Design of real time system to measure the voltage signal in high voltage power supply

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Abstract. The output voltage signals should be measured in real-time, and it is sent to a control system for feedback control and protection in the high-voltage power supply with high-voltage, strong magnetic field, or strong power condition. In order to obtain a stable output voltage and a rapid response of the protection in the high-voltage power supply system, the measurement of the voltage signal needs to meet three requirements: response in real-time, accurate, and high isolation. Using the voltage-to-frequency (V/F) converter AD650 to transmit the analog signals as frequency form through the digital optical fiber is the best mode to measuring the signals with high precision, real-time, long-distance, and high isolation. The composition and principle of the real-time voltage measuring device are described in this paper. The design of the hardware and the parameters are analyzed and discussed in detail. The experimental results show that the circuit structure based on the AD650 chip is simple. The optical fiber transmission can achieve high isolation and high accuracy (better than 0.1%). The low response time (under 30us) can meet the requirements of the real-time voltage signal measurement system. The signal will not be affected by the high electromagnetic field in the transmission process. The measurement system has been applied in the high voltage power supply with excellent linearity and high isolation.

Keywords: Real-time measurement system; Signal transmission; Voltage-to-Frequency (V/F) converter; Frequency-to-Voltage (F/V) converter.

1. Introduction

The output voltage and current of high-power devices and high-voltage power supply systems should be stable under the control of computer programs. High power devices or equipment need to be detected and controlled in high voltage and strong magnetic power supply systems. In order to avoid damage to the measurement system and control system by complex factors such as high voltage and strong magnetic field, a measurement device or system is required to obtain real-time and accurate voltage or current signals, and the transmission circuit has to transmit the signals quickly and accurately. Simultaneously, the real-time measurement device ensures that the power supply control system and the output end of the high voltage system are electrically isolated completely [3]. The isolation voltage of an ordinary isolation converter is about several thousand volts, which cannot meet the harsh occasions where the isolation voltage level is over ten thousand volts. However, long-distance signal transmission and high isolation can be achieved by optical fiber transmission with large frequency bandwidth, large information capacity, low transmission loss, strong anti-interference ability, high insulation, and easy maintenance [4]. The transmission loss of the optical fiber is minimal, and the output accuracy of the electro-optical conversion circuit is the critical factor. Sometimes, the voltage signal is subject to strong electromagnetic interference and fluctuates greatly, so the accuracy of the input signal will be affected, and the measurement of the feedback signal will be inaccurate if the voltage signals are directly converted to optical signals by an electro-optical conversion circuit. However, the frequency signal has the characteristics of strong anti-interference ability...
The input accuracy of the voltage signal can be improved by converting the voltage signal into a frequency signal with voltage-frequency conversion technology (V/F).

The measurement device is composed of VFC, optical fiber link and FVC to realize the characteristics of high accuracy, high isolation voltage, strong anti-interference ability, wide input signal range and real-time detection of sampled signals.

### 2. Structure of the measurement device

The optical fiber real-time measurement device is composed of a sampling signal conditioning circuit, an impedance matching circuit, a V/F conversion circuit, an optical fiber drive circuit, an optical fiber, an optical fiber receiving circuit, an F/V conversion circuit, and a signal restoration circuit. The principle block diagram is shown in figure 1.

![Figure 1 The principle block diagram](image)

Optical fiber can be divided into two parts: the transmitting part and the receiving part. The measurement data is transmitted between the two through the optical fiber. The transmitting part mainly includes a sampling signal conditioning circuit, impedance matching circuit, V/F conversion circuit, and optical fiber driving circuit. The receiving part mainly includes the optical fiber receiving circuit, F/V conversion circuit, and signal restoration circuit. Both V/F and F/V converters can be obtained with high-precision AD650. The voltage-frequency conversion circuit V/F converter converts the linear input voltage/current signal into a pulse frequency signal. The frequency of the pulse signal is proportional to the input DC voltage/current. The pulse frequency signal can be transformed into an optical signal for transmission through the optical fiber. The optical fiber receiving circuit’s function is to receive the optical signal transmitted by the optical fiber, restore the optical signal to a pulse frequency signal, and then convert it into a voltage signal through F/V.

### 3. The analysis and design of the circuit

#### 3.1 The front-end modulation circuit

The front-end modulation circuit comprises a sensor and an amplifier, which has the characteristics of suppressing temperature drift and flexible setting of gain. It is an effective method to suppress interference using an amplifier to adjust the gain of the sensor’s output voltage or current signal in the presence of induced, leaked, or coupled electromagnetic interference noise. The amplifier model and peripheral circuit parameters should be determined by actual needs. The circuit is shown in figure 2.

When the input voltage of AD650 is 0–10V, the corresponding output frequency range is the widest (0–1MHz). The input signal should be within the range of 0–10V, which has better conversion results. OP27 is selected as the amplifier chip in the measurement device. The input voltage of OP27 is -11V to +11V. The OP27 and peripheral circuit can get a follower. The measurement signal passes through the first stage operational amplifier. The output signal of the follower and the (0 ~ 15V) voltage signal are added at the input end in inverse phase, so that the (-
11V ~ 11V) input signal is converted to (-8V ~ -2V), and then it is converted to (2V ~ 8V) through the first stage inverter.

3.2 High-precision Voltage-to-Frequency (V/F) Converter AD650

AD650 is a high-precision voltage-to-frequency (V/F) converter. It consists of an integrator, a comparator, a precision current source, a monostable multivibrator, and an output transistor. AD650 can be used as a voltage-to-frequency converter or a frequency-to-voltage converter [7].

The V/F converter can directly convert the input DC voltage into a pulse frequency signal. Its functional relationship is described in formula (1):

$$ f_o = kV_{in} $$

In this formula, $V_{in}$ is the input DC voltage; $k$ is the conversion coefficient; $f_o$ is the output pulse signal frequency.

When the V/F converter the inputs voltage (0~10V), the corresponding output pulse signal frequency is 0~1MHz. The chip is a precision single-chip voltage-frequency conversion device, which can be used for voltage-frequency conversion and frequency-voltage conversion. The dynamic range is broad, and the maximum operating frequency can reach 1MHz. Simultaneously, the device is small in size. It has high accuracy, and few external components. Its connection diagram for V/F conversion is shown in figure 3. The peripheral circuit is simple and easy to implement, convenient for adjusting the operating range of input and output, and ensuring conversion accuracy. AD650 chip and its circuit have the following characteristics: high full-scale frequency, up to 1MHz, and very low nonlinearity [8].
The input signal $V_{IN}$ generates an input current through the input resistor $R_{IN}$. The input current can be directly provided by the power supply or generated by the input voltage $V_{IN}$ on the resistor $R_{IN}=(R_1+R_3)$. Through the 1mA internal current source switch control, the current on the integrating capacitor $C_{INT}$ and the operational amplifier AMP's internal feedback current form a loop to achieve a precise balance of the current source, as shown in figure 4. This current pulse can be regarded as a specific charge group. The number of charge groups that required for an open-collector transistor to generate a pulse depends on the input current signal's amplitude. Since the amount of charge transferred to the summing point (both ends of the integrating capacitor $C_{INT}$) per unit time is a linear function of the input signal current amplitude, voltage-frequency conversion can be realized. The open-collector transistor provides the frequency output terminal. The following describes in detail how to achieve voltage-frequency conversion. When the output of the monostable multivibrator OUT1 is low, the current source control switch S1 is turned to the right of the operational amplifier AMP as shown in figure 4(a). This process is called the integration process. When the monostable multivibrator OUT1 outputs high power, the current source control switch S1 is turned to the left side of the operational amplifier AMP as shown in figure 4(b). This process is called a reset process.

![Integrate Mode and Reset Mode](image)

**Figure 4** Process of integrating capacitor

The positive input voltage develops a current ($I_{IN}=V_{IN}/R_{IN}$) that charges the integrator capacitor $C_{INT}$. When charges build up on $C_{INT}$, the gradient of the output voltage from integrator ramps is negative, as shown in figure 5. When the integrator output voltage (Pin 1) crosses the comparator threshold (-0.6 V), the comparator triggers the monostable multivibrator. The time period $t_{OS}$ is determined by the capacitor $C_{OS}$.

$$t_{OS}=C_{OS}\times6.8\times10^3\text{sec/F}+3.0\times10^{-7}\text{sec}$$

**Figure 5** Voltage Across $C_{INT}$
The reset period is initiated as soon as the integrator output voltage crosses the comparator threshold, and the gradient is positive.

\[ \Delta V = t_{\text{on}} \times (1\, \text{mA} - I_{\text{IN}})/C_{\text{INT}} \]  (3)

After the reset period has ended, the device starts another integration period, as shown in figure 8, and the gradient becomes negative again. The amount of time required to reach the comparator threshold is given as

\[ T_{\text{F}} = t_{\text{on}} \times (1\, \text{mA}/I_{\text{IN}} - 1) \]  (4)

The output frequency is now given as

\[ f_{\text{OUT}} = 1/(T_{\text{F}} + t_{\text{on}}) = (0.15 \times V_{\text{IN}}/R_{\text{IN}})/(\text{Cos} + 4.4 \times 10^{-11}) \approx V_{\text{IN}}/(7.5 \times \text{Cos} \times (R_1 + R_3)) \]  (5)

The output frequency is directly proportional to the input charge when the capacitance Cos and resistance \( R_{\text{IN}} = (R_1 + R_2) \) are determined. The characteristic frequency is proportional to \( V_{\text{IN}} \), and it is affected by the capacitor. It has an excellent anti-noise performance because the charge balance structure integrates the input signal continuously.

In order to give full play to the AD650 chip, the peripheral components of the chip must be selected well. These key parameters will directly affect the conversion accuracy of the AD650 chip. For this reason, capacitors with small temperature coefficients must be strictly selected. In addition, the influence of parasitic capacitance should be minimized during circuit design and actual installation, and Cos should be as close as possible to the circuit pins. If possible, Cos should be shielded to prevent the interference from outside. Moving objects in the environment affect the capacitance of the capacitor, especially in high accuracy requirements (0.05%). Therefore, we choose EVOX-PFR series capacitors with correction function. The V/F conversion circuit is shown in figure 6, and the specific parameters are designed as follows. In the figure, the frequency-converted by the AD650 is reshaped by a 7414 chip, and then the next electro-optic conversion is performed.

\[ f_{\text{OUT}} = 1/(T_{\text{F}} + t_{\text{on}}) = (0.15 \times V_{\text{IN}}/R_{\text{IN}})/(\text{Cos} + 4.4 \times 10^{-11}) \approx V_{\text{IN}}/(7.5 \times \text{Cos} \times (R_1 + R_3)) \]  (5)

Figure. 6 Design diagram AD650 conversion circuit

3.3 Optical fiber link

Optical fiber is an excellent insulator, so there is no direct electrical connection between the transmitting and receiving ends of the optical fiber link. A simple optical fiber data link comprises optical fiber transceivers, optical fibers, and optical fiber connectors. This system selects the HFBR-1414 and HFBR-2412 produced by AVAGO Technology as the transmitter and receiver, and has the following technical characteristics:

- Wavelength of emitted light: 820nm
- Maximum data transfer speed: 155MBd
Maximum transmission distance: 4km
Range of working temperature: -40℃～+85℃

The HFBR-1414 optical fiber transmitter contains an aluminum gallium arsenide optical transmitter with high-efficiency optical power excitation. The optical transmitter can feed the optical fiber with an optical power of 820nm at a wavelength of -12dB under the 60mA direct current excitation. The HFBR-2412 optical receiver consists of a high-efficiency PIN photodiode and a low-noise transimpedance preamplifier circuit. Due to the amplifier's transimpedance effect, the amplifier's bandwidth and nonlinearity have been greatly improved, and a larger dynamic range has also been obtained. The optical signal is converted into an analog electrical signal by a photodiode and then amplified and buffered by the transmitter. The maximum dynamic range is 23dB, and the frequency response is from DC to 125MHz. Appropriate forward current IF of the LED can be selected at the transmitting end according to the parameter table. The transmission process is shown in figure 7.

3.4 Frequency to voltage conversion circuit
AD650 can also be used for F/V conversion and has outstanding performance. The specific design circuit is shown in figure 8. The voltage signal after F/V conversion is conditioned to obtain the original signal. The frequency signal fIN after photoelectric conversion is added to the input comparator's inverting input terminal through a differential circuit composed of R1 and C1. When the input pulse's falling edge arrives, the input comparator outputs a high level, and the monostable multivibrator is triggered to output a high level. Currently, the I0 current source charges the integrating capacitor CINT, and the capacitor C05 determines the charging time. The higher the input pulse frequency, the more charge accumulates on the capacitor CINT, and the higher the output voltage (the voltage across the capacitor CINT). The input frequency and the output voltage become a linear function, which realizes the frequency and voltage conversion. The choice of capacitor C1 should not be too small. It is necessary to ensure that the input pulse has sufficient amplitude to trigger the input comparator after differentiation. However, a smaller capacitor C1 will help improve the anti-interference ability of the conversion circuit. The value of C1 in this system is 200pF.
3.5 Test results of experiments
In order to test the performance of this transmission mode, a sine signal is connected to the circuit, after modulation, V/F and F/V conversion and restoration, the waveform of input signal waveform is shown in figure 9(a). While testing the linearity, the response time was tested, and the square wave signal was connected to the transmission system. The test waveform is shown in figure 9(b). It can be seen from figure 9 that the maximum linearity error is less than 0.1% under the test conditions. The system has good linearity and accuracy. It is insensitive to temperature, has a strong anti-interference ability, and has a relatively fast response time. The VFC-FVC analog optical fiber isolation transmission system constructed by AD650 has certain dynamic performance and can meet the requirements of measurement and control systems with medium or low speed.

The high-voltage power output measured by the real-time measurement system is shown in figure 10, which are 47.9kV and 51.8kV. Real-time measurement of high isolation potential with accurate data is now being realized.

![Figure. 9 Waveform of transmission system](image)

**Figure. 9** Waveform of transmission system

![Figure. 10 High-voltage power output measured by the real-time measurement system](image)

**Figure. 10** High-voltage power output measured by the real-time measurement system

3.6 Application of conversion in data acquisition and control system
Generally, the analog signal is converted by A/D sampling and then processed by an industrial computer. Considering that the signal passes through V/F conversion circuit to optical fiber transmission and then go through F/V conversion circuit, and then at last undergoes A/D conversion, the circuit is complicated, and there are many conversion links. Therefore, this system is designed to use V/F conversion circuit and cooperate with the counter circuit to realize data Collection and conversion functions. The output voltage required by the feedback system V/F has been transferred to frequency signal by V/F conversion circuit. The frequency signal will be input to the capture unit CAP (TMS320F2812 DSP). The capture unit captures each frequency signal's edge and interrupts to read the count value of the timer at this time. The difference between the consecutive count values is the period value of the frequency signal at this time.

4. Conclusion
The real-time measurement system based on A/D650 designed in this paper has the characteristics of strong anti-interference ability, simple structure, high data transmission rate, and the maximum linear error is less than 0.1%. It has good linearity and accuracy, and is insensitive to temperature. The system realizes the measurement of the output high voltage of the pulsed high voltage power supply system, and is successfully applied to the 50kV high
voltage power supply system, realizes the feedback control of the power supply, and runs well, which fully shows that the device has high potential isolation and real-time measurement characteristics.

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