Carrier Frequency and Bandwidth Requirements for Data Transmission in Power Distribution Automation System.

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ABSTRACT

Inadequate monitoring and control of some major portions of the power distribution network has been identify as one of the major factors responsible for poor performance of our distribution system in Nigeria. This research is the development of a scheme that will ensure real-time automation for the monitoring and control of distribution network parameters. With this system the distribution network signal status can be processed, and sent through a control system or carrier to the base substation via a personal computer through Power Line Carrier Communication (PLCC).

The work emphasizes the determination of appropriate carrier frequency and bandwidth for effective serial data transmission between distribution network and base station. Attenuation of system signals were examined when varying carrier frequency at a given length, but subjected to the same system parameters. Using the Simulink facility in Matlab®, an 11kv, 150km distribution line was modeled to study system voltage signal responses. Here, attenuations were examined when we pressed voltage of 25V on a 11kv voltage using carrier frequencies of 50kHz, 100kHz, and 500kHz, respectively, and at a given load. Results showed that for a loaded line, the signal alternation decreases as carrier frequency increases, when appropriate coupler has been chosen.

(Keywords: power system, distribution automation, carrier frequency, bandwidth, data transmission, remote terminal unit)

INTRODUCTION

The major objective of every electricity utility is to provide electric energy to consumers without interruption and at minimum cost. In Nigeria, the demand on electric power supplies for domestic, commercial, and industrial uses has increased in recent time both quantitatively and qualitatively. With the increasing awareness in technological development the dependence on the electric power supply will continue to increase considerably.

To maintain a steady power supply system with minimum interruption and fast fault restoration especially at the distribution end, a major link between electricity utilities and consumers of electricity, there is the need to provide a good scientific monitoring and control system. Hence, automation of the power distribution system is essential. To cope with the complexity of the distribution network, the latest computer, communication, and distribution technologies need to be employed [1, 2]. The word “automation” means doing the particular task automatically in a sequence with faster operation rate [3]. Automation in the power distribution allows utilities to implement flexible control of distribution systems through effective data communication between base station and load centers, which can be used to enhance efficiency, reliability, and quality of electric service [4].

This research is the determination of carrier frequency and bandwidth that would provide effective data transmission in Power Automation System. This automation system makes use of communication system techniques and computer software to transport data to and from base station to load end. With this system, the operator can receive substation status signals and send commands or control signals to the substation via a Personal Computer (PC) connected to the substation through Power Line Carrier Communication (PLCC). The distribution automation system is also referred to as the Distribution Management System [2].

Power Distribution System

Electric power distribution system is an integral part of the electrical power system in the delivery of electricity to the consumers. It is the final stage in the delivery of electricity to end users. A distribution systems' network carries electricity from the transmission system and delivers it to consumers. The Distribution automation system is also referred to as the Distribution Management System [2].

Primary Distribution Systems: The primary distribution system is that portion of the power network between the distribution substation and the utilization transformers. The primary distribution system consists of circuits, referred to as primary or distribution feeders, which originate at the secondary bus of the distribution substation. The primary distribution substation is usually the delivery point of electric power in large industrial or commercial applications [5].

Secondary Distribution Systems: The secondary distribution system is that portion of the network between the primary feeders and utilization equipment. The secondary system consists of step-down transformers and secondary circuits at utilization voltage levels. Residential secondary systems are predominantly single-phase, but commercial and industrial systems generally use three-phase power [5].

Distribution Automation (DA) Realization

In distribution automation system, the various quantities (*e.g.*, voltage, current, switch status, temperature and oil level, etc.) are recorded in the field at the distribution transformers and feeders, using a data acquisition device called Remote Terminal Unit (RTU). These quantities are transmitted on-line to the base station through a communication media. The acquired data is processed at the base station for display on computers through a Graphic User Interface (GUI). In the event of a system quantity crossing a pre-defined threshold, an alarm is generated for operator's intervention. Any control action, for opening or closing of the switch or circuit breaker (CB), is initiated by the operator and transmitted from the 33kV base station through the communication channel to the RTU associated with the corresponding switch or CB. The desired switching takes place and the action is acknowledged back to the operator [6].

In this work, attention has been given to how to choose appropriate bandwidths for modulating and demodulating above quantities with minimum losses.

Distribution Automation Scheme

The distribution automation system will be made up of features as described in the Figure 1. The RTU collects substation parameters at the DSS and routes same to the MODEM at the DSS side. The MODEM converts the digital signal (representing the measured parameters – voltages and currents) to modulated analog signal and vice versa. There are two MODEMs – one used for the DCC side and one used for the DSS side. The MODEM at the DSS converts the digital signal to modulated analog signal by impressing it on the carrier. The digital signal is obtained from the RTU while the carrier signal is internally generated by the MODEM. The modulated signal is then coupled to the power line through the line coupler. The line coupler blocks the 50Hz power voltage, preventing from reaching the MODEM and the RTU. The line trap prevents the high frequency communication signal from being short-circuited by the low impedance of the Distribution substation (DSS) transformer or the DCC transformer.

At the DCC side, the modulated signal present on the transmission line is coupled to the modulation and demodulation module (MODEM) at the DCC by the line coupler. The MODEM then demodulates the modulated signal (extracting the original modulating digital signal initially impressed on the carrier at the DSS). The digital signals are then transmitted to the PC via the serial interface (RS-232).

The DA Software Interface gives visual indication of the various readings of the transformer at the DSS and commands can be sent to remotely shutdown the substation in case of unsatisfactory readings. This makes the communication a full-duplex (two-way) communication. This shutting down can also be automatically performed by the microcontroller in the RTU if configured in software to do so.

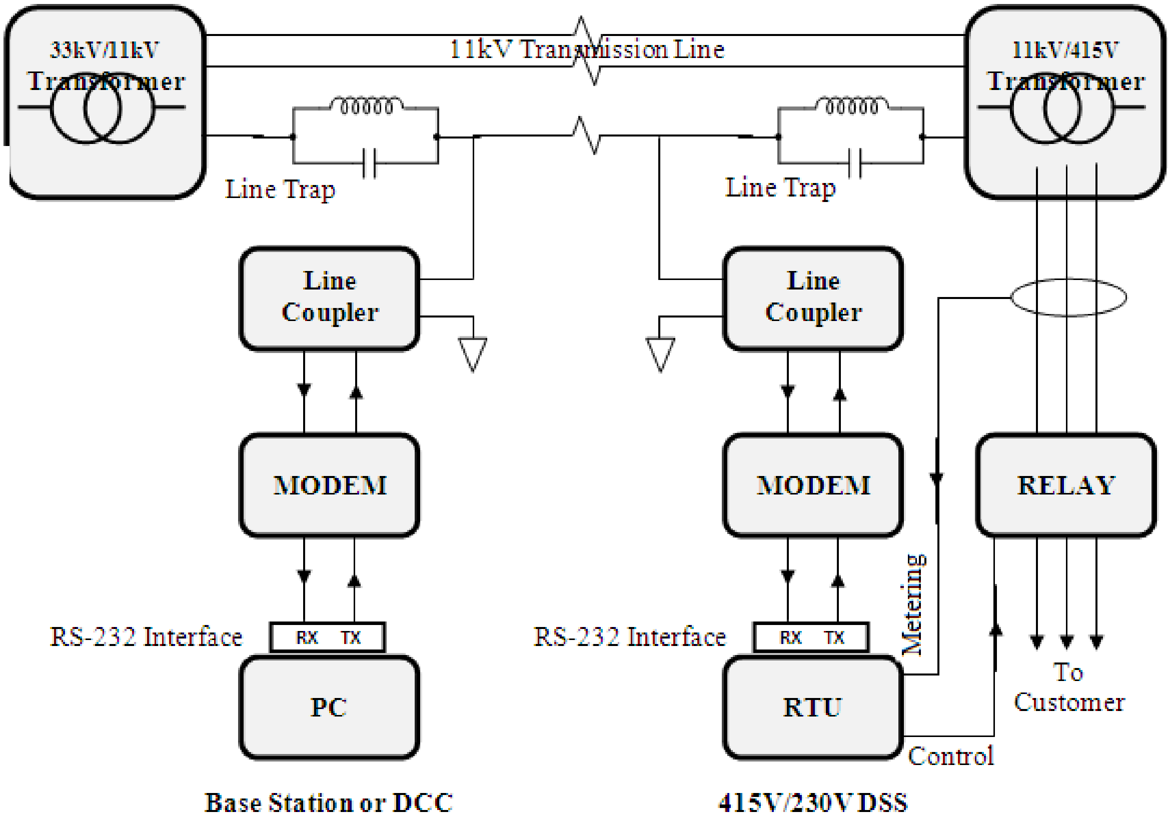

Figure 1: The Distribution Automation Scheme.

Remote Terminal Unit (RTU)

All the functions of data acquisition, monitoring, transmission, and processing are usually performed by a single unit called the Remote Terminal Unit (RTU). As the name implies, a remote terminal device, RTU, is an IED (Intelligent Electronic Device) that can be installed in a remote location, and acts as a termination point for field contacts. IEDs are I&C (Instrumentation and Control) devices built using microprocessors [7]. The RTU records and checks measured values before transmitting them to control station and in the opposite direction transmits commands, set point values and other signals to the monitored substation.

Design Consideration for the Line Coupler

The line coupler is designed for interfacing with the 220V single phase (Phase–to–Earth Coupling). A toroid is used for the coupling transformer core [38].

The line coupling circuit employed is a broadband circuit that will allow frequencies between the range of 50kHz and above to be used. This is so as to accommodate the 100/120kHz and 200/220kHz frequency groups used for the duplex communication [8] and accommodate the 100/120kHz and 200/220kHz frequency groups used for the duplex communication. Shown in Figure 2 is the line coupling circuit [8].

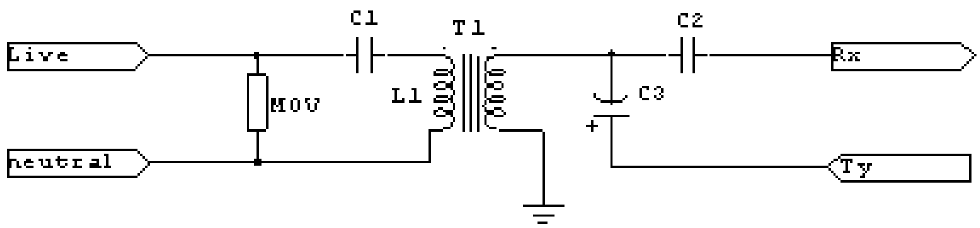

Figure 2: The Line Coupling Circuit.

MOV is a metal oxide varistor which serves as a surge protection unit, minimizing the effect of transients. The capacitor C1 and the self-inductance, L1, of the transformer, T1, form a series resonance circuit, a high-pass filter to effectively remove the 50Hz power signal and its harmonics, but also other spectral components with low frequencies. Capacitors C2 and C3 prevent the transformer from shorting out the DC offset of the receiver and the transmitter, respectively.

At resonance, the summation of the complex impedances of the capacitor C1 and inductance L1 becomes zero and is given by [9]:

$$\frac{1}{j2\pi f C1} + j2\pi f L1 = 0 \quad \textbf{(1)}$$

This gives a cut-off frequency of,

$$f_c = \frac{1}{2\pi\sqrt{L1C1}} \quad \textbf{(1.1)}$$

To determine L1, the design of the transformer must first be considered. The design of a transformer involves careful determination of the number of windings and two major parameters considered include the maximum operating voltage and the lowest operating frequency.

$$L1 = \frac{\mu N^2 A}{2\pi r} \text{ [9]} \quad \textbf{(2)}$$

Where, μ = permeability = 200 x 4π x 10^{-7} H/m for iron,
N = number of turns in the toroid,
A = cross-sectional area of the toroid, and
r = toroid radius to centre line.

And

$$C1 = \frac{1}{L1 \times 4\pi^2 f_c^{\,2}} \quad \textbf{(3)}$$

Line Trap

When the carrier signal is coupled to the power line it can propagate in two directions, either to the remote line terminal or into the station bus and onto other lines. If the signal goes into the station bus much of its energy will be shunted to ground by the bus capacitance. Also some of this energy would propagate out on other lines thus transmitting the signal to a large portion of the system. This is undesirable since the same frequency may be used on another line. Because of these problems, a device is needed to block the energy from going back into the bus and direct it toward the remote line terminal. This device is called a line trap.

The general design of a line trap is that of a parallel LC circuit. This type of a circuit presents high impedance to the carrier signal at its resonant frequency. Thus if the parallel LC circuit were placed in series with the transmission line, between the bus and the coupling capacitor, then the carrier signal would propagate toward the remote terminal. The line trap must be capable of providing a very low impedance path to the power frequency current. The inductor in the trap provides this path, and it is designed to carry the large currents required. Another important function of the line trap is to isolate the carrier signal from changes in the bus impedance, thus making the carrier circuit more independent of switching conditions [10].

Power Line Carrier Communication (PLCC)

Power Line Carrier Communication involves the transmission of data over power lines. Since power lines are designed to carry high voltages, coupling circuits are usually made use of to block the 50/60Hz voltage from the communications circuit and impress the high frequency communication signal on the line. Also, the fact that power lines are actually designed to carry low frequency signals imposes some technical challenges at the high frequency needed for communication. Of importance also are the huge noises and ever varying levels of impedance and attenuation attendant in the power line.

DATA COLLECTION

This involves the collection of information regarding the parameters to be monitored. Acquired data can be used locally within the device collecting it, sent to another device in a substation, or sent from the substation to one or several databases for use by operators, engineers, planners, and administration [7].

Data Transmission and the Application of Modulation and Demodulation Module (MODEM)

Data transmission includes all the features required to transmit the collected and processed data from the substation/process location to the base station (distribution control centre) and in converse to transmit commands and set points from the control centre to large number of remotely located devices. Acquired data can be used locally within the device collecting it, sent to another device in a substation, or sent from the substation to one or several databases for use by operators, engineers, planners, and administration [7]. A good data communication system is therefore a prerequisite for good performance of DA system.

A wide range of communication technologies is available to perform the task of DA system [7]. Some of these include public telephone communication (leased or dedicated line), power line carrier communication (PLCC), UHF MARS (Ultra High Frequency Multi Address Radio System). Data rates over a power line communication system vary widely. Low-frequency (about 100-200 kHz) carriers impressed on high-voltage transmission lines may carry one or two analog voice circuits, or telemetry and control circuits with an equivalent data rate of a few hundred bits per second; however, these circuits may be many miles long[11].

Modulation Method: Since the system relies on the microcontroller for its working and microcontrollers operate basically on digital data, it will be necessary only to consider digital modulation schemes. Three of the available digital modulation schemes are Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK) and Phase Shift Keying (PSK) [12].

Usually, the power line is a hostile environment for communication. This is partly due to its intense noise levels and the harmonics due to switching and corona [2, 13]. With the use of Frequency Shift Keying modulating method, the effects of noise are highly reduced [13]. Hence the Frequency Shift Keying modulating method has been adopted for this work.

Frequency Shift Keying (FSK): Frequency shift keying is a digital modulation technique in which two frequencies (at least) are used for communication – the 'mark' frequency and the 'space' frequency. Data is transmitted by shifting the frequency of a continuous carrier in a binary manner to one or the other of two discrete frequencies. The lower of the two frequencies is assigned as the space frequency while the other is the mark frequency. The words 'mark' and 'space' come from the on/off nature of digital signals. A comparative advantage of FSK is that the receiver is always loaded at either the mark or space frequency meaning that the effects of noise are highly reduced.

Demodulating FSK Signal: To demodulate the FSK signal, several approaches can be employed. Among these is the Phase Locked Loop (PLL). This method can be used to detect the two frequency levels in the Binary FSK signal. The PLL works on the principle of negative feedback and tracks frequency within a certain limit based circuit parameters. A PLL is a control system that generates a signal (usually by using a Voltage-Controlled Oscillator (VCO)) that has a fixed relation to the phase of a reference signal (input signal). A phase-locked loop circuit responds to both the phase and the frequency of the input signal, automatically raising or lowering the frequency of the controlled oscillator (VCO) by producing an error voltage, until it is matched to the reference in both frequency and phase and then it "locks" at this frequency and phase[14].

The Choice of Carrier Frequency and Bandwidth Requirement: The bandwidth of a system is the range of frequency over which the system will work satisfactorily. The bandwidth of a communication system determines to a great extent, the amount or speed of data transmitted. This is because there is a close relationship between the range of frequencies allowable or used for transmission and the data transmission rate (measured in bps – bits per second). The bandwidth requirement of a BFSK analog modulation system is as illustrated in Figure 3 [15].

The bandwidth BW is given by [28]:

$$BW = S(1+m) + 2\Delta f \quad \textbf{(4)}$$

where, *S* = baud rate, *m* = modulation index, and,

$$2\Delta f = f_2 - f_1 \quad \textbf{(4.1)}$$

The modulation index is the ratio of the frequency deviation to the modulation frequency and this is equal to [6]:

$$m = \frac{frequency\ deviation}{modulation\ frequency} \quad \textbf{(5)}$$

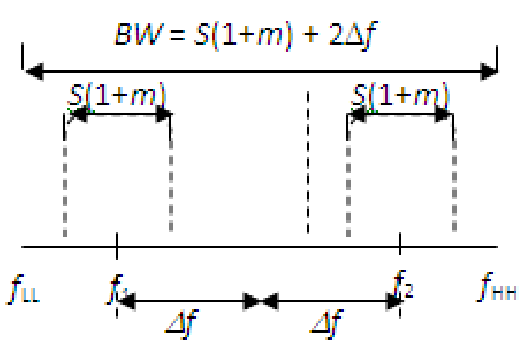

Figure 3: The Bandwidth of BSFK.

The baud rate is used as a measure of serial data transmission. It measures the number of signal or symbol changes per second as against the data rate which measures the bit rate (bits per second – bps). A baud represents 1 symbol/s. Since a signal element can actually represent more than one data element, it will be incorrect (as is sometimes done) to assume that baud rate and data rate are the same. For example, a so-called 9600-baud modem that encodes 4 bits per event actually operates at 2400 baud but transmits 9600 bits per second (2400 events times 4 bits per event) and thus should be called a 9600-bps modem [17] or 2400 baud modem.

The relationship between baud rate and data rate can be expressed as:

$$S = \left(N \times \frac{1}{r}\right)\ baud \quad \textbf{(6)}$$

where, *N* is the data rate (bps) and *r* is the number of data elements carried in one signal element. The data element is the smallest piece of information to be exchanged, which is the bit (1 or 0). On the other hand, the signal element is the smallest unit of a signal that is constant.

It may have to be noted that in analog transmission r can be expressed as:

$$r = \log_2 L \quad \textbf{(7)}$$

where, *L* is the type of signal element, not the level. *L* is 2 for BFSK [17].

Serial Communication: Serial communication involves the transmission of data by sending one bit (binary digit) at a time over a single communication channel. Compared to parallel communication, where a byte (group of eight bits) are sent at the same time over eight separate communication media (one bit per time over each of the lines), serial communication requires only one channel and thus is more economical though relatively slow because of the additional bits needed for synchronization. And if we are to consider the fact that the power line cannot render more than three communication channels (three-wire, three-phase system is used for distribution at the primary level), then it is clear that the best mode of communication to use is the serial data communication.

Signal Attenuation: Attenuation the value of the signal loss when transferring data. Given the propagation function, γ (for lossy line) where [18]:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \qquad \textbf{(8)}$$

or

$$\gamma(\omega) = \alpha(\omega) + j\beta(\omega) \qquad \textbf{(8.1)}$$

Where *R* = resistance per unit length
L = Inductance per unit length
G = Leakage per unit length
C = Capacitance per unit length

α is called attenuation constant and it shows the amount of attenuation the signal suffers for a given unit length of transmission line, whereas β shows the phase angle (distortion) over a given length [12]. By assuming a low loss transmission line,

$$\alpha = \frac{G}{2}\sqrt{\frac{L}{C}} + \frac{R}{2}\sqrt{\frac{L}{C}} \qquad \textbf{(8.2)}$$

With a loss-free line, $\gamma = j\omega\sqrt{LC}$, α = 0 (no attenuation), and $\beta = \omega\sqrt{LC}$.

Data Flow: Communication between two devices can be simplex, half-duplex, or full-duplex [15]. In simplex mode of communication, the direction of data transfer is fixed – one device can only transmit while the other can only receive (Figure 4).

The half-duplex mode (*see* Figure 5) is used in cases where there is no need for communication in both directions at the same time; the entire capacity of the channel can be utilized for each direction. At a particular point in time, device A can be transmitting and B, receiving while, at another instance of time, B can be transmitting while A is receiving.

The full-duplex mode (*see* Figure 6) as used in this work, is used when communication in the two directions at the same time is essential; the two devices can both transmit and receive at the same time. However, the capacity of the transmission channel must be divided between the two directions.

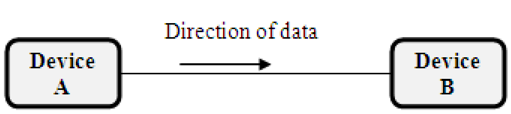

Figure 4: Simplex Mode of Data.

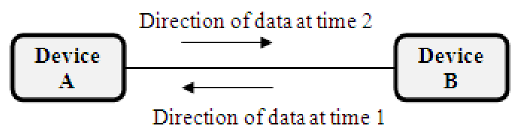

Figure 5: Half-Duplex Mode of Data Flow.

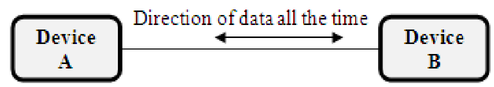

Figure 6: Full-Duplex Mode of Data Flow.

Frequency Allocation and Regulatory Standards: Frequency spectrum is not free and has thus been allocated such different services are given license specific range of frequency. Frequencies used by the devices communicating over the power line are restricted by the limitations imposed by the regulatory agencies [19]. These regulations are developed to ensure harmonious coexistence of various electromagnetic devices in the same environment.

According to the Committee for Electro technical Standardization (CENELEC), which governs regulatory rules in Europe, the range of frequency between 3kHz and 148.5kHz for power line communication [19]. On the other hand according to Federal Communications Commission (FCC) which governs frequency regulation in North America, the frequency range of 50 – 500kHz can be used for power line communication [19].

Man-Machine Interfacing: The Man-Machine Interface (MMI) is the interface between man and technology for control of the technical process. The computer system at the master control centre or central control room integrates with RTU over the communication link with its transmission protocol, acquires the remote substation or distribution transformer/feeder data and transfers the same to the computer system for man-machine interface.

The Use of Microcontroller: The microcontroller is a specialized microprocessor that houses much of the support circuitry onboard, such as ROM, RAM, serial communications ports, A/D converters, etc. In essence, a microcontroller is a minicomputer, but without the monitor, keyboard, and mouse. They are called microcontrollers because they are small (micro) and because they control machines, gadgets, etc. With one of these devices, one can build an "intelligent" machine, write a program on a host computer, download the program into the microcontroller via the parallel or serial port of the PC, and then disconnect the programming cable and let the program run the machine.

RESULTS AND DISCUSSION

Using the Simulink facility in Matlab®, an 11kV distribution line was modeled and a high frequency source was used to impress signal on the line having connected line traps in the end of the 150-km distribution line as shown in Figure 7. In this simulation, signals at the sample carrier frequencies within the acceptable range, of 50kHz, 100kH and 500kHz were impressed upon distribution feeder of 150km and a load of **5.7Ω**, **6.03H** attached at the receiving end. The RLC of the 150-km single branch distribution line are 0.045 Ohms per km, 0.0009536 Henry per km and 12.02nF per km.

The following steps were then taken:

- The High-Frequency Source is used as the transmitter of the DCC MODEM to vary frequency to 50kHz , 100kH and 500kHz whereas the Coupling Circuit Terminator is used as the receiver of the Load Centre (DSS).
- The coupling capacitors are simulated with the designed value (C = **0.22μF**).
- The high-frequency transmitter is set at 25V (25√2 = **35.35V** peak as needed by the simulator).
- For the simulation the voltage sources at the DCC end were set at 11kV/√3 x √2 which is equal to **8981.46 Volts peak phase voltage** for each of the sources.

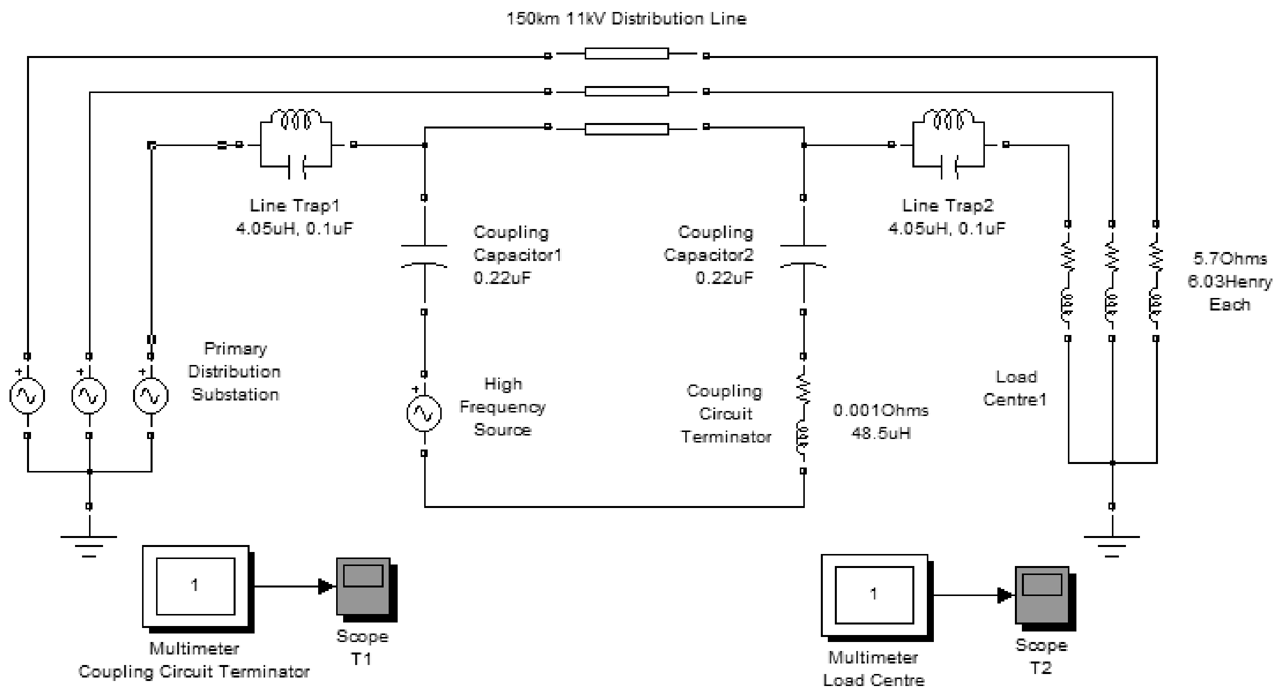

Figure 7: A Single Branch 150km 11kV Distribution Network: Simulation of Signal Response Varying Carrier Frequency.

- The line traps are simulated with the calculated values of C = **0.1μF** and L = **4.05μH**.
- The oscilloscope 1 with the associated multimeter is used to measure the amplitude of the high frequency voltage across the coupling circuit terminator. In the same vein, the oscilloscope 2 with the adjoining multimeter is used to measure the amplitude of the 50Hz power voltage across the loads at the load centre.

The simulation results for the single branch 150-km distribution line are as shown in Figures 8 a,b,c and 9 a,b,c.

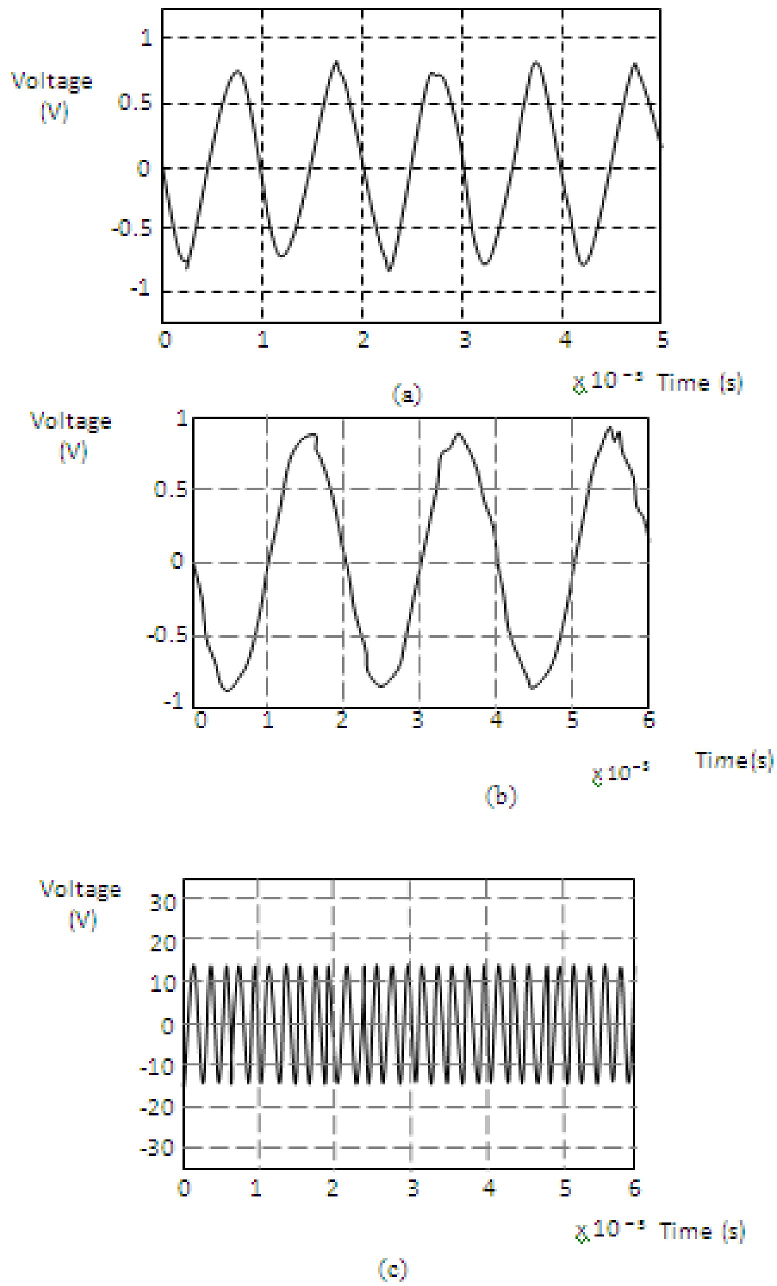

Figure 8: The Wave Across the Coupling Terminator with 5.7Ω, 6.03H Load at (a) 50kHz, (b)100kHz, and (c) 500kHz Carrier.

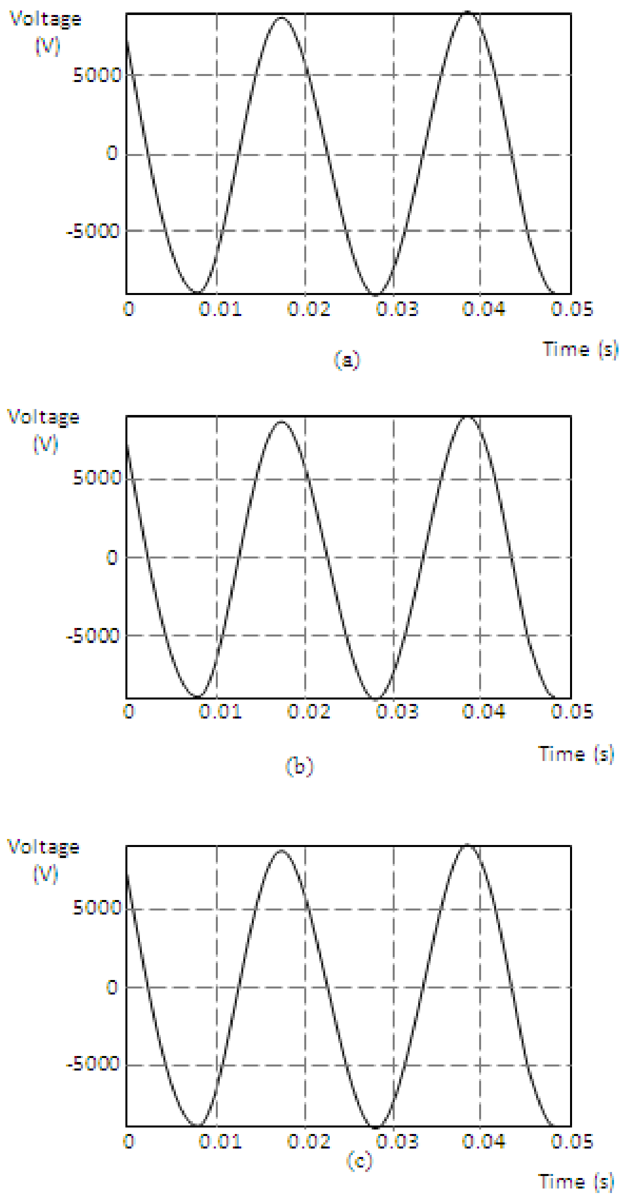

Figure 9: The Waveform at the Load Center with 5.7Ω and 6.03H load with (a) 50kHz, (b) 100kHz, and (c) 500Khz Carrier Frequencies.

As it can be seen from Figures 8 a, b, and c, the amplitude of the high frequency voltage response is more than that of the low frequency. At 50kHz and 100kHz, the maximum amplitude noted is about 0.75V and 0.9V out of the 35.35V impressed upon the line at the DCC side as against about 15V for the 500kHz signal. This means there is a huge attenuation loss on the line at frequency extremes close to the 50kHz for the load and the line length.

This huge attenuation will also be due to more noise on the line at lower frequencies. Thus, it will be more advantageous to make do with higher frequencies, when the appropriate line couplers have been chosen. However, the above responses where 35.35V are impressed and carrier frequencies of 50kHz, 100kHz and 500kHz applied are within the acceptable limits. Any amplitude voltage response equal to or above 150mV is acceptable [20].

Once the acceptable frequency ranges have been established, it is convenient to determine modulation index using Expression 4 and 5.

Figures 9 a, b, and c show the corresponding waveform at the load centre of Figure 7.

The peak power voltage transmitted at the DCC is 8981.46 Volts peak phase voltage as calculated. Now, a consideration of figure 9a,b,c reveals that the power voltage amplitude remains unchanged as we increase the frequency from 50kHz through 100kHz to 500kHz and is within the expected 8981.46 Volts. This is because the appropriate line trap have been chosen. The line trap would not allow signals above 50Hz frequency to pass.

CONCLUSION

Automation in the power distribution allows utilities to implement flexible control of distribution systems through effective data communication between base station and load centers, which can be used to enhance efficiency, reliability, and quality of electric service. Application of Power Distribution Automation system at the distribution base substation for proper monitoring of system signals would provide solution to poor power distribution.

From the results obtained from the simulations in this work, it is clear that there is more attenuation at lower frequencies and longer distribution lines. However, the signal (voltage amplitude) responses in Figures 8 a, b, and c are still within the acceptable limit of being greater than 150mV. Once a proper carrier frequency ranges are established, the choice of band frequency for data communication is easy. Thus, for power line carrier communication application, in order to ensure reliable communication, higher power transmitters must be used to overcome the attenuation on long lines provided the appropriate corresponding designed coupler is used.

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