

**A NOVEL APPROACH IN LARGE SIGNAL  
POWER LINE COMMUNICATION**

**ALIREZA NAZEM**

**UNIVERSITI SAINS MALAYSIA**

**2014**

**A NOVEL APPROACH IN LARGE SIGNAL  
POWER LINE COMMUNICATION**

**by**

**ALIREZA NAZEM**

**Thesis is submitted in fulfilment of the requirements**

**for the degree of**

**Doctor of Philosophy**

**January 2014**



*In the name of Allah  
The compassionate  
The merciful*

## ACKNOWLEDGMENTS

First, I would like to express my sincere gratitude to the Almighty; with His Blessing, I've been given the opportunity to complete this thesis.

This thesis will not be possible without endless support, advice and encouragement from my supervisor Assoc. Prof. Dr. Mohd Rizal Arshad and his continuous guidance.

Special thanks to my beloved wife, Dr. Homeira Shams Kolahi and my daughters, Sara and Golnaz for their invaluable supports and encouragements.

I also wish to thank my parents for their endless love and prayers.

My heartfelt appreciation goes to all URRG members of Universiti Sains Malaysia, who has been providing great working environment throughout the four years.

Last but not least, to all the lecturers, staff and the financial support of the National Oceanography Department, Malaysia, under grants NOD-USM 6050124 and USM-RU-PRGS grant 1001/PELECT/8043012.

## TABLE OF CONTENTS

<b>Acknowledgements</b>	ii
<b>Table of Contents</b>	iii
<b>List of Tables</b>	x
<b>List of Figures</b>	xiii
<b>List of Abbreviations</b>	xxiv
<b>List of Symbols</b>	xxx
<b>Abstrak</b>	xxxvii
<b>Abstract</b>	xxxix
 <b>CHAPTER 1: INTRODUCTION</b>	
1.1 Overview	1
1.2 Research background	2
1.3 Problem Statements	3
1.3.1 Conventional Power Line Communication (PLC) systems	3
1.3.2 Supervisory Control And Data Acquisition (SCADA)	4
1.3.3 Conventional optical transmission method	4
1.4 Objectives	5
1.5 Research scope	6
1.6 Thesis organization	6
 <b>CHAPTER 2: LITERATURE REVIEW</b>	
2.1 Introduction	8
2.2 Conventional communication system model	8

2.2.1	Source	9
2.2.2	Source encoder	9
2.2.3	Chanel encoder	9
2.2.4	Modulator	10
2.2.5	Channel	10
2.2.6	Demodulator	10
2.2.7	Channel decoder	10
2.2.8	Source decoder	11
2.3	The power line as a communication channel in conventional models	11
2.4	Frequency and modulation of the power line channel	12
2.4.1.	Modulation	12
2.4.1.1	Single Side Band (SSB)	13
2.4.1.2	Orthogonal Frequency Division Multiplexing (OFDM)	13
2.4.1.3	Coded Orthogonal Frequency Division Multiplexing (COFDM)	13
2.4.1.4	Gaussian Minimum Shift Keying (GMSK)	13
2.4.1.5	Frequency Shift Keying (FSK)	14
2.4.1.6	Phase Shift Keying (PSK)	14
2.4.1.7	Differential Phase Shift Keying (DPSK)	15
2.4.1.8	Quadrature Amplitude Modulation (QAM)	15
2.5	Types of PLC systems	16
2.5.1	Low voltage	16
2.5.2	Medium voltage	17
2.5.3	High voltage	19

2.6	Industrial Power Line Communication (IPLC)	20
2.7	Remotely Operated Vehicle (ROV) control using PLC	21
2.8	Summary	22

**CHAPTER 3: Frequency and Amplitude Modulations Power Line Communication (FAMPLC)**

3.1	Introduction	24
3.2	FAMPLC server	27
3.2.1	Frequency modulated DC to AC power inverter	27
3.2.2	Thevenin equivalent concept	29
3.2.3	Processing unit	32
3.3	FAMPLC receiver	33
3.3.1	Analysis and management of the incoming power	34
3.3.1.1	Power Management Unit (PMU)	35
3.3.1.2	Transient distortion analysis of the frequency modulated power	43
3.3.2	Current Amplitude Modulation by the receiver	50
3.3.2.1	The Mayer-Norton model concept	51
3.3.2.2	Analysis of the Thevenin equivalent value	53
3.4	Transfer functions	59
3.5	Pulse wave management	61
3.5.1	Frequency and duty cycle optimization	61
3.5.1.1	Uncategorized frequency model	65
3.5.1.2	Frequency categorization model	67

3.5.1.3	The duty cycle	70
3.5.2	Calibration	71
3.6	Protocols and solutions	72
3.6.1	Point to point model	73
3.6.1.1	Digital mode	73
3.6.1.2	Analog mode	74
3.6.2	Point to multipoint model	74
3.6.3	Multipoint to multipoint model	76
3.6.4	Half and Full Duplex Asynchronous Serial Transmission (HDAST/FDAST)	77
3.7	Accuracy and resolution	78
3.8	Summary	79

## **CHAPTER 4: FAMPLC – SETUP AND IMPLEMENTATION**

4.1	Introduction	80
4.2	Preparation for ROV control and monitoring	80
4.2.1	Server (Master) system analysis	87
4.2.1.1	DC to AC inverter block	87
4.2.1.2	Pulse wave demodulation management in TEC block	89
4.2.1.3	Analog wave demodulation management in TEC block	93
4.2.2	Slave node system analysis	98
4.2.2.1	Video transmission mode	98
4.2.2.2	On Screen Display (OSD) option	100
4.2.2.3	General Purpose Input/Output (GPIO) ports	101



4.2.3	The processors	102
4.3	Fire alarm setup in Building Automation System (BAS)	105
4.3.1	The point to multipoint solution	105
4.3.2	Hardware preparation	106
4.3.3	RLC circuit simulation	113
4.4	Hardware preparation for extended remote I/O	115
4.5	Virtual simulating environment	125
4.6	Summary	125

## **CHAPTER 5: RESULTS AND DISCUSSIONS**

5.1	Introduction	127
5.2	Simulation criteria	127
5.2.1	Power pulse edge transient response in point to point ROV model (FM mode)	128
5.2.2	Current pulse edge transient response (AM mode)	143
5.2.3	Power pulse count steady state results	151
5.2.4	Current pulse count steady state results	155
5.3	FAMPLC to control and monitor an ROV	160
5.3.1	The list of specified commands	162
5.3.2	Detected values by the ROV system	162
5.3.3	Result of informative data transmission from ROV to server	167
5.3.4	Analog signal transmission in AM mode	170
5.3.5	Black and White Video (BWV) signal transmission in AM mode	172
5.3.6	On Screen Display (OSD) results	181

5.3.7	The results of establishment of UART port over the power line	184
5.4	Point to multipoint communication results	187
5.4.1	Pulse width counter mode	187
5.4.1.1	The uncategorized frequency model	187
5.4.1.2	The frequency categorization model	197
5.4.2	UART port as a replacement for RS485	204
5.5	The extended remote I/O	209
5.5.1	The port handling value	214
5.5.1.1	Irregular port scanning method	214
5.5.1.2	Regular port scanning method	216
5.6	Summary	219
<b>CHAPTER 6: CONCLUSION AND FUTURE WORK</b>		
6.1	Conclusion	221
6.2	Contributions	222
6.3	Future work	223
<b>REFERENCES</b>		225
<b>APPENDIX I</b>		236
<b>APPENDIX II</b>		254
<b>APPENDIX III</b>		269
<b>APPENDIX IV</b>		274
<b>APPENDIX V</b>		286
<b>APPENDIX VI</b>		287
<b>APPENDIX VII</b>		293

<b>APPENDIX VIII</b>	296
<b>LIST OF PATENTS, PUBLICATIONS &amp; SEMINARS</b>	300

## LIST OF TABLES

		<b>Page</b>
Table 2.1	House codes used by X10 protocol	23
Table 2.2	Device codes used by X10 protocol	23
Table 2.3	Function codes used by X10 protocol	24
Table 3.1	Partial analysis study of the sensed current $i_s$	74
Table 3.2	An example of frequency categorization model	84
Table 3.3	Point to point data transmission based on categorized information	90
Table 3.4	Point to multipoint data transmission based on addressable nodes	91
Table 4.1	A comparison between conventional and FAMPLC techniques in some remote applications	96
Table 4.2	Inputs capabilities for various definitions	118
Table 5.1	The summary of the simulated pulse edge delays per cable length and current consumption	157
Table 5.2	Simulation outcome of the $C_p$ values in various consumptions and lengths	169
Table 5.3	Tabulated $C_p$ values of the current mode simulation	171
Table 5.4	The improved $C_p$ values in presence of CIV block	175
Table 5.5	Navigational positions of an ROV	176
Table 5.6	Defined lookup table to control the ROV through the FMPS	178
Table 5.7	Server to ROV transmitted values in ideal mode (no load)	180

Table 5.8	The results of server to receiver node transmitted values in presence of loads and based on the action took	181
Table 5.9	The lookup table for the informative data transmission from ROV	183
Table 5.10	The propagation constant “ $\gamma$ ” and the protective gap “ $g_c$ ” for an errorless informative ranges	184
Table 5.11	An example of code 8 informative data values	185
Table 5.12	The simulation result of the power pulse falling edge delays	205
Table 5.13	The comparison of the count variations in the simulation results and the practical experiment	205
Table 5.14	$C_p$ values of the mark of the pulse for 32 I/O commands in the uncategorized experiment of the FM mode	205
Table 5.15	The simulation result of the current pulse falling edge delays	208
Table 5.16	The comparison of the count variations in the simulation results and the practical experiment	208
Table 5.17	$C_p$ values of the mark of the pulse for 32 input data in the uncategorized experiment of the AM mode	208
Table 5.18	The operational calculated frequencies	210
Table 5.19	$C_p$ values of the mark of the pulse for 32 I/O commands in the categorized experiment of the FM mode	210
Table 5.20	$C_p$ values of the mark of the pulse for 32 input data in the categorized experiment of the AM mode	211

Table 5.21	The calculated frequencies for in real operation	213
Table 5.22	$C_p$ values of the mark of the pulse for 32 I/O commands in the randomized frequency setup of the categorized experiment of the FM mode	213
Table 5.23	$C_p$ values of the mark of the pulse for 32 input data in the randomized frequency setup of the categorized experiment of the AM mode	214
Table 5.24	The defined protocol for the server's communication purpose	216
Table 5.25	The defined protocol for the nodes' communication purpose	217
Table 5.26	The comparison between the two different developments of the extended remote I/O	221
Table 5.27	Pulse width counting results, in the irregular port scanning for 1000, 3000 and 5500 meters of length in the FM mode	226
Table 5.28	The pulse width counting results, in the irregular port scanning method for 1000, 3000 and 5500 meters of length in the AM mode	226
Table 5.29	Example for $D_x$ and some selected port values in binary and decimal modes	227
Table 5.30	$C_{cal}$ and the consequent $F_x$ in AM and FM communication layers for four different cable length	229
Table 6.1	The comparison between a normal copper and a hybrid (copper/fibre) cables.	233

## LIST OF FIGURES

		<b>Page</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	2
Figure 2.1	A simplified conventional model of a digital communication system	9
Figure 2.2	Power Line as Communication Channel in Communication System	11
Figure 2.3	Topology of the typical Low Voltage Distribution Network	17
Figure 2.4	The Structure Chart of Medium Voltage PLC System	17
Figure 2.5	The maximum output level in frequency range 3 kHz-148.5 kHz	22
Figure 2.6	The OSI Layer Model	32
Figure 2.7	Reduction of the signal transmission lines by industrial power line communication	37
Figure 3.1	A conceptual illustration of the FAMPLC technique	41
Figure 3.2	Combination of the frequency and amplitude modulation over the power	43
Figure 3.3	The fundamental components in FAMPLC server architecture	43
Figure 3.4	The server's Frequency Modulated Power Supply circuitry	44
Figure 3.5	A series of pulses generated for three different aims	45
Figure 3.6	Data loss intervals of current mode modulation for sine-wave	46

	and square-wave supplying voltage	
Figure 3.7	DC to AC Bridge configuration in connection with the Thevenin resistance	46
Figure 3.8	$V_T$ and supplying power in various switching sequences of a full duplex transmission mode	48
Figure 3.9	The CPU block consist of two MCUs in server system	49
Figure 3.10	Overall components of a receiver node	51
Figure 3.11	Typical damping and phase shifting effect of pulses due to increase of cable length or the frequency, detectable at the consumer's point	52
Figure 3.12	The PMU infrastructure	52
Figure 3.13	Typical LDO regulatory architecture	56
Figure 3.14	Typical VI characteristic of a LDO regulator	57
Figure 3.15	Ground Noise Rejection in TTL buffer block using Zener effect	59
Figure 3.16	Power line model used for FMPT	60
Figure 3.17	Simplified RLC model of the node's consuming devices	60
Figure 3.18	Illustration of $\zeta_s$ in 3 different conditions	65
Figure 3.19	The fundamental concept of a capacitor: a) Theoretical b) Practical	66
Figure 3.20	A recommended design concept for maximizing the reliability for long distance range transmission in FAM technique	66
Figure 3.21	Active resistance in conjunction with the receiver node's transmission circuitry	67



Figure 3.22	Active resistance circuitry as Norton model	68
Figure 3.23	Line impedance as the function of $\omega$ and $R_{AM}$	69
Figure 3.24	The operational amplifier circuit used to amplify the voltages means across the Thevenin resistor	70
Figure 3.25	The transmission line model in figure 3.1 for the current Amplitude Modulation concept from the receiver node to the server	71
Figure 3.26	Simplified node to server transmission concept for transmission of the current overlaid step function using the node's active resistance	71
Figure 3.27	Signal layers of a current base transmission	73
Figure 3.28	A sample caption to present $i_s$ as a function of $i_{AM}$	75
Figure 3.29	Two Port Network (2PN) transmission model	75
Figure 3.30	Typical point to multipoint network topology in FAMPLC technique	80
Figure 3.31	Distribution concept of the command/Data pulses and protective gap pulses in a meaningful transmission	81
Figure 3.32	An illustration of the Pulse Width Modulation (PWM) for three different commands	81
Figure 3.33	The output of the Schmitt-trigger gate used to filter the glitches	87
Figure 3.34	Transmission sequences align with calibration process	88
Figure 3.35	Flowchart of communication sequences in point to multipoint model	92

Figure 3.36	The process flow of multipoint to multipoint model between two nodes	93
Figure 3.37	AST pulse waves using FAMPLC technique	94
Figure 4.1	An illustration of a hybrid cable	98
Figure 4.2	13 AWG copper cable used for ROV application	98
Figure 4.3	The components block diagram of the hardware a) master server b) slave node	99
Figure 4.4	Assembly completion of the evaluation board (Master)	100
Figure 4.5	Inverter shunt resistor used by the TEC block	101
Figure 4.6	Master board with display and keyboard installed	101
Figure 4.7	Assembly completion of the evaluation board (Slave; ROV receiver)	102
Figure 4.8	ROV slave node with display and keyboard installed	103
Figure 4.9	DC to AC inverter block designed for the evaluation board	104
Figure 4.10	TEC circuitry armed with CIV feature	107
Figure 4.11	Contribution of signals in the signal adder model	108
Figure 4.12	TEC pulse wave sequences	110
Figure 4.13	TEC circuit to demodulate analog signals	110
Figure 4.14	The magnitude respond of the high-pass analog filter	111
Figure 4.15	The phase characteristic of the high-pass filter used in TEC analog demodulator	112
Figure 4.16	Single horizontal line video signal	113
Figure 4.17	Transreceiver elements of the slave node	115

Figure 4.18	The video signal in preparation stage for the active resistance block	115
Figure 4.19	AEC-100 black & white camera used in this research	116
Figure 4.20	OM708 OSD module	116
Figure 4.21	OSD technique used for integration of data into BWV	117
Figure 4.22	The processing flowchart of server evaluation hardware	119
Figure 4.23	The processing flowchart of slave node evaluation hardware	120
Figure 4.24	The wiring arrangement between the campus buildings for point to multipoint model	122
Figure 4.25	Semi-assembled server board	123
Figure 4.26	The slave node assembled board	123
Figure 4.27	The final mounted master module for point to multipoint concept	124
Figure 4.28	Complete mounted slave node at location (3)	125
Figure 4.29	Dual core processing flowchart of the server unit in point to multipoint communication concept	127
Figure 4.30	The processing flow of the slave node	128
Figure 4.31	The RLC model used during programming stage in lab environment	130
Figure 4.32	The “8 X 8” developed model for I/O extension experiment	132
Figure 4.33	First hardware development for extended I/O a) Master b) Slave	133
Figure 4.34	Improved (second) developed hardware for extended I/O	134

	a) Master b) Slave	
Figure 4.35	Port arrangement model in Hardware preparation stage	135
	a) Irregular b) Regular	
Figure 4.36	The processing flowchart of the first development of the master unit of the extended I/O	137
Figure 4.37	The processing flowchart of the first development of the slave unit of the extended I/O	138
Figure 4.38	Transmitting process of the second development in both master and slave units	139
Figure 4.39	Receiving process in both master and slave units of the second development	140
Figure 5.1	FAMPLC transmitting elements in conjunction with a Low-pass filter	144
Figure 5.2	The schematic diagram of simulation	146
Figure 5.3	The result of unloaded power pulse edge transmission in 1000 meters	148
Figure 5.4	Power pulse edge response at 40 mA consumption of the dummy load and in 1000 meters of length	149
Figure 5.5	Power pulse edge response at 200 mA consumption of the dummy load and in 1000 meters of length	150
Figure 5.6	Power pulse edge response at 400 mA consumption of the dummy load and in 1000 meters of length	151
Figure 5.7	Power pulse edge response at 8A load and in 1000 meters of	152

	length	
Figure 5.8	Power pulse edge response at 2A load and in 1000 meters of length	154
Figure 5.9	Power pulse edge response at 4A load and in 1000 meters of length	155
Figure 5.10	Power pulse edge response at 6A load and in 1000 meters of length	156
Figure 5.11	Underdamped effect due to the cable characteristics (a): 2A@10m (b): 2A@1000m	158
Figure 5.12	Experimental setup for testing the Stabilizer effect	159
Figure 5.13	Sample waveforms of the vehicle's power (FM) and transmitted data (AM), a) In presence of the stabilizer, b) In absence of the stabilizer	160
Figure 5.14	The circuit diagram used to simulate the AM transmission	161
Figure 5.15	Current pulse edge response at 138.3mA dummy load's drain and 1000 meters of length	162
Figure 5.16	138.3 mA current pulse edge response at 1ADC consumption and 1000 meters of length	164
Figure 5.17	138.3 mA current pulse edge response at 4ADC consumption and 1000 meters of length	165
Figure 5.18	138.3 mA current pulse edge response at 8ADC consumption and 1000 meters of length	166
Figure 5.19	Counter triggering threshold compensated proportional to the	167

	gain of TEC circuit	
Figure 5.20	The schematic diagram used to simulate the pulse width counting process	168
Figure 5.21	The graphical screen shot of the simulation results	169
Figure 5.22	The schematic diagram used to simulate current mode pulse transmission	171
Figure 5.23	The simulation result in presence of the CIV block	173
Figure 5.24	The indication of the improved rising delay in presence of CIV block	174
Figure 5.25	Falling edge delay study in presence of the CIV block	175
Figure 5.26	Typical thruster arrangement in an ROV	176
Figure 5.27	A sample shot of the embedded displays demonstrating the received values for the “Stop” command	179
Figure 5.28	The display shot of a calibration sequence in full load condition	182
Figure 5.29	The simulation result for a 100 Hz sinusoidal transmission over current	186
Figure 5.30	The conceptual offset block used to shift an analog signal over the zero crossing level	187
Figure 5.31	Current mode Sinusoidal transmission with offset value	187
Figure 5.32	The preparation stages of the video signal for current mode transmission (modulation)	188
Figure 5.33	An example of amplified and level shifted video signal	188
Figure 5.34	A conceptual expectation of a detected video signal by the	189

	server module	
Figure 5.35	The original BWV screenshot a) Screenshot b) Line signal	190
Figure 5.36	Signal results in ~100 mA receiver node's draining current a) Screenshot b) Line signal	190
Figure 5.37	Signal results in ~1A receiver node's draining current a) Screenshot b) Line signal	191
Figure 5.38	Signal results in ~2A receiver node's draining current (affected sync) a) Screenshot b) Line signal	191
Figure 5.39	Signal results in ~4A receiver node's draining current (dimmed) a) Screenshot b) Line signal	191
Figure 5.40	Signal results in ~8A receiver node's draining current (dimmed and distorted) a) Screenshot b) Line signal	192
Figure 5.41	The outcome of simulating AM pulse-wave transmission in presence and absence of diodes of Figure 5.14. a) With the bridge diodes b) Without the bridge diodes	194
Figure 5.42	The outcome of simulating AM pulse-wave transmission while reactive components of inverter switches intervene in the receiving signal	195
Figure 5.43	The BWV improved transmission result in the lab environment (a): Source screenshot (b): Destination screenshot	195
Figure 5.44	An example for OSD pixel generation on a black screen	196
Figure 5.45	A typical OSD project using a low-end MCU	197
Figure 5.46	A sample screenshot of the circuit of figure 5.79	197

Figure 5.47	The demonstration of a typical OSD in the current research	198
Figure 5.48	The result of full-duplex UART communication at 19200 baud rate using hyper terminal. a) FM mode (from the server unit) b) AM mode (from the receiver node)	199
Figure 5.49	The result of full-duplex UART communication at 38400 baud rate using hyper terminal. a) FM mode (from the server unit) b) AM mode (from the receiver node)	200
Figure 5.50	The overall sequential calibration procedures in the initialization stage of the uncategorized point to multipoint application	203
Figure 5.51	Simulation result of the pulse edge in nodes 1&2 shows 5.6 $\mu$ s rising delay	204
Figure 5.52	Simulation result of the current pulse edge in nodes 1&2 shows 3.74 $\mu$ s rising delay	207
Figure 5.53	The screenshots of the hyper terminal in all of the eight conditions for 1200 bad rate, a) node 1 b) node 2 c) node 3 d) node 4 e) node 5 f) node 6 g) node 7 h) node 8	220
Figure 5.54	The sample screenshot of some the received errors in 38400 baud rate: a) recorded by the server (for node 7) b) recoded by node 8	220
Figure 5.55	The hardware architecture of the isolated I/Os	222
Figure 5.56	The cable dynamic values in 1000 meters of length	223
Figure 5.57	The distorted voltage pulse edge in 12000 meters in comparison	224



with the source pulse

Figure 5.58 The TEC output in comparison with the dummy load activity to 224  
overlay the current pulses in 12000 meters of length

Figure 5.59 The growth of communicating frequencies proportional to the 230  
reduction of the cable length in a remote I/O application. a) FM  
b) AM

## 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 <sup>th</sup> 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 <sup>th</sup> time

$L$	Inductor
$C$	Capacitor
$t$	Time
$t_n$	$n^{\text{th}}$ 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
$\epsilon_0$	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
$V_{DC}$	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
$H_R(f)$	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
$M_p$	Mark 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)
$S_{Q_n}$	Logic status of transistor “ $n$ ”
$A_{O_x}$	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
$O_{thruster}^n$	Operating status of thruster “ $n$ ”
$I_{sensor(FLTZ)}^n$	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 sendiri 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 Frequency and Amplitude Modulations in Power Line Communication (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.

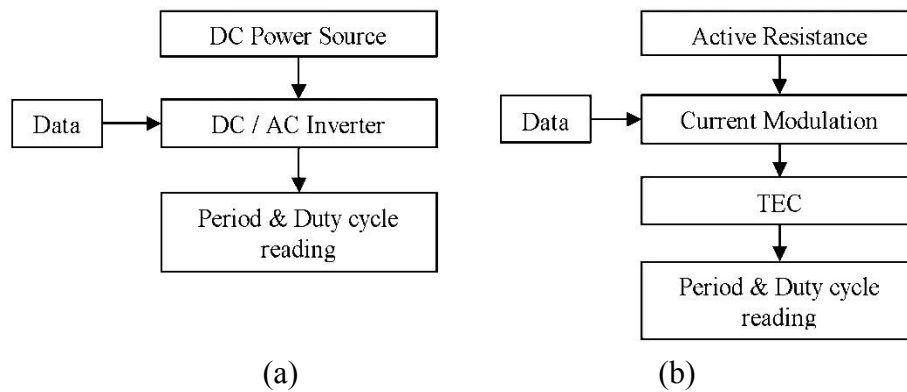


Figure 1.1: Comparison of computing processes, a) FM from the server unit to the receiver node, b) AM from the receiver node to the server unit.

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 (Henaio *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 Aynchronous 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).

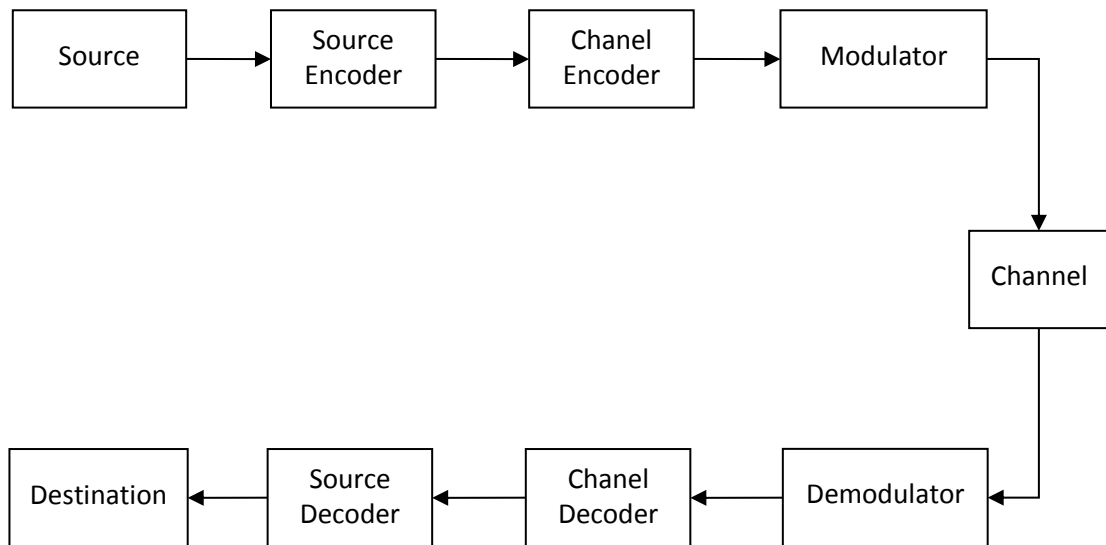


Figure 2.1: A simplified conventional model of a digital communication system.

### 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.

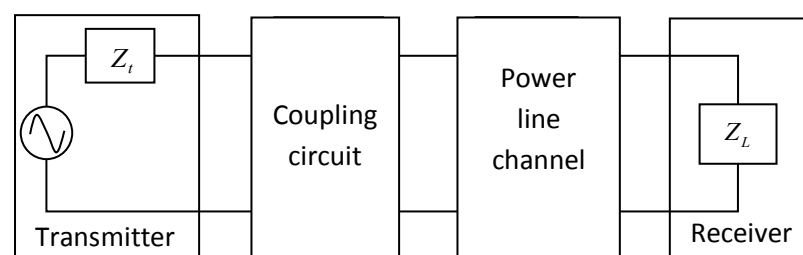


Figure 2.2: Power Line as Communication Channel in Communication System.

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  $90^\circ$  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).

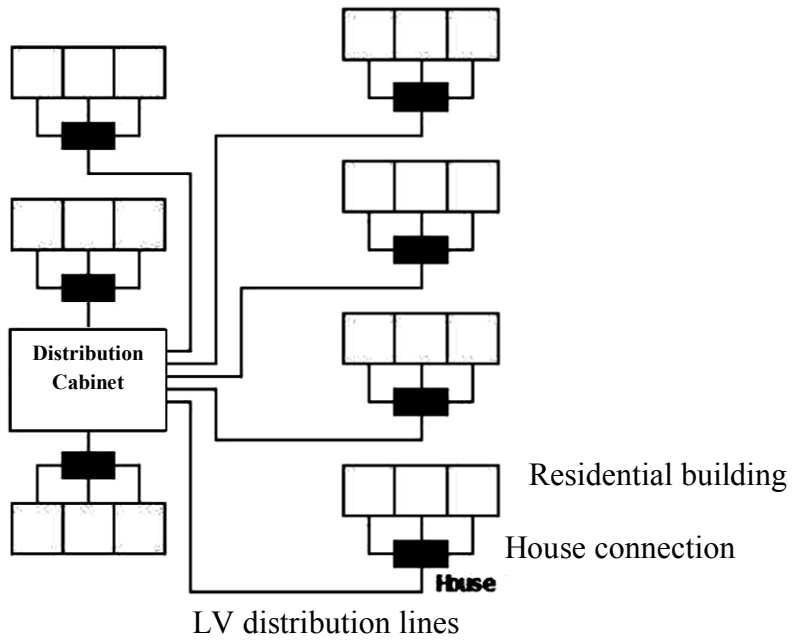


Figure 2.3: Topology of the typical Low Voltage Distribution Network.

### 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).

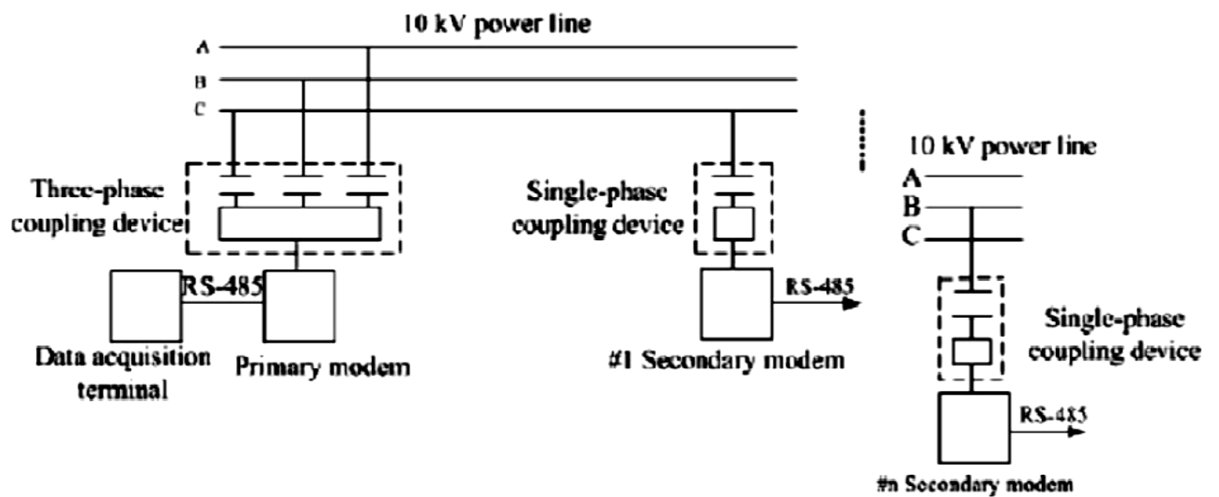


Figure 2.4: The Structure Chart of Medium Voltage PLC System (Biswas 2008).

The medium-voltage carrier communication system consists of medium voltage power line, data acquisition terminal, coupling equipment and carrier modem as its 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 communicates 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.

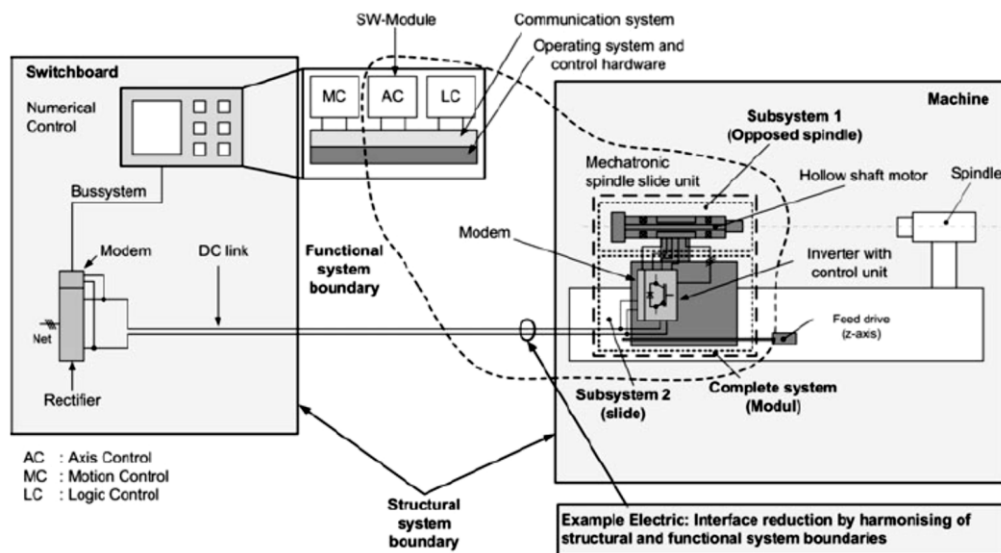


Figure 2.5: Reduction of the signal transmission lines by industrial power line communication (Alexander *et al.*, 2010).

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.

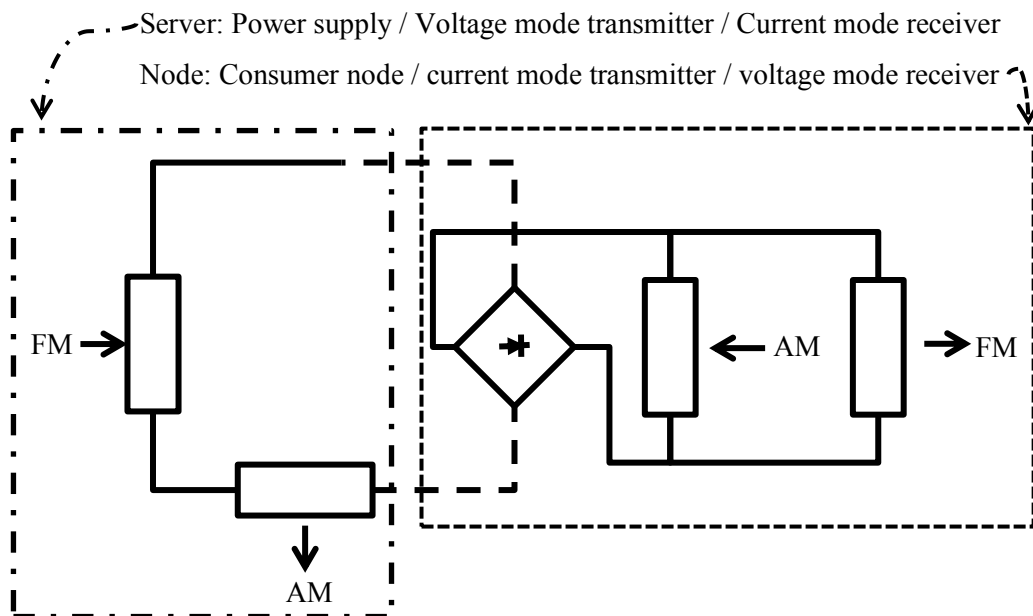


Figure 3.1: A conceptual illustration of the FAMPLC technique.