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Principles for reducing the phase shift between instantaneous analogue and discrete signals and the corresponding values in the sampled values (SV) stream of a digital substation

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Abstract. There are numerous publicly available articles on digital substations, including those dedicated to current and voltage measurements, time synchronization, test systems development, principles of substation design, and other aspects of this topic. But the phase shift between instantaneous signals and the corresponding values in the SV (sampled values) stream has been little discussed. We can list the following principles to reduce the phase shift between instantaneous analogue and discrete signals and the corresponding values in the SV stream. 1) Exclusion from the device, of non-essential elements that introduce additional propagation delays of analogue and discrete signals, provided that such exclusion does not adversely affect the device performance or characteristics. 2) Reduction of the delay time for the other device elements to the minimum values. 3) Adjustment of the delay time of some device elements or addition of special delay elements to equalize the time of signal propagation over analogue and discrete channels. 4) Consideration of the total delay time of signal propagation over analogue and discrete channels and adjustment of the time stamp in the SV frame. The article provides examples of application of these principles in signal generation and measuring devices and phase shift meters.

1 Principles for reducing the phase shift between instantaneous analogue and discrete signals and the corresponding values in the SV stream

There are numerous publicly available articles on digital substations, including those dedicated to current and voltage measurement [1-5], time synchronization [6-10], test systems development [11-12], principles of substation design [13-14], and other aspects of this topic [15-20]. But the phase shift between instantaneous signals and the corresponding values in the SV (sampled values) stream has been little discussed.

We can list the following principles for reducing the phase shift between instantaneous analogue and discrete signals and the corresponding values in a SV stream.

1. Exclusion from the device, of non-essential elements that introduce additional propagation delays of analogue and discrete signals, provided that such exclusion does not adversely affect the device performance or characteristics.
2. Reduction of the delay time for the other device elements to the minimum values.
3. Adjustment of the delay time of some device elements or addition of special delay elements to equalize the time of signal propagation over the analogue and discrete channels.
4. Consideration of the total delay time of signal propagation over the analogue and discrete channels and adjustment of the time stamp in the SV frame.

2 An example of application of the principles in a signal generation device and a phase shift meter

Figure 1 shows an example of a joint operation of a signal generator and a phase shift meter. These devices must be synchronized with the master clock (time server), for example, via the PTP protocol. This protocol ensures that the following relations will be satisfied:

$$
\begin{aligned}
&| T_{\mathrm{cur1}} - T_{\mathrm{cur2}} | \le 1 \text{ ms},\\
&| T_{\mathrm{cur}} - T_{\mathrm{cur1}} | \le 1 \text{ ms},\\
&| T_{\mathrm{cur}} - T_{\mathrm{cur2}} | \le 1 \text{ ms}
\end{aligned}
\qquad (1)
$$

T_{cur} is the current time of the time server (exact time), T_{cur1} and T_{cur2} are the current times of the first and the second devices.

The external computer sets the parameters of the signals generated by the first device. The internal computer generates a digital signal according to the task. This signal is amplified to the required level to be transmitted over a digital line. For transmission over an analogue line, the original digital signal must pass through a digital-to-analogue converter (DAC) and a

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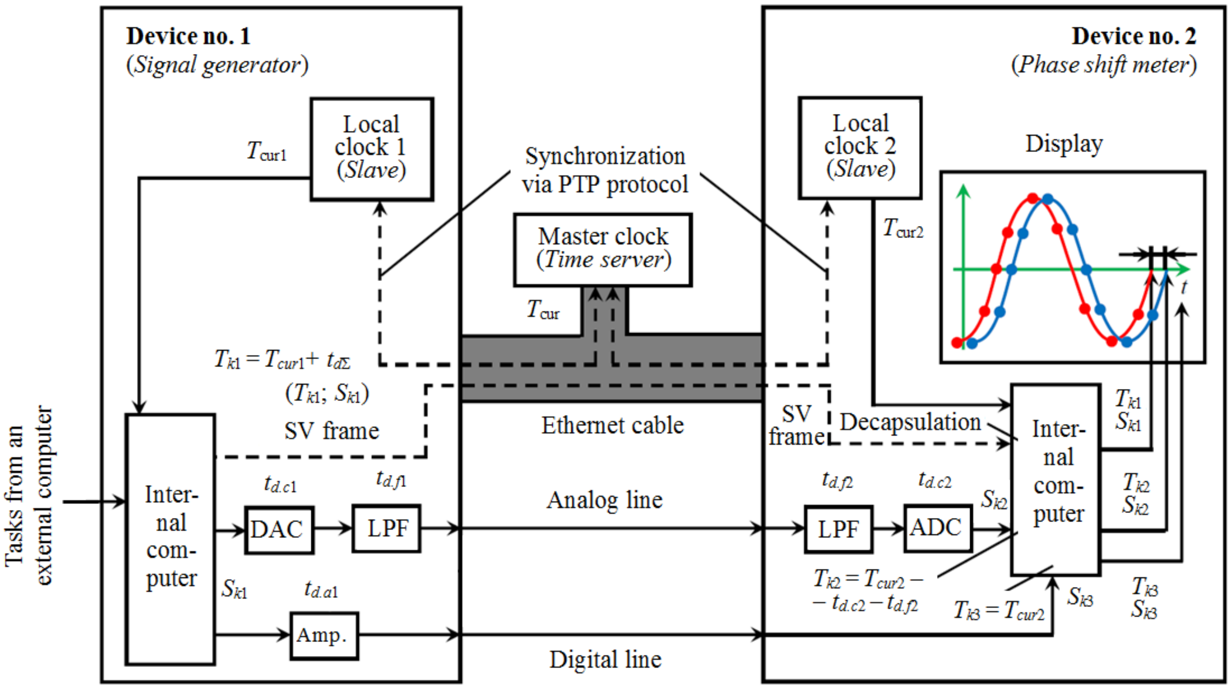

Fig. 1. An example of a joint operation of a signal generator and a phase shift meter.

low-pass filter (LPF). If necessary, the received signal must also be passed through the amplifier.

It is necessary to minimize the difference between the total delays in the analogue and digital channels using the above principles in order to satisfy the condition:

$$t_{d.a1} \approx t_{d.c1} + t_{d.f1} = t_{d\Sigma}\,. \qquad (2)$$

$t_{d.a1}$ is the delay time of the amplifier in the digital channel, $t_{d.c1}$ and $t_{d.f1}$ are the delay times of the converter and the filter in the analogue channel, $t_{d\Sigma}$ is the indication of the total delay in these channels.

The time delays can be calculated or measured at the device design stage, and the total time delays in the analogue and digital channels $t_{d\Sigma}$ can be made approximately the same. When forming the SV frame, this delay can be taken into account at time stamping

$$T_{k1} = T_{cur1} + t_{d\Sigma}\,. \qquad (3)$$

T_{k1} is the time value in the SV frame corresponding to the sample S_{k1}.

The described measures will allow reduction of the phase shifts between the analogue and digital signals and the signal values in the SV stream.

In the phase shift meter (in the second device), the SV frame undergoes decapsulation in the internal computer, so the current sample will have the same time value T_{k1} as set for the first device. The digital signal to the internal computer arrives without delay. In the analogue channel, there are delays $t_{d.f2}$ and $t_{d.c2}$ in the low-pass filter and the analogue-to-digital converter (ADC). The internal computer must take these delays into account and adjust the time value T_{k2} for the digitized value:

$$T_{k2} = T_{cur2} - t_{d.c2} - t_{d.f2}. \qquad (4)$$

After the adjustment, all the three signals can be displayed on the screen, for their phase shifts to be compared. The internal computer can also calculate these phase shifts and show them on the display, because they may be otherwise unnoticeable.

3 An example of application of the principles in a measuring device

In the signal meter (Figure 2), additional delays may appear in the current transformer $t_{d.ct1}$ and the voltage transformer $t_{d.vt1}$. It is desirable that the following conditions be satisfied:

$$t_{d.ct1} = t_{d.vt1} = t_{d.t1}. \qquad (5)$$

If the delay times $t_{d.ct1}$ and $t_{d.vt1}$ are sufficiently small, they can also be neglected.

Over the analogue lines, signals propagate without delays (unless delays in the transformers are taken in account). It is necessary to minimize delays in the digital channels in the low-pass filter $t_{d.f1}$ and the ADC $t_{d.c1}$, or introduce additional delays in the analogue channels to satisfy the condition:

$$t_{d\Sigma a} \approx t_{d\Sigma d} = t_{d\Sigma}. \qquad (6)$$

$t_{d\Sigma a}$ and $t_{d\Sigma d}$ are the total delays in the analogue and digital channels. For the case shown in Figure 2

$$t_{d\Sigma a} = t_{d.t1},\; t_{d\Sigma d} = t_{d.t1} + t_{d.f1} + t_{d.c1} + t_{d.a1}\,. \qquad (7)$$

When forming an SV frame, the internal computer must consider this delay at time stamping:

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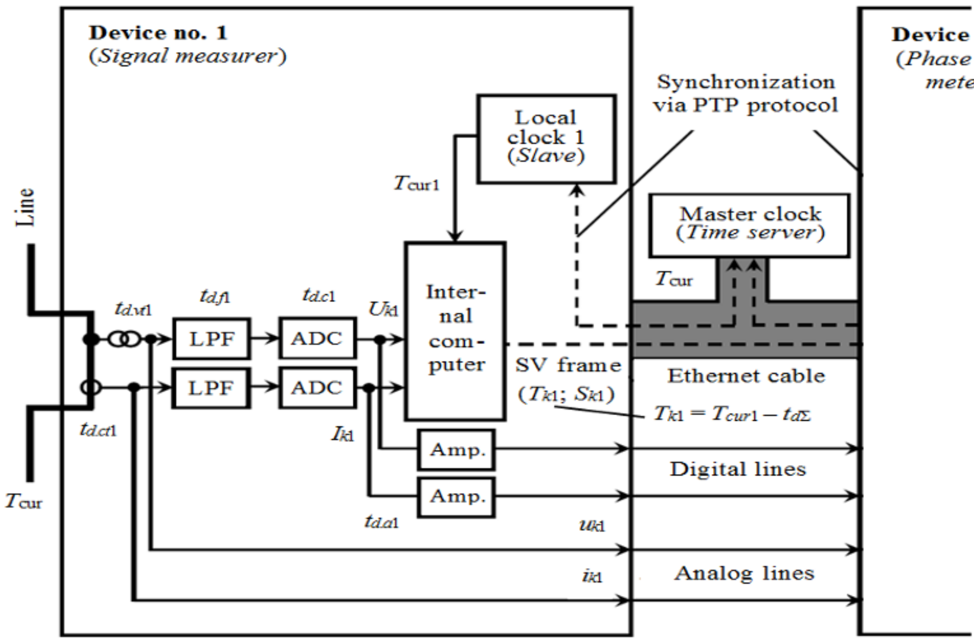

Fig. 2. The structure of the signal meter.

$$T_{k1} = T_{cur1} - t_{d\Sigma}. \quad (8)$$

As you can see, the $t_{d\Sigma}$ value needs to be subtracted from the current time value T_{cur1}.

4 Conclusions

This article lists the basic principles for reducing the phase shift between instantaneous analogue and discrete signals and the corresponding values in a SV stream in a digital substation. Two examples illustrate the practical application of these principles.

The structural diagrams of the generator and the signal meter, as well as the phase shift meter shown in the examples, can be very useful in designing the circuits of these devices. The formulas given in this article can be used in the algorithms of the internal computers of the said devices to reduce the phase shift between instantaneous analogue and discrete signals and the corresponding values in the SV stream.

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