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Precision time synchronization control method for smart grid based on wolf colony algorithm

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ABSTRACT

In order to satisfy the high accuracy and high security requirements of time synchronization in smart grid, this paper has conducted a research on high-precision time synchronization control algorithm based on IEEE 1588 protocol. A slave clock model is built considering both phase offset and frequency drift. A novel approach using proportional–integral–derivative (PID) controller in cooperation with the wolf colony algorithm (WCA) is proposed to eliminate the offset of the slave clock with respect to the master clock. As a new swarm-intelligence algorithm, WCA is introduced for self-tuning the optimal parameters of the PID controller, which simulates the intelligent predatory behaviors and prey distribution rule of the wolf colony. The WCA-based PID control approach is compared with the method based on standard Particle Swarm Optimization (PSO) and Back-Propagation (BP) neural network. The experimental results show that the proposed WCA-based PID control approach in time synchronization for smart grid has higher precision, can adaptively adjust compensation and keep the master–slave clock synchronization effectively.

Introduction

At present, since the expansion of power network scale, the grid-connection of the new energy and the development of ultra high voltage transmission technology, the power grid is becoming more and more complex and intelligent. In smart grid, the applications such as synchronous sampling, fault detection, sequence of events recording, event location estimation and coordination of the work among devices depend on the support of a unified and precise time Refs. [1,2]. Therefore the time synchronization in smart grid is of significant importance for the safe and stable operation of each node.

In order to meet the high precision and high reliability request of time synchronization for smart grid, a new and advanced time synchronization protocol-IEEE 1588 (Precision Time Protocol, PTP) [3] emerge as the times require. Compared with Global Positioning System [4], Network Time Protocol [5] and other time synchronization technologies [6,7], IEEE 1588 protocol has some advantages such as high synchronization precision (the time synchronization accuracy level can reach sub-microsecond and even nanosecond in theory), convenient installment, low cost realization and facilitate maintenance [8]. Its high precision and networking features can be widely adapted for the development of applications in smart grid. Therefore, studies on IEEE 1588 time synchronization have been of utmost interest in both academic and industrial community. Among them, the quality of the applied algorithm will directly affect the accuracy of time synchronization.

In recent years, many time synchronization algorithms based on IEEE 1588 have been proposed to achieve the master–slave clock synchronization such as postponed compensation algorithm [9], weighted least-squares algorithm [10], compensate algorithm in slave clock [11], neural network-based proportional–integral–derivative (PID) control algorithm [12–14], optimal linear quadratic Gaussian controller [15], and Kalman filter [16]. Because of the simple structure, robust performance and stable characteristic, the PID controller has been widely applied in the process control field [17–20]. Using the PID control algorithm to continuously adjust the frequency of the slave clock can realize the synchronization with the master clock. Now, with the development of PID controller parameters optimization method, a variety of techniques have been used to enhance the performance of the PID controller such as neural network [21], genetic algorithm (GA) [22] and particle swarm optimization (PSO) [23,24]. But neural network method is prone to numerical ill-conditioning problem due to the requirement of repeated training with large numbers of

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samples, GA has slow evolutional speed and premature convergence, PSO is easy to fall into the local minimum.

In practice, the neural network-based PID control algorithm [12] can achieve good results only if a suitable network structure is chosen. However, choosing a proper network structure is often difficult. So, in this paper, a new global optimization technique is combined with the PID control algorithm for optimal tuning the PID parameters, making the method more intelligent and flexible.

The idea of wolf pack search (WPS) was first proposed by Yang et al. in 2007 [25]. After that, polished and modified versions were developed in succession such as wolf colony algorithm (WCA) [26] and wolf colony search algorithm based on leader strategy (LWCA) [27]. The complete version-WCA is a new swarm-intelligence global optimization method that studies the intelligent predatory behaviors and prey assignment rule of the wolf colony. The algorithm has a good convergence and global searching ability, it is quite better than PSO and some other previous algorithms [26]. In addition, WCA has a good generalization and can be used in many fields of optimization. Based on the superior performance of WCA, this paper applied WCA to the design of PID controller for optimal tuning of the parameters to ensure an adaptive control for the slave clock rate. The WCA-based PID control algorithm can primely compensate the offset error between the master clock and slave clock, to realize the control of high precision time synchronization. It is suitable for applications such as the network offline decision [28], fault diagnosis and analysis [29], chronological record [30] which do not need strict real-time processing.

In our previous work [31], an adaptive filtering algorithm for time synchronization was proposed. However, this method only concentrated on the phase offset without the frequency adjustment, which limited the precision of the time synchronization. This paper extends the slave clock model to a full model considering both phase offset and frequency drift, and then uses the optimal PID controller to adjust the rate of the slave clock to minimize the time deviation between the slave clock and master clock to achieve a higher accuracy. The adaptive filtering method [31] will be compared in Section 'Experiments and results analysis' to prove the necessity to adjust the frequency of the slave clock.

The major aim and contribution of this paper is to introduce the IEEE 1588 time synchronization principle (Section 'IEEE 1588 time synchronization principle') and a new evolutionary optimization technique-WCA (Section 'WCA'). In addition, by analyzing the clock model (Section 'Clock modeling'), a novel approach using PID controller in cooperation with the WCA is proposed and introduced to the precision time synchronization technique for smart grid (Section 'WCA-based time synchronization control method'). The proposed method can adaptively and optimally adjust the frequency of the slave clock to eliminate the offset of the slave clock with respect to the master clock, so that the slave clock can accurately synchronize with the master clock.

IEEE 1588 time synchronization principle

IEEE 1588 defines a precise master–slave time synchronization protocol in networked measurement and control system. It relies on a precise master clock to correct the entire slave clocks in the network periodically. After a master–slave hierarchy has been established, time-stamped messages are exchanged between the master and slave clock to enable the slave to measure the time on the master clock [32]. The synchronization process mainly includes two steps: calculating the time offset and calculating transmission delay, which uses four kinds of messages to conduct a handshake communication: (1) synchronization message (Sync); (2) following message (FOLLOW_UP); (3) request message (DELAY_REQ); (4) delay response message (DELAY_RESP). The synchronization process diagram of PTP between the master clock and the slave clock is shown in Fig. 1.

The master clock periodically sends the Sync message to the slave clock at a default rate of once every 2 s (this time period can be set), and measures the sending time TM1. Upon the reception of the Sync message, the slave clock stores the arrival time TS1. Then the master clock sends a FOLLOW_UP message containing the actual value of the time TM1. After that, a DELAY_REQ message is sent from the slave clock to the master clock, and the sending time TS2 is recorded. The master clock receives the DELAY_REQ message, and sends back the DELAY_RESP message which includes the exact reception time TM2.

When the message exchange is completed, the slave clock processes all 4 time stamps. The equations used to calculate the time offset of the slave clock with respect to the master clock and the average transmission delay between two nodes are given as follows:

$$T_{m2s} = \mathrm{TS1} - \mathrm{TM1} = D_{DL} + Offset \tag{1}$$

$$T_{s2m} = \mathrm{TM2} - \mathrm{TS2} = D_{UL} - Offset \tag{2}$$

Assuming that the communication links are symmetrical, then

$$D_{DL} = D_{UL} \tag{3}$$

$$Delay = \frac{D_{DL} + D_{UL}}{2} = \frac{\mathrm{TS1} - \mathrm{TM1} + \mathrm{TM2} - \mathrm{TS2}}{2} \tag{4}$$

$$\begin{aligned} Offset &= \mathrm{TS1} - \mathrm{TM1} - Delay \\ &= \frac{\mathrm{TS1} - \mathrm{TM1} - \mathrm{TM2} + \mathrm{TS2}}{2} \end{aligned} \tag{5}$$

The slave clock adjusts its time to minimize the value of *Offset*, thereby achieving synchronization with the master clock [33].

Clock modeling

The ideal clock is usually measured by the crystal oscillator pulse, i.e.

$$c(t) = k\int_{t_0}^{t} \omega(\tau)d\tau + c(t_0) \tag{6}$$

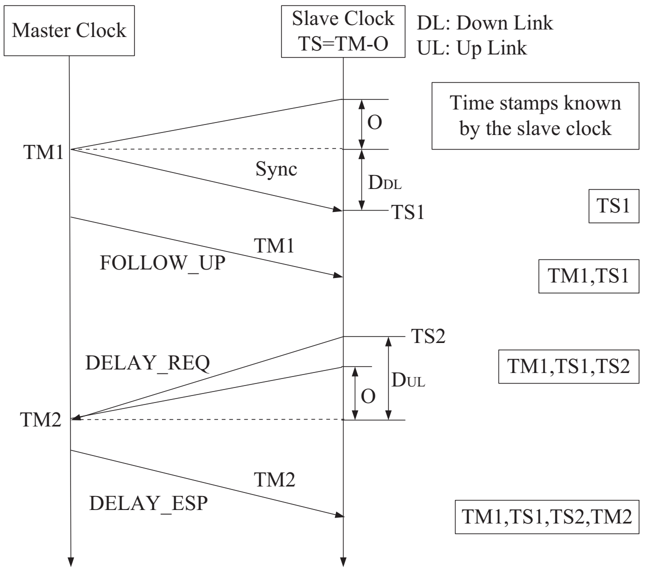

Fig. 1. PTP synchronization process.