POWER LINE COMMUNICATION IN A DISTRIBUTION NETWORK: METHODOLOGY, DESIGN AND APPLICATION

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Abstract - Recently, many methods of transmitting data have been studied and employed in power system in order to acquire measuring parameters (power, voltage, etc) and to control electric devices in power system. The advantage of power-line communication is to utilize the existing infrastructure, but existing harmonics in power system have certain impacts on the accuracy of obtained information. This paper proposes a method of transmitting data on lines of distribution network. The paper utilizes a proper modulation method as well as proposes designs, especially filters, to minimize impacts of existing harmonics in power system on the accuracy of obtained information.

Key words - power line communication; distribution network; carrier frequency; frequency shift keying; modulation; electric frequency.

1. Introduction

Consumption electricity can be considered as a major reason for greenhouse or global warming effects that cause environmental impacts due to use of fossil fuels, especially coal. Smart grid technology is an essential requirement that reduces overall these effects with demand management that manages electricity more efficiently and effectively [1]. In the technology, the operation of switching devices has been becoming automatic and optimal in order to save electrical energy, to stabilize loads, to abate the length of time of blackout, to reduce the usage of human resource, etc. And in order to perform the operation of switching devices in a fast and accurate way, the act of data transmission plays a significant role. There are many method of data transmission; among the methods, power-line communication is concerned by scientists.

Power-line communication (PLC) uses existing infrastructure which is power system infrastructure; therefore, it can be easily applied in a wide area, regardless of geographic factors. However, transmission lines are not designed to transfer data; they also do not have an identical characteristic admittance. The data which is transferred by power system lines has high frequency. Thus, admittance of the lines weakens the amplitude of signals. Besides, devices connected to power system lines are quite diverse with different resistances; they can generate harmonics with different frequencies. Hence, there is noise in PLC method. Although there are many ways to overcome the two disadvantages, but researchers point out that PLC can be applied for the following fields [2]: smart metering infrastructure, communications between electric vehicles and power grid via power line without introducing other wired or wireless equipment, transferring data seamlessly from smart gird controllers to home networks and vice versa.

In Vietnam, research works and application of PLC have been applied, for instance: acquire distant comptometer indices at Central Power Corporation and Southern Power Corporation. However, such applications have not been used widely.

With the current situation of power system of Vietnam, the authors aim to apply PLC technique in distribution network for the purposes:

- Acquire comptometer indices and transfer them to transformer stations 22/0,4kV.
- Inform to system in case of broken lines.
- Control home devices for reducing consumption electricity.

With the purposes, our PLC mode can be used in the following constraints:

- For systems with small scale: transmission distance is about 800 m.
- Transmission speed can reach to 100 bps or higher.
- Noise resistance: this is an important standard.

With a good noise-resistance system which well resists any noise from other devices, obtained signals will be accurate. If obtained signals are not accurate, electric devices can be malfunctioned. And our PLC must have:

- Simple software and easy operation,
- The lowest price,
- Additional impact: having no impact on other electronic devices such as TV, computer, recorder,
- Small power losses.

In this paper, structure and principle of power-line communication are introduced. Then, manufacturation, installation and practical measurement of PLC devices proposed will be presented.

2. Methodology Background

2.1. Modulation for power line communication

Usually, a carrier (or modulated) signal is needed to convey data in a PLC system. Depending on the speed of digital information transmission, different modulation techniques can be used. With low transmitting bit rate (up to a few hundreds of kbits/s), it may be suitable to use ASK (Amplitude Shift Keying) where the information is represented by the presence or absence of the carrier signal [3]. Similarly, we can also use FSK (Frequency Shift Keying) or PSK (Phase Shift Keying) in which the information values 0/1 are differentiated respectively by frequencies or phases of the carrier. In cases of higher bit rates (up to dozens or hundred of Mbits/s), more sophisticated modulation techniques should be used in order to eliminate the intersymbol interference (ISI) [3]. Modulation techniques suitable to this purpose can be CDMA and OFDM.

In our application, which requires rather low transmitting bit rate, we preferred the FSK modulation.

The digital data signal can be represented by:

$$s_C(t) = \sum_k A_{C,k} Rect_{Tc}(t - k.T_C)$$

Where $Rect_T(t)$ is a rectangular function with duration T, $A_{C,k}$ is the sequence of bit "0" and bit "1", T_C is the bit duration.

In the FSK modulation, a bit "1" will be represented by a sinusoidal function with frequency f_1 in the bit duration T_C, meanwhile a bit "0" is assigned to frequency f_2. With this FSK modulation technique, the modulated signal can have constant amplitude but has two different frequencies ($f_1 \neq f_2$). Consequently, a FSK signal can be written as follow:

$$s_{FSK}(t) = Acos(2\pi[F_C \pm F_\Delta]t) = Acos([W_C \pm W_\Delta]t)$$

Where $-F_\Delta$ corresponds to bit "0" and $+F_\Delta$ corresponds to bit "1". F_C is the carrier frequency, $\pm F_\Delta$ is the amount of frequency shifting from the carrier frequency.

2.2. FSK demodulation

There may be several methods to demodulate a FSK signal. The first one is to multiply the signal with its delayed version then low-pass filtered. If we choose the delay T in such a way that $W_C.T = \frac{\pi}{2}$, then the low pass filter result is proportional to the deviation from the carrier frequency; hence the corresponding bit value can be determined [4]. This method can be explained as follows.

Let $w = W_C \pm W_\Delta$, then:

$$\cos(wt)\cos\big(w(t-T)\big) = \frac{1}{2}(\cos(wT) + \cos(2wt - wT))$$

After the low-pass filter, the term cos(wT) is obtained. Yet we have:

$$\cos(wT) = \cos(W_C T \pm W_\Delta T) = -sin(\pm W_\Delta T)$$
$$= \mp \sin(W_\Delta T)$$

Therefore, we can determine the transmitted bit value.

Another method [5], which is a bit more complex, is presented in the following figure.

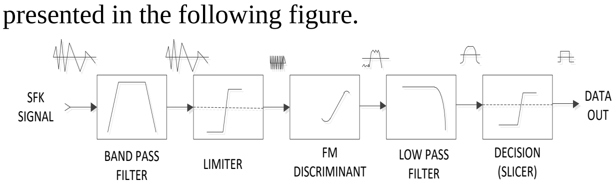


Figure 1. *Demodulation for FSK signal*

In this FSK demodulation, the band pass filter is used to remove noise with frequencies outside the FSK signal bandwidth. The limiter allows eliminating noise with high amplitude if this noise falls inside the FSK bandwidth. Finally, the low-pass filter removes noise with frequencies above the baud rate. More details can be found in [5].

2.3. Noise problem in FSK demodulation

In reality, noise can prevent us from correctly demodulating FSK signals. From the above analysis, we can carefully design a band-pass filter to remove noise components with frequency outside the FSK signal bandwidth (f_A in Figure 2). Noise inside the FSK signal bandwidth can also be eliminated by using Limiter if its amplitude is higher than the FSK signal amplitude (f_B in Figure 2). However, it could be a problem if noise frequency is inside the FSK signal bandwidth and its amplitude is smaller than the FSK signal amplitude. A solution to this situation is to use "matched filter". More details about this method can be found in [5].

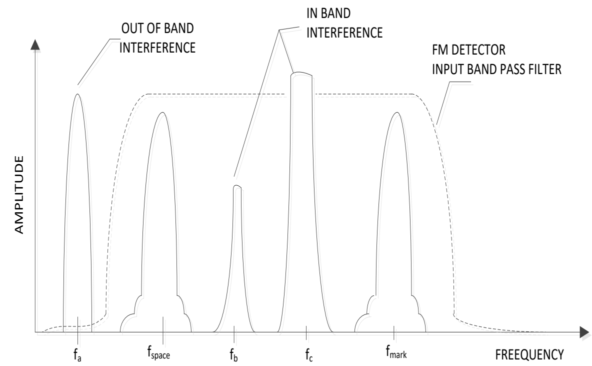


Figure 2. *Examples of noise in FSK signal (from [5])*

2.4. Amplitude equalization before filtering

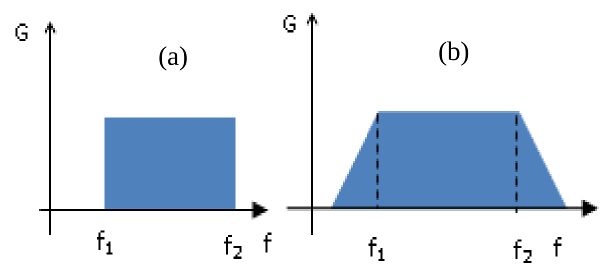


Figure 3. *(a) Ideal band pass filter, (b) Real band pass filter*

We often use a band-pass filter to get signal components between frequency f_1 and f_2, which can be represented in Figure 4a. However, we cannot in reality design such an ideal filter that has an abrupt change between the pass band and the stop band. In fact, we can only have band-pass filters like one in Figure 4b. Yet, in this case some components with frequencies outside the interval [f_1, f_2] can still be present. In a worst case, these unwanted components can mask the useful signals inside the interval [f_1, f_2] if the amplitudes of these wanted signals are small. Hence, a solution to this problem is to make all components have the same amplitude before filtering.

This can be done by estimating the frequencies and amplitudes of all sinusoidal components in the signal. The spectrum of the latter is analyzed using DFT (Discrete Fourier Transform). In the frequency domain, we can determine the frequencies and amplitudes of the components. From this information, the amplitude of each component can be amplified appropriately to the same value. The resulting signal is then applied to the selected filtering.

3. Design of power-line communication devices

3.1. Choice of power-line carrier frequency

Currently, there is no concrete study on determining the frequency of digital data signal which is transmitted on power lines. If low frequencies are employed, noise will be high, that makes it difficult to filter and rectify information and lowers transmission speed. If high frequencies are employed, it requires a high accuracy of components in circuit board as well as electromagnetic disturbances (Electromagnetic Compatibility). From references of PLC criterion as well as many studies, the frequency range 3 – 3000 kHz is employed [6]. Through experiments of transmission quality, the authors chose the frequency of 100Hz for digital data signal.

3.2. Signal Modulation

As it was presented in section 2.2, FSK method is employed in our study. Each data packet (perhaps powers, voltages or device addresses, etc.) is encoded into 16-bit: 1 start bit, 7 device addresses bits, 8 data bits with the structure as the below figure.

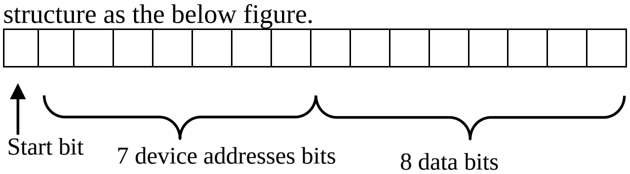


Figure 4. *Structure of each data packet*

As we know, transmitted data on power lines has noise and that could result in data losses. Thus, it is necessary for each bit to be transmitted with a band of sinusoidal pulse, which has a frequency of 100Hz. And each band of pulse is introduced into power system when voltage is 0. Sent data packets are encoded differently:

- Start bit: a band of 400 sine pulses (span 4 ms).
- Bit 1: a band of 300 sine pulses (span 3 ms).
- Bit 0: no information is emitted (no pulse).

Figure 5 present principal wave (50Hz) of power system and carrier ware of 16-bit data (including 1 start bit) which are introduced into power lines.

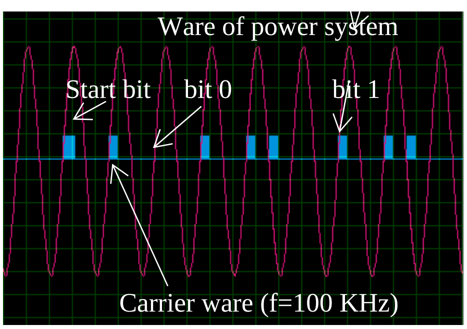


Figure 5. *Carrier ware of 16-bit (start bit + device addresses bits 0100010 + data bit 11001011)*

So, At signal receiving unit, data bits are determined in accordance with the number of 100Hz-sinusoidal pulses which are received at the moment of 0.

- 350-400 pulses: start bit.

- 250-300 pulses: bit 1.

- <250 pulses: bit 0.

So, at signal receiving unit, data reading begins when the start bit is trigged and stops after 16 bits are read (about 0.16 s).

3.3. Schematic circuit

Two main parts of a PLC device are emitting module and receiving module.

- **Emitting module**

In order to introduce signals into power lines, emitting module needs to integrate with function blocks:

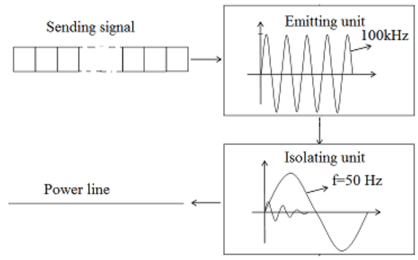


Figure 6. *Block diagram of emitting part*

Emitting unit: emits signals by microprocessors with nominal voltage, 5V. The signals pass amplifying unit with the shape of sinusoidal pulses (peak amplitude 6V, frequency 100 kHz).

Isolating unit: uses pulse transformers with the ratio 1:4 and capacitors in order to alleviate low frequencies. The signals will be introduced into power lines with peak amplitude 20V, frequency 100 kHz.

- **Receiving module**

Receiving modules receive and analyze signals. There are two parts of the receiving module: filter unit and retrieving unit:

Filter unit: filters existing signals on power lines and captures signals with frequency of 100 kHz.

Retrieving part: this part is comprised of two small parts: comparator and solving unit. Signals which were filtered are introduced into comparator, if their amplitude is sufficiently high (about mVs), they'll return to 1; otherwise they'll return to 0. In the solving unit, pulses with the value of 1 are counted in order to determine different bits (start bit, bit 1, bit 0). Alter solving 16 bits, mainboard will determine the sending signal.

There are many studies and researches concerning the design of the modules [7]. A simple model is proposed, contains two parts:

- *High-pass filters:* block low frequency signals; only high frequency signal is allowed to pass through.

- *Resonant filters:* are employed for filtering bands of frequency which are adjacent to the frequency of emitting signal. (fc±10% fc, fc: carrier frequency).

However, there remain certain difficulties. With real band pass filters, frequencies which do not belong to limitations will not efficiently be cut as it was presented in section 2.4. Therefore, obtained information could be inaccurate.

The authors propose to add amplification in retrieving part, as it is presented in the Figure 7. The aim of this unit is to amplify and limit all amplitudes of harmonics (including carrier waves 100 kHz) up to a given voltage value (in the present study, this value was 0.9V). With this application unit, there is no need to concern about the amplitudes of harmonics (only the frequencies of harmonics are to be considered). So, building filters only depends on frequency characteristics.

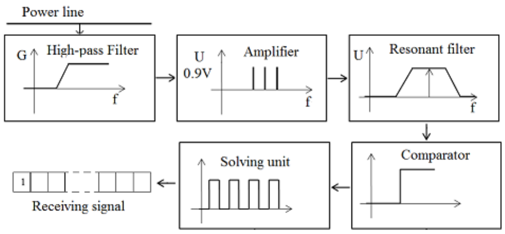


Figure 7. *Block diagram of receiving part*

3.4. Calculation and design of PLC device

The authors develop existing reference to design parts of emitting unit and receiving unit [8]. PIC 13f877 was used as mainboard. In addition to that, IC LM339 was used to detect and receiving signals.

In this paper, structure as well as parameters of receiving module is presented explicitly. This is also a new novelty of our method.

- *High-pass filter*

Structure of high-pas filter is presented in Figure 8.

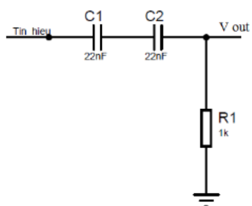


Figure 8. *Structure of high-pas filter*

The cut-off frequency is $f_c = \dfrac{1}{2\pi RC}$

$$=> R = \frac{1}{2\pi C}$$

The cut-off frequency is chosen to be 15 kHz and C contains two compensators 11 nF in parallel.

Thus: R1 = 1 kΩ.

- *Amplification*

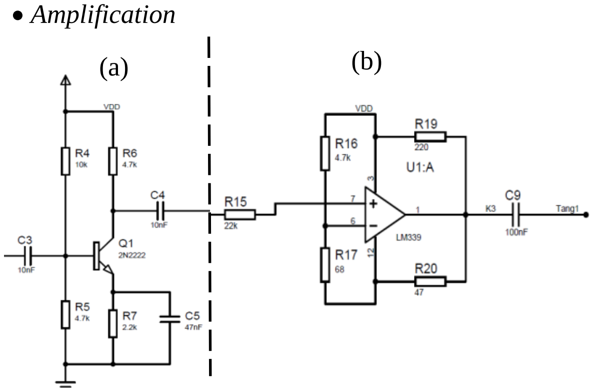


Figure 9. *Amplification structure:*
(a) amplitude amplification; (b) comparator

This component contains two parts (see Figure 9):

One amplifies all harmonic amplitudes (gain 250). This part uses basic BJT amplifier configurations type of CE. Utilizing [8], parameters are determined as follows:

R4 = 10 k; R5 = 4.7 k; R6 = 4.7 k; R7 = 2.2 k

C3 = 10 nF; C4 = 10 nF; C5 = 47 nF

Other part is comparator. The objective of comparator is limiting all harmonic amplitudes at 0.9 V. Parameters in this part are calculated by using formulas [8]: R16 = 4.7 k Ω, R17 = 68 Ω, R19 = 220 Ω, R20 = 47 Ω.

Resonant filter: After crossing amplification circuit, all signals are taken amplitude 0.9 V, this signal is passed through resonant filters with 100 kHz at center frequency to eliminate interference.

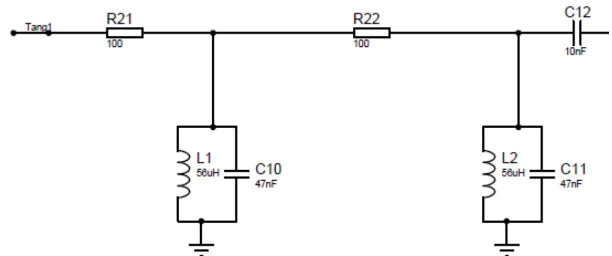


Figure 10. *Resonant filter*

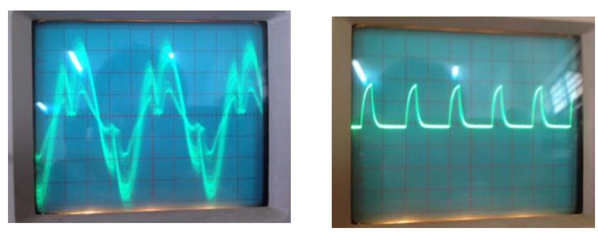
The circuit consists two circuit parallel LC filters. Its resonant frequency is: $f_o = \dfrac{1}{2\pi\sqrt{L.C}}$.

Carrier wave has frequency at f_0= 100 kHz. Thus, the value of L and C can be chosen: L = 56 and C = 47 nF.

By using [8], the resonance bandwidth of the filter is 90-100 kHz.

3.5. Analysis and assessment of filter

After designing, manufacturing, the receiving module is experimented in various cases. Through pulse generator, which increases harmonic source and existing harmonics in power system, harmonic source which is needed to study has a frequency range from 100 Hz to 100 kHz. Figure 11.a. presents high frequencies harmonics in the tested system.



Time/div = 2 us *Vol/div= 2V*

(a) *(b)*

Figure 11. *Signal input (a) and output (b) of the receiving module*

Figure 11.b present out-put signal of the filter, it is seen that undesirable parts of harmonics were all filtered, and there exists only a harmonic part of the carrier wave (100 kHz).

In comparison of currently existing PLC filters, the authors' filter has some prominent characteristics:

-The input voltage at resonant filter is limited at 0.8V; thereby, the current is limited too. Thus, it ensures that the inductor of resonant filter works at linear state.

-With the fact that amplitudes of all harmonics are returned to same value, values of all undesirable harmonics will be eliminated at resonant filter (hence, not being affected by real filter as in section 2.4). Thus, the width of bandwidth filter reduce (at ± 10%. 100 kHz), it increases signal reliability.

4. Application

The authors apply the theory and the new approach of receiving module in order to manufacture PLC devices. Objective of this system is to regulated the load demand.

Our system includes 1 master and many slavers. Master administrates general information of loads (in this case, it is active power), order slavers to transmit information of load or perform switching tasks.

Slaver: each slaver regulates one device or a group of devices such as lights, engine, etc. (which are marked 1, 2, 3,…, to be maximum of 6 devices); each slaver is equipped with address bar comprised of 7 bits. Slaver receives orders from Master and then effectuates them (sending signal or switching tasks).

Information exchange contains:

- Master sends 16 bits command code, including start bit, address of slaver (7 bits) and necessary task (the other 8 bits). Command code is presented at Table 1.

- Slaver receives and performs. Slaver must send feedback to master, which is comprised of 16 bits: start bit, self-address of slaver (7 bits) and finished task (the other 8 bits). There are two types of finished task: if it is data transmission task (power), the 8-bit-structure is comprised of: bit ‘0’ + 7 bits containing data (for example active power), if it is order task, it’ll transmit 8 bits of ‘1’.

- Within 3s, in the case that Master cannot receive information from slavers, then repeat the sending process. After 3 times of repeating, if master cannot still receive, sending - receiving process is considered to be failed.

Table 1. *Command code of some tasks*

Order	Command code
Transmission of active power	11111111
Transmission of reactive power	11110000
Tripping the 1st device	11000001
Tripping the 2nd device	11000010
…	…
Tripping the 6th device	11100000
Connecting the 1st device	10000001
Connecting the 2nd device	10000010
…	…
Connecting the 6th device	10100000

Some remarks should be retained:

- The time of a half circle of power system (50Hz): 10ms;

- The maximal length of each range of pulse (equivalent to 1 bit): 4ms;

- The time to send information (16 bits); 16x10=160ms;

- The time for Master and a slaver encodes information is negligeable.

Clearly, length of a range of information is negligible in comparation with the time of a circle (4/10=40%); thereby, there’s no risk of overlapping pulses. The time to conduct completely an order (sending an order, performing the order, receiving feedback) takes 160x2=320ms=0.32s. With load control and information acquisition (power), this amount of time is also negligible.

Experiment on devices were carried out at our laboratory (PLC devices are in different rooms). The orders in Table 1 were carried out.

After days of experiment, the difference between sending signals from slaver and receiving ones of master is negligible. Switching signals are performed precisely.

With the presence of making-noise devices; such as drilling machine, grinding machine, etc.; the system operates well. In the test of the influence on ‘sensitive’ devices: such as TV; there appears no negative effect. Measuring results of harmonics when the system operates proves that the Vietnam quality criterion of guaranteed.

5. Conclusion

In the paper, the authors propose a proper method of design for power-line communication on distribution network. The authors also built a practical experiment model. The model proves to be reliable with high accuracy when it is utilized for communication in a building.

The devices based on the result of the study can be applied for acquiring comptometer index of households from a transformer station 22/0.4 kV. Besides, they can be used for controlling home electric devices in order to save the power. This is the aim of future research.

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