time. An advantage of FSK is that it potentially allows for additional data to be transmitted with the unique identifier. There is not a limit to the number of bits that can be transmitted; however, transmission of additional bits will increase the time that a particular slave device is communicating. This time increase could be significant because the devices are communicating at low frequencies and there could be a larger number of devices all needing to communicate.

An implementation example for this communication scheme is in order. Assume that the desired data signal for transmission is binary 101. A plot of the data signal is illustrated in Fig. 5. The carrier frequency is chosen to be 6 Hz, while 3 Hz and 12 Hz are for a binary 0 and 1 respectively. The slave device will first transmit the carrier signal for time τ, where τ is one second. It is now time to begin data transmission. A 12Hz sinusoid is transmitted followed by a 3 Hz sinusoid and then finally a 12 Hz sinusoid is transmitted. The 6 Hz carrier signal is retransmitted to indicate to the master device that data transmission is complete. A plot of the transmitted signal is illustrated in Fig. 6.
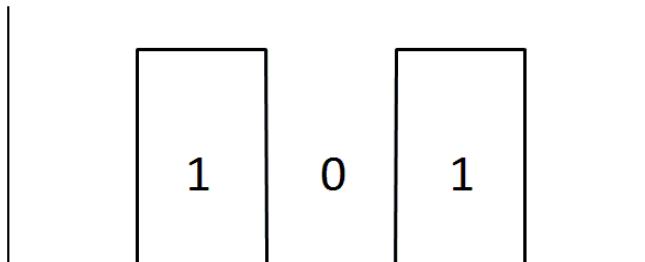
Figure 5: Data Signal
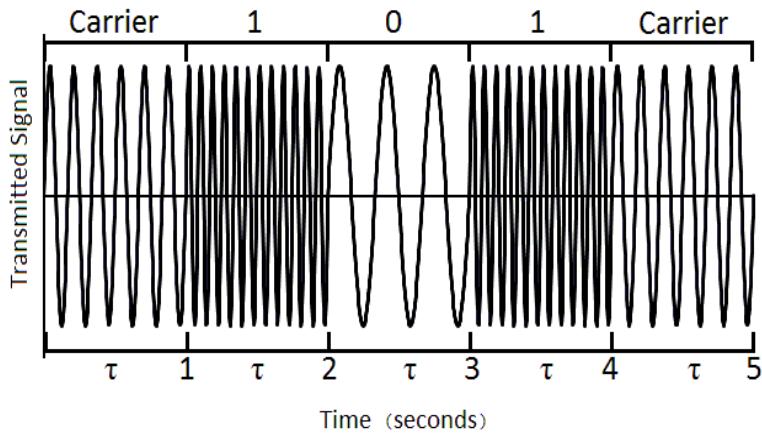
Figure 6: Example of FSK

2.2: Master Asks and Slave Responds

A second communication strategy requires the master device to send out an identifier on all three phases. The slave device will receive its identifier and respond. It will respond with a sinusoid at some frequency (e.g. a tone) for a predetermined length of time. The master will receive the tone and record the phase on which the tone was received. This method avoids the potential problem of multiple slave devices trying to communicate at the same time because the master device initiates the communication. Unfortunately, this method severely limits the amount of information that can be communicated between the master and slave devices.

Chapter 3: Coupling Introduction

3.1: Signal Coupling

Signal coupling involves connecting the communication hardware input and output to the power system. There are two different situations that exist that have different constraints. The first is that the slave device must be small enough to fit into the standard meter socket equipment. This is problematic because as the slave device gets smaller the strength of the output signal may decrease. This results in the device being unable to communicate as distance increases because the line impedance increases with line length. The second is that the substation equipment may have electromagnetic compatibility (EMC) issues. It is possible that the injected signal levels could be large enough to compromise EMC for other equipment. The working assumption adopted is that the meter socket size is a limiting constraint whereas the substation EMC issues can be managed. Therefore, the primary focus is to design a slave device that will fit into the standard meter socket equipment.

3.2: Data Signal Strength for Successful Recovery

It is important to know how big the data signal, from the slave device, needs to be for successful recovery by the master device. A typical data acquisition (DAQ) card is 16 bits. If the card is set to a 10 V range, ± 5 V, then the value of the least significant bit (LSB) is about 150 µV, from (2).

$$V_{LSB} = \frac{10V}{2^{16}} = 152.6\mu V \tag{2}$$

The smallest measurable data signal is taken to be 300 µV. This allows for variations of about 2*LSB in the data acquisition hardware.

The typical current supplied by a substation is about 200 A. If 10 A is coupled onto the load conductor, at the standard meter, then there would be about 300 mA at the substation assuming a standard 7200:240 distribution transformer is used, from (3).

$$I_1 = 10A * \frac{240}{7200} = 333.33mA \tag{3}$$

If a standard 5000:5 winding CT is used for decoupling at the substation then the output signal will be 300 µA from the communication signal and 200 mA from the power signal, from (4) and (5).

$$I_{2,comm} = 300mA * \frac{5}{5000} = 300\mu A \tag{4}$$

$$I_{2,power} = 200A * \frac{5}{5000} = 200mA \tag{5}$$

Assume that there is a 1 V per 1 A transducer connected to the output of the CT. If this is the case then the master device must be capable of measuring a 300 µV communication signal in the presence of a 200 mV power signal.

As an example, the measured output of the transducer, with the 200 mV, 60 Hz signal and a 300µV, 130 Hz signal, could be filtered by a highpass chebyshev filter with a cutoff frequency of 60 Hz. A fast fourier transform (FFT) would then need to be performed on the output of the filter. The output of the FFT is illustrated in Fig. 7. The 130 Hz signal can be successfully recovered by the FFT. Therefore, the coupled signal, at

the load, must be at least 10 A for successful recovery by the master device. This 10 A level will be taken as a design requirement in this work.
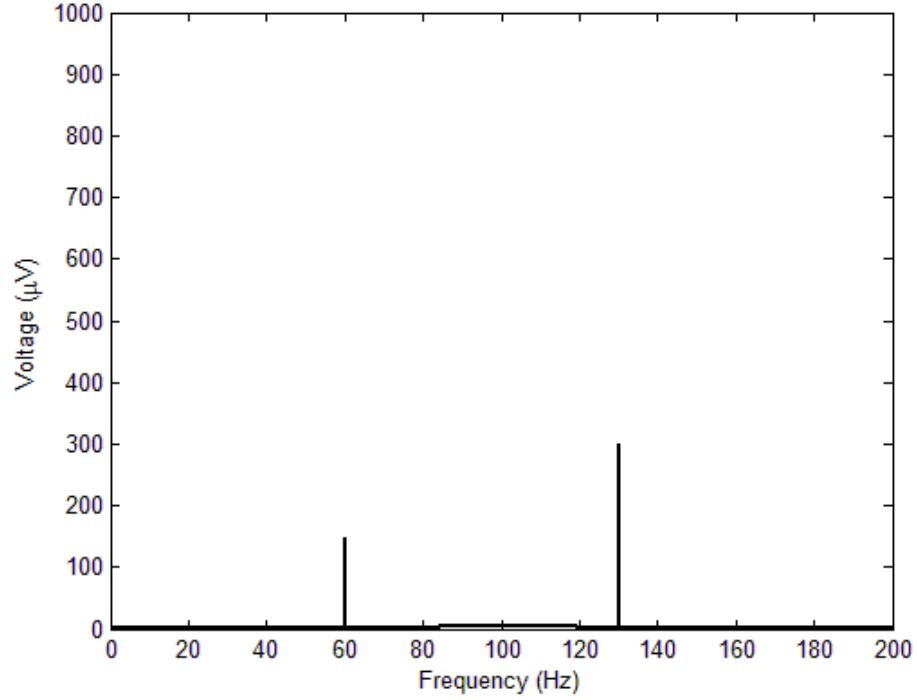
Figure 7: 130 Hz Signal Recovered by FFT

3.3: Assumptions

The coupler design must be compatible with any service that meets flicker and voltage drop criteria. The majority of available standard meters are used in residential applications. Houses typically have a maximum current of around 100 A at 240 V. The maximum voltage drop is 5%, usually based on flicker criteria. If a motor starts and pulls 100 A at 240 V then the Thévenin equivalent impedance magnitude seen by the load is 0.12 Ω for a 5% voltage drop from (6).

$$Z_{TH} = \frac{0.05 * 240V}{100A} = 0.12\Omega \tag{6}$$

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The calculated impedance value includes the impedances of the line, distribution transformer, and substation equivalent impedance. Also, a typical home has a minimum impedance magnitude of 2.4 Ω when it is operating under maximum load from (7).

$$Z_{home} = \frac{240V}{100A} = 2.4\Omega \tag{7}$$

These assumptions are important because they set operation requirements for the master and slave devices.

Chapter 4: Coupling Techniques

It is possible to couple either a voltage or a current onto the load conductor. There are four conventional techniques and one unconventional technique that were explored in coupling a communication signal onto the power line. These techniques are series and shunt current injection, series and shunt voltage injection, and a switched impedance method. Each of these techniques has their own advantages and disadvantages in coupling a communication signal onto the power line. It is necessary for these coupling techniques to allow communication to occur at any time during the day and under any load condition.

4.1: Series Current Injection Technique

The series current injection technique will be discussed first. This technique involves placing a toroid around the load conductor as illustrated in Fig. 8. There is some number of windings placed on the toroid.
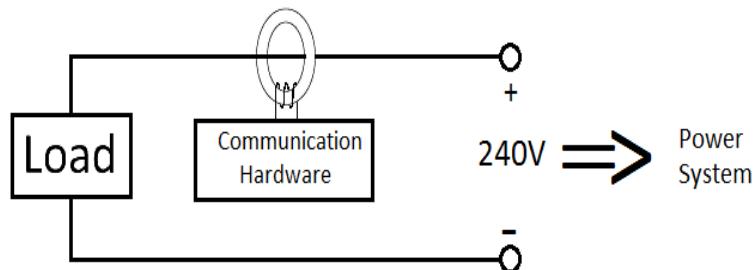
Figure 8: Series Current Injection Technique

The load conductor and the windings on the toroid act as a current transformer (CT) with a ratio of N:1 with N being the number of windings on the toroid. A current is driven through the communication side of the CT which is then magnetically coupled onto the load conductor. The coupled current is a series injected current. One of the first concerns is coupling of the power signal back to the electronic side of the toroid. If there is too much power signal transferred across the toroid, it will damage the communication hardware. The current of the power signal that is reflected will be the ratio of the windings on the CT times the current through the CT on the load conductor. If the load current is 100 A with N equal to 50 turns, then the communication hardware must be able to handle 2 A at the power frequency, from (8).

$$I_{comm} = 100A * \frac{1}{50} = 2A \qquad (8)$$

It is possible to decrease the current that the communication hardware has to handle by increasing N. Some type of power frequency bypass filter, not shown in Fig. 8, would probably be used to manage the current.

Core saturation is an issue with this approach at low frequency operation. The magnetic flux, ϕ, is found by integrating the magnetic flux density B that is passing through a surface [4].

$$\phi = \int B \cdot dS \qquad (9)$$

Equation (9) reduces to

$$\phi = BA \qquad (10)$$

under idealized operating conditions where the magnetic flux density, B, evenly intersects the cross sectional area, A, of the toroid. The magnetic flux is also equal to

$$\phi = \frac{\lambda}{N} \qquad (11)$$

where λ is the flux linkage. Faraday's Law states that the time rate of change of the flux linkage results in an induced voltage, v, in the coil [6].

$$v = \frac{d\lambda}{dt} \qquad (12)$$

If the induced voltage is a sinusoid with amplitude, V_{pk}, and radian frequency, ω, then solving (12) for λ gives

$$\lambda = \frac{V_{pk}}{\omega} \sin(\omega t). \qquad (13)$$

Solving for B using (10) and (11) results in

$$B = \frac{\lambda}{NA}. \qquad (14)$$

By using (13) and (14) the magnetic flux density for the toroid can be represented as

$$B = \frac{V_{pk}}{\omega NA} \sin(\omega t) \qquad (15)$$

with units V·s/m^2 or tesla, T. A tesla is also equivalent to 10 kilo-gauss, kG.

It can be seen from (15) that B is a function of the input voltage, operating frequency, number of windings, and core size. Notice that the operating frequency is in the denominator of (15). The amount of magnetic flux density increases as the operating frequency decreases; this drives the core into saturation based on Fig. 9. The operating frequency will be limited to the range of 6-130 Hz because of the low pass filter nature of the power system. Another pre-determined variable in (15) is the cross sectional area, A, which is controlled by the size of the core that is able to fit into the standard meter. The input voltage, V_{pk}, and the core windings, N, are the variables that can be manipulated to keep the core from saturating. The magnetic flux density is related to the magnetic field

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intensity, H, by the core relative permeability, μ_r, and the permeability of free space, μ_0, and is provided in (16) [4].

$$B = \mu_0 \mu_r H \qquad\qquad (16)$$

A common type of core material is a W-type material, which has a relative permeability of about 10,000. Saturation curves for core materials are typically plotted as a B versus H curve or B-H curve. The B-H curve for the W-type material is illustrated in Fig. 8 [7]. It is easy to see that a small change in B can quickly push the core from the linear region of operation into the saturation region.
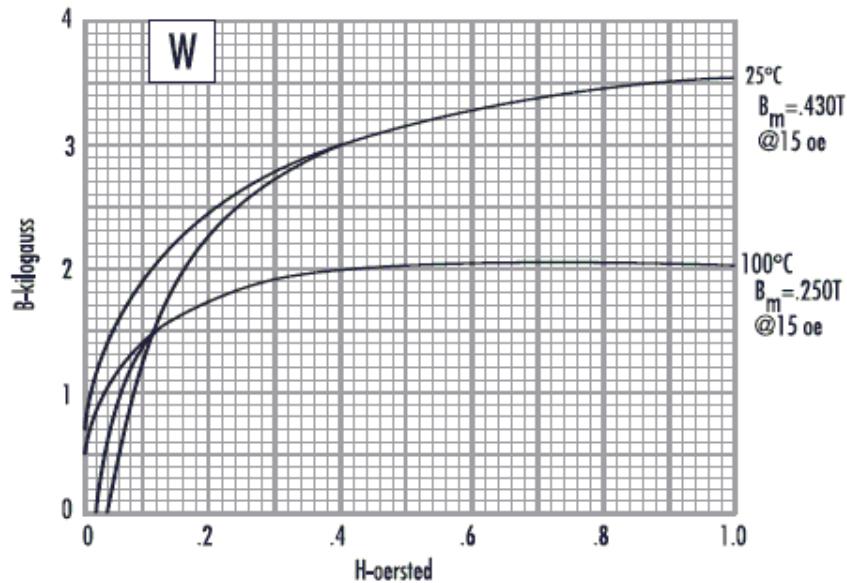
Figure 9: B-H Curve of a W-type Material

Electromagnetic saturation occurs when the magnetic core material is not able to contain all of the magnetic flux that is produced by a current that is flowing through windings that are wrapped around the magnetic material. An alternate form of the

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magnetic field intensity, H, for a toroid is provided in (17). The variable l is the mean length path of the toroid which is roughly equal to its average circumference [4].

$$H = \frac{NI}{l} \tag{17}$$

Assuming there is 1 turn placed onto a toroid with a mean length path of 10π cm with a 10 A current flowing through the turn, then H is approximately

$$H = \frac{1 * 10A}{10\pi cm} \approx 31.8 \; \frac{A}{m} \approx 0.4 \; Oe. \tag{18}$$

The result from (18) can be compared to Fig. 9 which is the B-H curve for a W-type material. Notice that the plot is beginning to saturate at 0.4 Oe for a radiant temperature of 25 °C and is saturated if the radiant temperature is 100 °C. It is important to note that the 10 A current that was chosen is necessary for successful recovery by the master device and the mean length path is such that the core would be almost too big to fit into the approximately 5.5 inch diameter standard meter socket. If the mean length path is decreased then this will cause H to increase which will increase the core saturation. Also, if there are more turns placed onto the core then the core saturation will increase. Unfortunately core saturation is a problem that is primarily due to the large current necessary for successful recovery by the master device and the small core material that is necessary to fit into the standard meter.

Core saturation is a big issue with the series current injection technique; however, the primary issue is that performance cannot be guaranteed when the load is low to off (e.g. a house at night). It is appropriate to ignore the core saturation issue for now because it is not the primary concern with this technique. A line diagram of a typical

load is presented in Fig. 10 with a series connected current transformer. The distribution

line and the load conductor are considered to be ideal for this model.
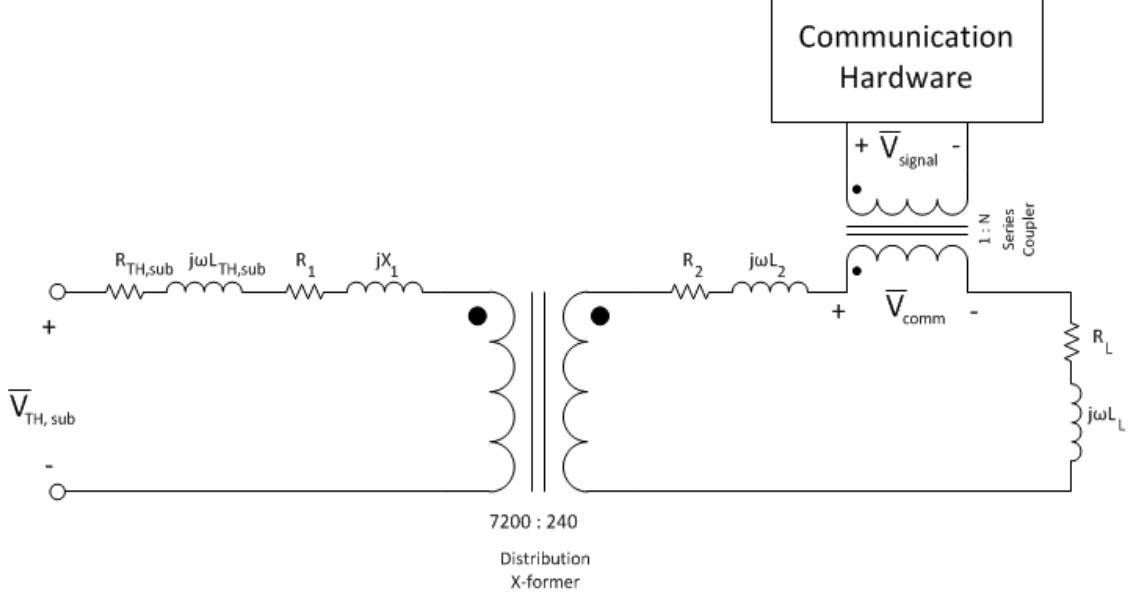
Figure 10: Line Diagram of the Shunt Current Injection Technique

The Thévenin equivalent voltage and impedance $(\overline{V}_{TH,sub}, \overline{Z}_{TH,sub} = R_{TH,sub} +$

$j\omega L_{TH,sub})$ are the open circuit voltage and open circuit impedance as seen at the

distribution side of the substation towards the source. Resistances, R_1 and R_2, and

reactances, ωL_1 and ωL_2, are the non-ideal circuit elements of the distribution

transformer. The core elements for the distribution transformer are assumed to be

infinite. $\overline{V}_{signal}$ is the voltage supplied by the communication hardware to drive the

necessary current into the shunt coupler for a 10 A output current. $\overline{V}_{comm}$ is the

communication voltage that exists when the required 10 A communication current is

output by the CT. The load is represented by the resistance R_L and reactance ωL_L.

Notice that the CT is modeled as an ideal transformer for this discussion. This is

obviously not realistic, however the non-ideal factors (e.g. saturation) are ultimately not a limiting factor and are ignored.

Series current injection involves magnetically coupling a current onto the load conductor. Because this is the case, it is appropriate to simplify Fig. 10 and only look at the load impedance, the ideal coupler and the Thévenin equivalent impedance at the standard meter where the device is connected. The simplified circuit is illustrated in Fig.11. The coupled current from the CT will flow through the load impedance and through the Thévenin equivalent impedance. Because the communication frequency is not 60 Hz it will not be affected by the source, thus the source is modeled as a short circuit. Recall that it is desired that the load conductor current be at least 10 A for successful recovery by the master device at the substation.
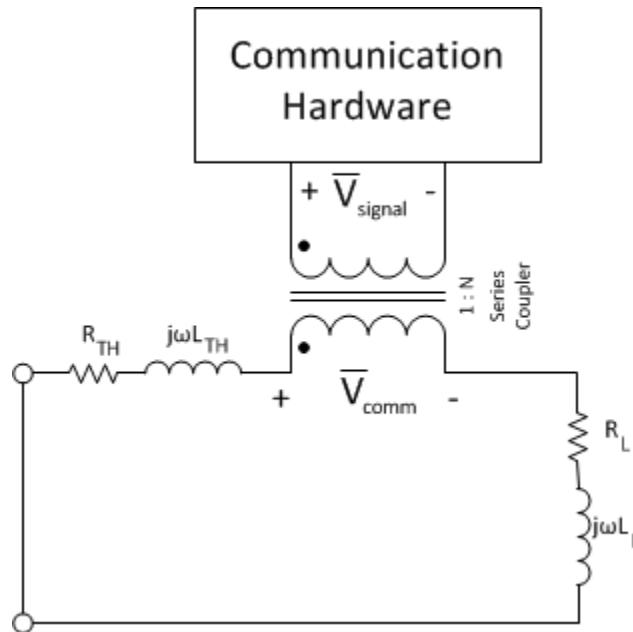
Figure 11: Thévenin Equivalent Line Diagram from Substation to Load

In order for 10 A to flow on the load conductor the voltage $\overline{V}_{comm}$ must be a factor of 10 greater than the load and Thévenin equivalent impedance from (19).

$$\left|\overline{I}_{coupled}\right| = \left|\frac{\overline{V}_{comm}}{\overline{Z}_{equ}}\right| = \left|\frac{\overline{V}_{comm}}{R_{TH} + j\omega L_{TH} + R_L + j\omega L_L}\right| = 10A \qquad (19)$$

The Thévenin impedance can be considered constant; however the load impedance will fluctuate. If the load is operating at maximum power and then the power is decreased by 50% then the corresponding load impedance will be increased by 50%. This will require the communication voltage, $\overline{V}_{comm}$, to also increase by 50% so that the required 10 A is still coupled onto the load conductor. This becomes problematic because $\overline{V}_{comm}$ has to increase by the same amount that the load impedance increases. For small impedance variations this is not a very big problem, however when the load power significantly decreases or the load is turned off, then the impedance becomes very large. It is very important to be able to control the magnitude of $\overline{V}_{comm}$ in the presence of the varying load impedance so that there is always 10 A coupled to the load conductor during communication. Unfortunately it becomes impossible to drive 10 A for a no load condition because the load is now an open circuit.

In order to couple the required communication current onto the load conductor it is necessary to be able to control the communication voltage, $\overline{V}_{comm}$. The voltage $\overline{V}_{comm}$ is related to the voltage at the communication hardware, $\overline{V}_{signal}$, by (20) because it is assumed that issues such as saturation are neglected.

$$\overline{V}_{comm} = \frac{1}{N}\overline{V}_{signal} \qquad (20)$$

The communication hardware will be able to directly control the magnitude of $\overline{V}_{comm}$ because of the linear relationship between $\overline{V}_{comm}$ and $\overline{V}_{signal}$ that is presented in (20).

Unfortunately, the maximum magnitude of $\overline{V}_{signal}$ is limited by the low voltage nature of the communication hardware. As the load impedance increases a threshold will be crossed where $\overline{V}_{comm}$ cannot be increased enough to supply the necessary 10 A current because $\overline{V}_{signal}$ has reached its maximum magnitude.

An application example to calculate $\overline{V}_{signal}$ is in order. Assume that the Thévenin impedance is a short circuit and the magnitude of the load impedance is 2.4 Ω. Also assume that there are 5 turns on the communication side of the coupling CT. By utilizing (19) and (20) it is possible to calculate that $\overline{V}_{signal}$ has to be 120 V in order to couple the required 10 A onto the load conductor. This calculated voltage will increase as the load impedance increases. It could be difficult to produce 120 V because of the low voltage nature of the communication hardware but it is possible. Now consider a situation where the load impedance is 24 Ω instead of 2.4 Ω. This would require the low voltage communication hardware to produce 1.2 kV which would be problematic if not impossible.

The series current injection coupling method is therefore an unrealizable PLC coupling method. This is due to both the saturating nature of the small core and the required potentially large voltage at the low voltage communication hardware. While core saturation is an issue that will have to be considered it is not the primary problem with this methodology. In fact, saturation issues were ignored while discussing the necessary voltage magnitude to couple the 10 A communication signal. The series current injection technique is an unrealistic coupling methodology because of the large voltages that must be supplied by the communication hardware in order to always be able to couple the required communication current onto the load conductor.

4.2: Shunt Current Injection Technique

The second technique to be discussed is the shunt current injection method. This technique involves connecting a conventional instrument CT in shunt with the load. The communication hardware is connected to the secondary side of the CT. A 60 Hz blocking filter will be connected, in series, with the shunt connection. The blocking filter will keep the shunt connection from shorting out the load at the power frequency. A diagram of how the components are connected is illustrated in Fig. 12. Unfortunately, the core saturation issues that were discussed for the series current injection technique will still apply to this method. However, this method does have an advantage over the series current injection method, in that the load impedance does not severely impact the coupled current.
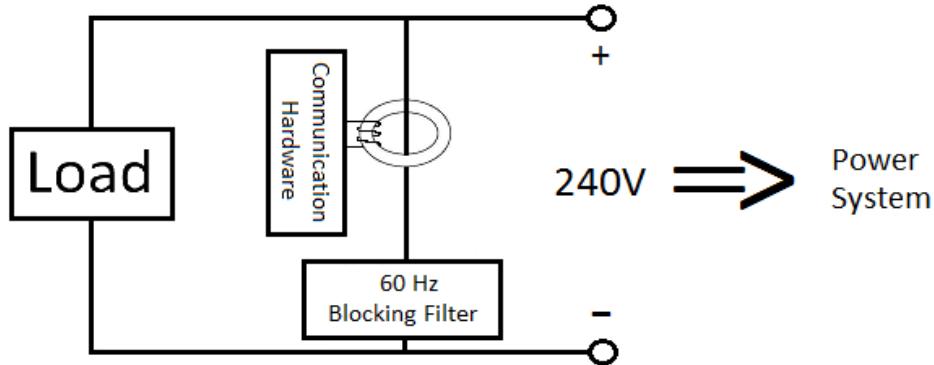
Figure 12: Shunt Current Injection Technique

It is appropriate to analyze the circuit provided in Fig. 12 and compare the results to the series current injection method. The equivalent circuit line diagram for Fig. 12 is illustrated in Fig. 13. The distribution line and the load conductor are considered to be ideal for this model. The Thévenin equivalent voltage and impedance ($\bar{V}_{TH,sub}$, $\bar{Z}_{TH,sub} = R_{TH,sub} + j\omega L_{TH,sub}$) are the open circuit voltage and open circuit impedance

as seen at the distribution side of the substation towards the generator. Resistances, R_1 and R_2, and reactances, ωL_1 and ωL_2, are the non-ideal circuit elements of the distribution transformer. The core elements for the distribution transformer are assumed to be infinite. $\overline{V}_{signal}$ is the voltage supplied by the communication hardware to drive the necessary current into the shunt coupler for a 10 A output current. $\overline{V}_{comm}$ is the communication voltage that exists when the required 10 A communication current is injected by the CT. The load is represented by the resistance R_L and reactance ωL_L. Notice that the CT is modeled as an ideal transformer for this discussion. The non-ideal elements are not a limiting factor for this coupling scheme and are ignored.
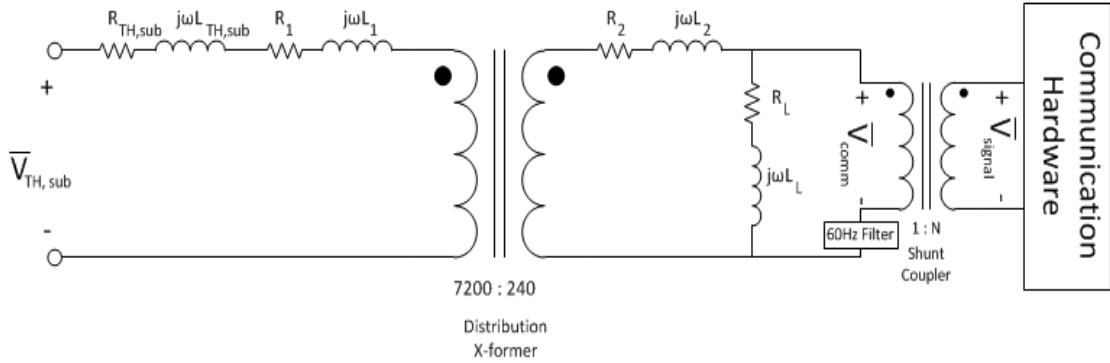
Figure 13: Line Diagram of the Shunt Current Injection Technique

The circuit provided in Fig. 13 can be further reduced by making a Thévenin equivalent at the low voltage (LV) side of the transformer. This removes the distribution transformer from the circuit and simplifies the analysis of the system modeled in Fig. 13. The new simplified model is illustrated in Fig. 14. The Thévenin equivalent impedance in Fig. 14 is modeled by resistance $R_{TH,L}$ and reactance $\omega L_{TH,L}$. and the Thévenin voltage is modeled as a short at the communication frequency.
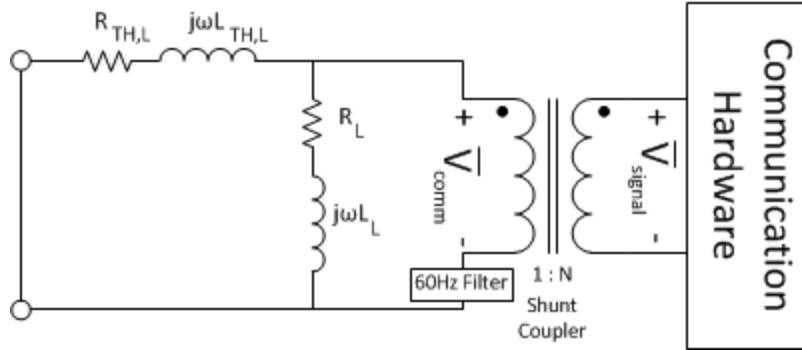
Figure 14: Thévenin Equivalent of the Shunt Current Injection Technique at the Load

The output current from the shunt coupler needs to be at least 10 A in order for there to be successful communication between the master and slave devices. This current is calculated in (21). An approximate Thévenin impedance magnitude was found in (6). The minimum load impedance would be 2.4 Ω for a load operating at 240 V and 100 A. The calculation in (21) can be further reduced by ignoring the load impedance because it is at least an order of magnitude larger than the Thévenin impedance. The new current equation is provided in (22).

$$\left|\bar{I}_{coupled}\right| = \left|\frac{\bar{V}_{comm}}{(R_{TH,L} + j\omega L_{TH,L})||(R_L + j\omega L_L)}\right| \tag{21}$$

$$\left|\bar{I}_{coupled}\right| = \left|\frac{\bar{V}_{comm}}{R_{TH,L} + j\omega L_{TH,L}}\right| \tag{22}$$

This method does not have the high voltage implications at the communication hardware when compared to the series current injection technique. Substituting 10 A and the results from (6) into (22) will result in the necessary voltage output from the shunt coupler for successful communication between the master and slave devices. The

calculated voltage is 1.2 V for the 0.12 Ω Thévenin impedance found in (6). If there are 5 turns on the shunt coupler then the voltage $\overline{V}_{signal}$ will be 6 V from (20). This result is much more realistic than the 100 V (or more!) result from the series current injection technique. The low voltages necessary at the communication hardware, for communication between the master and slave device, make this technique much more realistic to implement than the series current injection technique.

The shunt current injection technique removes the problem involving a high voltage at the communication hardware that plagues the series current injection technique. However, there is a new issue with the shunt current injection technique that needs to be addressed. A series filter is necessary with the shunt coupler to prevent the 60 Hz power signal from short circuiting. This filter will also need to fit into the standard meter socket with the shunt coupler.

A notch filter is desired to block the 60 Hz power signal from short circuiting when the shunt coupler is connected. The filter will need to block a 240 V_{RMS} signal because that is the voltage present at the standard meter. It is necessary for the filtered magnitude of the 60 Hz power signal to be no bigger than the voltage that is produced by the 10 A coupled current. The actual filtered magnitude will probably need to be much smaller than the voltage produced by the 10 A coupled current. This is to prevent the sum of the 60 Hz signal and the produced voltage from exceeding any current or voltage limits that are present at the communication hardware.

It is very likely that the components that are used to make the notch filter will be too large to fit into the standard meter socket. A first order notch filter can be considered to see how big the passive components are that comprise the filter. The magnitude of the frequency response, Z(ω), for a first order notch filter is illustrated in Fig. 15. The 1st order notch filter does an excellent job of filtering out the 60 Hz power signal and is very easy to implement.
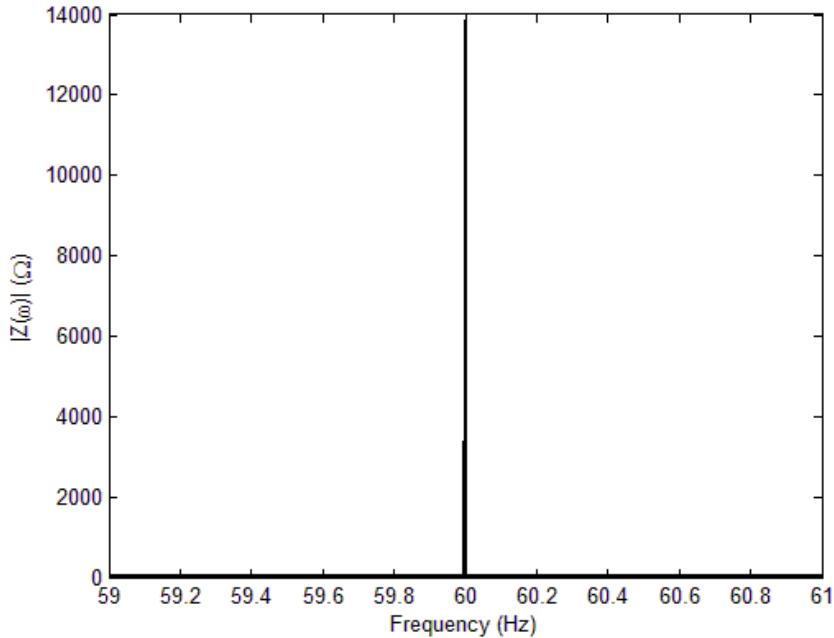
Figure 15: Frequency Response of the 1st Order Notch Filter

Implementing the filter requires an inductor and a capacitor to be in parallel with each other. These parallel components are then connected in series with the communication hardware. The size of the inductor is selected as 3.2 μH and the size of the capacitor is calculated to be 2.2 F. A 2.2 F capacitor with a voltage rating of 240V_{RMS} is not available for purchase. This can be solved by connecting multiple

capacitors in parallel to obtain the required 2.2 F capacitance. A typical $250V_{DC}$ capacitor (which is only considered to give an idea of the physical size requirement) will have a capacitance range between 470 µF to 38 mF. It will take approximately 58 of the 38 mF capacitors in parallel to create an equivalent capacitance of 2.2 F. Each of these 38 mF capacitors is 3.5 inches in diameter and 8.625 inches long [8]. It would be impossible to fit this number of capacitors with these dimensions into the standard meter socket so as to implement the notch filter for the shunt current injection technique. Other combinations of L and C values would lead to similar size problems.

The shunt current injection technique is unlikely to be implemented because of the size issue with the 60 Hz notch filter. The components that are necessary to build the filter will be too large to fit into the standard meter socket; one of the design requirements would clearly be violated. Even though the shunt current injection technique solves the problem involving high voltages at the communication hardware, it is an undesirable coupling strategy due to component size.

4.3: Series Voltage Injection Technique

Series voltage injection is the third coupling technique covered. This technique involves placing a voltage transformer in series with the load. The communication hardware is connected to the secondary side, N2, of the transformer. Some type of power frequency bypass filter is likely to be required but it is not depicted in Fig. 16 because it is not relevant to the discussions that follow. A diagram of how the components are connected is illustrated in Fig. 16.
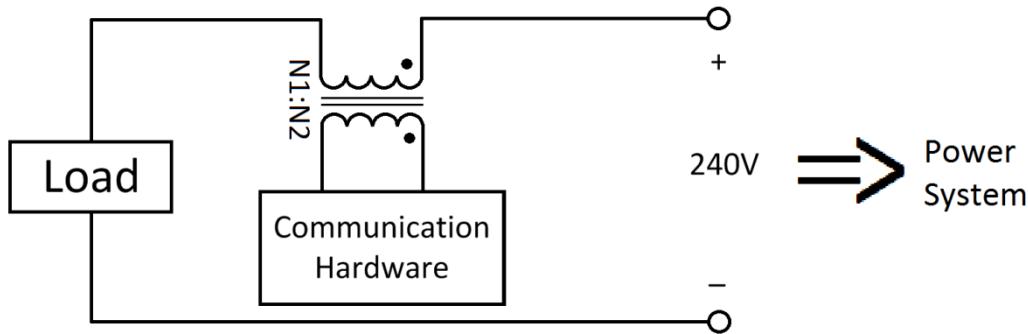
Figure 16: Series Voltage Injection Technique

The major drawback to this method is that the primary winding, N1, of the transformer has to carry the full load current. In order for the primary side to carry the load current, it has to be wound with wire that is large enough to carry the current. Winding the transformer with large wire will result in a large transformer that will not fit in the standard meter socket. This coupling method is undesirable because the size of the coupler will be too big for the application.

An alternate option is to utilize a toroid as the magnetic material of the voltage transformer. This implementation is similar to the series current injection technique; however the emphasis is on coupling a voltage instead of a current. The load conductor will be passed through the toroid which will make the primary winding, N_1, equal to one.

An example of the physical connection of the coupler is illustrated in Fig. 17. The shaded area represents the secondary windings, N_2, that are placed on the coupler.
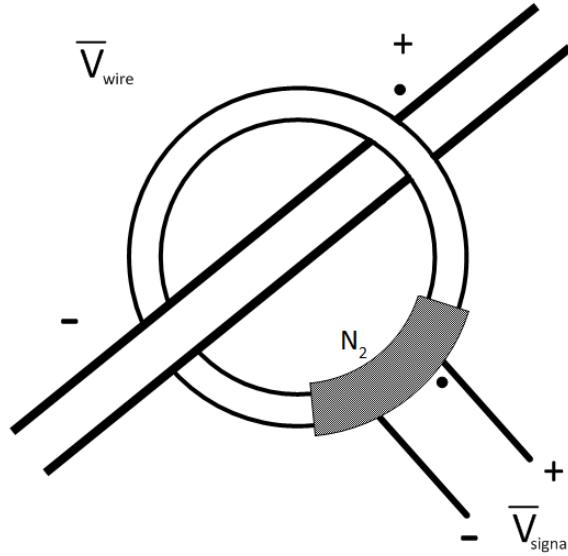
Figure 17: Physical Connection of the Toroidal Coupler

In order for there to be successful communication the voltage that is dropped across the Thévenin equivalent source impedance at the substation needs to be large enough to be recovered by the master device. The Thévenin equivalent source impedance for the substation is unknown. It is appropriate to assume that the impedance magnitude found in (6) is the Thévenin equivalent source impedance, Z_{TH}', at the substation. The actual value of Z_{TH}' will be less than the value provided in (6) because (6) includes the distribution line and distribution transformer impedances. Note that the assumed equivalent source impedance is reflected onto the LV side of the distribution transformer and is denoted by the prime. Reflecting Z_{TH}' to the high voltage (HV) side of the distribution transformer will result in an impedance of 108 Ω for Z_{TH}. Z_{TH} is the assumed magnitude of the Thévenin impedance at the substation towards the source.

An equivalent circuit model is provided in Fig. 18. This circuit model ignores the distribution transformer and distribution line impedances. It also ignores impedances associated with the series voltage coupler and assumes that the transformer magnetic material is infinitely permeable. The source voltage is modeled as a short because the communication frequency is not 60 Hz.
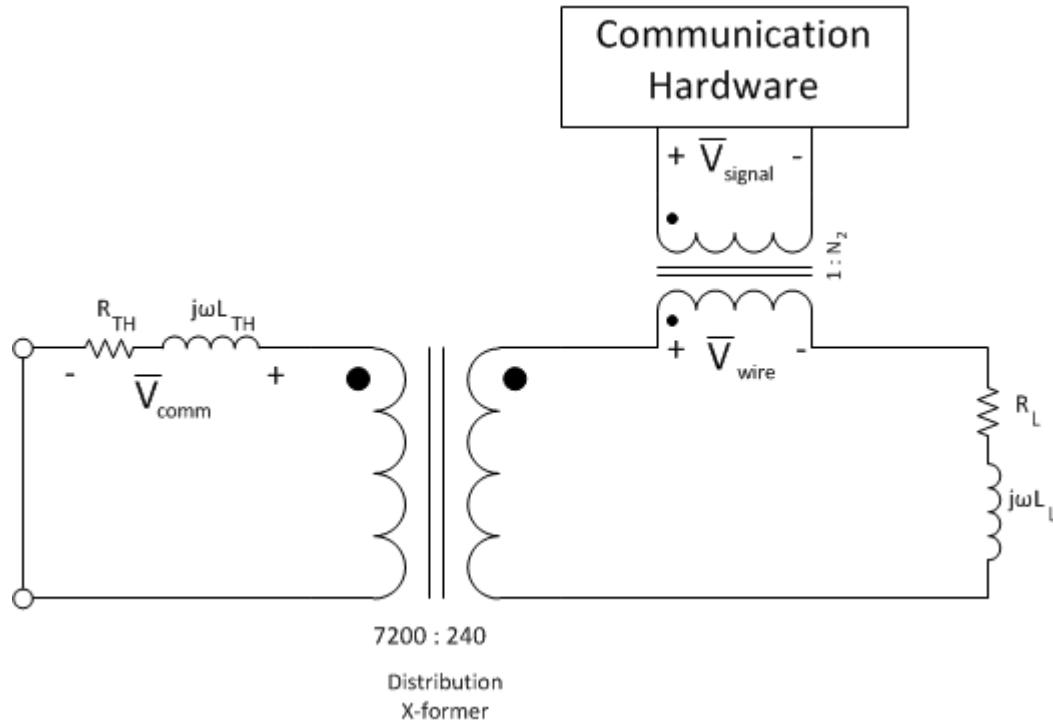
Figure 18: Thévenin Equivalent of the Series Voltage Injection Technique at the Substation

The max voltage drop across Z_{TH} will occur when the load impedance, Z_L, is at a minimum. If Z_L is 2.4 Ω, from (7), then V_{comm} can be calculated as a function of the input signal voltage V_{signal}.

$$V_{comm} = \frac{V_{signal}}{N_2} \left(\frac{Z_{TH}}{Z_{TH} + Z_L \left(7200/240 \right)^2} \right) \left(\frac{7200}{240} \right) \tag{23}$$

A typical data acquisition unit has 16 bits. The medium voltage (MV) power signal is assumed to be 7200 V_{RMS} line to neutral. Each bit will represent 311 mV for the ±10.2kV or 20.4 kV input range from (24). The smallest measurable data signal is taken to be 622 mV. This allows for an error of 2*LSB in the DAQ unit's hardware.

$$V_{LSB} = \frac{2 * (\sqrt{2} * 7200)}{2^{16}} = 311 \; mV \tag{24}$$

An application example is in order to see how the varying load impedance will affect the output communication signal. Assume that the secondary side of the series coupler is wound with 50 turns and that the magnitude of V_{signal} is 5 V. The output voltage V_{comm} is equal to 143 mV for a load impedance of 2.4 Ω. This voltage is below the smallest measurable signal and will be unrecoverable by the master device.

The main problem with the toroid approach to the series voltage injection technique is the load impedance. When the load is operating at max power the voltage that is at the substation is too small to be measured by the master device. Note that it is assumed that there are not any magnetic saturation issues with the core material. The coupled voltage will be dropped across the load impedance instead of the substation equivalent impedance. This results in a data signal that cannot be detected by the master device unless the communication voltage is unacceptably high.

There were two approaches that were discussed for implementing the series voltage injection technique. The first involved placing a voltage transformer in series with the load. This approach is problematic because the primary winding of the transformer will have to carry the full load current. Wrapping wire that is large enough to carry the full load current will result in a large transformer. The second approach was to use a toroid as the magnetic coupler and to place the load wire through the toroid. This

approach removes the problem of a large transformer that is due to large windings; however its problem is the load impedance. Even when the load is operating at max power (minimum impedance), its impedance prevents communication between the master and slave devices. In summary, the series voltage injection technique is an undesirable technique because of either large transformer windings or load impedance.

4.4: Shunt Voltage Injection Technique

The shunt voltage injection is the last conventional coupling technique discussed. This technique involves placing a conventional transformer in parallel with the load. The communication hardware will put a voltage signal onto the secondary side of the transformer which will then be coupled to the primary side. Some type of power frequency blocking filter is likely to be required but is not shown because it is not relevant to the discussions that follow. A diagram of how the components are connected is illustrated in Fig. 19.
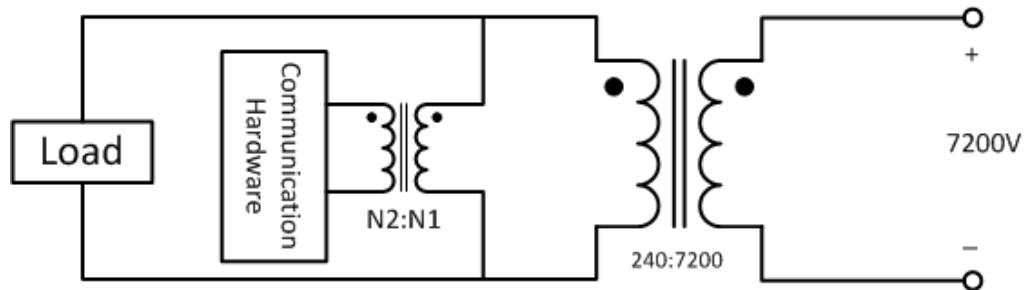
Figure 19: Shunt Voltage Injection Technique

Trouble arises due to impedance issues with this technique. The coupling transformer has a high impedance relative to the Thévenin equivalent impedance of the source at the substation. An equivalent circuit of Fig. 19 is illustrated in Fig. 20. The

Thévenin equivalent voltage and impedance ($\overline{V}_{\text{TH,sub}}$, $\overline{Z}_{\text{TH,sub}} = R_{\text{TH,sub}} + j\omega L_{\text{TH,sub}}$) are the open circuit voltage and open circuit impedance as seen at the substation towards the source. The distribution line impedance and transformer equivalent circuit impedance are assumed to be ideal. The load impedance is represented by resistance R_L and reactance ωL_L and the load conductor impedance is assumed to be ideal. The resistances, R_1 and R_2, and reactances, ωL_1 and ωL_2, are the equivalent circuit elements for the shunt coupling voltage transformer. The equivalent shunt elements of the coupling transformer equivalent circuit are assumed to be very large and are disregarded.
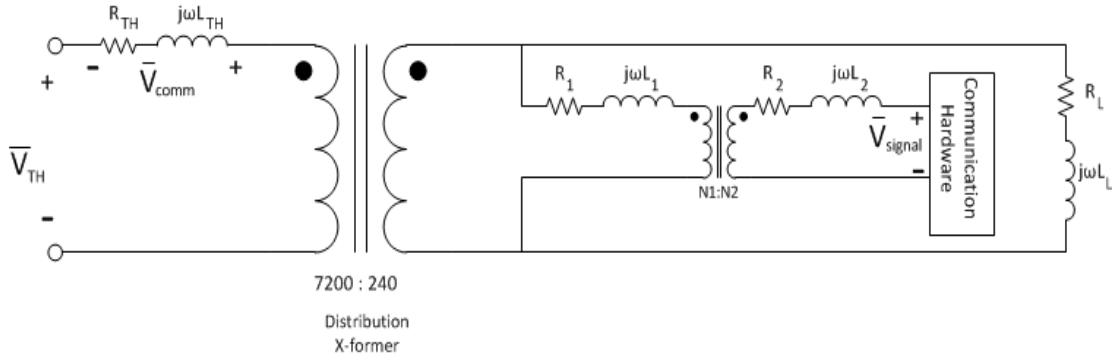
Figure 20: Line Diagram of the Shunt Voltage Injection Technique

The issue arises due to the nature of the coupling transformer. A low power signal transformer will have numerous windings on the primary side with a small gauge wire. The large number of windings translates into a long wire that will have a large resistance which will make R_1 a large value. The resistance R_1 is not the total resistance that will be present. By reflecting R_2 across the transformer to the primary side, it is possible to find the total resistance of the coupler which includes both R_1 and R_2.

It is possible to calculate the magnitude of $\overline{V}_{\text{signal}}$ that is necessary for successful communication with the master device. The Thévenin equivalent impedance at the

substation is unknown. It is appropriate to make the same assumption for this discussion as was made in the series voltage injection technique. The assumption is that the Thévenin equivalent impedance at the substation is the same as the impedance found in (6). Note that the impedance in (6) is on the LV side of the distribution transformer. It needs to be reflected to the HV side of the distribution transformer to apply to the equivalent circuit in Fig. 20. This calculation is provided in (25).

$$Z_{TH,sub} = \frac{7200^2}{240^2} * 0.12\Omega = 108\Omega \tag{25}$$

A small transformer with a primary to secondary winding ratio of 480 to 4 will have a resistance of about 4 kΩ for R_1 and a resistance of about 0.5 Ω for R_2. To simplify calculations the coupler reactances ωL_1 and ωL_2 and resistance R_2 are ignored. The new simplified model involves the Thévenin impedance at the substation, an ideal distribution transformer, the coupling transformer's primary winding resistance, and the load impedance. The Thévenin source voltage is a short because the communication frequency is not 60 Hz. A circuit of the model is illustrated in Fig 21.
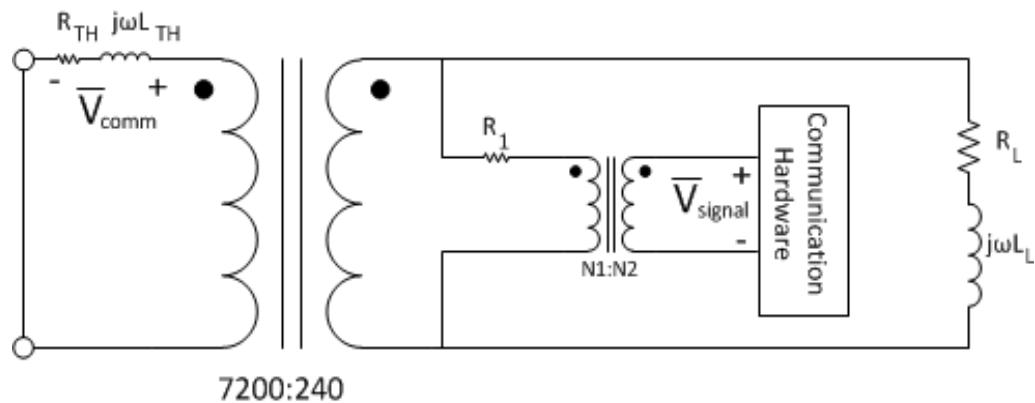
Figure 21: Thévenin Equivalent of the Shunt Voltage Injection Technique at the Substation

The communication voltage, V_{comm}, can now be found as a function of the input voltage V_{signal}. The equation describing this relationship is provided in (26).

$$V_{comm} = V_{signal}\left(\frac{N_1}{N_2}\right)\left(\frac{7200}{240}\right)\left(\frac{Z_{TH,sub}}{Z_{TH,sub} + R_1\left(\frac{7200}{240}\right)^2}\right) \qquad (26)$$

If the maximum voltage output by the communication hardware is 5 V then the communication voltage calculated in (26) will be 540 mV for a communication transformer turns ratio of 480 to 4. This calculated voltage does not meet the 622 mV minimum voltage requirement for successful recovery by a 16 bit DAQ.

There were several assumptions made to maximize the output voltage. If all of the impedances that were omitted were accounted for in (26), then the communication voltage would be decreased further. It is possible to overcome the attenuation by increasing the signal voltage level. However, this is also problematic because higher voltages equates to larger components. These larger components will not fit into the standard meter thus breaking the size requirement.

One possible solution would be to increase the Thévenin equivalent impedance at the substation for the desired communication frequency. There could be sufficient space at the substation to build a device that has a large impedance at the communication frequency. If this were implemented then the impedance $Z_{TH,sub}$ in (26) could be adjusted such that a desired communication voltage could be measured. Unfortunately this device will be complex and expensive to build which will make implementation unlikely.

The shunt voltage injection technique avoids the varying load impedance problem that plagues the series voltage and series current injection techniques. However, the attenuation of the communication signal by the coupling transformer will render the data

signal unrecognizable by the master device. This could be resolved by implementing a device that increases the Thévenin equivalent impedance at the substation for the desired communication frequency. Implementation of the device is unlikely because of cost and complexity.   In summary, utilization of the shunt voltage injection technique is improbable as the communication signal will likely be too small to be successfully recovered by the master device. Of all the magnetic coupling options, however, this one appears to have the greatest potential.

4.5: Switched Impedance Method

The last technique covered is the unconventional switched impedance method. This method involves switching an impedance on/off at some frequency to produce a desired transmit signal. In this scheme, the master device will transmit a slave's identifier that the slave device will receive. When the slave device receives the signal it will begin switching an impedance. This switched impedance will draw current that will have spectral content at the desired transmit frequency. The master will detect the content at the communication frequency and record the phase on which it was received. It is important to note that the transmitter encounters the same coupling challenges previously discussed, but it is assumed that solutions are possible because size is not an issue at the substation where the master transmitter is located.

There are two examples of the switching technique presented for discussion. The first example involves switching the impedance on for one cycle of the 60 Hz power signal and then off for 9 cycles. The second example involves switching the impedance on for 5 cycles and off for 5 cycles. Both of these examples will produce a current on the power line that will have spectral content at the desired example transmit frequency of 6Hz.

The first example involves a 60 Hz power signal being applied to an impedance for 1 cycle and then disconnected for 9 cycles to produce a current. The resultant current is illustrated in Fig. 22. An FFT of the current in Fig. 22 is illustrated in Fig. 23. The FFT recovers a 6 Hz component and its magnitude is almost 1 A. The 1 A component is an order of magnitude lower than the required 10 A for signal recoverability by the master device. Also, the 50 A current peak in Fig. 22 is too big for the communication

hardware and could create undesirable short-term voltage fluctuations. Implementing this particular switching method to produce a 6 Hz current is undesirable because of the large 60 Hz currents necessary to establish communication.
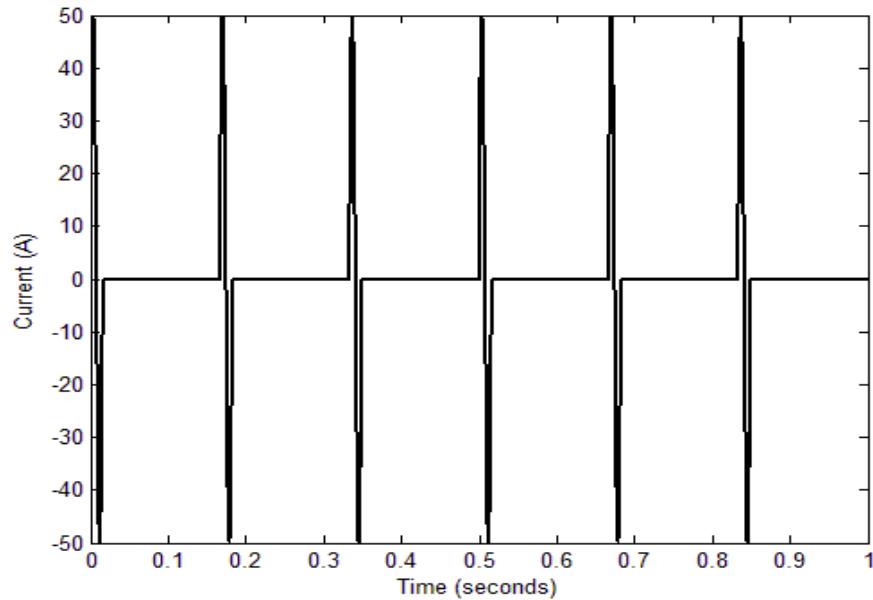
Figure 22: Switched Impedance Current Signal – on 1 cycle and off 9 cycles
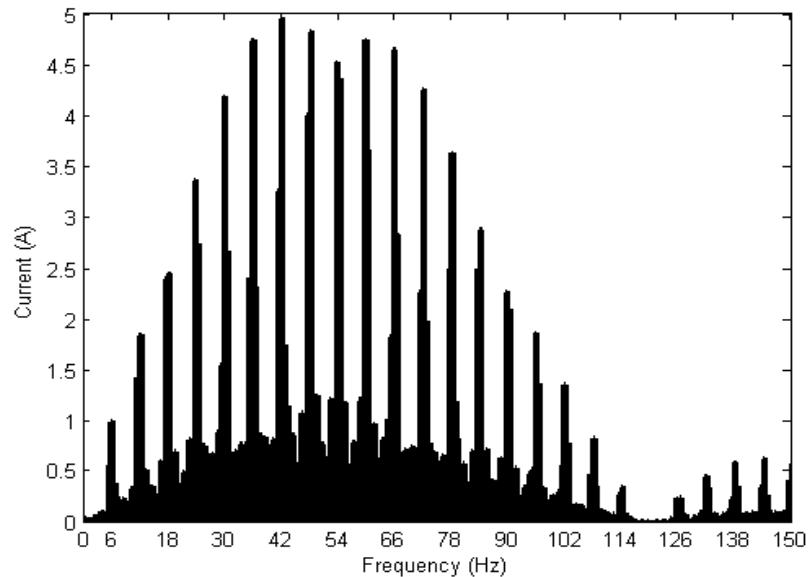
Figure 23: FFT of the Switched Impedance Current Signal – on 1 cycle and off 9 cycles

In the second example the 60 Hz power signal is applied to an impedance for 5 cycles and then disconnected for the next 5 cycles to produce a current. The resultant current is illustrated in Fig. 24. An FFT is performed on the current to verify the existence of the desired frequency component that is necessary for communication. The result of the FFT is illustrated in Fig. 25. There is a 6 Hz component recovered with a magnitude of approximately 1 A, however this signal is too small for successful communication to be established with the master device.

Both of the discussed examples are successful in getting a 6 Hz current onto the power line. The primary issue, with both examples, is the large 60 Hz current that is necessary to produce a 6 Hz component that the master device will be able to recover. Both examples involve a large 60 Hz current to produce a 6 Hz component with a magnitude of 1 A. Unfortunately, a 10 A magnitude is necessary (assuming no special CTs at the substation), which would require the 60 Hz current peaks in Fig. 24 and Fig.25 to be increased by a factor of 10. These current peaks will be too large for the communication hardware and would almost certainly create other problems as well. This technique is unlikely to be implemented because of the large 60 Hz current that is necessary to produce a 6 Hz component in the power line.
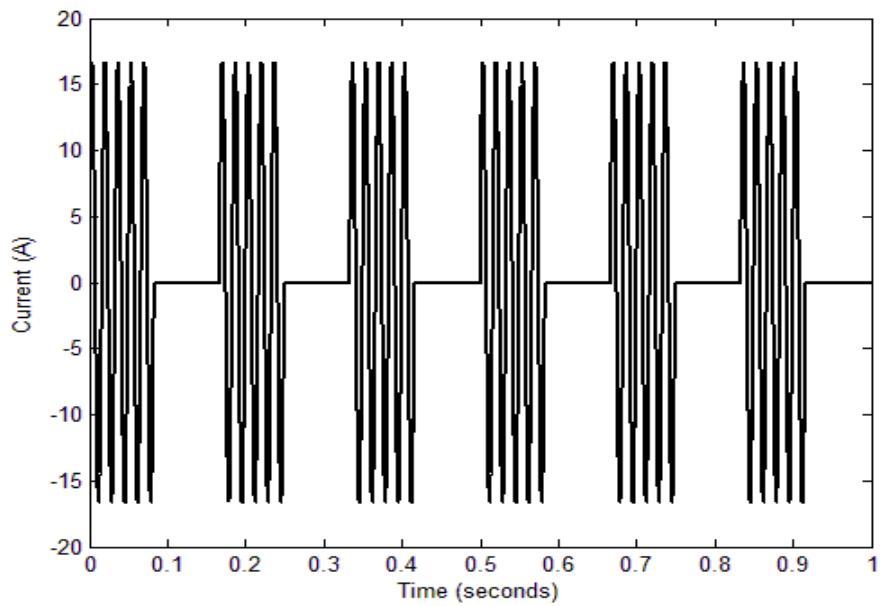
Figure 24: Switched Impedance Current Signal – on 5 cycles and off 5 cycles
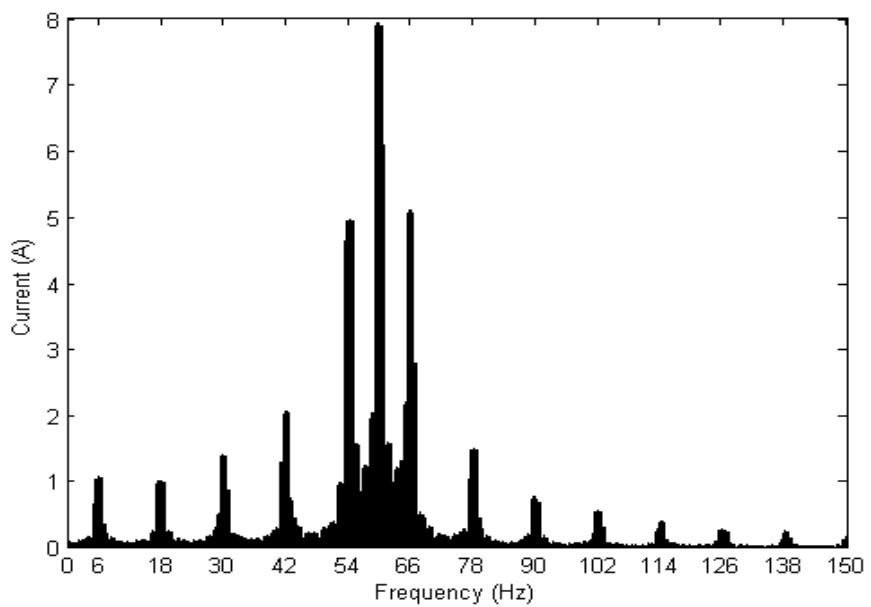
Figure 25: FFT of the Switched Impedance Current Signal – on 5 cycles and off 5 cycles

Chapter 5: Summary

It is desirable to establish communication between a central location (e.g. substation) and the loads that are supplied by the source. Successful communication involves two main processes. The first process is to establish a communication protocol that the devices will be able to interpret. The second process is a coupling scheme to connect the communication signal to the power line.

There were two types of communication strategies discussed. The first required the slave device to wait until the transmission channel is open before it begins transmission. The second method involves the master device sending out the slave's identification number on all three phases of the power system. When the slave receives its identification number it responds to the master device.

Several methodologies were presented to couple the data signal onto the power line to establish communication between the master and slave devices. It is apparent from this research that it is difficult to couple a signal onto the load conductor. Low frequency signal coupling is not straightforward due to the magnetic saturation issues arising from using cores that will fit into the standard meter socket. The series current injection technique is undesirable due to the varying load impedance. Shunt current injection is not going to work well because of the large size of the required power frequency blocking filter. The series voltage injection method is limited by the primary coupling transformer winding having to carry the full load current or the large load

impedance. Shunt voltage injection will not work well because of the signal attenuation by the coupling transformer. The most promising technique is the switched impedance method. However, it is unlikely to be implemented because of the large currents at the power frequency that are required to get the necessary low frequency current at the transmit frequency.

Chapter 6: Recommendations and Future Work

The idea of establishing communication between a master and slave device is still of interest. Using magnetics to couple a signal onto the load conductor should be avoided. A directly coupled signal generator operating at the desired data transmission frequency should be implemented. This can be accomplished by using an "active filter" in the standard meter socket. Once there is active communication at the load side, the "master ask then slave respond" methodology appears to be best suited. Conventional coupling techniques should be used with the master device for communication as there is enough space available to avoid a directly coupled scheme. All of the previous issues at the load side are also issues at the source side in relation to coupling. However, the issues at the source side will be manageable because there is adequate space available for the large components that may be necessary for coupling and decoupling signals onto or from the power line.

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