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Demonstrative DC Motor Control under Power Communication Network

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Abstract

Power line communication (PLC) has been used to transmit and receive digital data via power line in wide application. However, power lines weren't built for data transmission originally. In practice, data transmission is commonly subjected to switching noise by the multi-path effect. The objective of this research is to establish a platform for easily tune the controller for motor control system under the PLC environment. We build up a dynamic model to simulate the power line environment for communication and propose a frequency-shift keying (FSK) technique to modulate and demodulate the signal for the purpose of network control in the disturbed feedback control loop. A modified proportional-integral-derivative controller (PID controller) on positioning control a DC servo motor is proposed to against noise corruption while achieving tracking performance.

Keywords: Power line communication; Control; Frequency-shift keying (FSK); Modelling; Performance

Introduction

Power line communication (PLC) has been developed for more than two decades. It starts since mid-1980s for data transmission to power grids [1]. The PLC-based distribution networks are increasingly being utilized to support smart grid communication infrastructure and in-home local area network connectivity recently [2]. It is becoming popular recently because it doesn't need additional transmit line to transmit the data and the power line is widely spread everywhere [3,4]. In addition, the data rate can be up to megabits per second. However, the power line wasn't used for delivering messages originally leading to problems which are not in common in traditional network connection. For example, the quality of data transmission is significantly degraded if the power line is too old or many branches existed. For the later, the electric equipment switching causing impulse transients may induce noise disturbance and interfere data communication [5].

On the other hand, DC motors are the popular actuating devices for driving machines in wide industrial applications. For remote control application, the machines need power lines to supply electric power while the controller needs network wires for control command transmission. Simplifying complexity of wire connection base on the available power line provides a potential solution to the problem of cost minimization. That is, one can utilize one power cable for simultaneously power and data transmission [6,7]. Kosonen et al. [8] studied and analysed the performance of the motor control under PLC with simulations and laboratory experiments. Comparison measurements with a commercial drive were carried out. In which a PI speed controller. However, using PI control alone might not be efficient to against the noise dwelled in the PLC environment. The paper of Konate et al. [9] presents a control application that uses the power cable of an induction motor as a feedback loop in an inverter-fed electric drive without considering the noise effect. Recent practical implementation of DC motor control based on a micro controller over power line has been realized by Colak et al. [10].

Currently, the single-carrier modulation schemes are widely adopted in communication applications. In general, each modulation technique has its own advantages and disadvantages. A single-carrier scheme such as FSK is a good solution for a low cost and low data rate such as the PLC scheme. This method delivers data to superimpose the high frequency data signal onto the low frequency power signal as a currier and sends it via the power line. However, the equipment for PLC could be easily disturbed by power surges and line noise due to other high power facilities connected to the same network. The two noise sources can result in computer lockups, lost productivity, video snow, audio static, slow electronic degradation and ultimately catastrophic equipment damage.

This paper proposes a design scheme which includes a network of power line with a representative motor control system. The control system operates with the general objective of motor positioning control. The data to be transported within the power line includes rotor position, control commands, and rotational speed of the motor. We establish a variety of noise sources which may happen in the power line based control system and propose an appropriate filter to eliminate noises as the first step of signal processing. A modified PID controller is then proposed to against noise corruption while achieving tracking performance.

The information sent to the receiver or feedback to the controller is modulated using the binary frequency-shift keying (BFSK) technique [11]. It deals with digital signal transmitted with discrete frequency change of a carrier wave. It uses two discrete frequencies to transmit binary information with logic "1" being the mark frequency and "0", the space frequency. Different binary codes are modulated into different frequency. On the basis of this scheme, we can modulate control commands and sensor signals while expelling power surges and line noises.

This paper is ordered as follows. In "Control System and Description" section, we introduce architecture of the PLC-based feedback control system. A modified PID control is presented in "Tuning of Control Gains" section. Different types of noise sources might appear in PLC environment are introduced in "Noise in PLC Environment" section. Simulation study for network control of a DC

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motor is given in "Simulation Results" section. Finally, a brief summary of the propose method and conclusion is presented in "Conclusion" section.

Control System Description

In practice, a power cable is always installed between a motor and a frequency converter for power supply, and hence it may be applied as a communication medium for sensor level data. Considering the current objective of motor control, the block diagram of the PLC-based control system can be illustrated as showed in Figure 1. It consists of two parts. The first part, in the PLC modem, when the input signal comes in, it will be converted into the FSK modulated signals next.

The digitized data sent forward to the receiver or feedback to the controller is modulated via the BFSK technique [10]. It deals with digital signal transmitted with discrete frequency change of a carrier wave. The operation of a general FSK can be mathematically expressed as follows:

$$v_{FSK}(t) = v_c \cos\{2\pi[f_c + v_m(t)\Delta f]t\} \tag{1}$$

where v_c is carrier amplitude, v_{FSK} is binary FSK waveform, *fc* is carrier centre frequency, v_m is binary input signal, Δf is peak shift in the carrier frequency. For the input binary signal v_m, 1 V is referred to logic 1 and -1 V referred to logic 0. Thus, (1) can be rewritten as,

$$v_{FSK1}(t) = v_c \cos[2\pi(f_c + \Delta f)t] = v_c \cos\ (2\pi f_m t) \tag{2}$$

$$v_{FSK0}(t) = v_c \cos[2\pi(f_c - \Delta f)t] = v_c \cos\ (2\pi f_s t) \tag{3}$$

where f_s is space frequency and f_m is mark frequency.

Both of (2) and (3) can find the carrier frequency is shifted Δf back and forward as logic 0 and 1 in the frequency domain shown as in Figure 2.

The data modulated by FSK can be demonstrated in Figure 3. The carry wave uses 110 V/60 Hz power line to delivers signal. The noise is preliminarily eliminated by a filter before the FSK inverter shown as in Figure 4. Two different frequency outputs f_m and f_s are referred, respectively, to logic 1 and 0 (Figure 5).

PID control is the mostly economy way for control in industry applications especially for DC or AC motor control. It is quite effective provided that the control gains are finely tuned. In the second part, the measured output signal y gives a feedback signal through the power line to compare with the reference input. A PID speed controller generates commands after the feedback signal comes in and goes through the power line to the receiver.

Transfer function of the controller *C(s)* is:

$$C(s) = \frac{K_D s^2 + K_P s + K_I}{s} \tag{4}$$

where K_P , K_I and K_D are, respectively, proportional, integral and derivative gains. However, if there are noises involved in the desirable signal, the derivative part may boost a small noise to be a huge one at the system output. This should be handled carefully under the PLC environment.

To deal with the problem mentioned, we incorporate a filter with the derivative gain like that given in the traditional control applications [12] as shown in Figure 4. The filter removes noise first before the feedback signal fed to the derivative part of the PID control, or it can be placed after the derivative part, does the differentiation first and removes the noise later [13]. Either ways can be used to avoid amplifying the noise effect.

Now, a low pass filter denoted $1 / (1 + \tau_f s)$ with τ_f being the time constant placed before the derivative part is adopted here for the purpose. The modified PID controller is given by

$$C'(s) = \frac{(K_D + K_p \tau_f)s^2 + (K_P + K_I \tau_f)s + K_I}{s(1+\tau_f s)} \tag{5}$$

The appropriate time constant is involved in the control gains for selection.

The torque and back emf in the DC motor shown in Figure 6 is given by,

$$T = K_T i, \quad e = K_e \omega \tag{6}$$

where K_T is torque constant, *T* is motor torque, *e* is back emf generated, K_e is electromotive force constant, θ is angle of rotation and ω is angular rate.

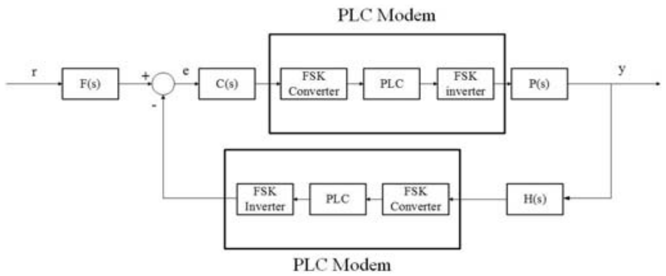

Figure 1: Block diagram of DC motor control via the power line.

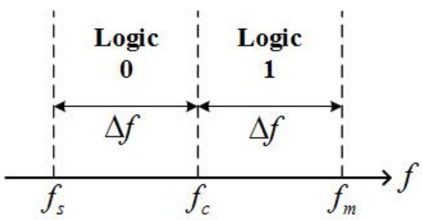

Figure 2: Logic 0 and 1 of FSK in frequency domain.

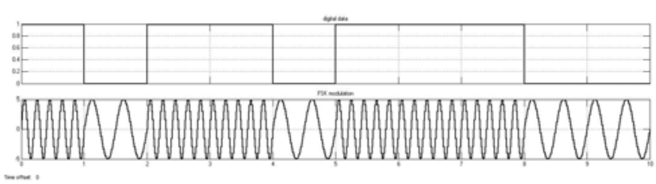

Figure 3: Example of signal after conducting FSK modulation.

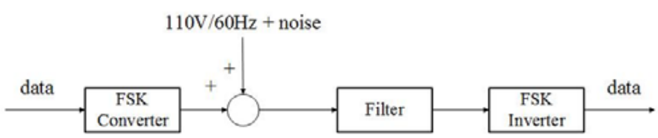

Figure 4: PLC modem with filter.

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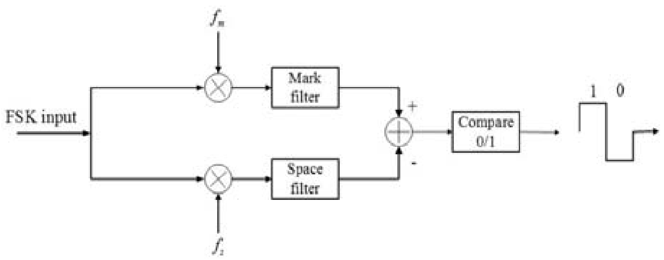

Figure 5: FSK demodulation.

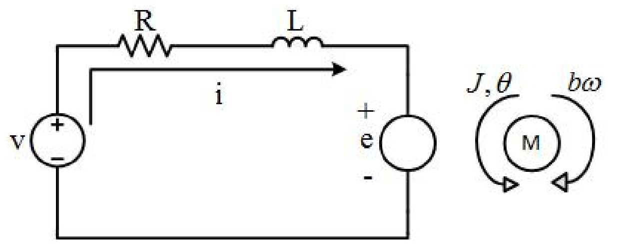

Figure 6: DC motor model.

Furthermore, we can have

$$\begin{cases} J\dot{\omega} + b\omega = T \\ L\dot{i} + Ri = v - e \end{cases} \quad (7)$$

where b is viscous friction constant of motor, J is moment of inertia of the motor, L is inductance, i is current, R is resistance and v is voltage source. The transfer function of the motor is easily obtained as

$$\frac{\Omega(s)}{V(s)} = \frac{K_T / JL}{s^2 + \left(\frac{R}{L} + \frac{b}{J}\right)s + \frac{Rb + K_T K_e}{JL}} \quad (8)$$

Tuning of Control Gains

The control gains are to be determined to drive the motor for desirable performance and against noise corruption under the PLC environment. In the current design, K_p works to reduce the rise time (t_r) and steady-state error with respect to step input (e_{ss}), K_I reduces the steady-state error, however, it may degrade the transient response. K_D is used to increase stability of the system, reduce the overshoot (OS) and improve the response time (Table 1).

There are four key factors t_r, OS, t_s and e_{ss} with the respective allowable upper bounds t_{rmax}, OS_{max}, t_{smax} and $e_{ss\,max}$. The control system performance is indexed by integral-of-inverse time-multiplied square-error (IITSE) which places a heavier weight while tracking errors occurring early in the transient response.

$$J(K_P, K_I, K_D, \tau f) = \int_0^\infty \frac{1}{t+\varepsilon} e_{all}^T Q e_{all}\, dt \quad (9)$$

where $e_{all} = [\tilde{t}_r \ \tilde{OS} \ \tilde{t}_s \ \tilde{e}_{ss}]^T$ is total error with $\tilde{t}_r = t_r / t_{r\max}$, $\tilde{OS} = OS / OS_{\max}$, $\tilde{t}_s = t_s / t_{s\max}$, $\tilde{e}_{ss} = e_{ss} / e_{ss\max}$; $Q = Q^T > 0$ is a weighting matrix and ε > 0 is a small constant.

The criterion is used to determine the PID control gains which minimize the performance index J. As the selection of role of τ_f and K_d are not separable, they are placed with the same weight. The performance index proposed above has better than the traditional integral square-error (ISE) criterion and is proper for the current purpose as a variety of noise may easily corrupt the closed-loop. A variety of optimization algorithms based on the evolutionary computation can be applied to determine the control gains and filtering constant [14].

The DC motor adopted for experiments is a SANYO C-100-20 servo motor with its parameters given in Table 2. To consider the nominal control design, the disturbances sources are temporarily removed.

The blue line in Figure 7 is the motor step response without control. The red line is the response with PID control. With control, the rise time is reduced to 0.013 s and settling time 0.023 s. The FSK modulation / demodulation scheme is then placed to the system to modulate the control command.

After that, the FSK modulation/demodulation puts into the system. The control command is modulated by the FSK technique and transmitted via the PLC. When the signal is received, it will be demodulated to recover the control command and send to the motor driver as shown in Figure 8.

When the motor speed is measured, it goes through the same FSK process for recovery. The recovered signal is compared with the reference command and sent to the controller.

Noise in PLC Environment

Power line was not built for high frequency data transmission originally. A control system works under this environment and the control signal might be contaminated by a variety of noise sources. When the high frequency signal transmitted in power line, the signal may be suffering from colored background noise, impulse noise

	t_r	OS	t_s	e_{ss}
K_p	Decrease	Increase	Slightly change	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_D	Slightly change	Decrease	Decrease	Slightly change

Table 1: Relationship between PID parameters and system performance.

b	0.000153 kg·m
J	0.0001 kg·m²
K_T	0.046 kg·m/A
K_e	0.454 V/(rad/sec)
R	4.7 Ω
L	11 mH
Maximum angular speed	1000 rpm

Table 2: Specifications of the DC servo motor under consideration.

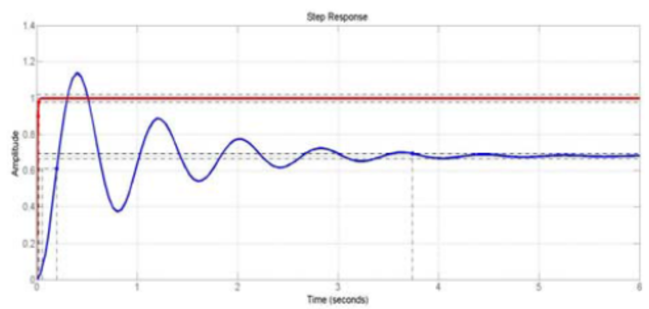

Figure 7: Transient response of the PID control system.

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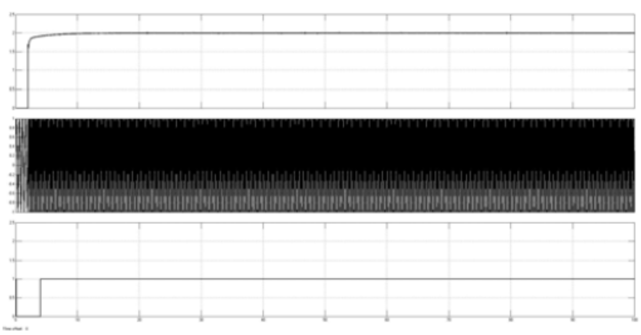

Figure 8: Reference speed with FSK modulation/demodulation.

narrowband noise and more [15]. These noise effects can be modelled as follows:

Colored background noise

Colored background noise is caused by superposition of different source noises. It can be given by

$$n_{color} = n_{\infty} + n_0 e^{-f/f_0} \quad (10)$$

where f_0 is noise fading rate , n_{∞} is constant noise density, $n_0 = n_{color}(0) - n_{color}(\infty)$ is power spectrum density (PSD) in decibel (dB).

The noise is time-invariant in PSD. The frequency range of noise is in general spread from 50 to 20 kHz. In PSD, as the frequency increases, the value of power decreases range between -120 dB and -140 dB [16].

Impulsive noise

In general, the impulse noise is caused by a variety of noise sources such as switching status of the household electric facilities and so on [17]. It occurs randomly and has different amplitude. This kind of noises is of short duration and with relatively high amplitude. The impulse noises can be classified into three types.

1) Periodic and synchronous to the main frequency: This noise was generated by noisy devices. Its repetition rate can be 50 or 60 Hz depending on the power line frequency.

2) Periodic and asynchronous to the main frequency: Its frequency is higher than the previous one; the rate can be up to several kHz.

3) Periodic impulse noise: It has strong impulse with no periodicity and is unpredictable.

On the basis of the description, the impulsive noise can be modelled as follows [18]

$$n_{impulse}(t) = \begin{cases} A\sin(2\pi f)e^{c_1(t-t_0)} & 0 \le t \le t_0 \\ A\sin(2\pi f)e^{-c_2(t-t_0)} & t_0 \le t \end{cases} \quad (11)$$

where t_0 is the time when the maximal amplitude in the impulse noise appears.

Narrow band noise

The narrowband noise also exists on the power line. Its amplitude and frequency vary from different environment and time. The noise can be modelled as the sum of multiple exponentials with different amplitude from different frequencies [19] given by,

$$n_{narrow}(f) = \sum_{i=1}^{N} A_i(f)e^{-(f-f_{0,i})^2/2B_i^2} \quad (12)$$

where A_i is amplitude, f_0 is center frequency, N is number of disturber and B_i is bandwidth of the narrowband disturber.

Simulation Results

Consider the DC motor control system with its simplified diagram illustrated as in Figure 1. The signal processing via FSK modulation under power line transmission was simulated under the MATLAB/Simulink environment.

Binary data was generated randomly where 1 V and 0 V refer, respectively, to logic 1 and 0 shown as in Figure 9. When the signal comes in, it is modulated based on the FSK. This can be observed from Figure 10. The FSK signal was then sent to the receiver via a power line with 110 V/60 Hz power and noise (Figure 11). Figure 12 demonstrates noisy FSK signal. After the signal went through the power line (Figure 13), the filter filtered out the power signal and the noise to recover the FSK signal (Figure 14). Before the receiver got the FSK signal, it demodulated the signal back to the binary type as illustrated in Figure 14.

As shown, the waveforms of binary data string obtained in Figures 9 and 14 show no difference at their steady state values. This implies after the FSK signal transmitted via the power line, the modified PID controller works well to eliminate the noise influence resultant from AC power source and all kinds of noises under consideration and successfully demodulate the signal back to its original waveform. This displays performance robustness of the control design to against noise corruption under the PLC environment.

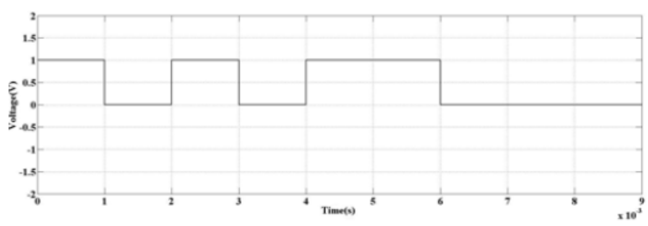

Figure 9: Modulated FSK Signal.

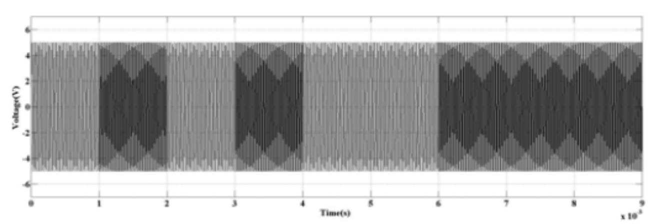

Figure 10: FSK signal transmitted.

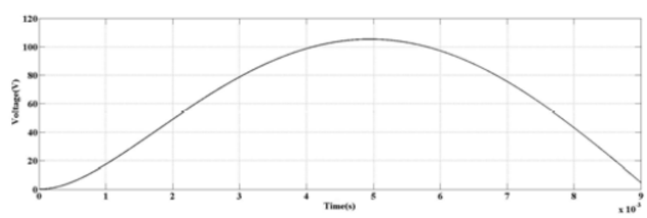

Figure 11: Utility power 110 V/60 HZ.

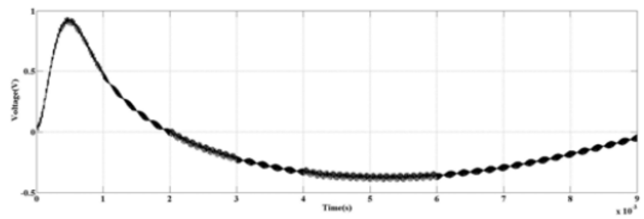

Figure 12: Noisy FSK signal.

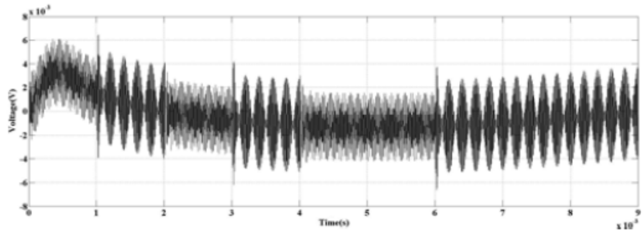

Figure 13: FSK signal received.

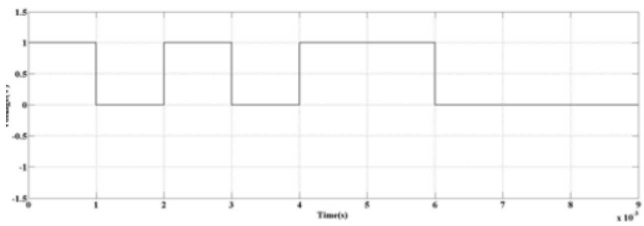

Figure 14: Demodulated FSK signal.

Conclusion

Power line transmission technology provides a useful way to construct currently available power cables to transmit digitized messages without the need to build up additional network wires. With the progress of time, technology and science change, the ideas related to smart home technology increase rapidly. That means that increasing electric facilities need to be monitored and controlled. The PLC technology capable of transferring power and data within the same network saves considerable cost in hardware facilities for network construction.

This paper proposes an easy-to-use simulation platform which mathematically models the environment of PLC for feedback control. The FSK technique is proposed which provides a simple way to modulate the digital data and transmit on power carrier wave. The controller is designed to against disturbance corruption in power line while keeping control performance. Preliminary simulation study shows that it is capable of suppressing the influence due to AC voltage surge and noise in the PLC network.

Acknowledgement

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