

# Modeling of IEEE1588 on OPNET and Analysis of Asymmetric Synchronizing Error in Smart Substation

Jiongcong Chen<sup>1</sup>, Haizhu Wang<sup>2</sup>, Chunchao Hu<sup>1</sup>, Kai Ma<sup>1</sup>, Zexiang Cai<sup>2</sup>

<sup>1</sup>Electric Power Research Institute, Guangdong Power Grid Corporation, Guangzhou, China

<sup>2</sup>South China University of Technology, Guangzhou, China

Email: 20801244@qq.com

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## ABSTRACT

The IEEE1588 network time synchronization, matched with smart substation information network transmission, is becoming the next generation advanced data synchronization of the smart substation. It is known that the inherent asymmetry error of the network synchronization approach in the smart substation is highlighted, which is concerned particularly. This paper models the synchronization process of the IEEE1588 based on the communication simulation software of OPNET Modeler. Firstly, it builds the models of master-slave clock, IEEE1588 protocol and network synchronization model, and analyzes the composition and influencing factors of the asymmetry error. Secondly, it quantitatively analyzes the influence of the synchronous asymmetric error of the IEEE1588 affected by the network status differences and the clock synchronization signal transmission path differences. Then its correction method is analyzed, in order to improve the IEEE1588 synchronization reliability and gives the solutions to its application in smart substation.

**Keywords:** Smart Substation; IEEE1588; Synchronization; Asymmetric Error

## 1. Introduction

As the important node of the smart grid, the smart substation based on network communication provides grid application oriented integration data platform, its biggest feature and advantage is information sharing [1-3]. The synchronization of high precision data is the important premise and basic properties to realize information sharing. Application system such as relay protection, SCADA, PMU and so on has a high requirement on the data synchronization which is paid much attention as the core problem of smart substation technology [4-6].

At present, the smart substation data synchronization usually adopts IRIG-B, and uses point-to-point link with exclusive fiber optic, sending the unidirectional synchronization signal. This type of flow reliability conflicts with the network information transmission mode of smart substation [7-8]. IEEE1588 as precision clock synchronization protocol matches with Intelligent substation network transmission mode based on IEC61850 [9], can share network resources with other packet, and eliminates the timestamp mark error of NTP/SNTP protocol mode and its synchronization is accurate to sub-microsecond, which is becoming the next generation synchronization mode of the smart substation, with good development prospects.

At the same time, with the inherent defect of uncertain

network synchronization, synchronized asymmetry error may occur in the synchronization of IEEE1588 because of differences running state and transmission path in the network.

Under the high data synchronization requirements of smart substation, the issue becomes more prominent [10-12]. At present, due to the lack of quantitative analysis tools and methods, the study of IEEE1588 is limited to the field test, the study on the forming mechanism, influence degree and countermeasure of the dissymmetric error is nearly in a gap, which limits its popularization and application [13-14].

This paper develops a IEEE1588 synchronization process modeling of smart substation with a communication simulation software named OPNET Modeler, and analyzes the differences of network status and the master-slave clock synchronization signal transmission path quantitatively [15], then studies the influence on IEEE1588 synchronous asymmetry error[16], as also as its correcting method.

## 2. Asymmetric Synchronizing Error

IEEE1588 precision clock synchronization protocol was promulgated by the IEEE standard committee in 2002, which is to meet the high-precision requirement of the measurement and control applications in a distributed

network of timing synchronization. It's a brand-new attempt to introduce IEEE1588 into power domain that is consistent with smart substation network transmission, and is beneficial to take advantage of information sharing. But as a network synchronization mode, the problem of uncertainty is also prominent which needs to be studied in depth.

### 2.1. IEEE 1588 Protocol and Synchronization Process

#### 1) IEEE 1588 protocol feature

IEEE1588 protocol is a distributed network synchronization protocol, and it doesn't need networking singly [17]. It can share hardware resources on network, and chooses multiple transmission paths flexibly, also can get the real-time status of other nodes on network. It ensures the reliability of the synchronization system.

Traditional network synchronization time stamp was performed by the software, and the position of time stamp is on application layer, so the message parsing and packaging processing delay constitute a part of synchronization error. As IEEE1588 Protocol time stamps on physical layer exit by hardware using the technology of accessing MAC by Ethernet media, which eliminates part error of time delay, as shown in **Figure 1**.

#### 2) Synchronization process

IEEE1588 synchronization process is shown in **Figure 2**.

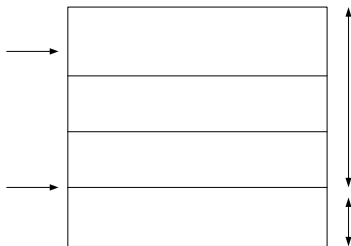


Figure 1. Time stamp of network synchronization.

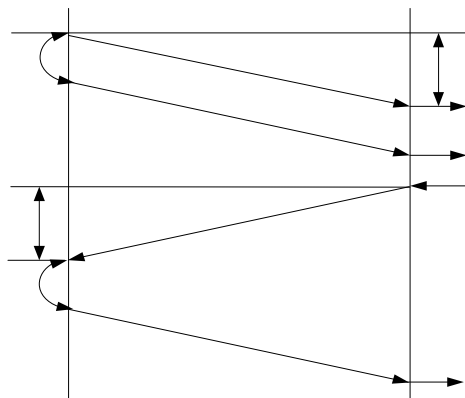


Figure 2. Synchronization process of IEEE1588.

Assuming that the master clock and the slave clock deviation is *offset*, that is  $offset = t_{slave} - t_{master}$ , the slave clock at the local time  $t_1$  sends synchronization request packets to the master clock, the master clock receives synchronization request packets at the local time  $t_2$ . Assuming transmission delay from the slave clock to the master clock is  $\delta_1$ , so

$$t_2 = t_1 + offset + \delta_1 \tag{1}$$

The master clock sends synchronization packets to the slave clock at  $t_3$ , and the synchronization packet includes two time scales as  $t_2$  and  $t_3$ . The slave clock receives the synchronization packet at  $t_4$ . If transmission delay from the master clock to the slave clock is  $\delta_2$ , so

$$t_4 = t_3 - offset + \delta_2 \tag{2}$$

All  $t_1, t_2, t_3$  and  $t_4$  are known quantities in formula (1) and (2), but *offset*,  $\delta_1$  and  $\delta_2$  are unknown quantities. Assumes  $\delta_1 = \delta_2$ , so the slave clock can solve and correct the time error offset based on the formula (1), so

$$offset = \frac{(t_2 - t_1) - (t_4 - t_3)}{2} \tag{3}$$

### 2.2. The Influences of IEEE1588 Asymmetric Error

The importance assumption of IEEE1588 synchronization is round-trip transmission path symmetry, transmission delay  $\delta_1 = \delta_2$ , since the differences in both network status and transmission path dynamics, transmission delay  $\delta_1$  and  $\delta_2$  generally are not equal, which cannot be deleted directly, so formula (3) should be corrected as:

$$offset = \frac{(t_2 - t_1) - (t_4 - t_3) + \delta_2 - \delta_1}{2} \tag{4}$$

$$\Delta t = \frac{\delta_2 - \delta_1}{2} \tag{5}$$

$\Delta t$  is asymmetric error, the influences of IEEE1588 asymmetric error mainly includes:

#### 1) The difference of transmission path

Transmission delay  $\delta$  is composed of link transmission delay  $D_{link}$  and switch transmission delay  $D_{switch}$ , so

$$\delta = D_{link} + D_{switch} \tag{6}$$

Synchronous packet is stored and forwarded by the switch address analytical table dynamically, as round-trip transmission path may be different when the synchronous packet passes switch and link,  $D_{link}$  and  $D_{switch}$  are not symmetrical generally. The transfer rate of optical fiber link is 2/3 of velocity of light, that is to say the transmission delay of one 1000-meter link is 5 $\mu$ s. A switch packet processing delay is microsecond level, but

the synchronous precision requirement of IEEE1588 protocol is sub-microsecond level, so the unequal  $\Delta t$  from transmission path cannot be ignored.

2) The difference of network status

The communication running state is dynamic, and running state  $S_i$  is closely related to load conditions of network, so the switch processing delay  $D_{switch}$  is different under different running state  $S_i$ . As a result, even round-trip transmission path is symmetry, as the network status is different, then transmission delay  $\delta_1$  and  $\delta_2$  are not equal.

All the people hold the same attitude that the asymmetric error makes IEEE1588 synchronization precision jitter, but the study of asymmetric error stays on qualitative analysis level because of limited to the research methods. Once the synchronous system of smart substation out of step, the protection device may lock, wrong operator miss operate, even more severe is that the secondary system becomes breakdown. So it is necessary to build a synchronous process simulation model of IEEE1588 and quantitative analysis IEEE1588 asymmetric error and then formulate countermeasures.

### 3. Synchronous Process Modeling and Asymmetric Error Analysis

IEEE1588 synchronous process model includes master-slave clock model and synchronous network model, and the model reflects several features: IEEE1588 protocol packet processing mechanism, the technique of time stamp on the physical layer exit by hardware, synchronization network made by switch and optical fiber and asymmetric error [18].

#### 3.1. IEEE Master-Slave Clock Model

Figure 3 is based on IEEE1588 master-slave clock model, it mainly completes following several functions:

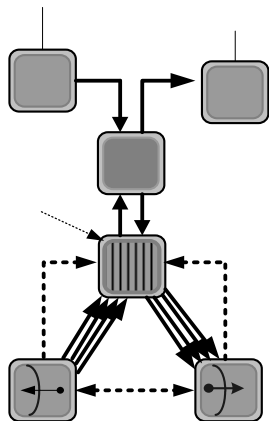


Figure 3. Clock model based on IEEE1588.

1) Synchronous packet formation

Master-slave clock sending model produces four main synchronous packets according to different trigger conditions, master clock produces a Sync packet per second, then put Sync packet sending time  $T_1$  on Follow up, after receiving the request Delay\_req from slave clock, put receiving time  $T_4$  on response Delay\_resp packet.

2) IEEE1588 protocol package and analysis

The four main synchronization packets of IEEE1588 are sync, follow up, delay\_req and delay\_resp, and they have the same format and the same 64Byte long frame with padding bytes, but their time stamps have different information. Use the following up packet model as an example, origin Timestamps master clock sends time  $T_1$ , and sync interval is synchronous period(usual is 1 second), grandmaster Clock Variance is the change rate of master clock. The data link layer package and analysis packet MAC address, and interface module is general module, completing the protocol analysis and the data packet filling from the data link layer to application layer in IEEE1588.

3) Time stamp marker and read

Different from NTP/SNTP traditional synchronization protocol which is marking and reading time stamp on application layer, time node model of IEEE1588 puts time stamp marker function `op_pk_stamp(pkptr)` and reading function `op_pk_stamp_time_getpkptr` on the exit of the data link layer, to realize time stamp marker and read function of clock, and reduce protocol analysis time.

4) Calculation and correction of Master-slave clock offset and asymmetric error

The slave clock uses formula (7) to calculate and correct master-slave clock offset and asymmetric error  $\Delta t$ .

$$offset_{(i+1)} = offset_{(i)} - T_{(i)} - delay\_offset_{(i)} \quad (7)$$

$T$  is master-slave clock's correction value through the calculation of  $t_1$ ,  $t_2$ ,  $t_3$  and  $t_4$  according to formula (3), and  $delay\_offset$  is asymmetric error  $\Delta t$ .

Some codes of master clock model areas follows:

```

/* Setpacket formal,send information and so on,and
put sending time  $t_1$  on the */
/* package of follow_up */
pkptr =op_pk_create (pksize);
t1=(op_pk_creation_time_get(pkptr))*1000000000;
pkptr_Sync=op_pk_create_fmt("Sync");
pkptr_Follow_up=op_pk_create_fmt("Follow_up");
op_pk_nfd_set(pkptr_Follow_up,"originTimestamp",t
1);
....
op_pk_fd_set(pkptr,1,OPC_FIELD_TYPE_INTEGER
,1,16);
op_pk_fd_set(pkptr,2,OPC_FIELD_TYPE_PACKET,
pkptr_Sync,464);
/* Put receiving time  $t_4$  of Delay_req packet on

```

```

response packetDelay_resp. */
pkptr = op_pk_get (op_intrpt_strm ());
op_pk_stamp(pkptr);
t4=(op_pk_stamp_time_get(pkptr))*10000000000;
op_pk_nfd_set(pkptr_Delay_resp,"originTimestamp",t
4);
Some codes of slave clock model areas follows:
/* Calculate and correct master-slave clock offset and
asymmetric errordelay_offset. */
T=((t2-t1)-(t4-t3))*0.5;
delay_offset=((t2-t1)+(t4-t3)) *0.5;
offset=offset-T- delay_offset;
    
```

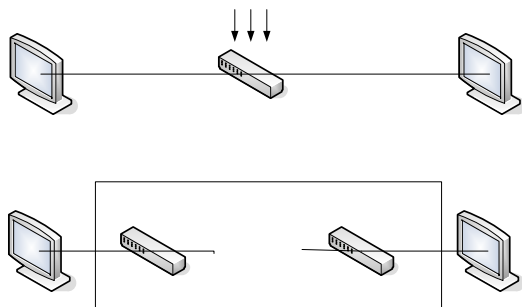
### 3.2. Network Synchronization Model

Network synchronization model includes running status network model, transmission path network model, the switch with 500000 p/s processing capacity and the 100M optical fiber link, shown as **Figure 4**. In **Figure 4(a)**, to observe the transmission delay with different network running status, inject background traffic into switch. In **Figure 4(b)**, to observe the transmission delay with different transmission path, increasing the number of switch from 0 to 3 on master-slave synchronous packet transmission path.

Different network running status

### 3.3. Asymmetric Error Simulation

**Table 1** is the performance of transmission delay, injects different background traffic to the switch. When background traffic is 25%, transmission delay is 262.993  $\mu s$ , which costs 1  $\mu s$  more compared to transmission delay without background traffic. Transmission delay becomes 2.667  $\mu s$  when background traffic is 40%. When background traffic increases to 95%, transmission delay is 337.993  $\mu s$ . Value of transmission delay varies from 0.211  $\mu s$  to 76  $\mu s$  on different background traffic, and it enlarges constant. Asymmetric error  $\Delta t$  from different network running status could not be ignored.



**Figure 4. Network synchronization model.**

### 2) Different transmission path

From **Table 2**, when the number of switch increases one more, transmission delay will increase 87. So when configuration of communication network switch change and master-slave clock round-trip transmission path differ one or one more switch, correction of asymmetric error  $\Delta t$  must exist.

So assumption of master-slave clock round-trip transmission path is equal exists defect, asymmetric error from different network status and transmission path should be a necessary link of synchronous correction.

## 4. Asymmetric Error Correction

There are some differences between smart substation communication network and general LAN: 1) the structure of network is simple. Configuration of smart substation secondary system is normative according to voltage level, the number of devices are limited, switches are no more than four in general; 2) Traffic flow is specific. All automatic business such as measurement, protection, test and control and etc. have their corresponding SV/GO-OSE/MMS/Synchronization information flow, and the feature of information flow is specific, little uncertain flow. Specific feature of smart substation communication network makes asymmetric error correction feasible.

### 4.1. Asymmetric Error Correction Method

Assuming at time  $t$ , master-slave clock transmission delay is measured by network monitoring device.

**Table 1. Impact of background traffic on transmission delay.**

Background traffic	Delay( $\mu s$ )
0%	261.993
5%	262.204
10%	262.438
20%	262.993
40%	264.660
80%	277.993
95%	337.993

**Table 2. Impact of path on transmission delay.**

The number of switch	Delay( $\mu s$ )	The increase of transmission delay( $\mu s$ )
0	88.553	/
1	176.207	87.654
2	261.993	85.786
3	349.145	87.152

$$\delta_{1t} = D_{link1t} + D_{switch1t} \tag{8}$$

$$\delta_{2t} = D_{link2t} + D_{switch2t} \tag{9}$$

According to formula (5), asymmetric error  $\Delta t_i$  is:

$$t_i = \frac{\delta_{2t} - \delta_{1t}}{2} \tag{10}$$

Put  $\Delta t_i$  from formula (10) into master-slave clock correction, that is  $delay\_offset(i)$  in formula (7).

Since  $\delta_{1t}$  and  $\delta_{2t}$  are got from measurement in operation, correction error exists because of measurement.

### 4.2. Asymmetric Error Correction Simulation Analysis

#### 1) Simulation scenario setting

Asymmetric error correction simulation model is shown as **Figure 5**. Master clock transmission path is from *switchA* to slave clock, while return path is composed of EDCB.

Setting parameters of asymmetric error simulation as **Table 3**:

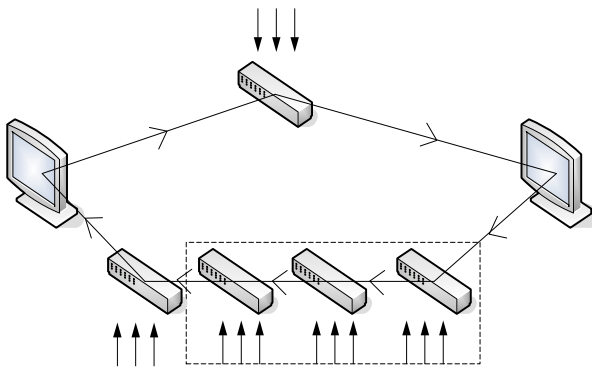
#### 2) Analysis of asymmetric error simulation results

Results of asymmetric error simulation are shown in **Figure 6**. *Curve1* is uncorrected asymmetric error  $\Delta t$ , from 0 to 34 s, range of  $\Delta t$  is 0-0.987  $\mu s$ , synchronous error less than 1  $\mu s$ , from 35s to 100s, with the increasing

background traffic,  $\Delta t$  enlarges to 1.143-41.937  $\mu s$ . Obviously  $\Delta t$  has completely over the minimum requirement that IEEE1588 synchronous precision should less than 1  $\mu s$ . At the time of 101s, 116s and 131s, the number of slave clock path switch turn into 2, 3 and 4,  $\Delta t$  enlarges to 43.5010-136.169  $\mu s$  further.

As correction error is 1%, *curve2* is asymmetric error  $\Delta t$  which uses the corrected method of this paper to correct. From 0 to 100s, and when master-slave round-trip switches have the same number, the range of background traffic is 0-100%,  $\Delta t$  is 0-0.419  $\mu s$  after correction. From 101 to 130s, the differ number of round-trip switch is 2, and the range of background traffic is 0-14%,  $\Delta t$  increases to 0.435-0.909  $\mu s$ . At the time of 131s, the number of switch turn into 3,  $\Delta t$  is 1.305  $\mu s$ , over 1  $\mu s$ , and it cannot meet the requirement of IEEE1588 synchronous precision.

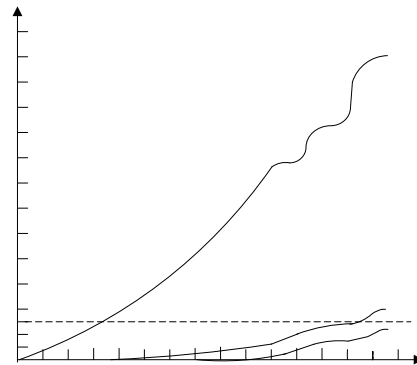
*Curve3* is the change condition of  $\Delta t$  after correction when assume correction error is 0.5%. The range of  $\Delta t$  is 0-0.681  $\mu s$  after correction, even the differ number of master-slave round-trip is 3, it still can meet the precision requirement of 1  $\mu s$ .



**Figure 5. Synchronization network model in asymmetric error simulation.**

**Table 3. Parameters of asymmetric error simulation.**

Simulation time(s)	Path of master-slave clock		Path of slave-master clock	
	switch	Background traffic(%)	switch	Background traffic(%)
0-100			B	0-100
101-115	A	0	CB	
116-130			DCB	0-14
131-145			EDCB	



**Figure 6. Results of asymmetric error simulation**

To sum up, asymmetric error  $\Delta t$  of master-slave clock link impacts IEEE1588 synchronous precision seriously, while the correction method of this paper will reduce the impact of asymmetric error greatly. Relative certainty of smart substation communication network makes the measurement of  $\delta_{1t}$  and  $\delta_{2t}$  feasible, the problem of asymmetric error of network synchronization can be solved effectively by the error correction which is according to this.

### 5. Conclusions

This paper develops IEEE1588 synchronous process model, quantitatively analyses asymmetric error from network running status and the difference of master-slave clock transmission path, researches that the correction can supply a new approach and method expecting for actual

measurement for the quantitative analysis of IEEE1588 synchronization process, and develops research thought of IEEE1588 synchronization uncertainly problem.

Although IEEE1588 has necessitated solved questions, IEEE1588 adapts to the development trend of smart substation network transmission. To search and improve reliable method of IEEE 1588 synchronization, overcome network uncertainly shortcomings, make full use of network synchronization is the inevitable trend for the synchronization technique of smart substation.

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