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# A NOVEL APPROACH IN LARGE SIGNAL POWER LINE COMMUNICATION

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# A NOVEL APPROACH IN LARGE SIGNAL POWER LINE COMMUNICATION

by

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*In the name of Allah*
*The compassionate*
*The merciful*

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| 2PN | Two Port Network |
| AC | Alternative Current |
| ACKD | Acknowledged |
| ADC | Ampere Direct Current |
| AM | Amplitude Modulation |
| AMRA | Automatic Meter Reading Association |
| AR | Active Resistance |
| ASCII | American Standard Code for Information Interchange |
| ASK | Amplitude Shift Keying |
| AST | Asynchronous Serial Transmission |
| AWG | American Wire Gauge |
| BACnet | Building Automation and Control networks |
| BAS | Building Automation System |
| BC | Byte Counter |
| BOM | Bill Of Material |
| BPLC | Broadband Power Line Communication |
| BWV | Black & White Video |
| CAD | Computer Aided Design |
| CC | Control Code |
| CDMA | Code Division Multiple Access |

| | |
|---|---|
| CEBus | Consumer Electronic Bus |
| CENELEC | Comité Européen de Normalisation Électrotechnique |
| CIV | Compared Intermediate Value |
| CM | Common Mode |
| CMRR | Common Mode Rejection Ratio |
| COFDM | Coded Orthogonal Frequency Division Multiplexing |
| CPD | Cumulative Probability Distribution |
| CPU | Central Processing Unit |
| CPSK | Coherent Phase Shift Keying |
| CRC | Cyclic Redundancy Check |
| CSMA | Carrier Sense Multiple Access |
| CSMA/CA | Carrier Sense Multiple Access/ Collision Avoidance |
| DA | Destination Address |
| DAB | Digital Audio Broadcast |
| DC | Direct Current |
| DCSK | Differential Code Shift Keying |
| DES | Digital Encryption Standard |
| DIN | Deutsches Institut für Normung |
| DPSK | Differential Phase Shift Keying |
| DQPSK | Differential Quadrature Phase Shift Keying |
| DSP | Digital Signal Processing |
| DVB | Digital Video Broadcast |
| ECC | Error Correction Code |

| | |
|---|---|
| EIA | Environmental Impact Assessment |
| ERM | Extremely Robust Mode |
| FAMPLC | Frequency & Amplitude Modulations Power Line Communication |
| FCC | Frame Check Code |
| FDAST | Full Duplex Asynchronous Serial Transmission |
| FFT | First Fourier Transform |
| FLTZ | Free Level Threshold Zone |
| FM | Frequency Modulation |
| FMPS | Frequency Modulated Power Supply |
| FSK | Frequency Shift Keying |
| FSS | FAM Send Signal |
| GMSK | Gaussian Minimum Shift Keying |
| GNR | Ground Noise Rejection |
| GPIO | General Purpose Input Output |
| HC | House Code |
| HDAST | Half Duplex Asynchronous Serial Transmission |
| HL | Host Layer |
| HV | High Voltage |
| Hz | Hertz |
| ID | Identification |
| IEEE | Institute of Electrical and Electronics Engineers |
| I/O | Input / Output |

| | |
|---|---|
| IPLC | Industrial Power Line Communication |
| KHz | Kilohertz |
| KVL | Kirchhoff's Voltage Law |
| KWH | Kilo Watt Hour |
| LED | Light Emitting Diode |
| LDO | Low Drop Out |
| LNLMS | Leaky Normalized Least Mean Squares |
| LV | Low Voltage |
| MAC | Media Access Control |
| MCU | Micro-Controller Unit |
| MDU | Multi-Dwelling Unit |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| MSK | Minimum Shift Keying |
| MV | Medium Voltage |
| NEK | Network Encryption Key |
| NL | Network Layer |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OSD | On Screen Display |
| OSI | Open Systems Interconnection |
| PCB | Printed Circuit Board |
| PFC | Power Factor Correction |
| PHY | Physical layer |
| PLC | Power Line Communication / Programmable Logic Controller |

| | |
|---|---|
| PLCC | Power Line Communication Carrier |
| PLL | Phase Locked Loop |
| PLN | Power Line Networking |
| PLT | Power Line Telecom |
| PMU | Power Management Unit |
| PN | Positive Negative. Refers to: P-N semiconductor junction |
| PR | Priority code |
| PSK | Phase Shift Keying |
| PTT | Permitted To Talk |
| PWM | Pulse Width Modulation |
| QAM | Quadrature Amplitude Modulation |
| RF | Radio Frequency |
| RLC | Refers to: Resistor Inductor Capacitor |
| RM | Reference Modulated. Refers to: DCSK6 with 4 bits per symbol |
| RMS | Root Mean Square |
| ROV | Remotely Operated Vehicle |
| SA | Source Address |
| SC | System code |
| SCADA | Supervisory Control And Data Acquisition |
| SCO | Sampling Clock Offset |
| SM | DCSK6 with 6 bits per symbol |
| SMD | Surface Mounted Device |

|  |  |
|---|---|
| SPO | Sampling Phase Offset |
| SSB | Single Side Band |
| TCP | Transmission Control Protocol |
| TCP-ACK | Transmission Control Protocol Acknowledgement |
| TCP-IP | Transmission Control Protocol Internet Protocol |
| TDMA | Time division multiple access |
| TEC | Thevenin Equivalent Converter |
| THD | Total Harmonic Distortion |
| TTL | Transistor Transistor Logic |
| UART | Universal Asynchronous Receiver Transmission |
| UPB | Universal Power-line Bus |
| URRG | Underwater Robotic Research Group |
| UTP | Unshielded Twisted Pair |
| VCO | Voltage Controlled Oscillator |
| VDC | Voltage Direct Current |
| VDE | Verband Der Elektrotechnik |
| VSI | Voltage Source Inverter |
| WLAN | Wireless Local Area Network |
| XTAL | Crystal |
| ZVZC | Zero Voltage Zero Current |

# LIST OF SYMBOLS

| | |
|---|---|
| $Z_t$ | Transmitter's impedance |
| $Z_L$ | Receiver's impedance |
| $s_{nm}(f)$ | CENELEC frequency Output level |
| $F$ | Frequency |
| $D$ | Pulse – width (duty cycle) |
| $i_s$ | MOSFET bridge Source current |
| $i_n$ | MOSFET bridge n$^{th}$ cycle current |
| $t_L$ | Consumer's On / Off time interval |
| $f_L$ | Consumer's On / Off frequency |
| $t_{SW}$ | Bridge switching time |
| $f_{SW}$ | Bridge switching frequency |
| $V_T$ | TTL voltage of the TEC block |
| $R_s$ | Thevenin resistor |
| $A_{TEC}$ | Amplification gain of TEC |
| $t_{rr}$ | Reverse recovery time |
| $t_d$ | Dead time |
| $f_{\max}$ | Maximum frequency |
| $T_{\min}$ | Minimum period |

| | |
|---|---|
| $t_C$ | Incremental time of the counter |
| $T$ | Pulse width period |
| $\delta$ | Dead time ratio |
| $f_C$ | Counter frequency |
| $f_{CPU}$ | CPU clock frequency |
| $K_P$ | CPU’s embedded counter prescaler value |
| $dv$ | Voltage derivative |
| $dt$ | Time derivative |
| $V_{IN}$ | Input voltage |
| $V_{OUT}$ | Output voltage |
| $\Delta i_n$ | Inadvertent current variance |
| $C_n$ | overall capacitance of the node’s controller |
| $V_D$ | Rectifying bias voltage |
| $V_T$ | Noise – free safe level voltage |
| $V_Z$ | Zener voltage |
| $T_{PWM}$ | Pulse Width Modulation period |
| $Z_n$ | Impedance of the entire node’s system |
| $i_C$ | Capacitor current |
| $i_L$ | Load’s inductance |
| $V_L(t)$ | Load’s inductor voltage in variable time |
| $V_L(t_n)$ | Load’s inductor voltage in $n^{th}$ time |

| | |
|---|---|
| $L$ | Inductor |
| $C$ | Capacitor |
| $t$ | Time |
| $t_n$ | n<sup>th</sup> time |
| $R_n'$ | Overall Ohmic value of system |
| $R_n$ | Total Ohmic value of system |
| $r_L$ | Total resistance of inductor coils |
| $di$ | Current derivative |
| $i_C(t)$ | Capacitor current in variable time |
| $V_C(t_0)$ | Capacitor voltage in initial time |
| $V_S(t)$ | Source voltage in variable time |
| $V_{FAM}$ | FAMPLC voltage |
| $i_R$ | Load's Ohmic current |
| $u_S(t)$ | Unity step function |
| $x(t)$ | Time variable solution for second order equation |
| $a_1 \& a_2$ | Coefficients for second order equation |
| $\zeta_s$ | Exponential damping ratio |
| $\omega_0$ | Undamped resonant frequency |
| $e$ | Exponential function |
| $\tau$ | Capacitive time constant |
| $V_0$ | Initial voltage |

| | |
|---|---|
| $K_1$ & $K_2$ | Coefficients for time variable solution of the second order equation |
| $s$ | Solution for second order RLC equation |
| $\varepsilon_0$ | Free space dielectric permeability |
| $K$ | Ratio of permittivity of dielectric to the permittivity of vacuum |
| $A$ | Area of the capacitor electrodes |
| $d$ | Distance between capacitor electrodes |
| $R_N$ | Mayer – Norton resistor |
| $VDC$ | DC voltage |
| $V_i$ | Input voltage |
| $i_{AM}$ | Amplitude modulation current |
| $i_b$ | Base current (bipolar transistor) |
| $R_b$ | Base input resistor (bipolar transistor) |
| $V_{be}$ | Base – emitter voltage |
| $R_e$ | Emitter ground resistor |
| $i_c$ | Collector current (bipolar transistor) |
| $\beta$ | Common emitter current gain |
| $V_{CE}$ | Collector – emitter voltage |
| $i_v$ | Norton current source |
| $x_C$ | Capacitor impedance |
| $CMRR$ | Common mode rejection ratio |

| | |
|---|---|
| $\delta_{AM}(t)$ | Dirac impulse function |
| $\delta'_{AM}(t)$ | Impulse derivative of $\delta_{AM}(t)$ |
| $Z_L$ | Load impedance |
| $Z_S$ | Entire cable impedance |
| $T_f$ | Forward transmission matrix |
| $T_b$ | Backward transmission matrix |
| $V$ | Voltage |
| $I$ | Current |
| $\begin{vmatrix} AB \\ CD \end{vmatrix}$ | Two – pole network transmission matrix |
| $H_S(f)$ | Server’s transmission matrix |
| $H_S(f)$ | Receiver node’s transmission matrix |
| $C_P$ | Counter pulse count |
| $CM_{ij}$ | Command “*j*” in node “*i*” (in uncategorized frequency model) |
| $CM_j$ | Command “*j*” in (categorized frequency model) |
| $d_{ij}$ | Data “j” in node “i” |
| $CM_T$ | Total commands in FM mode |
| $F_{CM}$ | Command frequency |
| $\gamma$ | Countable propagation constant |
| $g_C$ | Non-countable protective gap constant |
| $B_C$ | Counter bits |

| | |
|---|---|
| $M_{Y_x}$ | Mark of the period $T_X$ |
| $d_i$ | Total informative data in AM mode |
| $M_P$ | Marl of the pulse |
| $S_P$ | Space of the pulse |
| $T_P$ | Period of the pulse |
| $t_{delay}$ | Delay time |
| $t_{sys}$ | System processing time |
| $t_{process}$ | Pulse width measurement time |
| $D_j$ | Duty cycle in command "*j*" |
| $F_{cal}$ | Calibration frequency |
| $D_{cal}$ | Calibration duty cycle |
| $D_{dis}$ | Duty cycle distortion |
| $T_{cal}$ | Calibration pulse period |
| $C_P(F_A)$ | Count values for device *A* command frequency |
| $C_P(F_S)$ | Count values for sensor *S* communication frequency |
| $D_{ON}$ | Duty cycle to turn ON device |
| $D_{OFF}$ | Duty cycle to turn OFF device |
| $D_S$ | Duty cycle for sensor *S* information |
| $F_D$ | Frequency of device information |
| $F_S$ | Frequency to request sensor information |

| | |
|---|---|
| $D_B$ | Duty cycle of device $B$ information |
| $C_P(F_D)$ | Count values for device $B$ data frequency |
| $F_{A_n}$ | Communication frequency for device $A_n$ |
| $D_{ON}(A_n)$ | Duty cycle to turn ON device $A_n$ |
| $D_{OFF}(A_n)$ | Duty cycle to turn OFF device $A_n$ |
| $F_{S_n}$ | Frequency to request sensor $S_n$ information |
| $F_{D_n}$ | Frequency to request device $D_n$ information |
| $(D_{S_1})_n$ | Duty cycle for sensor $S_1$ information in node n |
| $(D_B)_n$ | Duty cycle for device $B$ information in node n |
| $F_m$ | Node “m” communication frequency (FM) |
| $F'_m$ | Node “m” communication frequency (AM) |
| $S_{Qn}$ | Logic status of transistor “n” |
| $A_{Ox}$ | Gain of operational amplifier “x” |
| $V_{AM}(t)$ | AM voltage in variable time |
| $A(j\omega)$ | Magnitude of filter |
| $\varphi(\omega)$ | Phase of the filter |
| $F_{BLV}$ | Black and white video frequency |
| $F_{PW}$ | Pulse wave frequency |
| $O^n_{thruster}$ | Operating status of thruster “n” |
| $I^n_{sensor(FLTZ)}$ | FLTZ status of sensor “n” |

# SUATU PENDEKATAN BAHARU BAGI KOMUNIKASI ISYARAT BESAR TALIAN KUASA

## ABSTRAK

Tujuan utama kajian ini adalah untuk mengenalpasti dan memperkenalkan satu kaedah kendiri dan lasak untuk pengawasan dan kawalan sebuah aplikasi jarak jauh. Tiga teknik yang biasa digunakan adalah teknik lapisan penghantaran gentian optik, Sistem Perolehan Data dan Kawalan (SCADA) dan Perhubungan Talian Kuasa (PLC). Kaedah PLC akan menghasilkan penggunaan kabel yang minima. Walaubagaimanapun, teknik ini tidak berupaya untuk membawa maklumat yang boleh-percaya untuk jarak yang jauh tanpa kemudahan pengulang. Di dalam teknik gentian optik, walaupun lesapan penghantaran optik adalah agak rendah, ia kebiasaannya masih memerlukan pengaliran elektrik tambahan bagi penghantaran kuasa. Lebih daripada itu, kabel hibrid yang mengandungi beberapa gentian fizikal dan lapisan kuprum tidak boleh diperbaiki sekiranya berlaku kerosakan ketika digunakan di lapangan dan kos penggantian pula adalah relatifnya terlalu tinggi. Manakala, sebuah sistem SCADA akan memerlukan kedua-duanya, iaitu sistem pengulang dan kabel kuasa tambahan, untuk aplikasi jarak jauh. Bagi mengatasi kesemua masalah ini, teknik Pemodulatan Frekuensi dan Amplitud bagi Perhubungan Talian Kuasa (FAMPLC) dicadangkan. FAMPLC, secara umumnya, menyediakan pelantar perhubungan jalur-sempit yang mengandungi blok Pembekal Kuasa Frekuensi Termodulat (FMPS) dan Penukar Setara Thevenin (TEC) di sebelah pelayan, dan pembaca PWM dan perintang aktif yang berfungsi sebagai beban tiruan di sebelah penerima. FMPS adalah pintu kuasa, dan juga pembawa isyarat besar Pemodulatan Frekuensi (FM), bagi menghantar gabungan voltan dibekal dan data maklumat sebagai PWM. Blok TEC pula membekalkan purata nilai voltan bagi arus

terkandung maklumat yang dimodulatkan ke atas arus yang digunakan oleh perintang aktif di sebelah nod penerima. Dengan memanfaatkan keseluruhan voltan yang dibekalkan dan arusnya pula sebagai isyarat besar, pelantar perhubungan jarak jauh dapat dihasilkan. Bagi pembuktian konsep, pengenalan dan pembangunan yang komprehensif telah dibentang dan dibincangkan di dalam tesis ini. Pelantar perhubungan yang diperbaiki ini telah dibangunkan dan dibincangkan bagi penyelesaian titik ke titik dan rangkaian pelbagai titik.

# A NOVEL APPROACH IN LARGE SIGNAL POWER LINE COMMUNICATION

## ABSTRACT

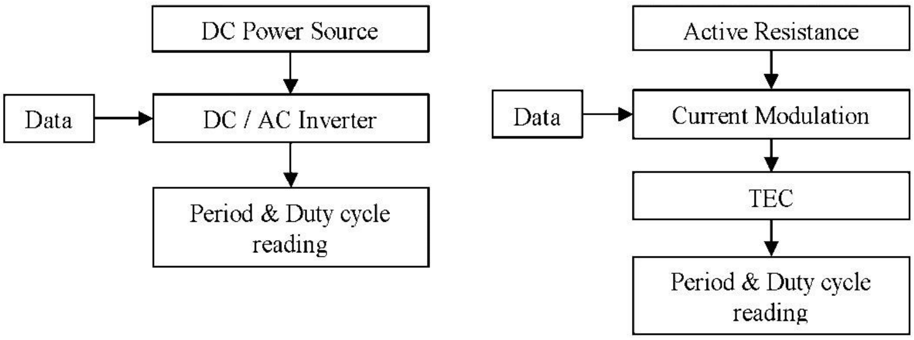
The main aim of this research is to identify and introduce a novel stand-alone and robust method for monitoring and control of a remote application. Among the three common techniques using fibre optic transmission layer, Supervisory Control And Data Acquisition (SCADA) and Power Line Communication (PLC). PLC method will result in minimizing the cabling usage. However, this technique will be unable to carry reliable information for long distance without the repeater facilities. In fibre-optic technique, although the attenuation of an optical transmission through a fibre layer is considerably low it will normally require additional electrical conductivity for transmission of power. Moreover, a hybrid cable, which consists of multiple physical fibre and copper layers, is irreparable in case of any damage during deployment and the cost of replacing such cables is often relatively high. While, A SCADA system will need both repeater facilities and additional power cable for remote applications. In order to overcome these problems, the Frequency and Amplitude Modulations Power Line Communication (FAMPLC) technique is proposed. FAMPLC, in general, provides a narrowband communication platform which consists of a Frequency Modulated Power Supply (FMPS) and Thevenin Equivalent Converter (TEC) block at the server side and the PWM reader and an active resistance as a dummy load at the receiver side. FMPS is a power gateway, as well as the large signal carrier for the Frequency Modulation (FM), to transmit the combination of the supplying voltage and the informative data as PWM. Meanwhile, the TEC block provides the voltage mean of the current overlaid information which is modulated onto the consuming current by the active resistance in the receiver node. By utilizing the full boundary of the supplying voltage and the current as large signal definition, distant communication platform has been established. For the proof of concept, comprehensive introduction and developments are presented and discussed in the thesis. The improved communication platforms have been developed and further discussed as the point to point and multipoint network solutions.

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Combined **F**requency and **A**mplitude **M**odulations in **P**ower **L**ine **C**ommunication (FAMPLC) is an approach to the real time bidirectional Power Line Communication in remotely controlled applications. FAMPLC complies with an open protocol that lets the user to define a lookup table which enables the processor for generation of respected frequencies and Pulse Width Modulations (PWM). The square wave AC Power which is derived from an embedded H-bridge inverter in the server (or Master) unit is to supply the receiver node(s). The embedded power supplying block is also known as Frequency Modulated Power Supply (FMPS). Hereafter it may also be called as the "FM" communication layer. Both the frequency and the duty cycle of the PWM waveform are decoded for comparison with the receiver's predefined lookup table for a desired action. The independent current layer communication as Amplitude Modulation (AM) for transmission from the receiver node to the server is more complex in comparison with the FM mode (from the server unit to the receiver node). A Thevenin Equivalent Converter (TEC) block is an embedded circuitry in the server unit to extract equivalent voltage means from the current waveform. Figure 1.1 shows the flowcharts of computing processes based on the individual transmission layers. According to the server's flowchart in Figure 1.1-(a), a DC power source that supplies the server is inverted to the frequency modulated square wave. The next process is the receiver node to read the pulse width (also known as the *Mark* or the *Space*) and the frequency of the receiving power (voltage) pulse train. For the sake of data transmission from the receiver node, the active resistance behaves as a dummy load and overlays current pulse train onto the existing consumer line which is sensible by the TEC block in the server side.



(a) (b)

Figure 1.1: Comparison of computing processes, a) FM from the server unit to the receiver node, b) AM from the receiver node to the server unit.

Both Thevenin equivalent parameters and load impedance are not constant, and they depend on the network topology structure, system operating pattern, generation status and reactive elements (Tianyu 2006).

## 1.2 Research background

Comprehensive studies for existing PLC systems do not indicate a remarkable emphasis on large signal concept in this technique. The overall investigation about the conventional developments shows superimposing modulation technique in which small signalling is utilized. Thus, in most of the cases the signal attenuation along the physical transmission layer is considerably high. Furthermore, repeater facilities are required for distant communications. Moreover, multiple stages of signal processing require complex circuitry implementation. The Digital Signal Processing (DSP) as the analyser technique also requires medium to high – end processor device that collaborates in the said complexity. Hence, the idea of introducing a novel large signal communication over the power line was created.

## 1.3 Problem statements

### 1.3.1 Conventional Power Line Communication (PLC) systems

The knowledge of advantages and drawbacks of the existing PLC technologies motivates to introduce, design and develop improved techniques. Moreover, the existing and the improved techniques are generally application oriented. The inconveniences and the benefits of using the conventional power line communication techniques can be listed as below:

I. One advantage of the conventional power line communication network models in comparison with other methods is the cost effectiveness as it uses the existing power layer for data or signal transmissions. The parameters such as noise, reactive effects and attenuation are unpredictable and may vary in time, frequency and environment which are of course not present in fiber optic transmission method (Yan *et al.*, 2013; Lu *et al.,* 2012; Haiyang & ShanDe 2011; Tlich *et al.,* 2008; Sutterlin 1998).

II. Certain factors like installation and performance are dependent on various architectures of the electrical network. The interoperability problems with different kind of equipment or protocols are also one of the major disadvantages of the conventional power line communication techniques (Yan *et al.*, 2013; Levente & Festila 2011; Haiyang & ShanDe 2011; Sutterlin 1998).

III. Comprehensive studies show that although the conventional model is a matured system at low voltage and is working fine, in application level, one of the main drawbacks which cause bulks of processing delay is the complexity of the analysis that is required to transfer the informative means from data level to the modulation and demodulation stages. Furthermore, the immunity of the delivered data with contribution in additional delay has to be guaranteed as well.

IV. In some cases the contamination of power line by noise may be a minor unreliability (Ma *et al*., 2010).

V. The level of signal information is low and not normally suitable for long distance applications.

VI. The conventional PLC systems in low voltage network channels and particularly for DC lines are not typically a common technique due to the fact that they are designed for the standard sinusoidal energy system.

### 1.3.2 Supervisory Control And Data Acquisition (SCADA)

There are many parts of a working SCADA system. These systems usually include signal hardware input and output, controllers, network, Human Machine Interface (HMI), communications equipment and software (Wiles *et al*., 2008). In wired communication methods using physical mediums such as coaxial cables or Unshielded Twisted Pair (UTP), additional power line to deliver the power to the distanced consumer is as well required (Wang 2012). While the distance from the remote application has to be importantly studied. Repeater devices may be required for the cable length of more than 1500 meters (Stamm 2013).

### 1.3.3 Conventional optical transmission method

An optical communication method is a technique in which a fibre layer is utilized as a physical layer for the transmission of light from one end to another. Although the technique has enabled a reliable distant access in many applications, the physical layer is very fragile and requires an earnest maintenance effort (Cowley 2003; Voronov *et al*, 2011). The fibre cable must be able to absorb energy from impact loads. The outer sheath must be designed to protect glass fibres from impact loads and from corrosive environmental elements (Bagad 2009).

In some applications such as the Remotely Operated Vehicle (ROV) where the power, data and signal transmission layers are all required, a hybrid medium consists of multiple copper, and fibre plies is used. The fleet angle between the layers of the cable in a huge winch causes a torsional stress (Henao *et al.,* 2011). Thus, the health of the cable is always in a high risk. On the other hand, if the released portion of the cable is bent more than the specified angle or damaged by any sharp object, the cable is physically split into two parts without any chance of rejoining (Kenneth & Calif 1982). A hybrid cable is an excessively expensive solution due to its fragile and irreparable characteristics.

## 1.4 Objectives

The main objective of the research is to establish a narrowband and stand-alone platform for a reliable point to point large signal power line communication in fundamental frequencies by development of robust embedded systems. While the sub objectives are:

I. To introduce a fundamental protocol for mutual access in large signal PLC.

II. To establish hardware platform for analog signal transmission over the large signal power line.

III. To establish a standard Universal Asynchronous Receiver Transmitter (UART) port over the power line.

IV. To expand the capability of the technique as a solution for the point to point and multipoint network solutions.

In order to address the main and sub objectives, systems are targeted to certain features as defined below:

a) A stand-alone server or master unit as the power gateway to supply a distant receiver node or slave module. Therefore, the foundation of the large signal transmission is built.

b) Receiver node(s) containing dummy load(s) for overlaying current modulation onto the existing current drain. The modulated current is sensible by the TEC in the server unit.

## 1.5 Research Scope

This research will focus on identifying and development of a narrowband and large signal power line communication technique. Despite the superimposing concept of the conventional PLC technique, the current thesis will discuss more particularly about the architecture of a non-superimposing minimum hardware system and a fundamental communication protocol for a mutual remote access.

## 1.6 Thesis organization

**Chapter One** presents an overview about the FAMPLC technique followed by the research background, problem statement, objectives and the research scope.

**Chapter Two** will discuss about the conventional PLC systems, modulation techniques and available communication protocols. Briefs about other communication techniques such as SCADA systems and fibre optic used in remote applications are also discussed.

**Chapter Three** will evaluate the large signal characteristic of the technique from the mathematical aspect. The components of the systems' architectures will be also discussed in detail.

**Chapter Four** will be about the implementation setups which are provided for the experiments of this research.

**Chapter Five** will present, compare and discuss the results of the experimental works in the virtual (PC simulation) and practical environments.

**Chapter Six** will conclude the overall outcome of the research and will discuss about the fulfilment of the objectives of the research. Furthermore, will offer recommendations for potential studies and researches as future work.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Power Line Carrier Communication (PLCC) refers to transmitting information data using power lines as the communication media. Power Line Carrier Communication which is also called Power Line Communication (PLC) is a platform for Power Line Telecoms (PLT), Power Band or Power Line Networking (PLN) (Shah *et al.,* 2011; Khan *et al.,* 2006). The communication signal is transmitted from one communication node to another through a physical path called communication channel. Power line communication is basically propagation of information that is carried by the electrical signal over power line.

In the conventional PLCs a high frequency signal is superimposed on AC electrical signal. The idea is to accomplish transmission at low energy levels. This high frequency signal is conveyed, acknowledged and decoded by means of the power infrastructure (Ferreira *et al.,* 2010). Thus the PLC transmitter and receiver are positioned on the same electrical network for the particular communication.

At the PLC receiver side, a coupler is integrated to eliminate low frequency components from the signal of interest. PLC network is a kind of telecommunication networks in cooperation with electrical supply network.

## 2.2 Conventional communication system model

The conventional communication system is an arrangement designed specifically so as to exchange analog or digital information between two locations at high feasible rates. The digital information is preserved in a sequence of binary digits and communicated over a channel that may have noise and interfering signals along it. A simplified model of a conventional digital communication system is shown in Figure 2.1 (Proakis & Salehi 2006).

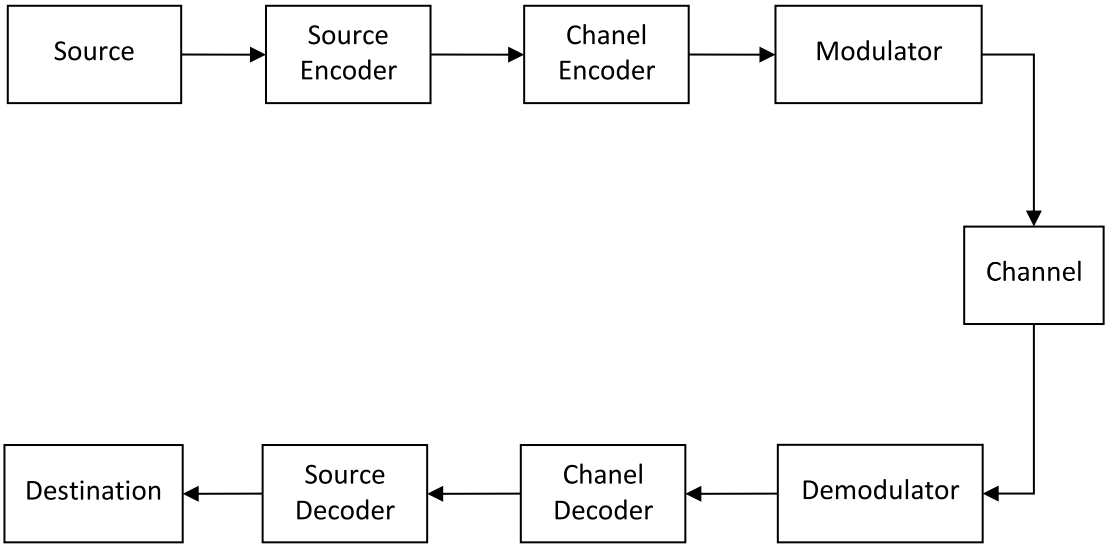


Figure 2.1: A simplified conventional model of a digital communication system.

### 2.2.1 Source

The information originates from any source that could give analog or digital data to be transmitted. An analog to digital converter may be placed ahead of transmitter.

### 2.2.2 Source encoder

The function of source encoder is to compress data thus minimizing the total number of bits to be transmitted over the channel. The source encoder produces data at a specific information bit rate that is conveyed over the channel. Bit error probability is defined if a bit is incorrectly recognized at the receiver end.

### 2.2.3 Channel encoder

Channel encoder adjoins extra control bits to the data to be transmitted. For consistent transmission of high-quality voice and digital data, error rate must be very small. The more redundant the data is, the more it can be compressed.

### 2.2.4 Modulator

The modulator superimposes information-carrying signal over carrier frequency. At this stage converts the stream of bits into an analog signal that the channel can transmit without upsetting its information carrying characteristics.

### 2.2.5 Channel

The communication signal travels from modulator to receiver through a physical path called Communication Channel. Any physical medium, such as coaxial cable, air, water or telephone wires might work as a communication channel depending upon the communication purpose and location. The characteristics of the channel are important to know because they directly affect the performance of the communication system.

### 2.2.6 Demodulator

The isolation circuit will isolate the modulated signal from the power line and then demodulator will demodulate the signal using the concept of the phase locking. It thus produces the output voltage proportional to the frequency using a VCO block. The difference between the modulated frequency and output frequency will be a feedback to the phase detector using a PLL block (Kumar 2012). In fact the demodulator acknowledges the received waveform and converts the analog information again into the stream of data.

### 2.2.7 Channel decoder

Channel decoder uses the added redundancy to detect and correct any possible error carried by the bit stream all the way through the channel. If it is not tolerable to extract information up to achieved bit error rate, then more redundancy can be added. Thus addition of redundancy depends upon the amount of correction looked for, however it is adjusted according to the channel characteristics.

### 2.2.8 Source decoder

At the receiver end the source decoder decompresses the bit stream such as an exact replica of the information could be retrieved. While lossless data compression is practically difficult, a lossy data compression results in a distorted copy of original information signal. If the received sequence is required to be an exact replica of the transmitted stream then the degree of compression can be decreased.

## 2.3 The power line as a communication channel in conventional models

Figure 2.2 shows a Digital Communication System utilizing the power-line as a communication channel. The leftmost block is identical to the transmitter of the digital communication system as well as rightmost block works as the receiver. The output impedance "$Z_t$" of the transmitter and the input impedance "$Z_L$"of the receiver are very important parameters in top-down modelling of the power line communication (Snyders *et al.,* 2010). For a typical PLC system, in order to improve communication performance, the transmitter power might be enhanced.

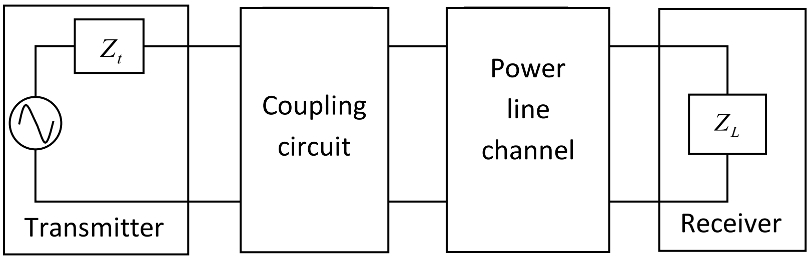


Figure 2.2: Power Line as Communication Channel in Communication System.

The coupling circuit block couples digital communication system to electrical lines. Basically it consists of a set of filters so that none of the undesirable frequencies enter certain parts of the system (Patel *et al*., 1995). There are two purposes of introducing a coupling circuit at the power line interface:

I. To prevent from possible damage from AC power distribution signal

II. To confirm that the major part of the received/transmitted signal resides within the frequency band allowed for communication.

## 2.4 Frequency and modulation of the power line channel

Researchers propose the use of 1-30 MHz for power line carrier however admittance of the whole range may draw to crucial stages of processing that may make it impossible. Various modulation techniques have been introduced as industrial PLC solutions. The most common methods are discussed below:

### 2.4.1 Modulation

Amplitude modulation is commonly applied in power line communication systems. Several other modulation techniques also exist e.g., spread-spectrum (Proakis, 1995), Orthogonal Frequency Division Multiplex (OFDM) (Edfors *et al*., 1996), Gaussian Minimum Shift Keying (GMSK) (Marubayashi 1997), Frequency Shift Keying (FSK), Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM) (Proakis, 1995).

Out of these all modulation techniques, Coded Orthogonal Frequency Division Multiplexing (COFDM) is mostly used due to its ease of implementation (Pavlidou *et al*., 2003).

#### 2.4.1.1 Single Side Band (SSB)

Although Single Side Band (SSB) modulation lacks in some areas of performance such as low communication speed, feeble anti-interference facility and small spectral efficiency, it is still being employed in traditional PLC Communication. Because it does not meet the data requirements in the present scenario hence it is not in demand now days (Spiess 2006).

#### 2.4.1.2 Orthogonal Frequency Division Multiplexing (OFDM)

There is no trouble to accomplish modulation or demodulation of OFDM by applying the Fast Fourier Transform (FFT) on digital signal processors. Applications of OFDM in power line communication include Digital Audio Broadcast (DAB), Digital Video Broadcast (DVB) and Wireless Local Area Network (WLAN). While considering the low voltage distribution power line, 14Mbps data transmission speed intended for the internet connection can be achieved (Anatory & Theethayi 2010).

#### 2.4.1.3 Coded Orthogonal Frequency Division Multiplex (COFDM)

The digital power line communication system based on COFDM modulation avails the data compression in addition to data coding to process the signals, and then transmit the data with OFDM modulation over the power lines. It can attain over 1Mbps data transmission speed in the available frequency band of PLC Communication System (Acton 2012).

#### 2.4.1.4 Gaussian Minimum Shift Keying (GMSK)

Gaussian minimum shift keying is a modulation technique in which a continuous phase frequency shift keying is used. This modulation technique is similar to Minimum Shift Keying (MSK) but in GMSK digital information is shaped with Gaussian filter before it is processed to a frequency modulator. This is done in order to reduce sideband power due to outer band interference between different signal carriers in adjacent frequency channels. The main function of Gaussian Filter is that it improves the modulation memory in the system but also results in inter-symbol interference (Davoli *et al.*, 2009).

### 2.4.1.5 Frequency Shift Keying (FSK)

Frequency Shift Keying (FSK) is one of the frequency modulation techniques. In FSK the information which is in form of digital data is sent via discrete frequency variations of a carrier signal. The simplest FSK is Binary FSK (BFSK). BFSK exactly implies to pass on binary (0s and 1s) sequence by making use of a pair of discrete frequencies while '1' is known as the mark frequency and the '0' is known as the space frequency (Ferreira *et al.,* 2010).

### 2.4.1.6 Phase Shift Keying (PSK)

Phase-shift keying (PSK) is a modulation technique in which data is conveyed by changing or modulating, the phase of a reference carrier wave. Other digital modulation schemes use a finite number of distinct signals to represent digital data. PSK uses a finite number of phases; each assigned a unique pattern of binary digits. Usually, each phase encodes an equal number of bits. Each pattern of bits forms the symbol that is represented by the particular phase. The demodulator, which is designed specifically for the symbol-set used by the modulator, determines the phase of the received signal and maps it back to the symbol that is represented, thus recovering the original data. This requires the receiver to be able to compare the phase of the received signal to a reference signal. Such a system is termed Coherent PSK and referred to as CPSK (Ferreira *et al.,* 2010; Vitetta *et al.*, 2013).

### 2.4.1.7 Differential Phase Shift Keying (DPSK)

As an alternative, the use of the bit patterns for setting the phase, a specified amount can be used instead. The demodulator then determines the changes in the phase of the received signal rather than the phase itself. Since this scheme depends on the difference between successive phases, it is termed Differential Phase-Shift Keying (DPSK). DPSK can be significantly simpler to implement than ordinary PSK since there is no need for the demodulator to have a copy of the reference signal for determining the exact phase of the received signal that results a non-coherent scheme (Ferreira *et al.,* 2010).

### 2.4.1.8 Quadrature Amplitude Modulation (QAM)

Quadrature amplitude modulation (QAM) is both an analog and a digital modulation scheme (Anatory & Theethayi 2010; Ferreira *et al.,* 2010). It conveys two analog message signals, or two digital bit streams, by modulating the amplitudes of two carrier waves, using the Amplitude-Shift Keying (ASK) digital modulation scheme or Amplitude Modulation (AM) analog modulation scheme. These two sinusoidal waves are out of phase with each other by 90° and thus called Quadrature carriers or Quadrature components. The modulated waves are summed, and the resulting waveform is a combination of both Phase-Shift Keying (PSK) and Amplitude-Shift Keying (ASK), or in the analog case of Phase Modulation (PM) and amplitude modulation. In the digital QAM case, a finite number of at least two phases and at least two amplitudes are used. PSK modulators are often designed using the QAM principle, but are not considered as QAM since the amplitude of the modulated carrier signal is constant. QAM is used extensively as a modulation scheme for digital telecommunication systems (Ferreira *et al.,* 2010; Carcelle 2006)

## 2.5 Types of PLC systems

The PLC systems are broadly categorized in three types, Low Voltage (LV), Medium Voltage (MV) and High Voltage (HV). The description of each type is discussed in below:

### 2.5.1 Low voltage

The low voltage power line network is a new setup for providing an access to high speed transmissions. The model of Broadband Power Line Communications (BPLC) is a feasible mode to build an in-house communication network or to access the internet. The topology of the typical low voltage network is given below in Figure 2.3 (Mingyue, 2006). In general, the low-voltage supply lines of 220/380V network begin at a transformer station and then extend over 250 meters, (Mingyue, 2006). For example, up to twelve supply lines can lead out from the transformer station, and every supply line can feed up to 30 residential connections. The network can meet all requirements of home automation and management system. Data broadcast over power lines begins after the Low Voltage side of the distribution transformer, which travels up to the customers' building through Low Voltage network. The Low Voltage electrical network has become the most attractive medium for high-speed digital communication down to an ever-increasing demand due to the progress in communication and information technologies. The Low Voltage network is an extensive spread network with the distribution transformer as the central node and many loads connected in parallel. In contrast to the other wired communication mediums, the power line arrangement was optimized mainly for 50 or 60 Hz and was not intended for data transmission. Therefore, Low Voltage power cables present an extremely harsh environment for high frequency signals (Guimarães 2009).

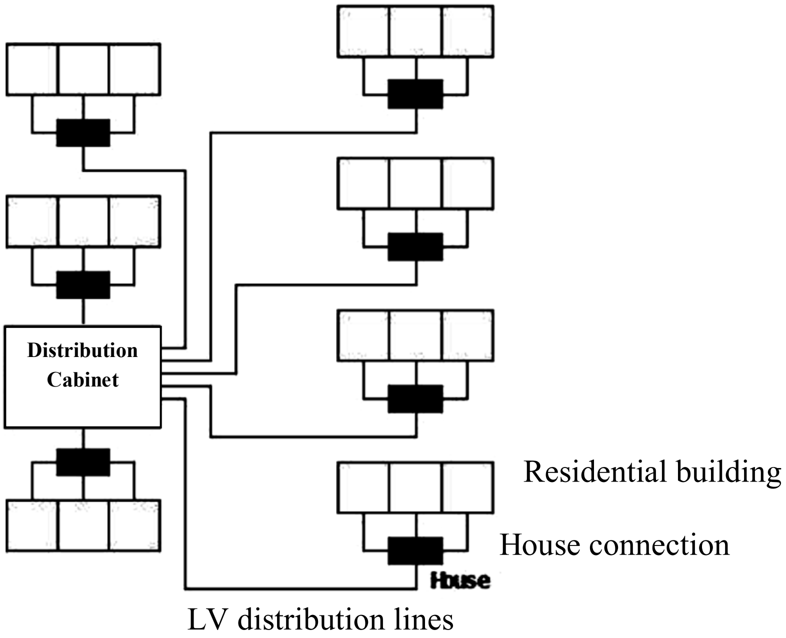


Figure 2.3: Topology of the typical Low Voltage Distribution Network.

### 2.5.2 Medium Voltage

This system is efficiently applied in distribution automation system such as remote reading meter, load monitoring and Supervisory Control And Data Acquisition (SCADA) system. The structure of medium voltage power line carrier communication system is shown in Figure 2.4 (Biswas 2008).

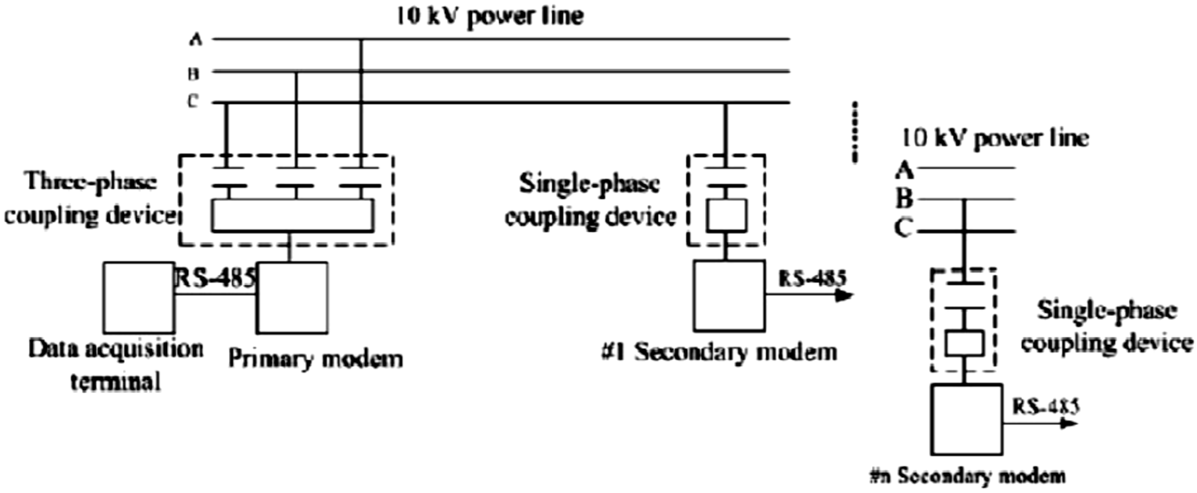


Figure 2.4: The Structure Chart of Medium Voltage PLC System (Biswas 2008).

The medium-voltage carrier communication system consists of medium voltage power line, data acquisition terminal, coupling equipment and carrier modem as it main system components. Electric Substation comprises data acquisition terminals, memory unit and clock. It can read meters automatically and restore the data for the time being by the means of RS-485 bus wire and complete data transmission with the centre substation.

Data transfer may be also possible through optical cable or phone line at the same time. The coupling device has coupling capacitance and filter. The electric substation carrier modem feeds the signals in the mode of one to N. Inside the electric substation, the main modem communicate with a number of second modems at the bus line (Carcelle 2006; Biswas 2008). The Carrier Modem has the following two divisions:

I. Main Modem as electric Substation Carrier Modem
II. Second Modem as distributing Point Carrier Modem

Medium voltage power line carrier is economical and practical communication technology for 10kV distribution electrical line. Medium voltage power line carrier communication system is a well-known method for communicating Radio Frequency (RF) signals over electrical lines. It is mainly used for:

a) Automation reading and collecting data of all kinds of meters
b) Management of the user's demand
c) Load automation monitoring and switching
d) Monitoring of features of electric power supply
e) Level of electric voltage disturbance and the harmonic wave in the far end

### 2.5.3 High Voltage

A High Voltage power line carrier system consists of three distinct components. They are the terminal assemblies, the coupling & tuning equipment and the high voltage system itself. Coupling information signals to power line through interfacing circuits is a difficult task because power line and the communication system operate at two distinct boundaries that is in very low frequency and high power for the power line and very high frequency and very low voltage and current levels for communication channel (*Hossain et al.,* 2012).

Coupling to power-line conductors are accomplished by using high voltage coupling capacitors to pass the carrier signals, while blocking 50 Hz power from the carrier equipment. The coupling circuit must be designed to be capable to withstand the high power at power line system as well as capable to prevent any damage being done to the electronic side of the communication system. At the same time it must be reliable enough to make certain that data bits are transported onto the power line correctly.

There are some draw backs of high voltage PLC including the expense of coupling and isolation components. Isolation is required because several independent PLC channels are used on each line Section of a large network. Since line sections are joined at substation buses, there is a possibility for mutual interference between PLC signals. High levels of isolation between channels on the same frequency are difficult to provide across substation buses. Transmitting electricity at high voltage reduces the fraction of energy lost to resistance. For a given amount of power, a higher voltage reduces the current and thus the resistive losses in the conductor. At extremely high voltages, more than 2 MV between conductor and ground, corona discharge losses are so large that they can offset the lower resistance loss in the line conductors (U. S. Department of Energy 2008). The amount of power that can be sent over a transmission line is limited. The origins of the limits vary depending on the length of the line.

For a short line, the heating of conductors due to line losses sets a thermal limit. If too much current is drawn, conductors may sag too close to the ground, or conductors and equipment may be damaged by overheating.

## 2.6 Industrial Power Line Communication (IPLC)

In 2009, Industrial Power Line Communication (IPLC) was also presented (Alexander *et al.,* 2010). In which, the power cables of the DC link are used as transmission medium and thus do not require any other cable. The IPLC is shown in figure 2.5.

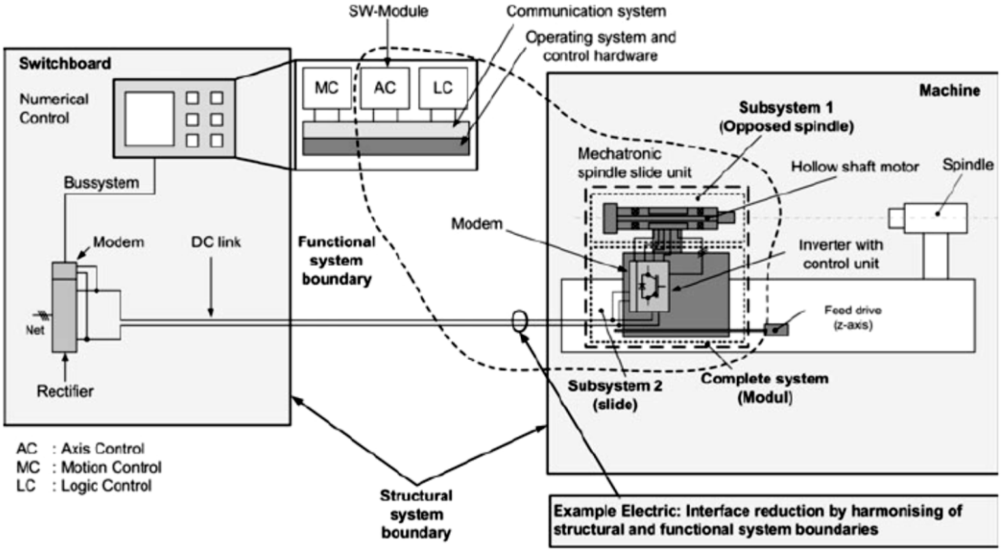


Figure 2.5: Reduction of the signal transmission lines by industrial power line communication (Alexander *et al.,* 2010).

The first approach is integrating functional components of the load inverter which is shifted decentrally to the opposite spindle module. This provides benefits with regards to:

I. The revised wiring in comparison with the conventional wiring.

II. The dimension of the switchboard.

III. Easier cable routing because of the intermediate circuit.

IV. Lower projecting.

V. The installation cost.

Consequently, the machines are easier to modularize and to maintain. The integration of the power electronics was already realized by Pritschow *et al.* (1994) for modular robot systems. In a second approach the remaining data cables such as interfaces are removed by employing the IPLC. This is achieved by a coupling unit that couples the data onto the power cables, thus reduces the cabling effort considerably.

## 2.7 Remotely Operated Vehicle (ROV) control using PLC

ROVs are conventionally powered up with an AC source of Electrical energy through one or more couples of multi-core copper wires. The control signals are serially transmitted using one or more optical fibres along the cable and transducers at both ends.

Yusoff *et al.* (2008) have developed the first fiber-less ROV using TCP-IP base HomePlug PLC system. They proved that the navigation signals through the PLC media can successfully bridle the vehicle while video signals are being transmitted over the same media for the pilot supervisory. For this purpose, 3 200Mbps Aztech HomePlug had been used. One pair was installed in the vehicle for video and navigation independently and the third was installed for the surface controller. The advantages of performing such a work had been:

I. Much lower cost using a single pair of copper wires in comparison with a hybrid solution.

II. Easy maintenance due to the employment of a non-hybrid (fiber-less) cable.

They were also experiencing difficulties as the technique's disadvantages as listed below:

a) One to two seconds delay was recorded for the video refreshing rate.

b) One to three seconds delay was recorded for the navigation responds.

c) Possibility of the system halting due to dynamic IP conflict.

d) Possibility of the program hanging due to the complexity of the analysis in MATLAB environment. In this condition, if any of the thrusters is ON, the possibility of overstressing of the cable due to an unwanted vehicle movement may occur.

## 2.8 Summary

This Chapter is the result of studies for the existing power line communication techniques. More information about conventional PLC's regulations and standards is discussed in Appendix I and some remarkable introduction and development histories of the past decade in power line communication is presented in Appendix II.

The review of the conventional PLC systems, although define various techniques, show two common fundamental characteristics:

I. The small signal feature

II. Superimposed signalling

Further investigations show that the current researches are intensively inclining toward enhancing the width of the transmission band rather than the improvements on attenuation issue. While in many control applications such as the digital point to multipoint network in Building Automation System (BAS), narrowband communication is an adequate way for transmission of a control command while, the use of multiple repeaters may be considered a discouraging issue. Repeaters not only increase the total energy consumption, but also increase the fault factor of the network model. Moreover, using multiple repeaters considerably increases the total development cost as well. Therefore, an encouraging motivation to identify a large signal method in which all the conventional disadvantages are addressed has been created.

# CHAPTER 3

# Frequency and Amplitude Modulations Power Line Communication (FAMPLC)

## 3.1 Introduction

A large signal and non-superimposed full duplex technique for long distance range and real-time remote communication will be introduced in this Chapter. By using the frequency and the duty cycle parametric values of the supplying power, any specific boundary limit for voltage peak is eliminated and thus longer communication distance can be achieved. The successful combination of the voltage Frequency and the current Amplitude Modulations over the Power-Line to transmit full duplex real time data between two or more nodes is the main aim of this research. Figure 3.1 shows the conceptual illustration of the technique for both the supplier and the consumer units containing their fundamental embedded components.

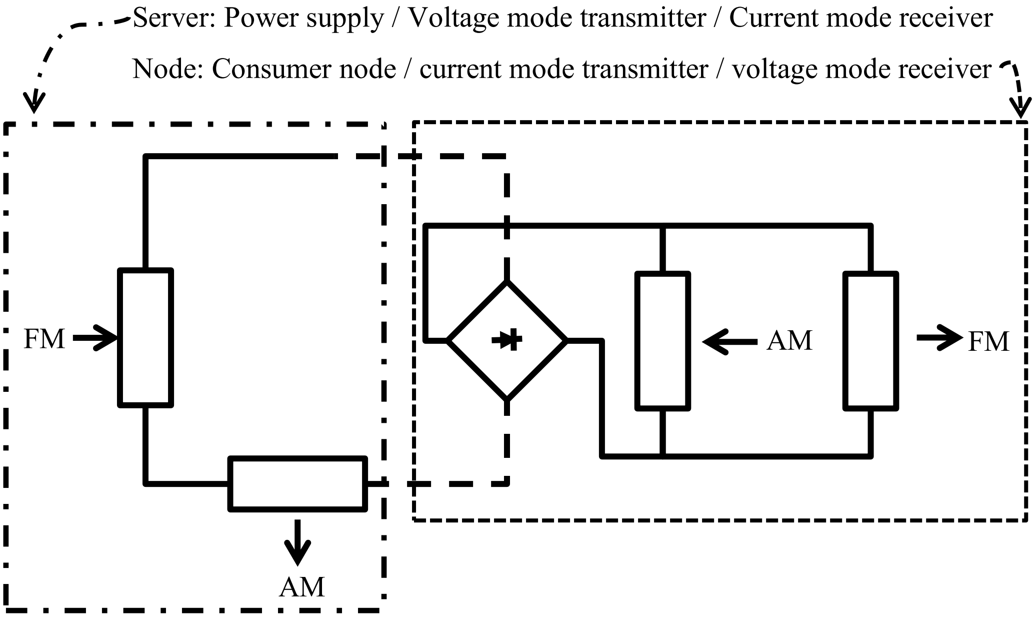


Figure 3.1: A conceptual illustration of the FAMPLC technique.