Design of broadband power line communication module for automatic meter reading

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Abstract: Low-power consumption and long-distance transmission are two problems that have to be solved by the application of broadband power line communication for the automatic meter reading system. To reduce the power consumption of the communication module, based on the analysis of the composition of the power consumption, some methods are proposed. From the communication chip level and the module circuit level, the design scheme of low-power consumption is given. To solve the problem of transmission distance, a frequency band of 2.44 MHz~5.6 MHz is used as the main working frequency band. The communication module supports multiple frequency bands. Using this feature, the optimal frequency band is adaptively selected for communication and automatic switching, which further improve the transmission distance. Field application shows that the above methods effectively decrease the power consumption of the communication module and extend the transmission distance.

Key words: automatic meter reading, low-power consumption, long-distance transmission, power line communication

1. Introduction

Low-voltage power line communication (PLC) is a kind of communication technology for electric meter reading and it has been widely used and deeply studied [1–3]. It uses low-voltage distribution power circuits (380/220 V, in China) as the medium for sending and retrieving information. Low voltage power lines are distributed all over urban and rural areas, connecting thousands of households. The biggest advantage of using power circuits as communication channels is that there is no need to lay new lines, saving construction costs, and they are not easy

to be damaged. So, it is especially suitable for automatic meter reading (AMR) or an advanced metering infrastructure (AMI) system.

In China, the research on the application technology of PLC in the distribution network was carried out in about 2000 [4, 5]. At present, PLC methods used in the AMR system are spread spectrum, narrowband frequency modulation or phase modulation. Among them, the equipment with the narrow-band modulation type is mostly used, and the communication frequency band is limited to below 500 kHz. In addition to the meter reading system, the main business applications have achieved certain results in load forecasting analysis, electricity fee settlement, demand side management, line loss statistical analysis, anti-stealing analysis and power quality management. In recent years, with the expansion of business requirements, narrowband PLC is difficult to meet the requirements due to its poor stability, a low communication rate, small communication capacity and other shortcomings. New business requirements, such as remote charge control, synchronous acquisition of voltage and current data at 15 minutes or shorter intervals, automatic identification of network topology in the station area, smart meter clock concurrent time calibration, etc., require a higher communication rate [6, 7]. Therefore, improving the performance of local communication technology will be an important condition for deepening the functional application of the power consumption and the mining system and enhancing the construction value of an AMR system. And now, the AMR expands to an AMI. Broadband PLC generally refers to power line communication technology with a carrier signal operating frequency above 2 MHz. The broadband PLC has been widely used in power grids due to the characteristics of occupied frequency bandwidth, a high data transmission rate, large data capacity, two-way transmission, and no need to lay communication lines. Taking Jiangsu Province as an example, the application of a smart meter has covered more than 80%. As an important communication technology for an AMI, low-voltage PLC has also been widely used. It has basically achieved "full coverage, full acquisition", and the overall acquisition success rate has reached more than 99%.

At present, the broadband PLC is mainly committed to broadband Internet access and large-capacity transmission of audio and video data, which is mainly used in home and small office networking. The goal of chip design is high-speed, which needs to broaden the working frequency band, and the upper limit of the working frequency band may be as high as 100 MHz. However, the higher the signal frequency is, the more attenuation will be with the extension of communication distance. When the communication capacity increases, its power consumption also increases. So, it cannot meet the requirements of long-distance communication, low-power consumption applied in an AMI. Therefore, it is necessary to analyze the power consumption factors of the communication module, and reduce the power consumption without affecting the service performance of the product. In addition, according to the requirement of communication distance, combined with the receiving sensitivity that broadband PLC products can achieve, the scheme design of long-distance transmission is also given to ensure the communication distance.

2. Broadband PLC in AMR

2.1. AMR

An AMR system is a system that collects, processes and monitors the power user electric meter information, it is also called a power user electric energy data acquisition system in China.

It realizes the functions of automatic meter reading, abnormal monitoring of a metering device, power quality monitoring, power consumption analysis and management. The system structure is shown in Fig. 1. From top to bottom, it includes a master station, concentrator, acquisition, smart meter and communication system. The concentrator can collect the data of each acquisition or smart meter, process and store the data, and exchange the data with the master station or handheld device. The acquisition is used to collect the information of multiple meters and exchange data with the concentrator. For smart meters with a remote communication function, they can communicate directly with concentrators without acquisition. The wireless communication system is generally adopted for the master station and concentrator; the broadband PLC is adopted between the concentrator and the acquisitions or smart meters; the RS485 wired communication mode is adopted when the acquisition and the smart meters are installed in the same box.
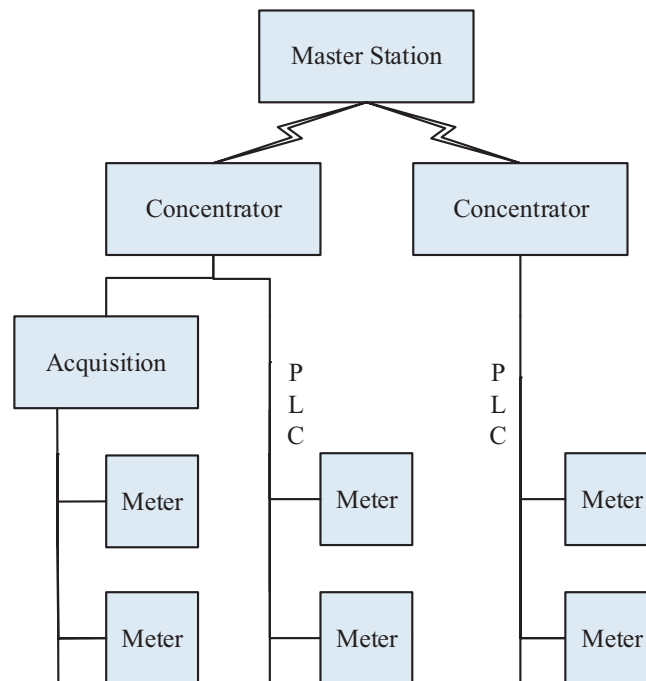
Fig. 1. Structure of AMR

PLC has three application scenarios: broadband network access, indoor equipment interconnection, AMR or AMI [8]. The first two are basically developed by IEEE Std 1901™ and ITU-T G.hn international standards. They emphasize large bandwidth and high performance. IEEE Std 1901.1™ is the medium frequency band (less than 12 MHz) PLC standard for smart grid applications [9]. At present, the AMR/AMI is the largest PLC market in China. There are two kinds of technologies, narrowband and broadband, both of which are limited by power consumption and need to meet Chinese standards [10]. The narrow-band PLC has the defects of a low communication rate, poor stability and reliability. With the increase of data communication, it cannot meet the need of the AMR information two-way interactive service of the smart grid.

The broadband PLC has obvious advantages in communication speed, anti-interference ability, etc., but it has large power consumption and a short communication range. The AMR generally requires a communication rate of > 500 kbps and a communication distance of > 300 m.

2.2. Power consumption requirements

According to the technical specifications of the communication unit of State Grid Corporation of China [11], the upper limit requirements for the power consumption of narrowband PLC and broadband PLC communication units are shown in Table 1.

Table 1. Power consumption requirements of PLC module

Consumption	Narrowband single-phase	Broadband single-phase	Narrowband routing	Broadband routing
Static (W)	0.25	0.6	1	1
Dynamic (W)	1.5	1.5	6	6

Compared with the static power consumption, the requirement of the broadband PLC in the meter side module is twice that of the narrowband device. For power consumption, if all smart meters use the broadband PLC module, the total power consumption in one year will exceed that of the narrowband PLC module. The power consumption of the broadband PLC needs to be reduced. Therefore, low-power consumption is an important index of the broadband PLC. In practical application, more than 95% of communication units are used in a single-phase meter, and the power consumption requirements are also the most stringent. The static power consumption of the broadband single-phase meter communication unit is ≤ 0.6 W, while that of the narrowband carrier single-phase meter communication unit is ≤ 0.25 W. Combined with the standard of the narrowband module, the static power consumption required is ≤ 0.35 W.

2.3. Transmission distance requirements

Although PLC can extend the acquisition radius through relay, the distance between two acquisition points is more than 200 m or even 300 m in the field of a low-voltage distribution network. However, there are many "isolated islands" for acquisition. The field application effect of using a long underground cable in rural or suburban areas is not good, which also restricts the broadband carrier to be widely used in the power information acquisition system. Therefore, the transmission distance is required to be more than 300 m.

3. Low-power design

3.1. Composition of communication module power consumption

As shown in Fig. 2, a broadband PLC module is composed of a broadband PLC chip, a line driver (LD), a band-pass filter, a coupling transformer, and a flash memory. The broadband PLC chip and LD are the core chips. The line driver is used to amplify the transmitted analog signal,

and the output voltage is as high as 12 V or more. It usually adopts a bipolar process and cannot be integrated with a broadband PLC chip. The line driver is a device with high power consumption in the board level. Its power consumption is directly related to the signal power spectral density. The State Grid has strict regulations on the power spectral density of broadband PLC, which is not more than −45 dBm/Hz inside the band and −75 dBm/Hz outside the band, respectively [11]. To reduce the power consumption of the line drive, we can reduce the bandwidth and transmit power. However, this will lead to a decrease of the communication rate and the reduction of the communication distance, so the system needs to be comprehensively traded off.
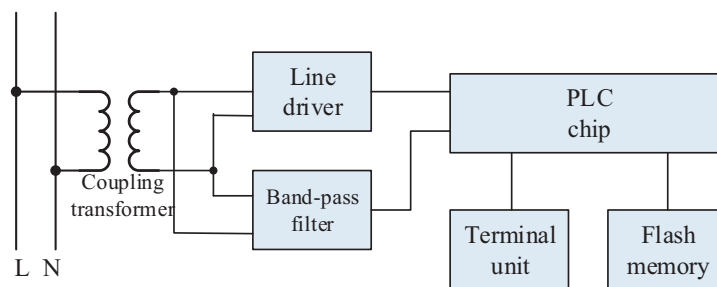

Fig. 2. PLC structure diagram

PLC adopts a baseband transmission mode, without the radio-frequency part. The chip consists of a digital circuit and analog circuit. The digital circuit transistors works in the cut-off region and the saturation region, and is a kind of switch circuit. Its power consumption consists of dynamic power consumption, (P_D), and static power consumption, (P_L), and the dynamic power consumption includes switching power consumption, (P_{sw}), and short-circuit power consumption, (P_{sc}), as (1). P_{sw} is the power consumed by the circuit to charge and discharge the load capacitance of the output node during the switching process. The input voltage waveform is not an ideal step input signal. There is a certain rise time and fall time, which result in that both the NMOS and PMOS transistors are turned on, and a DC conduction current from the power source to the ground appears. This is the short-circuit power consumption, (P_{sc}). In CMOS circuits, the static power consumption is mainly the power consumption caused by leakage current.

$$P = P_D + P_L = P_{SW} + P_{SC} + P_L = 0.5CV_{DD}^2 fN + Q_{SC}V_{DD}fN + I_{\text{leak}}V_{DD}, \qquad (1)$$

where: C is the load capacitance, V_{DD} is the supply voltage, f is the operating frequency, N is the switching factor, Q_{SC} is the short-circuit charge, and I_{leak} is the leakage current. Implementation forms of analog circuits vary widely, and it is difficult to define power consumption components as a digital circuit. The analog circuit transistors work in the linear amplification region and need to set an appropriate bias voltage (or current). When it works in a sub-threshold mode, it can greatly reduce power consumption. In addition, the analog module usually provides a low-power shutdown mode, which is set by an external digital control pin. The static power consumption of the broadband PLC module is mainly related to the current consumed by the module in the receiving state. Therefore, how to reduce the power consumption depends on how to reduce the current of the module in the receiving state. It can be optimized from two aspects: communication chip design and module circuit design.

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3.2. Low-power communication chip design

The broadband communication chip is Huawei Hisilicon Hi3911. For the outdoor power line channel, the chip selects 2~12 MHz as the basic working frequency band. At the same time, the chip can work below 6 MHz by applying a small bandwidth mode or carrier shielding method. The working frequency of the chip avoids high-frequency bands with fast attenuation and low-frequency bands with narrow-band PLCs with large noise, which improves the communication distance. The chip uses OFDM technology same as an IEEE Std1901 FFT physical layer. Due to the narrow bandwidth, it adopts 1024 point FFT. The effective subcarrier is between 80 and 490, and the subcarrier interval is 24.414 kHz. The sampling rate is 25 MS/s, and in the small bandwidth mode, it can be further reduced to 12.5 MS/s, which is several times lower than an IEEE Std1901 FFT physical layer sampling rate (75 MS/s or higher). A lower sampling rate and data rate combined with lower order modulation technology can make the physical layer of the system on the chip (SoC) and PLC transceiver work at a lower clock frequency, while greatly reduce the performance requirements of an analog front-end and line driver, so as to reduce the cost and power consumption of the communication chip.

In addition, several measures have been taken to further reduce power consumption. Turn off the internal transmission circuits of the chip, such as the modulation circuit and digital-to-analog converter. The input and output of the chip are set to a high resistance state to reduce leakage current, etc. The processor is set to a low-power mode, and the DSP and MCU inside the chip remain in the low-power state. The processor is activated only when a valid signal is received on the power line or there is data communication on the serial port. Adopting advanced signal detection mechanism, even when an extremely weak carrier signal appears, can effectively realize the signal identification, and avoid the misuse of synchronization to activate the processor and consume current.

3.3. Low-power module circuit design

In the receiving mode, the current consumption of the module can be reduced by turning off the peripheral power amplifier and the access to the off chip memory. Furthermore, the low-power design can reduce the current consumption of the working part of the circuit and effectively control the power consumption of the analog circuit.

The power supply of the communication module is 12 V, and the power supply of the chip is usually 3.3 V. Therefore, a power conversion circuit is required. By using a synchronous DC–DC circuit to replace the traditional low-voltage regulator, the current consumption can be reduced.

4. Long-distance design

4.1. Main factors affecting transmission distance

The transmission distance of the carrier signal is affected by many environmental factors, including loads, signal attenuation, line interference, etc. Due to the impact of loads, there is no systematic modeling to achieve quantitative analysis in academia. Therefore, the carrier scheme mainly considers controlling the transmission level, improving the receiving sensitivity, selecting

the appropriate signal frequency and so on, so as to achieve a longer communication distance and better communication effect in various field environments.

4.2. Methods for improving communication distance

For the noise interference on the line, the broadband carrier uses adaptive carrier modulation technology to avoid the interference of burst noise and pulse noise automatically. The carrier used for transmitting data is automatically adjusted according to the attenuation of the signal and the quality of the received signal. When the signal-to-noise ratio of the received signal fails to meet the requirements of the correct received signal, the carrier used for transmitting data will be abandoned and automatically adjusted to another carrier channel. The technology of automatically adjusting the carrier wave improves the reliability of data transmission and extends the communication distance.

For the signal attenuation, the problem is solved by the transmission voltage and reception sensitivity. The transmission voltage limit requirements of the carrier module in technical specifications of the communication unit of China State Grid Corporation are shown in Table 2. The sensitivity of a narrowband carrier is generally less than 10 dB μV, while that of a broad-band carrier is usually more than 20 dB μV.

Table 2. Transmission and reception voltage of PLC

	Transmit (μV)	Receive (μV)	Attenuation (dB)
Narrowband PLC	120 dB	10 dB	110
Broadband PLC	117 dB	20 dB	97

It can be seen from Table 2 that the anti-attenuation ability of the narrowband carrier is better than that of the broadband carrier by about 13 dB. Therefore, the theoretical transmission distance of the broadband carrier is smaller than that of the narrowband. The influence of impedance and noise should also be considered in the actual field environment. The influence of impedance and noise in the high frequency band of the broadband carrier is weaker than that in the low frequency band. Therefore, the sensitivity disadvantage of the broadband carrier will not be obvious in the urban network environment.

There are four frequency bands in 2 MHz~12 MHz as follows: 0.488~3.66 MHz, 2.44~5.62 MHz, 5.37~8.55 MHz, 8.79~11.96 MHz. In different frequency bands, the attenuation of the carrier signal on the line is different. Through laboratory and field comparison, the maximum difference of signal attenuation between low frequency (2 MHz) and high frequency (12 MHz) is more than 30 dB, and the difference of normal attenuation is also about 10 dB. So it is recommended to use band 2 (2.44 MHz~5.62 MHz) as the main working band. Considering the complexity of the field situation, taking into account the transmission rate and transmission distance, through the frequency automatic switching, the station area can adaptively select the optimal frequency band for communication.

5. Communication module test

5.1. Communication module

The communication module uses a Huawei Hi3911 chip. Hi3911 is the first broadband carrier chip developed for centralized metering of power lines. It employs the orthogonal frequency-division multiplexing (OFDM) and noise reduction technologies and optimizes the band scope to address the high power consumption and short transmission distance of broadband PLC. The system composition of a single-phase meter communication module is relatively simple, and the peripheral does not need EEROM, FLASH and other memory. Its module structure is shown in Fig. 3, which mainly includes a Hi3911 carrier chip, power supply circuit, transmit signal amplifier circuit, receive signal filter circuit, signal coupling circuit, external crystal circuit, interface circuit and indicator light.
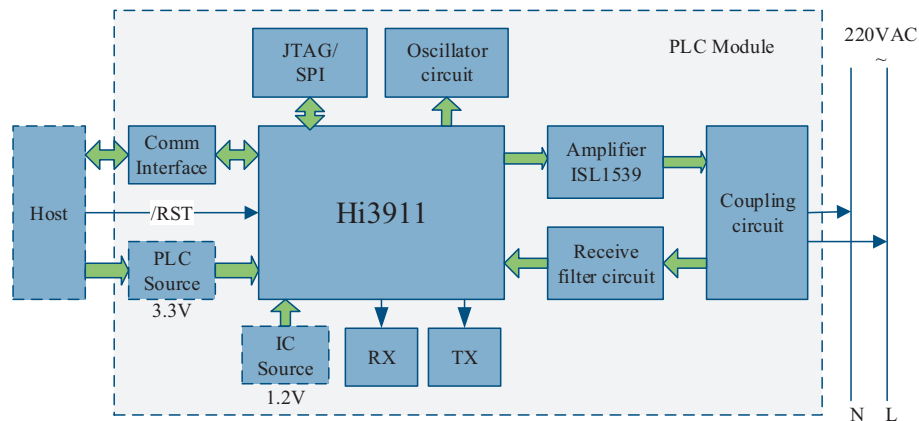

Fig. 3. Single phase meter PLC module

Under the test environment, as in Fig. 4, required by the State Grid of China [11, 12], the single-phase meter communication is tested strictly. All parameters meet the State Grid requirements.
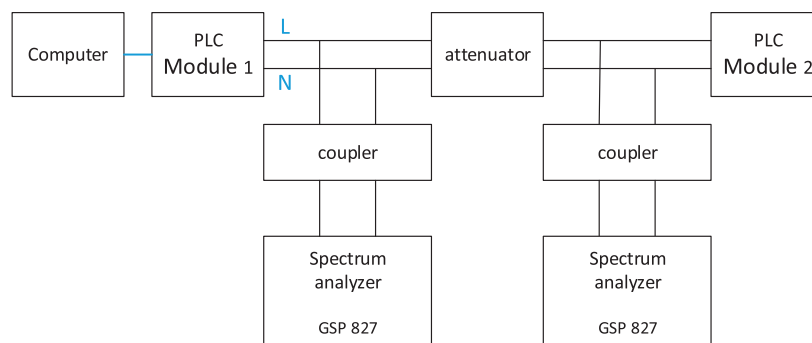

Fig. 4. PLC module test system

5.2. Power consumption test

A power consumption test includes static power consumption and dynamic power consumption. During the static power consumption test, there is only one meter with a PLC communication module in the whole test environment, and the PLC communication module is basically in the carrier listening state after the completion of power on initialization configuration. A dynamic power consumption test adopts a concentrator and collector to conduct one-to-one networking through the PLC communication module, and then a periodic meter reading test. The attenuator is used to simulate the channel attenuation between the concentrator and the meter, and the spectrometer is connected to the power line at the meter side nearby through the coupler to measure the signal power spectral density, so as to ensure that the power spectral density inside and outside the band meets the requirements of the State Grid. After the testing, the static power consumption is 0.25 W and the dynamic power consumption is 0.8 W, which meet the requirements of the State Grid Corporation.

5.3. Transmission distance test

Based on the power consumption test, a power line is used to connect a concentrator and meter. The test shows the communication distance of power lines with different lengths. In the laboratory, we mainly test the attenuation of different length lines to the signal. Take a 4×10 mm^2 cable as an example, the attenuation of a 300 m line is about 15 dB at 4 MHz. So, we set the attenuator to 15 dB to test the results of data communication. After 100 times of data transmitting; it was found that all the answers were correct. And 500 m long-distance communication has also been tested in the field. The distance from the building to the distribution station is about 500 m. The line is an XLPE copper cable of 4×120 mm^2. The meter of the building can be read correctly by the concentrator in the distribution station, and the accuracy is more than 95%.

6. Conclusions

From the design level of a communication chip and module circuit, low-power optimization is carried out. Through optimization, the chip can control the static current when listening at only 20 mA, which can save more than 30% power. A frequency band of 2.44 MHz~5.6 MHz is used as the main working frequency band. The carrier module supports several frequency bands. Through automatic frequency switching, the station area can adaptively select the optimal frequency band for communication.

And now, the broadband PLC communication module using Huawei Hisilicon Hi3911 has been applied in some areas of Jiangsu Province of China. The results show that it has obvious advantages over the narrow-band carrier in terms of the speed and success rate of data transmission, and meets the requirements of low-power consumption and long-distance. This will accelerate the transition of PLC technology from narrowband to broadband and improve the performance of the AMR/AMI.

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