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A New Power Line Communication Modem Design with Applications to Vast Solar Farm Management

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Abstract

This article presents a new power line communication (PLC) modem design which can control data flow with a new networking strategy to propagate signals for long distance without using extra cabling or signal repeaters. An investigation is also carried on the utilization of the twin core power line cables in vast solar farm for controlling solar trackers and data acquisition purposes. Frequency responses of these power lines are analyzed and tested according to different coupling circuits. A simple design is proposed for PLC modem based on such channel characteristics, data flow control strategy, collision avoidance technique and error detection.

Keywords: Solar farm management, Power line communication, Data flow control, Twin-core cable characteristics.

1. Introduction

The present revolution in communication systems, particularly stimulated by internet, offers the possibility of much greater monitoring and control of power system, leading to more effective, flexible and lower cost operation (Ekanayake, et al. 2012).

Some designs took only channels into consideration (Lienard, et al. 2008), or only discussed modulation technique without studying the frequency response of the channel and coupler (Kabalc, Kabalci and Develi 2012), or went with twisted pair cables but unavailable for high cross section cables (Grassi, Pignari and Wolf 2011). To reduce impulsive noises in channels a master controller was employed to control solar tracker running time. A number of costly techniques were presented and discussed in (Lopes, Pinto and Gerald 2013) and (Degardin, et al. 2008).

In the present article, the contention-detection and contention-resolution procedures proposed in (Amrani and Rubin 2007) are improved by adopting a strategy to control data flow based on channel sensing for multiple accesses under supervision of a master controller. The proposed modem is designed based on the frequency response of the twin wire power line with coupler.

The channel and coupler have been simulated from 1kHz to 20MHz and the modulation technique and used frequencies have been selected based on the channel response. The system has the ability to control a large number of trackers in vast farm with high efficiency and accuracy. The system consists of a master controller which is programmed to control and acquire data from all the solar trackers via its slave controllers.

A new networking protocol is proposed to control data flow and boosting the data for long distance. The remaining parts of the article are organized as follows. In Section 2, the preliminary aspects of DC power line are introduced. Section 3 presents the channel calculations, and in Section 4 the design aspects of the modem are addressed. Section 5 describes the solar tracking management strategies. Section 6 presents the result and discussions. The article ends with the conclusion in Section 7.

2. Preliminary Aspects for DC PLC

This section presents the twin core cable characteristics and the signal coupling circuits.

2.1 Channel characteristics

It is important to know the used channel characteristics before deciding on the used modulation technique, transmitted and received power, channel coding techniques, the used frequency and the available bandwidth. It is also important to know if the used channel has a frequency selective or a flat frequency response. The adopted channel is a power line cable consisting of twin cores, each with a radius (a) and the distance between the centers of the two cores is (d) as shown in the Fig. 1.

There are three important factors need to be calculated about this cable namely the capacitor per unit length, inductance per unit length and the characteristic impedance. The first two factors are important to expect the channel response and the last one is to achieve maximum power transfer through the channel. The main equations describing these factors are (Bird 2003):

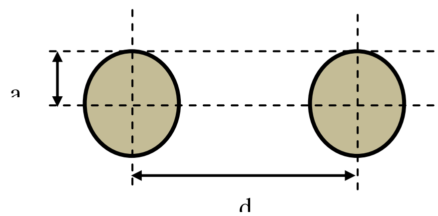


Figure 1. Twin core power line cable

The capacitance per unit length: $$C \approx \pi\varepsilon / \ln(d/a) \quad (1)$$

The inductance per unit length: $$L \approx \mu/(\pi \ln(d/a)) \quad (2)$$

Where the approximation is valid for d≫a.

The characteristic impedance: $$Z = \sqrt{(L/C)} \approx 1/(\pi \ln(d/a) \sqrt{(\mu/\varepsilon)}) \quad (3)$$

Equations (1), (2) and (3) show that all these factors are proportional to two main dimensions namely (a and d) and there is a tradeoff between the inductance and capacitance of the channel based on these factors; i.e., the increment of distance between cables increases the inductance and reduces the capacitance and vice versa, and the same matter with core diameter.

2.2 Coupling Circuit

The coupling circuit performs the connection with the communication channel. It acts as a filter that passes the communication signals, while attenuating out-of-band frequencies. Its design mainly depends on the line characteristics, such as voltage, frequency, wiring style, etc. In some applications, the coupling circuit can be required to provide safety isolation and protection from high voltage disturbances as mentioned in (Hendrik, et al. 2011).

2.2.1 *Capacitive Coupling*

The capacitive coupling is the method used in most applications, since it requires direct parallel connection with the communication channel. The main coupling element is a capacitor that blocks the line voltage, while passing the high-frequency communication signals. Fig. 2 shows the capacitive circuit.

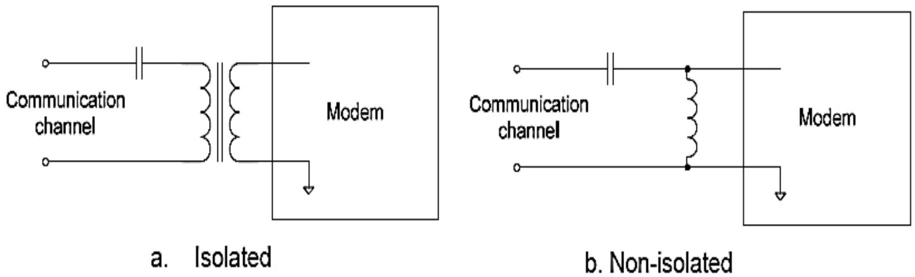


Figure 2. Capacitive coupler types

2.2.2 *Inductive Coupling*

The inductive couplers are connected in series on the communication channel and inject a PLC current signal on the line. This is achieved through a specialized current transformer using appropriate high frequency ferrites. The transformer also provides galvanic isolation. Inductive couplers can be with or without connection to the communication cable as shown in Fig. 3.

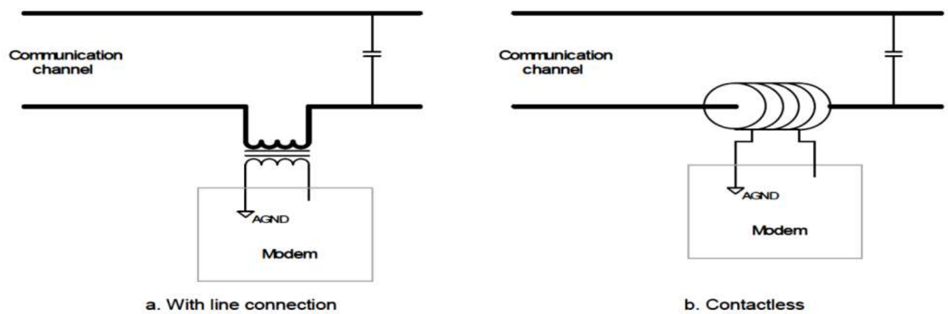


Figure 3. Inductive coupler types

2.3 Channel Calculations

The system frequency response depends on three factors: the power line characteristics, the signal trappers and the used coupler. The channel characteristics and the effectiveness of each coupling circuit on the frequency response of the system have been simulated.

The selected twin core copper cable has been used with the following features: cross section = 25 mm^2, PVC isolated, resistor = 4e-3 Ohm/ m, Inductance =5e-7 H/m and Capacitance =1.4e-10F/m. Two pieces of cable have been used each 500 m long with three couplers, one for the master and two for the slaves. Fig. 4 and Fig. 5 show the circuit diagram and the frequency response for the power line, capacitive coupler and the signal trappers.

The capacitive couplers with two different cables length have been searched for a good response as depicted in Table 1. Moreover, Fig. 6 and Fig. 7 show the circuit diagram and the frequency response for the inductive coupler with the cable used. The inductive couplers with two different cables length have been searched for a good response as depicted in Table 2.

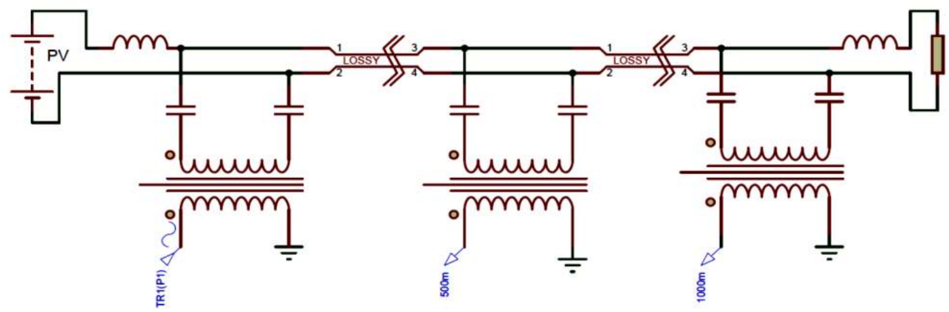


Figure 4. Capacitive coupling circuit

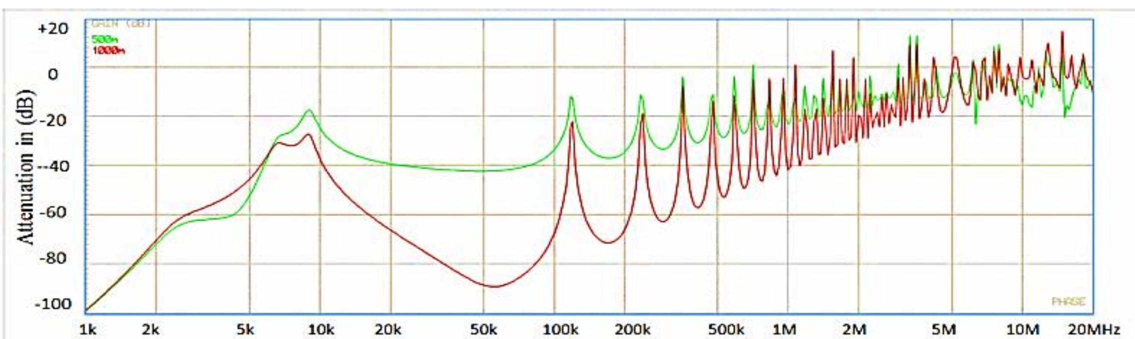


Figure 5. Capacitive frequency response

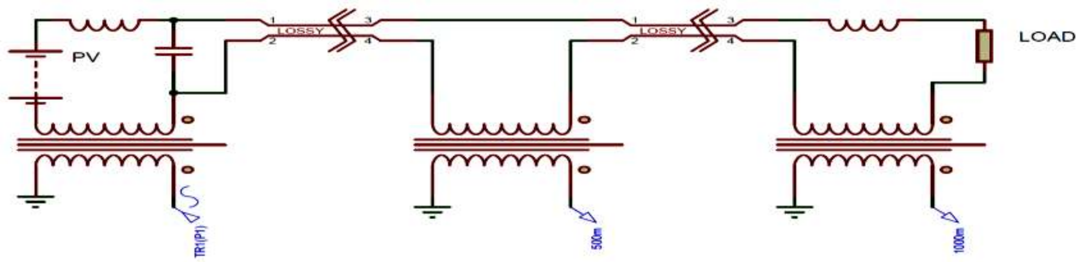


Figure 6. Inductive coupling circuit

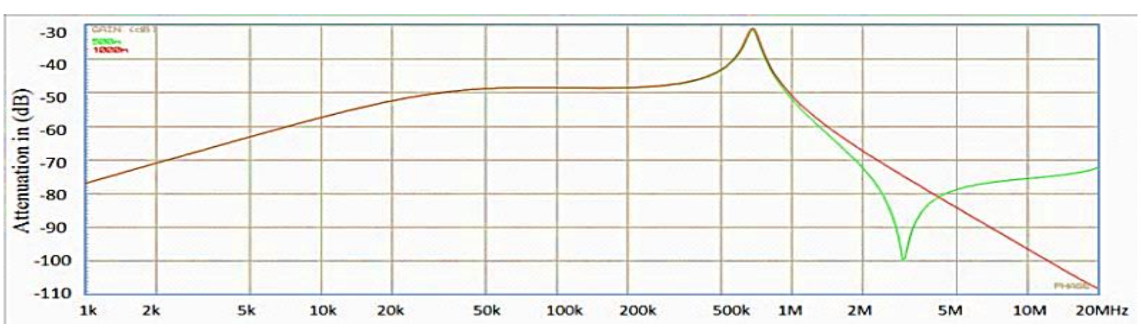


Figure 7. Inductive frequency response

Table 1. Selective Frequencies of the Capacitive Coupling

Frequency (kHz)		Gain (dB)	
		500m	1000m
f_0	8.9	-17.1894	-27.2834
f_1	119.1	-9.33683	-14.6116
f_2	236	-6.48368	-13.294
f_3	354	-3.7784	-10.1556
f_4	472	-1.59256	-7.60511
f_5	591	-1.92427	-4.86654
f_6	716	-7.19386	-4.50147
f_7	835	-7.3086	-4.77343
f_8	941	-3.86291	-11.7653

Table 2. Selective frequencies for the inductive coupling

Frequency (kHz)		Gain (dB)	
		500m	1000m
f_0	660	-32.2167	-31.09
f_1	16595	-43.7027	-83.1759

According to the channel response with frequency range from 10 kHz to 20 MHz at different cable's length (500 and 1000 m), the channel response is a selective and there is no flat frequency response range. Before selecting the carrier frequency it is important to observe that there are more items to be taken into consideration like signal trappers which allow the DC power and prevent RF signal. The impedances of such trappers are directly proportional to the signal frequency and coil inductance. Since the coil inductance in power line is a matter of cost and weight, it is therefore important to use a suitable high frequency to achieve the desired impedance. The modulation technique is also important because a narrow bandwidth is needed to achieve a flat response.

3. Modem Design Aspects

The channel frequency response shows that it is a narrow band frequency selective. Hence, it is required to adopt a narrow bandwidth modulation with carrier frequency within these resonated frequencies to achieve lowest attenuation on the receiver side which let the signal propagates for a long distance and cover the required vast area of the solar farm with no need of repeaters. According to these requirements and because the transmitted data in binary format, it follows that there are two nominated modulation techniques, namely the binary amplitude shift keying (BASK) and the binary frequency shift keying (BFSK).

To avoid the data collision in the channel, the transceiver should have a channel sensing circuit which detects the carrier frequency in the channel. But that will be difficult in case of using BASK. Also, using a BASK with two voltage levels will still be more complex than BFSK from the implementation point of view because its need for more multiplier and adder circuits. Hence, the design will adopt BFSK with two frequencies one for logic "0" and the other for logic "1". The used frequencies for BFSK should be selected carefully according to the channel response. Table 1 suggests many frequencies could be used in case of capacitive coupling. The channel has been established as an equivalent circuit consisting of 14 LC pi sections, each with a coil of 0.106 mΩ/m, 35.7μH and a capacitor of 1nF. This is equivalent to a power line 25 mm^2 in cross section and 1000 m in length. According to the conducted laboratory test a good response least dependent on the channel length is achieved by using f_2 = 236 kHz and f_3 = 354 kHz, see in Fig. 8.

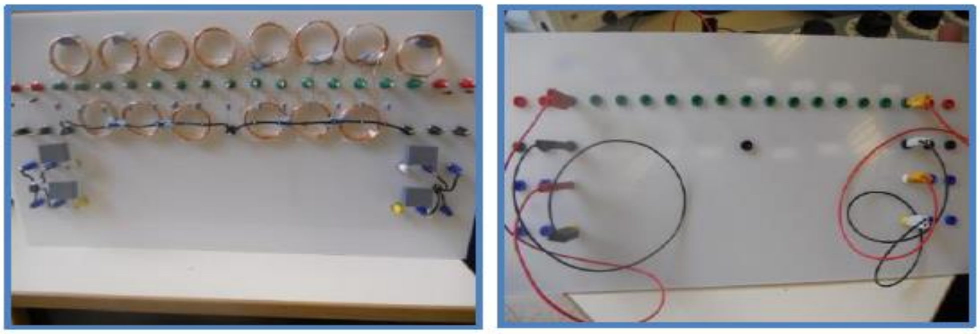


Figure 8. Cable equivalent circuits

The modem should have its own channel sensing technique to detect the channel for the signal. Also, the system should have auto shut down the carrier frequencies if idle. Finally it is important to prevent the echo signal in transmitting mode.

3.1 Transmitter Circuitry

3.1.1 *Voltage Control Oscillator*

The design adopts 74HCT4046A as a voltage control oscillator which has a center frequency of up to 17 MHz at VCC = 4.5 v. This VCO has been adjusted to generate the mentioned frequencies for logic "0" and "1" by selecting the right values for R_1, R_2 and C_{EXT}.

3.1.2 *Band Pass Filter*

This filter is used to pass the mentioned frequencies only.

3.1.3 Power Amplifier

A class AB power amplifier has been used to increase the transmitted signal power.

3.2 Receiver Circuitry

3.2.1 *Low Noise Amplifier*

The first stage in the receiver is the low noise amplifier. This stage is important because the circuit sensitivity will depend on its capability to detect low signal to noise ratio which leads to increase the range of the transmitted signal in meter.

3.2.2 *Parallel LC Resonator*

This circuit is designed to resonate at logic "0" frequency to make the signal with two voltage levels.

3.2.3 *Envelope Detector*

This circuit is designed to separate the carrier frequencies and get the data signal back. The design used this technique to demodulate the RF signal which is simple and low cost demodulator. An ultra-fast diode is used to pass the negative part of the signal followed by parallel RC circuit. It is important to select the appropriate RC time constant to detect the envelope of the required signal. An operational amplifier has been used to regenerate the signal by comparing the signal level with threshold level which is adjusted according to the received signal voltage. The RC time constant should be chosen according to the following equation:

$$1/fh \ll RC \ll 1/fm \tag{4}$$

where f_h is the highest carrier frequency and f_m =9600 Hz. So as a midpoint 1/RC is as 50 kHz or RC =20 μsec.

3.2.4 *Channel sensing circuit*

This circuit uses the same technique that has been used in the demodulation circuit. The circuit consist of an envelope detector and level comparator. The RC time is selected to detect the carrier only for sensing purposes ($RC \gg 1/fh$).

3.2.5 *Flow control*

There are two major matters in transmit and receive data in both directions. The first is to shut down the carrier wave in if there is no data to transmit since TTL level did not turn off the voltage control oscillator (VCO) in logic "0", this is so important because as mentioned before the transceiver used collision avoidance. The other matter is to avoid the echo of the transmitted data to the transceiver itself. The schematic diagram in Fig. 9 shows the proposed PLC modem.

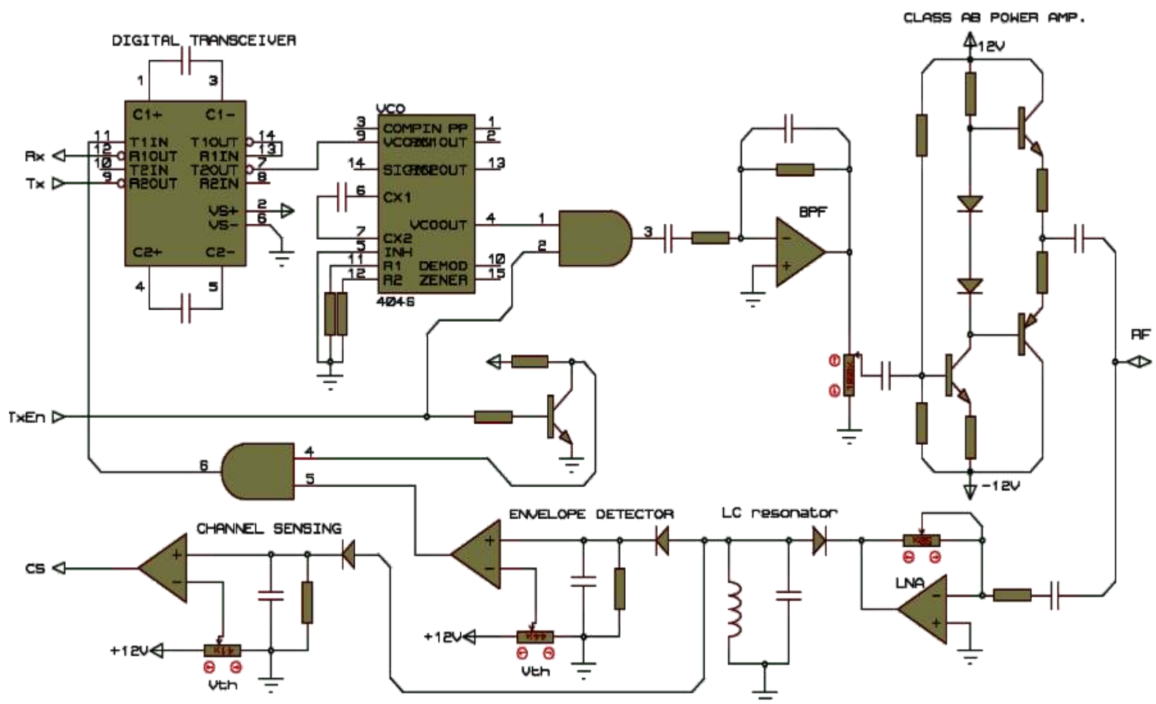


Figure 9. PLC modem

4. Solar Tracking Farm Management

The solar farm consists of many trackers separated by a specific distance to track the sun in the sky for maximum solar irradiance. To control and monitor these trackers, a master and slave control system has been adopted. This control technique has many advantages since it has a centralized administration, gateway role for PLC network, management of the roles of each device, PLC and IP network hierarchy, easier network supervision as mentioned in (Carcelle 2006).

The master controller calculates the sun location based on astronomical equation and the instance time, date and location. This master controller sends the sun location data periodically to all the slaves on the farm. At the same time it acquired the data from all these slaves, as the voltage, current and fault diagnostic code (Al-Naima, Ali and Abid, Design and implementation of a smart dual axis sun tracker based on astronomical equations 2012) and (Al-Naima, Ali and Abid, Design of a control and data acquisition system for a multi-mode solar tracking farm 2012). Fig. 10 shows the signal line diagram for the distributed units on the farm. Each slave controller manages two actuators to adjust the polar angle and the tilt angle of the solar panel.

The control box in Fig. 11.A shows the slave controller which controls the two actuators of the tracker. It also displays all the data on 4x20 characters LCD. The photo shows that the LCD displays time and date on the first row, latitude and declination angles on the second and tilt and polar angle on the third row (Al-Naima, Ali and Abid, Solar Tracking System:Design based on GPS and Astronomical Equations May 29-31, 2013). The tracker shown in Fig. 11.B has been designed to track the sun in two axes for maximum radiation. The used slave controller is ATmega8 and the master controller is ATmega32.

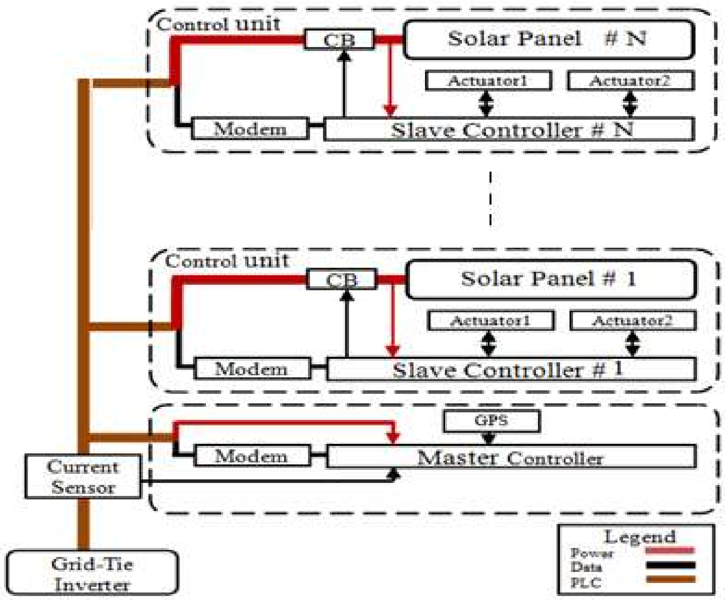


Figure 10. Signal line diagram

(A) (B)

Figure 11. A-Slave controller, B- Dual Axis Solar tracker

5. Data Network Design

5.1 Data Structure

The message consists of four parts; head, control byte, message body and message ends. Message head contains preamble data, source and destination address and data length while the message body contains the main data. The control byte has information about the message body contents and the last part is the message end which contains the inner error detection checksum. Fig. 12 shows this adopted structure:

MESSGAE HEAD					CONTROL BYTE	MESSAGE BODY	ACKNOLOGMENT	END	
PERMEABLE DATA	$	SOURCE ADDRESS	DESTINATION ADDRESS	MESSAGE LENGTH				CHECK SUM	**

Figure 8. Data Structure

- Permeable data: it is sent in the beginning of the message to avoid the transition error of the channel and it consists of a series of "10101010".
- The symbol "$": refers to the start of data.
- The source and destination addresses: the master controller has address "00" and the slaves address start from "01". It is important to use these addresses for the slaves from the nearest to the farthest because the master uses this address to calculate the slave reliability.
- Message length: it is used to give an indication for the receiver about the message end.
- Control byte: it gives the receiver an idea about the message body content.
- Message body: it has a variable length depending on the type of message.
- Acknowledgment: it could be "A" if the previous data acknowledged or "N" if not.
- End of the data: "**"characters, sent by the transmitter at the end of the message to give an indication to the receiver that the transmission is finished.

5.2 Data Flow Control

5.2.1 *Sharing the Message*

The master sends all slaves a general message which has information about the sun location as shown in Fig. 13. This message has information about the tilt angle, polar angle, tracking type (1= vertical tracking, 2= horizontal tracking and 3= full tracking) (Al-Naima, Ali and Abid, Smart Home Energy Management: Design Based on Power line Communication 2012).

$	00	,	00	,	25	,	01	,	45	,	105	,	3	,	A	,	CC	**
Pre.	Master		Master		Data		**Sharing**		Tilt		Polar		Full		Ack.		Checksum	End

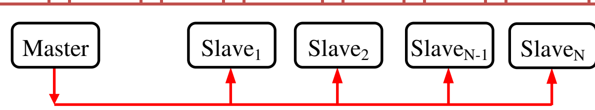
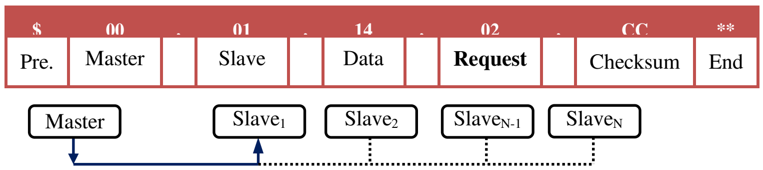


Figure 13. Shared Message

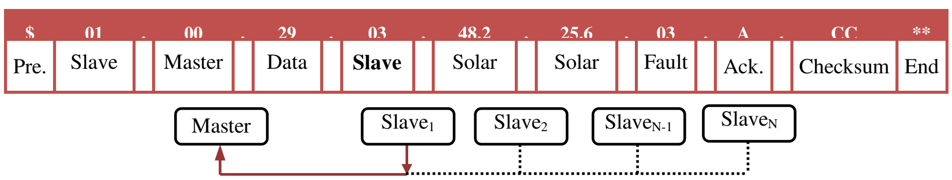
5.2.2 *Dedicated Message*

The master controller starts sending an addressable permission for each single tracker to send it data as shown in Fig.

14.A. When the slave tracker receives its own permission, it automatically replies a message containing the following data; panel voltage and current, fault code and acknowledgment of the general message as shown in Fig. 14.B. This acknowledgment gives the master controller an indication about the connection quality. If the general message reaches the slave correctly, the master controller will not send the data back again because it is already expired but it is used to evaluate the connection quality.



(A) Request to send

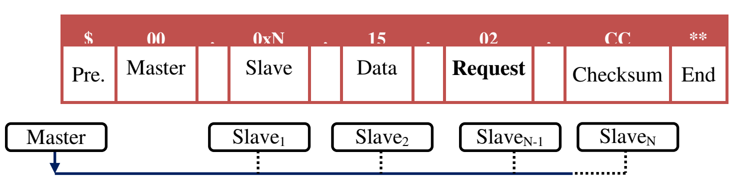


(B) Slave Status

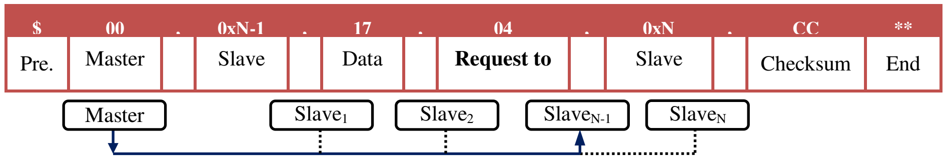
Figure 14. Dedicated Message

5.2.3 *Soft controlled repeating*

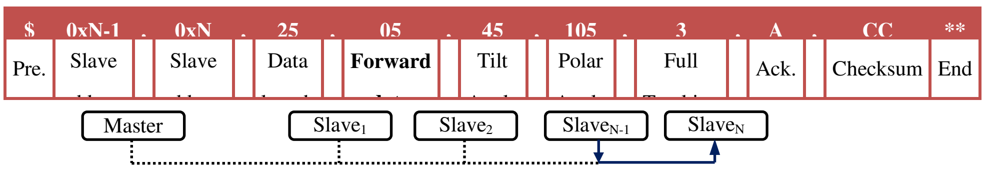
The master control memorizes the reliability of the connection of all the slaves in the farm. If the master control does not receive a reply to the dedication message or receiving one acknowledge for the shared data or the received data with error, the master controller starts to evaluate this salve and reduce its reliability with every time this happen and vice versa. Now the question is this, does this slave not receive the signal because it is so far from the slave? The answer of this question depends on the performance of the adjacent slaves. In case the answer is "Yes", such slave reaches a specific level of reliability and the master control starts sending the data to this slave in an indirect way. The master will ask a nearby slave to repeat the message for the unreachable slave, and then receives its reply to forward it to the master controller. Fig. 15 shows the soft repeating procedure. In Fig. 15.D, if the slave N does not answer slave (N-1) a fault code will reply the master controller with control byte equals to 0x08H.



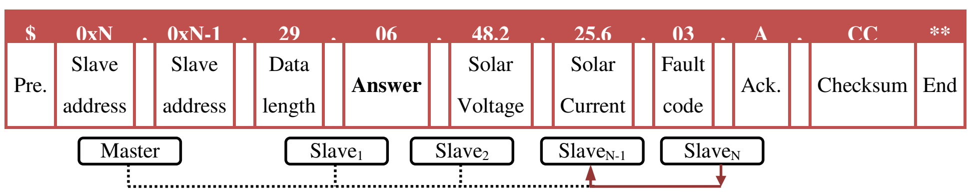
(A) Request to send



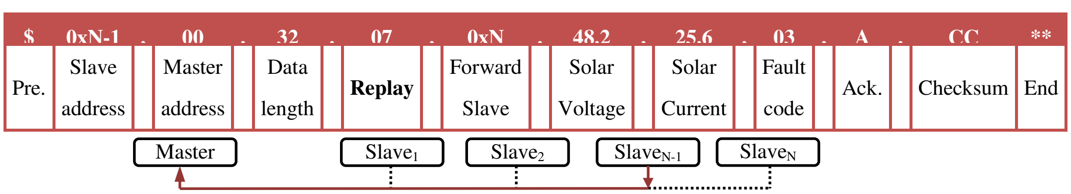
(B) Request to Forward



(C) Forward data



(D) Answer



(E) Replay

Figure 15. Soft controlled repeater

6. Microcontroller Software Duties

6.1 Error control and detection

Two coding techniques are used, namely checksum for the inner data and CRC-16 for the outer data. The microcontroller calculates the checksum and the CRC-16 code before sending the data to the transmitter; this value is transmitted after the End of Packet for error detection purposes at the receiver.

6.2 Flow Control

The microcontroller detects the channel sensing signal before transmitting any data. If this signal is low it means the channel is idle and the transmitter has a green light to transmit the data, if not the microcontroller will back off for a random time and detect the channel again according to N back off strategy. It is also programmed to set the "TxEN" signal high in transmitting mode. This signal enables the VCO output and disables the RX data to avoid echo signal.

6.3 Route Reliability estimation

One of the microcontroller important duties is to estimate the connection reliability level CRL between it and every slave in the field. In the initialization phase all slaves have the same CRL but this level could an increase or decrease based on the quality of connection which depends on the detected error.

6.4 Fault detection

When the master controller receives any fault code from the slaves it automatically translates this code for the operator with ability to save some solution under user permission if the same problem happens in the future.

6.5 Trackers running time management

To avoid impulsive noise slave controller does not run the actuators unless it receives its own dedicated message. The flow chart in Fig. 16 shows the master controller some of its software duties.

7. Results and discussion

The present modem is simple, low cost and able to control the data transmission and reception for long distance without using extra repeaters. The adopted soft repeating technique can easily control the data flow in both directions. The used coding techniques for inner and outer message body can control the error of the transmitted data with high efficiency.

The master controller displays all the details regarding the power supplied by each single tracker and the total power. In the event of any fault in the trackers the master controller will inform the user by translating the fault code received from the slave. The master controller asks the user every time a fault will happen to save the treatment in case of the same fault occur in the future. The complete circuit has been simulated using Proteus simulation software. This simulation includes the power line, coupling circuit, modem and microcontroller type ATmega32 for master controller and ATmega8 for the slave controllers. The controller detects the channel sensing signal before transmitting data. If this signal is low then the TxEN signal will be set to enable the VCO out and disable the echo signal. Fig.17 shows the simulated input and output signals of the transmitter.

The signal shown in Fig. 17 is frequency shift keying between the two selecting frequencies which guarantees the maximum channel response. Fig. 18 shows the received signals at low noise amplifier input, resonator output and the envelope detector output. The received radio frequency signal shows fixed amplitude in spite of the different frequencies and that came from the suitable selected frequencies. The resonated output has a sufficient drop in voltage which makes the digital signal regeneration easier.

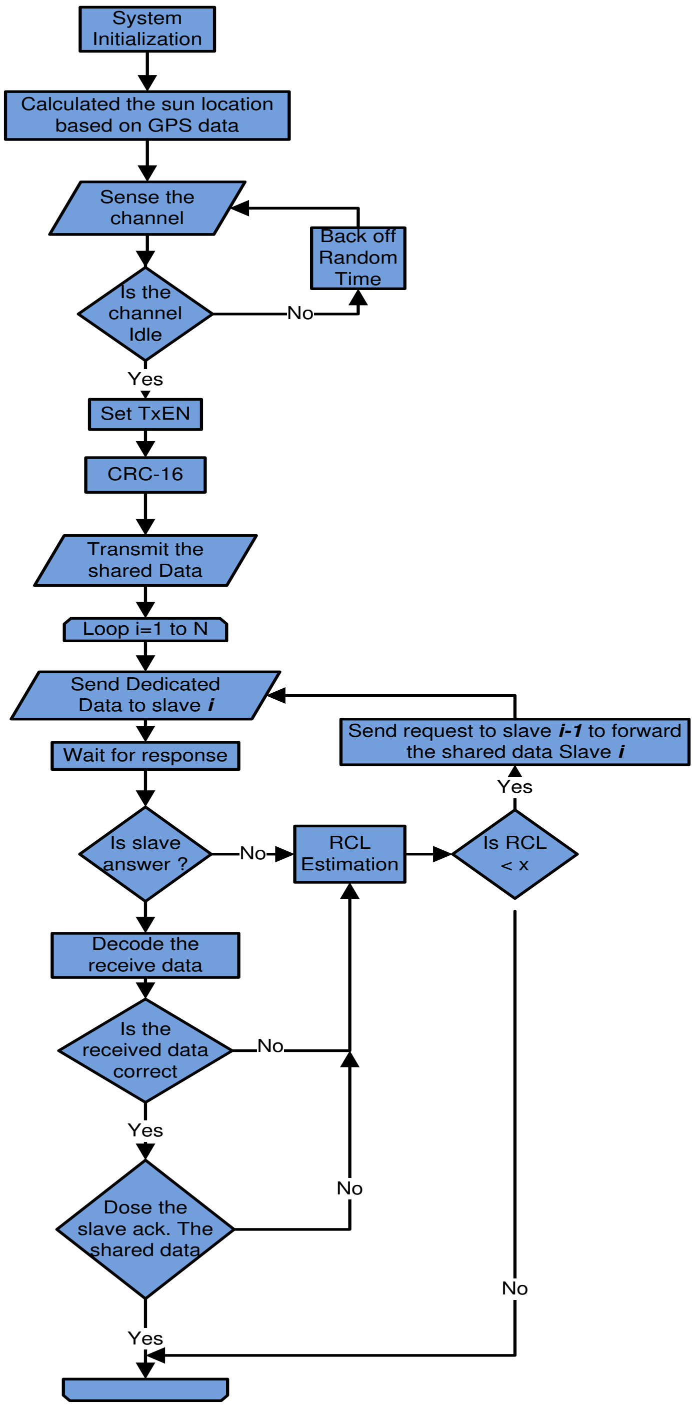


Figure 16. Master controller control duties

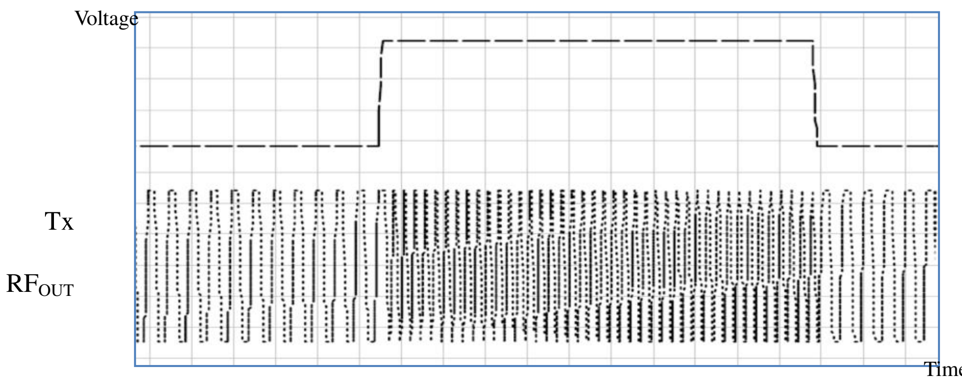


Figure 17. Transmitter signal

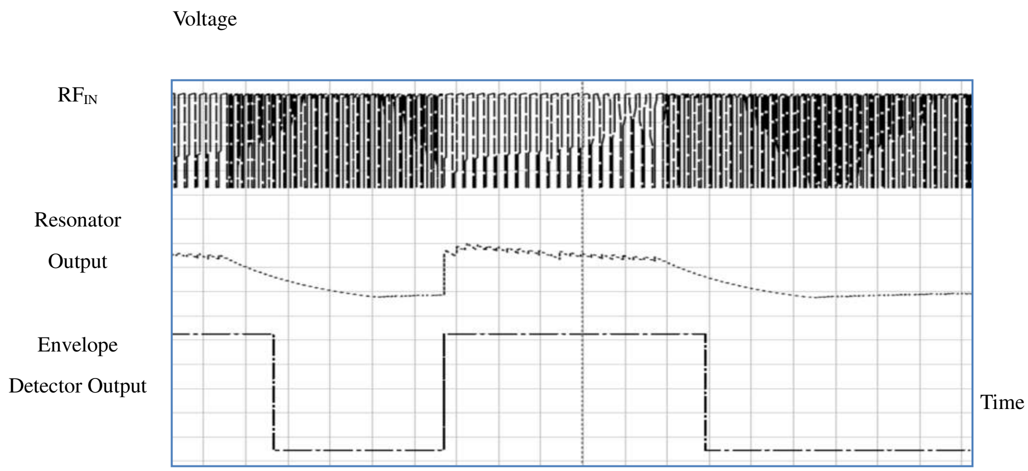


Figure 18. Receiver signal

8. Conclusion

In this article, a complete solution for PLC modem has been proposed based on existing power line characteristics. The frequency responses of the channel and coupler have been simulated for a wide range of frequencies. The designed modem has the advantages of simplicity, cost effectiveness and using new strategy to control the out of reach devices without increasing the transmitting power or changing the circuit specifications. The proposed design offers a simple solution to control the solar trackers in a vast solar farm. It can monitor the supplied power by each single tracker in the field and having the ability to diagnose the fault in each of them.

Acknowledgment

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