Abstract

Nowadays, most of high voltage switchgear are hermetically sealed and filled with SF$_6$ gas. The material properties of SF$_6$ gas which are essential for such applications, such as the electrical disruptive strength or the electric light arc quenching capability, are dependent on the density of the SF$_6$ gas. The required SF$_6$ gas density depends on the respective application. This means that the functional safety of the entire system is strongly dependent on the density of SF$_6$ gas which is why it must be monitored.

Electronic Transformers, as one of the important equipment of Digital Substation, have been paid much more attention for the establishment of the substation. Because it does not have iron core, Electronic Transformers not only eliminate the magnetic saturation but also eliminate the situation of ferromagnetic resonance. Now the monitoring of density of SF$_6$ gas in electronic Transformers is still inspection on periodic, which is extremely outdated. In this situation, the on-line monitoring technology will be much more needed.

This paper presents a design of the on-line monitoring system of the density of SF$_6$ gas of electronic transformer. The full-text elaborates the theory and the design proposal of this system, and discusses the various components else. The system is mainly built by two parts: hardware part and software part. The hardware part included sensor characteristics and sensor selections, conditioning circuit design and achievement, data transmission framework establishment and so on. Sensors were chosen in proper size and circuits were designed properly are all included in hardware; The software part included the acquisition and transmission of microprocessor’s coordinated signal control, serial interface communication realization by virtual instrument, measured signal correction, data storage and so on. Finally, combined the measured data and then analyzed error uncertainty.

This paper built the monitoring system on Virtual Instrument. The monitoring system based on virtual instrument technology can decrease the source of the measurement error. The system enhances both the flexibility of digital signal processing and the computing speed. On the other hand, the software exploitation, debugging and improving are easier, compared with the hardware circuit. The realization with virtual
instrument is flexible and with low fabrication costs and shorten the period.

**Key Words:**  
SF$_6$ density  SF$_6$ gas density On-line Monitoring System  
Virtual instruments  Electronic transformer
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1 Introduction

1.1 The importance of SF$_6$ gas density of electronic transformer on-line monitoring system

1.1.1 Brief introduction of electronic transformer

To ensure the safe operation of power system, we need to measure related parameters of power system and their equipment. In order to measure, monitor and protect, we will connect transformer to primary and secondary side of the power transmission system by one or more current transducers and voltage transducers for the purpose of transmit the ratio signal to instruments, meters and protection relays or control devices.

The main purpose of transformer is transmitting the current and voltage signal of primary side of power system to secondary side. Achieve an electrical isolation of high voltage primary side equipment and secondary side equipment. Ensure the safety of secondary equipment and persons. And transform the high voltage, high current of the primary side to be low voltage, low current of secondary side. Standardize the measurement and relay protection. In the power system, we call electromagnetic current transformer, electromagnetic voltage transformer and capacitive voltage transformers as traditional transformer. The biggest difference between electronic transformer and traditional transformer is, the electronic transformer has digital output, but the output of traditional transformer is analog quantity. International Electrotechnical Commission (IEC) standard require that the electronic transformer should keep analog output voltage for links up with metering system of traditional transformer and protective equipment.

In addition of the functions of traditional transformer, electronic transformer also has the following advantages$^{[1]}$:

(1) Eliminate the magnetic saturation and ferromagnetic resonance phenomenon. The measured signal of electromagnetic transformer pass through secondary coil by magnetic-core coupling method. Inevitably produce magnetic saturation and ferromagnetic resonance problem. Electronic transformer has not contains magnetic core so that eliminate the magnetic saturation and ferromagnetic resonance problem.
(2) Fast response for the power system fault. By using transient signal quantity as a protection parameter judgment. From advantage of the development of microprocessor-based protection. Microprocessor-based protection requires a transformer that has good linearity and dynamicity characteristic. The traditional transformer cannot satisfy these performances, but electronic transformer can meet.

(3) Excellent insulation property. Traditional transformer insulation structure is complex and the cost increase exponentially with voltage relationship. Electronic transformer insulation is relatively simple compared to traditional transformer. High voltage side and low voltage side of the signal transmission using optical fiber as insulation materials, with excellent insulating property.

(4) Wide dynamic range, high accuracy and wide range of frequency response. Because traditional transformer has magnetic saturation problem, so that difficult to realize measurement range and difficult to satisfy the need of measurement and relay protection. Frequency range of electronic transformer depends on the relevant part of the electronic circuit, and it has wide frequency response. Moreover, electronic transformer can detect high-voltage power line harmonics and can measure grid current transient, large high-frequency current and direct current. Traditional transformer is difficult to work in this area.

(5) Small volume and light weight. Electronic transformer without iron core, so the weight at the same voltage level much smaller than the traditional transformer.

High voltage electronic transformer is hermetically sealed and filled with SF₆ gas. The material properties of SF₆ gas which are essential for such applications, such as the electrical disruptive strength or the electric light arc quenching capability, are dependent on the density of the SF₆ gas. The required SF₆ gas density depends on the respective application. This means that the functional safety of the entire system is strongly dependent on the density of SF₆ gas which is why it must be monitored.

1.1.2 Brief introduction of SF₆ gas

Sulfur hexafluoride (SF₆) is an inorganic, colorless, odorless, non-toxic and non-flammable greenhouse gas. SF₆ has an octahedral geometry, consisting of six fluorine atoms attached to a central sulfur atom. It is a hypervalent molecule. Typical for a nonpolar gas, it is poorly soluble in water but soluble in nonpolar organic solvents. It is
generally transported as a liquefied compressed gas. It has a density of 6.08 kg/m³ at sea level conditions, which is considerably higher than the density of air.[2]

$\text{SF}_6$ is used in the electrical industry as a gaseous dielectric medium for high-voltage circuit breakers, switchgear, and other electrical equipment, often replacing oil filled circuit breakers (OCBs) that can contain harmful PCBs. $\text{SF}_6$ gas under pressure is used as an insulator in gas insulated switchgear (GIS) because it has a much higher dielectric strength than air or dry nitrogen. This property makes it possible to significantly reduce the size of electrical gear. This makes GIS more suitable for certain purposes such as indoor placement, as opposed to air-insulated electrical gear, which takes up considerably more room. Gas-insulated electrical gear is also more resistant to the effects of pollution and climate, as well as being more reliable in long-term operation because of its controlled operating environment. Although most of the decomposition products tend to quickly re-form $\text{SF}_6$, arcing or corona can produce disulfur decafluoride ($\text{S}_2\text{F}_{10}$), a highly toxic gas, with toxicity similar to phosgene. So, when $\text{SF}_6$ is used, original insulation may soon be recovered after arc is quenched thanks to its excellent thermal conductivity under the high temperature condition and strong electron-capturing capacity.

In addition, install $\text{SF}_6$ gas density on-line monitoring system to electronic transformer will be provided: (1) Real-time monitoring; (2) Elimination of false alarms; (3) Leak trending data; (4) Employee safety; (5) Accurate density calculations; (6) Remote access to data; (7) Prediction of future alarms; (8) Equipment safety; (9) Maintenance planning[3].

1.2 The current situation of research on $\text{SF}_6$ gas density of electronic transformer on-line monitoring system

In 1951, John S. Johnson of Westinghouse company. Because slot discharge in the operation of generator lead to motor damage phenomenon. So, he researched and monitored the slot discharge phenomenon in the running motor. In the 1960s, The United States takes the lead in official start of on-line monitoring technology and established a large research institution. They meet 1-2 times a year for academic exchange meeting. In the 1970s, Canada, Japan, the former Soviet Union etc. started and rapidly developed the
on-line monitoring technology. In 1975, Canada successfully developed gas-in-oil on-line monitoring device. In 1980s, Japan developed on-line monitoring device for transformer’s partial discharge. The on-line monitoring technology of the former Soviet Union is developing very quickly too. Especially in the capacitive equipment insulation monitoring and partial discharge on-line monitoring has the strong technical strength.

Electric power system of China was first mentioned in condition-based maintenance at maintenance work conference in 1986 and issued “Power plant maintenance procedures” in 1987, which explicitly stated to “Application of diagnostic techniques to predict equipment maintenance repair is the development direction of equipment examine and repair. In June 1996, Ministry of Electric Power issued “Strengthen the power grid management regulations” which put forward in “In conditional unit, there should be carried out on-line monitoring and condition-based maintenance work”. In 2007, State Grid Corporation of China continually released “State Grid Corporation of power transmission and transformation equipment condition-based maintenance test procedures”, “Power transmission and transformation equipment condition evaluation standard” and “Power transmission and transformation equipment condition maintenance guideline”. Researching on electronic transformer in China has just only up to 35 years. A small number of electronic transformer on-line monitoring systems that put into practice. The accumulation of operating knowledge is very limited. This situation cannot be intelligent substation system. At present, the monitoring of electronic transformer in China remains the level of periodic switch-off maintenance. So, there is necessary to come up with an electronic transformer on-line monitoring device. For time to time monitor of each operating condition of internal part of running electronic transformer, to ensure that all parameters are in a safe operating range and to reduce the occurrence of irreparable equipment failure. In recent years, there are increasingly concerned about on-line monitoring system of transformer and already have some research on on-line monitoring.

In 2011, Vaisala company of Finland introduces on-line monitoring system of SF6 insulation in high voltage equipment which combines online dew point monitoring with pressure measurement, creating a superior tool for assessing the condition of SF6 insulation continuously and in real-time.
1.3 Brief introduction of SF$_6$ gas density of electronic transformer on-line monitoring system

Electronic transformer is important component part in substation. The measurement of both pressure and temperature of SF$_6$ gas in it is two important parameters to calculate its density to guarantee the normal and safe operation of the equipment. In this paper a solution for on-line monitoring of SF$_6$ gas is proposed.

The object of the monitoring system is divided into three parts. First, there are the pressure parameters of SF$_6$ gas within the transformer. Second, there is the monitoring of temperature. Third, it can be collected pressure and temperature data to calculate for SF$_6$ gas density by mathematical model. It can also determine the performance of insulated gas.

1.4 The topic of this paper and main work

The topic of this paper is come from Hunan Ruicheng Electric Co., Ltd. In order to measure SF$_6$ gas density of 110kV combined electronic transformers. The main topic of this paper is to monitor pressure, temperature and calculate the density of SF$_6$ gas in electronic transformers when they are in operation. Then transmit these monitored data to the monitoring center to make staff able to know the state of SF$_6$ gas in time. The author had comprehensively researched on SF$_6$ gas on-line monitoring system of electronic transformer when studied in this Master. The main contents were:

1. Realized the principle of design of electronic transformer, output characteristics and data transmission issues according to IEC61850 standard.

2. Selection of signal acquisition devices and designed conditioning circuit board for these devices according to electronic transformer on-line monitoring object characteristic.

3. Selection of corresponding signal processing microcontroller, A/D converter and using embedded C language method to controlled sending and receiving function of microcontroller in order to accomplished information transfer.

4. Using the method based on virtual instrument to achieved signal reception of
PC and carried out comprehensive treatment of signal in accordance with project requirements. Including displayed data in tabular and graphical form. Moreover, including data storage and allocation.

(5) Participated in experimental test of the entire system and carried out error analysis of that data.
2 SF₆ gas density of electronic transformer on-line monitoring system design

In consideration of physical properties of SF₆ gas, it may be concluded that measurement of leakage in SF₆ gas in an electronic transformer is an important guaranty for normal and safe running of the transformer. Quality of SF₆ gas must be inspected prior to filling, and monitored and processed during the operation of the transformer as the provided in GB 8905-1996, The guide for processing and measuring SF₆ gas in power apparatus, which provides that annual leakage rate in each compartment in the SF₆ apparatus is not allowed to exceed 1%. [4]

SF₆ gas density of electronic transformer on-line monitoring system, the object of monitoring is divided into three parts.

1. The pressure of SF₆ gas inside the transformer.
2. The temperature inside the transformer.
3. The density of SF₆ gas in the transformer.

2.1 SF₆ gas pressure and temperature monitoring principle analysis

By the formula, we derived the relation of bus voltage of electronic transformer and pressure. We can use the value of internal pressure of pressure sensor monitoring equipment, and then apply software to correct voltage. With taking safety into consideration, pressure sensor place in inner-chamber of bottom base of low potential side of transformer. When select pressure sensor, we should consider the high quality of digital output that weakened the magnetic field intensity at the base of equipment. The general analog voltage output pressure sensor is more appropriate, but in order to reduce the effect of electromagnetic interference, we have to pay attention to shield protection too.

Primary voltage of the device under test is 110 kV, operating temperature of internal high voltage arm is -25°C ~+40°C. Electric field effect is mainly around. When close to primary current-carrying conductor we should consider to magnetic field effect. In order to accurately measure the temperature near the bus pole as we can, we should put the
temperature sensor as close as to the primary pole. Now, the temperature sensor is under intensive electromagnetic interference. General analog output cannot properly transmit signal. So, we have to use the digital output sensor.

### 2.2 SF₆ gas density monitoring principle analysis

To determine whether or not the high voltage equipment after filled with SF₆ gas in gas chamber meet the insulation and arcing requirements, we often use the concept of SF₆ gas density to measure. Because the dielectric strength in SF₆ gas chamber depends on SF₆ gas density value, regardless of temperature. Moreover, the density value is through 20°C of inflation pressure to realize. In order to ensure the reliability and safety of gas-insulated equipment, we have to monitor SF₆ gas density value rather than gas pressure (see figure 2.1). Curve 1 show gas density at constant value, breakdown strength of SF₆ gas is not correlated with temperature. Moreover, curve 2 show that when the pressure constant, breakdown strength of SF₆ gas decreases with increasing temperature (because when the temperature increase, SF₆ gas density gradually decrease).

![Figure 2.1 Relation of SF₆ gas dielectric strength and temperature](image_url)

Figure 2.1 Relation of SF₆ gas dielectric strength and temperature
In the case of a certain density, temperature changes will lead to changing in pressure. The curve that correspond different density has distinct characteristic. The variation patterns show in Figure 2.2. So, in order to accurately reflect that the variation of pressure is caused by gas leaked or by temperature variation, there must be corrected by temperature compensation or correction method. Cause no matter what the ambient temperature changed, the reading of pressure indicating meter results are always refer to standard pressure value of 20°C. This value is equivalent to the SF$_6$ gas density value in the gas chamber. When leakage occurs, the density relay can immediately indicate density variation that cause by gas leakage. When it indicate the value of the SF$_6$ gas density lower than the pre-set alarm values, the density relay will send a gas-reinflation alarm contact signal. This case is the leakage is not too much, it should be filled the gas and the equipment can continue to run, so it prevents insulation performance from degradation. If there is a serious leak, the density relay will send a pair of latch contact signals to lock the switch operation. This means that the equipment cannot be in the normal operation at this time. If operate, accident will occur.

![Figure 2.2 Three states diagram of SF$_6$ gas](image)

There are two methods that refer to temperature compensation and correction.

1) Using the most common formula of SF$_6$ gas state parameter equation, that is Beattie-Bridgman empirical formula.
\[ P = 0.57 \times 10^{-4} \rho T (1 + B) - \rho^2 A \]

\[ A = 0.75 \times 10^{-4} \left(1 - 0.727 \times 10^{-3} \rho\right) \]

\[ B = 2.51 \times 10^{-3} \rho \left(1 - 0.846 \times 10^{-3} \rho\right) \]

Where,  
\[ P = \text{pressure (MPa)} \]
\[ T = \text{temperature (K)} \]
\[ \rho = \text{density (kg/m}^3\text{)} \]

Coefficient A and B are
\[ A = 0.75 \times 10^{-4} (1-0.727 \times 10^{-3} \rho) \]
\[ B = 2.51 \times 10^{-3} \rho (1-0.846 \times 10^{-3} \rho) \]

2) Use modern electronic sensor technology, measure the value of different density under pressure and temperature relations, based on experiments, supplemented by computing, using microcontroller storage and computing power to accomplish the measurement (pressure value) compensation to the pressure value at 20°C.

2.3 The main technology requirements of on-line monitoring system

2.3.1 Data transmission method

At present, sensor signal acquisition has two type of output. That is digital output and analog output. Digital signal directly access into microcontroller unit (MCU), analog signal have to pass through analog-to-digital converter (A/D) to convert to digital signal and then access into MCU. Converted data have two types of output method: parallel output and serial output. Output mode of parallel data use multiple data cables with long numeric data simultaneous output. 16 bits of A/D converter output usually need 8 data cables time-division output. Although, the output rate of this type of output is good, they need latch circuit to assist realizing the output of data. Moreover, synchronous receiving port of long numeric data consumed more power and took up more resources. In recent years, serial data output development is along with the development of serial bus and applied gradually into the data output of A/D converter. At present, SPI (Synchronize Periphery Interface) data output is low power consumption and high speed method. There is more common used in A/D converter and SPI module interface of MCU is convenient to
perform analog-to-digital conversion. SPI method is a kind of full-duplex synchronous serial data transmission methods. The output data just only need clock line, chip selection line and data output line to complete. Using this data output method can reduce the use of auxiliary devices, gets faster speed, low power consumption and takes up less resource. In A/D converter applications, parallel data output A/D converters has been gradually replaced with serial data output A/D converters. According to the advantages of serial output, this system use serial output method.

2.3.2 Data transmission process

Monitoring PC is necessary for on-line monitoring of electronic transformer in substation. For this reason, this system proposed to bring data signal of every transformer into Ethernet design scheme. There is convenient for PC to centralized monitoring and management. Data signals of high voltage side pass through optical fiber to low voltage side. The output after photoelectric conversion is serial data. At this time need to access serial port for transfer to Ethernet converter to achieve serial data to Ethernet conversion, then access to Ethernet switch to achieve centralized monitoring and fault diagnosis management of all electronic transformer of the whole substation. So, after access to microprocessor, there have to access to serial port to pass data to Ethernet switch, and then access to network switch for realize the establishment of the Ethernet. The whole process of data transmission is shown in Figure 2.3.
2.4 The overall structure of the on-line monitoring system

The object of SF$_6$ gas density of electronic transformer on-line monitoring system is to measure SF$_6$ gas pressure and temperature in the transformer and then pass through transmission system to send these data to PC in monitor and control center. And then calculate the SF$_6$ density. The overall structure of the system is shown in Fig. 2.4
The design of this SF₆ gas density on-line monitoring system is in a layer distributed multi CPU structure. Use modular design and Ethernet communications technology. By composition of data acquisition of every transformer that installed in the plant, process, transmission unit and PC data management system and monitoring system in control room of substation together. From level division, the self-diagnostic system can be divided into three levels: acquisition layer, processing layer and monitoring management layer. The system used the distributed structure in the whole structure. So, it made the whole system level distinct, well organized and good for installation and maintenance. Moreover, the system adopts modularizing design method. So, there will convenient to upgrade the system in the future. The system function structure diagram is shown in Fig. 2.5.
This chapter introduces the principle of measuring SF$_6$ gas density of electronic transformer. Analyzed SF$_6$ gas pressure, temperature and density measurement methods, then elaborated in detail about the main technical requirements for on-line monitoring. Finally, came up with the overall design of the monitoring system architecture.
3 Hardware achievement

Starting from signal transmission aspect, hardware part of the on-line monitoring system can be divided into sensor, analog-to-digital converter, conditioning circuit, microprocessor, electro-optic/optic-electro converter and network switch. This chapter will describe all kinds of hardware that used in this system.

3.1 Sensor selection

Sensor is the signal input terminal of the entire system, the quality of sensor has an impact on the whole system measurement accuracy, stability, reliability and as well as played a decisive role on the subsequent insulating condition analysis. Associate with the characteristics of adopted signal, selection of the suitable sensor is very important.

3.1.1 Pressure sensor selection

Before select pressure sensor, we have to know the type of gas pressure measurement.

1. Absolute pressure is zero-referenced against a perfect vacuum, so it is equal to gauge pressure plus atmospheric pressure.
2. Gauge pressure is zero-referenced against ambient air pressure, so it is equal to absolute pressure minus atmospheric pressure. Negative signs are usually omitted.
3. Differential pressure is the difference in pressure between two points.

In this case, there is obviously to choose gauge pressure sensor to accomplish the pressure monitoring.

From the experiment shows that the normal operating pressure range of gas medium is between 0.35 MPa to 0.5 MPa. Ambient temperature is between -25°C to +50°C. So that common pressure sensor can meet the requirements. Here, the system used SMC18B pressure sensor. SMC18B is a kind of dry-type ceramic piezo-resistive gauge pressure sensor. It has advantages of high precision, good stability, overload resistance, interference resistance characteristics and so on. The supply voltage is 5 V. Operating temperature range is between -40°C to +125°C. Measuring range is between 0 MPa to 0.5 MPa. Safety
overload is 1 MPa. Burst pressure is 2 MPa. Output voltage is 0.5 to 4.5 V. And comprehensive precision is 0.25%.

Figure 3.1 SMC18B pressure sensor series

From experimental measurement obtained that, when the pressure inside the equipment is 0.3 MPa then the output voltage is 2.9027 V, when the pressure inside the equipment is 0.45 MPa then the output voltage is 4.1260 V. So, each 1 Pa changing in pressure, the output voltage will change $8.0 \times 10^{-6}$ V.

3.1.2 Temperature sensor selection

The system uses a digital output temperature sensor: DB120 digital temperature sensor probe is one of cable-type sensor of digital temperature sensor series. The internal part uses SHT11 temperature sensing chip. The internal part of DB120 including a measuring temperature component that is made from metal material with a 14 bit A/D converter and serial interface circuit for seamless connectivity. DB120 has high reliability and excellent long-term stability. The temperature measuring range is -40°C to +120°C. The accuracy is $\pm 0.3^\circ$C.
3.2 Microcontroller

The monitored physical quantities are converted to digital form and enter to microcontroller (MCU). After integrate data by MCU, the data will be encapsulated and sent out. When transmit the collected data, MCU will control SPI module of A/D port to easier for low power level-shifting circuit to using integrated chip. MSP430 series microcontroller from Texas Instruments Company is a 16 bit with a compact, economical rapid processing wake up time and ultra-low power microcontroller series containing only 27 instructions and 16 registers. Supply voltage is low voltage as 1.8-3.6 V. RAM data holding method just require only 0.1 µA. MSP430 series microcontroller has 6 modes. There are one active mode (AM) and 5 low power modes (LPM0-LPM4). In addition, MSP430 series microcontroller uses vector interrupt so it can support more than ten interrupt sources and can be arbitrarily placed a routine inside another routine that is at a higher hierarchical level (nest)\(^{[30]}\).

MSP430F16xx series is a new type of mixed signal microprocessor. It mainly includes the following advantages: (1) Ultra-low power; (2) Powerful processing capability; (3) High-performance analog technology and plenty of on-chip peripheral modules; (4) System is stable; (5) Convenient and efficient to development environment. In view of these considerations, we choose MSP430F1611 ultra-low power microcontroller from Texas Instruments Company.
3.3 Analog-to-Digital Converter

The selection of A/D converter mainly consider to two aspects: First is the operation of converter. Now, the operation of A/D converter is mainly divided into Flash type A/D converter (Parallel A/D converter), Successive-approximation-register A/D converter (SAR), Dual Slope A/D converter (Integrating A/D converter), Pipeline A/D converter, Sigma-Delta A/D converter, etc. The main characteristic of these converters is shown in table 3.1. Which Successive-approximation-register A/D converter has minimum conversion power, the required device is less, sampling rate can reach a higher level and mainly used for data acquisition in industrial control. In view of these considerations, the
system uses Successive-approximation-register A/D converter chip. The other is selection of the number of converter bits. The selection of converter bits not only related with the quantization error and testing precision of the system. For accurate measurement of insulation especially dielectric loss angle, there will have to ensure the speed of data acquisition and precision of acquisition unit. Due to the on-line monitoring system needs high precision of dielectric loss factor measurement (up to 1% absolute accuracy). In order to ensure A/D converter can achieve high signal to noise ratio (SNR), precision and resolution, the number of bits should be ten bits or more. In view of these considerations, we use AD7685 chip for converting analog to digital data. AD7685 is a 16 bits successive-approximation type A/D, conversion rate is 250 kHz, single power supply, supply voltage can be 2.3 V to 5.5 V, degree of linearity 1~2 (± bits) and output is in serial form. The encapsulation of AD7685 has MSOP-10 and LFCSP from and chip normal working temperature is -40°C to 85°C.

**Table 3.1 The main characteristic of A/D converter**

<table>
<thead>
<tr>
<th>Application</th>
<th>Flash</th>
<th>SAR</th>
<th>Dual Slope</th>
<th>Pipeline</th>
<th>Sigma-Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultra-High Speed</td>
<td>Medium to high</td>
<td>Monitoring DC signals, high resolution</td>
<td>High speeds, few Msp to 100+ Msp, 8 bits to 16 bits, lower power consumption than flash</td>
<td></td>
</tr>
<tr>
<td></td>
<td>when power</td>
<td>resolution (8 to 16 bit), 5 Msp and under low power, small size</td>
<td>resolution, low power consumption, good noise performance</td>
<td></td>
<td>High resolution, low to medium speed, no precision external components, simultaneous 50/60 Hz rejection, digital filter reduces anti-aliasing requirements</td>
</tr>
<tr>
<td></td>
<td>power consumption</td>
<td>not primary concern</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conversion method</td>
<td>Flash</td>
<td>SAR</td>
<td>Dual Slope</td>
<td>Pipeline</td>
<td>Sigma-Delta</td>
</tr>
<tr>
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</tr>
<tr>
<td>N bits-$2^{n-1}$ Comparators Caps increase by a factor of 2 for each bit</td>
<td>Binary search algorithm, internal circuitry runs higher speed</td>
<td>Unknown input voltage is integrated and value compared against known reference value</td>
<td>Small parallel structure, each stage works on one to a few bits</td>
<td>Oversampling ADC, 5-Hz-60Hz rejection programmable data output</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Encoding method</th>
<th>Thermometer code encoding</th>
<th>Successive approximation</th>
<th>Analog integration</th>
<th>Digital correction logic</th>
<th>Over-sampling modulator, Digital decimation filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sparkle codes/metastability, high power consumption, large size, expensive</td>
<td>Speed limited to ~5Mmps. May require anti-aliasing filter</td>
<td>Slow conversion rate. High precision external components required to achieve accuracy</td>
<td>Parallelism increases throughput at the expense of power and latency</td>
<td>Higher order (4th order or higher) - multibit ADC and multibit feedback DAC</td>
<td></td>
</tr>
</tbody>
</table>

| Disadvantage | Speed limited to ~5Mmps. May require anti-aliasing filter | Slow conversion rate. High precision external components required to achieve accuracy | Parallelism increases throughput at the expense of power and latency | Higher order (4th order or higher) - multibit ADC and multibit feedback DAC |

<p>| Conversion Time | Conversion Time does not change with increased resolution | Increases linearly with increased resolution | Conversion time doubles with every bit increase in resolution | Increases linearly with increased resolution | Tradeoff between data output rate and noise free resolution |</p>
<table>
<thead>
<tr>
<th>Resolution</th>
<th>Flash</th>
<th>SAR</th>
<th>Dual Slope</th>
<th>Pipeline</th>
<th>Sigma-Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component matching typically limits resolution to 8 bits</td>
<td>Component matching requirements double with every bit increase in resolution</td>
<td>Component matching does not increase with increase in resolution</td>
<td>Component matching requirements double with every bit increase in resolution</td>
<td>Component matching requirements double with every bit increase in resolution</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>$2^N-1$ comparators, Die size and power increases exponentially with resolution</td>
<td>Die increases linearly with increase in resolution</td>
<td>Core die size will not materially change with increase in resolution</td>
<td>Die increases linearly with increase in resolution</td>
<td>Core die size will not materially change with increase in resolution</td>
</tr>
</tbody>
</table>

For AD7685 working properly, it also need to connect to an external reference voltage, external clock and external power supply. The reference voltage must be stable, because it directly determines voltage range of input A/D module. ADR42x series is the second generation with low noise, high-precision, ultra-accuracy XFET reference voltage device, which ADR421 reference voltage output is 2.5 V, normal operating temperature range is -40°C to 125°C. There are two types of encapsulation, that is SOIC-8 and Mini_SOIC-8. The system uses ADR421 as Voltage reference. External clock provided by MCU. AD7685 circuit is shown in figure 3.5. The A/D chip supply voltage and the reference voltage of ADR421 are designed to be +5 V.
3.4 Signal conditioning circuit

Before the analog signal go into analog to digital conversion, because the output range of sensor and the input range of A/D converter do not match. So, before the signal going into the A/D converter, there is necessary to carry out that output signal to a simple process for matching the follow-up equipment of connection.

For designing of the conditioning circuit of pressure sensor, because the output of SMC18B pressure transducer is 0.5 V to 4.5 V, and the supply voltage of MSP430 microprocessor is 3.3 V, when compare with the internal voltage 2.5 V, so the analog voltage of sensor output will be in the range of 0-2.5 V. The signal conditioning circuit of pressure transducer is shown in figure 3.6.
3.5 Signal transmission equipment

When the microprocessor send out data in serial mode, there needs to pass the data through fiber optic transmitter for sending that signal in light form for long-distance transmission by optical fiber. The light signal pass through receiver at the other end of the optical fiber for restoring into electrical signal, then pass through a serial port for transfer ring to Ethernet receiver to accomplish data communication system. Because the output signal power of microprocessor is weak, so it could not be transmitted for a long distance\cite{35-36}. So, before optical/electrical, electrical/optical conversion, there have to added NAND gate power drive SN75451 chip to increasing the drive capability of the microcontroller.

The system uses HFBR-1414 and HFBR-2414 of Agilent corporation to realizing electrical/optical and optical/electrical conversion. HFBR-1414 optical fiber transmitter contains a high efficiency light power excitation Gallium Aluminum Arsenide (GaAlAs) light emitter. This light emitter drive current is 48 mA. Under the condition of 62.5/125μm optical fiber (maximum attenuation is 4dB/km), the transmission distance can be up to 1.75km. Operating temperature range is -40°C to 85°C, propagation delay per meter is 5ns, therefore it comply with the requirements of the system. The combination of HFBR-1414/2412 is shown in figure 3.7.
Figure 3.7 HFBR-1414/2412

Microprocessor use serial port for sending output and for monitoring multiple devices at the same time as the experiment requirement. So, the output terminal of microcontroller will connect to serial port to transfer to Ethernet receiver for establishing the Ethernet form and realizing the requirement of parallel monitoring for multiple-devices. ATC-2000 is an RS232/RS422/RS485 to TCP/IP data exchange communication interface converter. The built-in RTOS (Real Time Operating System) and fully TCP/IP communication protocol make ATC-2000 not only provide reliable and stable operating platform, but will also make the management of existing system more easy and fast by performing Internet remote administration. There have to perform initial setup when using ATC-2000. IP address set between 192.168.168.1 to 192.168.168.254 and Subnet mask set to 255.255.255.0. The default IP address of ATC-2000 is 192.168.168.125 (IP address of PC could not be set to this IP address, otherwise it could not properly set)

The default fixed static state of ATC-2000: IP address default value is 192.168.168.125, Subnet mask default value is 255.255.255.0, Gateway default value is 192.168.168.254 and Primary DNS default value is 168.95.1.1. The picture of ATC-2000 is shown in figure 3.8. The output of ATC-2000 will access to switch, then from the switch access to PC and finally realize the establishment of Ethernet.
3.6 Summary

This chapter sequentially introduces hardware part of the on-line monitoring system. The first is selection of sensors, A/D converter, electrical/optical converter and optical/electrical converter, after that we were given a detailed description of the designed conditioning circuit and a brief introduction to the establishment of Ethernet and given a hardware process of signal acquisitioning from sensor to PC.
4 Software achievement

On-line monitoring system software designed section had been divided into three aspects. First, there is the software that according to the requirements of the system for obtaining the signal to software algorithm processing. Second, there is the software that utilizing embedded method for microcontroller operation control to complete the transmission of the signal from device acquisition to PC process. Third, there is the software that using virtual machines to complete the data analysis, management and storage etc. up to user’s requirements.

4.1 On-line monitoring system’s software main algorithm

The data acquisition could not be completely correct because of the sensor technology. So, the system managed the acquisition of data by according to some empirical formula to make it closer to the real value. This chapter introduces the pressure and temperature processing algorithm.

4.1.1 Pressure correction algorithm

SMC18B pressure sensor output is linear analog voltage value. Measure the pressure of 0-5 bar. Output voltage is 0.5-4.5 V. Which means that 0 bar correspond to 0.5 V and 5 bar correspond to 4.5 V. Then we can introduce:

\[
\frac{(\text{sensor output voltage} - 0.5) \times 5}{4} = \text{Measured pressure value} \quad (4-1)
\]

The output terminal of pressure sensor passes through the conditioning circuit before access to A/D converter. The conditioning circuit use resistor divider network proceeding voltage division. According to parameter setting of figure 3-5, we can introduce:

\[
\frac{\text{sensor output voltage}}{3.74 + 4.64} \times 4.64 = \text{Measuring voltage} \quad (4-2)
\]

Measuring voltage is measured by microcontroller and use 16 bit A/D converter that compared voltage is 2.5 V. Then, we will get voltage value expression of microcontroller measurement as:
MCU output value (Hexadecimal → Decimal) \times 2.5 = \text{Measuring voltage} \quad (4-3)

Combining (4-1), (4-2) and (4-3) to obtain pressure correction algorithm:

\[
\frac{\text{MCU output value (Hexadecimal → Decimal)}}{2^{16}} \times 2.5 \times 8.38 - 0.5 \times \frac{5}{4} = \text{Measuring pressure value}
\]

4.1.2 Temperature correction algorithm

Band-gap materials PTAT (Proportional to Absolute Temperature) temperature sensors have been developed to excellent linearity. So, we can use equation (4-5) to convert digital output to be temperature value.

\[ T = d_1 + d_2 \cdot SO_T \]

Temperature conversion factor are shown in table 4.1

<table>
<thead>
<tr>
<th>VDD</th>
<th>(d_1(\degree C))</th>
<th>(d_1(\degree F))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5V</td>
<td>-40.1</td>
<td>-40.2</td>
</tr>
<tr>
<td>4V</td>
<td>-39.8</td>
<td>-39.6</td>
</tr>
<tr>
<td>3.5V</td>
<td>-39.7</td>
<td>-39.5</td>
</tr>
<tr>
<td>3V</td>
<td>-39.6</td>
<td>-39.3</td>
</tr>
<tr>
<td>2.5V</td>
<td>-39.4</td>
<td>-38.9</td>
</tr>
<tr>
<td>SO_T</td>
<td>(d_2(\degree C))</td>
<td>(d_2(\degree F))</td>
</tr>
<tr>
<td>14bit</td>
<td>0.01</td>
<td>0.018</td>
</tr>
<tr>
<td>12bit</td>
<td>0.04</td>
<td>0.072</td>
</tr>
</tbody>
</table>

Microprocessor uses 14 bit pattern programming, DB120 power supply is 3.3 V. According to the table, the system temperature correction formula will be:

\[ T = -39.7 + (\text{MCU output Hexadecimal → Decimal}) \times 0.01 \]

(4-6)
4.2 On-line monitoring system’s microcontroller control

The purpose of establishment of the on-line monitoring system is to accurately reflect the real-time status of each device. Therefore it could be timely, read the data correctly and store data as the purpose of establishing the system. This section describes how to control microcontroller coordination between data collection and transmission.

4.2.1 The introduction of microcontroller development environment

Development environment of MSP430 series microcontroller is Embedded Workbench that was developed by IAR corporation[38], which can adapt to different CPU proposed system. It provides abundant function window interface and can show detailed operation of entire debugging process. Workbench window is shown in figure 4.1

![Embedded Workbench window](image)

Figure 4.1 Embedded Workbench window.

The system uses functional form when programming in order to enhance the readability of the program. This can cause programming ideas clearly and also easily find programming errors. C language is one of the most basic programming languages and also familiar with by most people. MSP430F1611 supports C language programming. So, the system uses C language to write MSP430 code. The system use MSP4301611 to receive
data and communicate with PC. The function that need to use including: void Init_CLK(void); void Init_PORT(void); void Init_SPI(void); void Init_UART0(void); void Init_UART1(void). Microcontroller’s procedure flow chart is shown in figure 4.2

![Microcontroller’s procedure flow chart](image)

**Figure 4.2 Microcontroller’s procedure flow chart**

### 4.2.2 Microcontroller’s analog signal processing

When the on-line monitoring system monitor pressure signal from equipment. Because there is analog signal output, so the microcontroller has to use A/D converter processing. Microcontroller processing procedures mainly consist of the clock procedure,
SPI communication procedure, transmission procedure, port initialization procedure and interrupt procedure.

Clock initialization of MSP430F1611 uses BCSCTL1 and BCSCTL2 to set up. First, it turns off the watchdog program, then BCSCTL1 close XT2 oscillator, control LFX1 to operate in low frequency mode and control nominal frequency range between 0.9 MHz - 2.5 MHz. Finally, BCSCTL2 will adjust clock source to XT2CLK, SELE selects to SMCLK, DCO selects internal resistance.

```c
void Init_CLK(void)
{
    unsigned int i;
    WDTCTL = WDTPW + WDTHOLD;

    BCSCTL1=0x00;
    BCSCTL1+=0x0C4;
    do
    {
        IFG1&=~OFIFG;
        for(i=0x20;i>0;i--);
    } while((IFG1&OFIFG)==OFIFG);
    BCSCTL2=0x00;
    BCSCTL2+=0xC0;
    DCOCTL=0x00;
    DCOCTL+=0x0E0;
    return;
}
```

The communication uses SPI Serial module synchronous mode, defines the microcontroller as the main processor, clock source is selected as SMCLK and transmission baud rate set to ACLK/2.

```c
void Init_SPI(void)
{
```
U0CTL|=SWRST;  //Data is 8 bit, select SPI mode, microcontroller is the main processor
U0CTL|=CHAR+SYNC+MM;
U0RCTL=0;      //Clear the contents of transfer register
U0TCTL|=SSEL0+STC;   //Clock source is SMCLK
U0BR0=0x02;     //transmission baud rate set to ACLK/2
U0BR1=0x00;
UMCTL0=0x00;
ME1|=USPIE0;
//SPI0 module enable
U0CTL&=~(SWRST);
IE1=0;
IFG1=0;
return;
}

Data transmission required that the reception and transmission baud rate must be consistent. The system set baud rate to 115200 and data width is 8 bit sending by pin P3.6.

void Init_UART1(void)
{
    U1BR0=0x22;     //4M--SMCLK baud rate 115200
    U1BR1=0x00;
    U1MCTL=0xED;
    U1CTL=CHAR;     //data width 8 bit
    U1TCTL=SSEL0;
    ME2=URXE1+UTXE1;
P3SEL=BID6+BIT7;
P3DIR=BID6;
return;
}

Select the most commonly used interrupt Timer_A interrupt mode, select the timer clock to ACLK and add counting mode.

Void Init_TimerA (void)
{
    TACCTL0|=CCIE;   // ON interrupt enable
4.2.3 Microcontroller’s digital signal processing

In the on-line monitoring system, because the temperature sensor DB120 has digital output and use custom communication protocol, therefore working procedures of the sensor will build another a library file. The temperature sensor require 3.3 V, power on rate could not be less than 1 V/ms. After switch on, the sensor needs 11 ms for resting state. Before this, it is not allow sending any command to sensor. Use a set of “Start transmission” to represent the data transmission sequence initialization. Including when the SCK clock is high level, the DATA will toggles to low level. Follow by the SCK changes to low level, soon after when the SCK clock is in high level, the DATA will toggles to high level. When the DB120 passes to falling edge of the 8th SCK clock, it drop down the DATA to low level (ACK status), to verify DB120 comes into operation. DB120 commands set is shown in table 4.2.

<table>
<thead>
<tr>
<th>Command</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserve</td>
<td>0000x</td>
</tr>
<tr>
<td>Temperature measurement</td>
<td>00011</td>
</tr>
<tr>
<td>Read status register</td>
<td>00111</td>
</tr>
<tr>
<td>Write status register</td>
<td>00110</td>
</tr>
<tr>
<td>Reserve</td>
<td>0101x-1110x</td>
</tr>
<tr>
<td>Soft Reset, Reset I/O, Clear status register, If clear to default value, wait for the next command at least 11 ms</td>
<td>11110</td>
</tr>
</tbody>
</table>

After sending “Start transmission” command, the microcontroller will send “Connection reset timing” to the sensor. Then it will send data acquisition command to the sensor. It include when the DATA keep high level time and trigger SCK clock 9 times or
more. The whole process of the digital signal transmission is run in 8 bit.

DB120 sends digital signal to the microcontroller. Then the microcontroller will send the digital signal to storing in an array $\text{dat} [n]$ according to the self-defining sequence. After that pass the data through a receiving buffer register U1RXBUF, transmitting buffer register U1TXBUF and send out to realize the data communication. The operation of the buffer registers as follows:

$$\text{dat}[n]=\text{U0RXBUF}$$
$$\text{while}((\text{IFG2}\&\text{UTXIFG1})==0);$$
$$\text{for}(k=0;k<1;k++);$$
$$\text{U1TXBUF}:=\text{dat}[n];$$
$$\text{while}((\text{IFG2}\&\text{UTXIFG1})==0);$$

4.3 PC software processing

4.3.1 Virtual instrument introduction

In the on-line monitoring system, program manipulation on PC uses virtual instrument platform. Virtual instrument is a programmable instrument and instrumentation system based on a common computer establishing. That mean, there use a common computer to be a core hardware platform. Define by the user designs, with a virtual front panel and measurement functions is performed by computer software measuring instrument system. In the virtual instrument, hardware is just to solve signal input and output but software is the key of the instrument[39]. At present, in the virtual instrument technology field, the most widely use of computer language is LabVIEW of NI company. The feature of this programming language is using a VI block diagram structure instead of tedious program code to write program in the form of block diagram. Widely adopt in industrial, academic and researching works. After recent years of development, LabVIEW gradually become a standard of data acquisition and instrument control software. It raises our working efficiency in researching, designing and measuring fields.

4.3.2 Data receiving module

When we use LabVIEW as data operation platform, we can use special Virtual Instrument Software Architecture (VISA) to receive data. VISA is a set of standard I/O function library and a general term of relative standard. Which resides in computer system
for perform specific function of instrument bus and acts as layer connection between the computer and the instrument and to provides channel for smooth communication between computer and instrument\(^{[40]}\). By using VISA, users can connect with most instrument bus including GPIB, USB, serial interface, PXI, VXI and Ethernet. No matter what the bottom of the hardware interface, users only need to deal with unified programming interface VISA, as shown in figure 4.3.

![VISA diagram](https://via.placeholder.com/150)

**Figure 4.3 Using VISA Connect to different types of hardware interface**

In other words, VISA can control GPIB, serial interface, USB, Ethernet, PXI, or VXI instruments, making the appropriate driver calls depending on the type of instrument you use so you do not have to learn instrument-specific communication protocol. It is platform independent, bus independent, and environment independent.

In LabVIEW version 10.0 (LabVIEW 2010), it call path of VISA module by: Instrument I/O → VISA. We can complete the operation of the serial interface communication by using VISA templates. VISA node functions are shown in table 4.3.

**Table 4.3 VISA node functions**

<table>
<thead>
<tr>
<th>Palette Object</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VISA write</td>
<td>Writes the data from write buffer to the device or interface specified by VISA resource name.</td>
</tr>
<tr>
<td>VISA read</td>
<td>Reads the specified number of bytes from the device or interface specified by VISA resource name and returns the data in read buffer.</td>
</tr>
<tr>
<td>VISA clear</td>
<td>Clears the input and output buffers of the device.</td>
</tr>
</tbody>
</table>
Palette Object Description

<table>
<thead>
<tr>
<th>Palette Object</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VISA read STB</td>
<td>Reads a service request <strong>status byte</strong> from the message-based device specified by <strong>VISA resource name</strong>.</td>
</tr>
<tr>
<td>VISA Assert Trigger</td>
<td>Asserts a software or hardware trigger, depending on the interface type. For software triggers, Default (0) is the only valid protocol. For VXI hardware triggers, Default (0) is equivalent to Sync (5).</td>
</tr>
</tbody>
</table>

At first, data reception use VISA to configure serial interface to initialize serial interface parameters. The system selected baud rate to be 115200, data bit was 8 bit, stop bit was 1 bit, odd parity and serial port number is fixed by USB port number of PC. After the initialization, the communication between PC and uploaded data had been finished. Follow by setting an I/O buffer of VISA. The buffer generally uses 4906 bytes default setting and then used a loop for reading VISA value. After finish the serial communication, using VISA close function with VISA resource name.vi dialogue that specified in each serial port to release corresponding resources. The error out contains string error message. The serial communication block diagram is shown in figure 4.4.

![Figure 4.4 Serial communication block diagram](image)

4.3.3 Data processing module

The array that had been sent by microprocessor is a hexadecimal array. In order to distinguish the pressure and temperature value, the array provides two check number. The
first is 80, the second is FF. The data that received by PC, First of all, it find 80FF and the following data successively correspond to pressure and temperature. The data that pass through serial port is in a string representation. So, it has to be performed digital search. First, there will put the string convert into an array form, then find the two check number. After find out 80, check it whether or not followed by FF. If it is, it will receive data and perform further process. If it is not, it will continue to search. In LabVIEW, searching system of one-dimensional array will automatically convert to the decimal. So, searching 80FF is to search 128 and 255 in actual operation.

In order to let the user more intuitive to watch the monitoring results, the system will save the collecting data with sampling time together in the form of waveform file. Then convert the subsequent numbers to a Y-axis waveform and define the sampling to an X-axis. After that, save converted array form of signal into a cluster form. Converting method is shown in figure 4.5.

![Figure 4.5 Waveform storage block diagram](image)

On-line monitoring system provides two ways of data storage. First, there is a data that write into the database for analysis in the next time. Second, there is a data that users select for a particular time period as specified in path storage. The process of specify the path to save is: First, convert the path into a string and then analyze the size of the array. At the same time, convert user-defined filename extension into string too, and then combine two of them to create a new array. Finally, restore the string back into the path form. Specify the path storage filename extension to .dat format. Then save system’s time from current computer time. LabVIEW 10.0 (LabVIEW 2010) can call this module
directly. The block diagram of specifying the storage path is shown in figure 4.6.

**Figure 4.6 Block diagram of specifying storage path**

### 4.3.4 Database module

Database is a necessary module of online monitoring system. By using database access technology, the collecting data will store in time sequence in the database. There is convenient for users to check the status of the equipment and provides evidence when the equipment has failure. Although LabVIEW does not have database access function, you can use LabSQL to call Microsoft ADO and SQL language to realize database access[^43^].

LabSQL is a collection of VIs that use the ADO object collection in LabVIEW so that you can connect to almost any database, perform SQL queries, manipulate records, etc. Essentially it is a collection of VIs that acts as wrappers for ADO properties and methods.

Creating database in LabVIEW can be completed by two steps: First, create Microsoft Access Driver (*.mdb) file in ODBC, after that call LabSQL module and then specify that Access file. Be careful when create Access file and edit LabSQL in write process, the attribute name will be one-to-one correspondence. The database establishment process of LabVIEW is shown in figure 4.7.
The function of ADO modules that used in figure 4.7 are shown in table 4.4.

**Table 4.4 some ADO module functions**

<table>
<thead>
<tr>
<th>Node name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADO Command Create.vi</td>
<td>Create ADO Command and then return to Refnum</td>
</tr>
<tr>
<td>ADO Connection Open.vi</td>
<td>Open Connection Object</td>
</tr>
<tr>
<td>ADO Connection Close.vi</td>
<td>Close Connection Object</td>
</tr>
</tbody>
</table>

The database establishment not only uses ADO module, it also uses SQL language to accomplish. The main function of SQL language is to communicate with all kinds of database. According to ANSI regulations, SQL is being used as a standard language of relational database management system that can be used to perform various operations. For example, update data in database, collect data from database, etc. At present, most popular relational database management systems such as Oracle, Sybase, Microsoft SQL Server, Access, etc. use SQL language standard. SQL contains four parts: Data Query Language (DQL) SELECT; Data Manipulation Language (DML) INSERT, UPDATE, DELETE; Data Definition Language (DDL) CREATE, ALTER, DROP; Data Control Language (DCL) COMMIT WORK, ROLLBACK WORK. The basic step of system database establishment as follow: The first step, call ADO Connection Create.vi and ADO
Connection Open.vi to establish connection with database. At first, using ADO Connection Create.vi to establish Connection Object, and then use ADO Connection Open.vi to establish connection with database. The database specify Connection String“DSN=moon”. The second step, use SQL Execute.vi to execute INSERT INTO command. After the INSERT INTO is the corresponding name of database, that is data_2. Insert the corresponding object attributes in the following bracket and separated each of them by comma. Then, the system can add data after the bracket sign of VALUES. The transferred data have to pass through the number turn into string operation. Use single quote mark indication according to the string adding method and use comma to separate each string. The detail is shown in figure 4.7. The third step, use ADO Connection Close.vi to close the database connection.

LabVIEW is a language that user can customize the library function. So, you can create SubVIs for common or frequent processes that you can reuse. The system bundle the database process to be a SubVI. So that, it has just only to call directly when it want to use, make it has a good versatility and scalability.

After establish the database and store data, the system must realize the data query. Query process is shown in figure 4.8. The difference is, there call ADO Connection Execute.vi and SQL Fetch.Data.vi. Query process use ADO Connection Execute.vi to execute “SELECT * FROM data_2” query command. The “FROM data_2” is to query all data items of data_2. If users want to query in only a certain items, they can use “Where” operation. Using SQL Fetch.Data.vi to get query results and send to the front panel window display. The process used Transpose two-dimensional array module and Index array module to make the data in database can separately display according to the order of storage. The other modules are similar to the database establishment module. As same as in the database establishment module, query process is bundled into a SubVI.
4.3.5 User interface achievement

The front-panel of LabVIEW program is the user’s operating area. By using front-panel display, the user can select to observe any equipment’s operation. They can select to manually save or select to automatically save. The program result can be displayed by various types of display control of front-panel, such as in numeric form and meter form. Make the users intuitive understanding of equipment condition.

The front-panel of on-line monitoring system mainly consists of two parts. The first part is to constantly measure physical quantity variation, display these quantities in the form of number, waveform and table to the user at the same time and raise the alarm when each physical quantity within the equipment exceed the safe range. The second part is to monitor the transmission condition of the system whether in the normal condition or not. For example, the communication condition and sensor condition monitoring. The front-panel of SF$_6$ gas density on-line monitoring system is shown in figure 4.9.
Figure 4.9 The front-panel of SF₆ gas density on-line monitoring system

Rear-panel design of LabVIEW like a text programming language’s source code writing. Realization of all functions is complete by it. Main achievement of the rear-panel of this system is data reception, data processing, data storage and data query. Data flow diagram of the program is shown in figure 4.10.
After the system finished, we will change the program into an installation program.
So, the user can use this program in a computer that has not installed LabVIEW program. Because purchasing LabVIEW program is expensive and the LabVIEW program installation and operation are very time-consuming and use more computer resources. That is the reason why it is necessary to convert the program into an executable application.

Although, generates this executable application is not complicate, there are some aspects that you have to pay attention. First of all is to ensure the program, that mean all of the VI can operate dependently. So that we can guarantee the generation of executable file will not appear failure. Second, the program had better not use absolute paths, general compilatory sub-VI are based on the path relative to the main VI. All of subVIs and the main VI of this system are stored in the same folder. Finally, if the program used MathScript node, LabVIEW Run-Time engine will not work. The system does not use the MathScript node. After completion of the preparatory work, we can start generating EXE file. In the menu bar do the following operation: File→New Project→Build Specifications →New→Application (EXE). In the popup dialog box, enter the name and path of the EXE file and insert user interface in the Startup Vis. Then add all of the SubVIs that used in the program into Dynamic Vis and Support Files and other states can choose to default. After finish preview, we can Build it. Although the EXE file has been generated, the computer that will run this EXE file must be installed LabVIEW Run-Time Engine in order to work. So, it also need to build the installation file.

In order to create the installation file, do the following operations in menu bar: File →New Project→Build Specifications→Installer. In the popup dialog box, select the EXE file path that will create to installation file (Installer) and enter name of the installation file. In the “Source File”, add the generated EXE file from Project View into Destination View. Other settings remain to default. Finally, we can Build the installation file and ready to use by users.

4.4 Summary

This chapter introduced how to control sensors by microcontroller and how to use C language for controlling microcontroller, then established the data transmission network layout and described how to perform data reception, data processing and database access,
bases on LabVIEW language. Finally, the procedure design was presented and made the program to EXE file for convenient use by users.
5 System test and analysis

This On-line monitoring system is designed for 110 kV high voltage combined electronic transformer. The main content of this chapter is for testing and analyzing on the condition at operation of the system. The 110 kV high voltage combined electronic transformer that had been tested is shown in figure 5.1 and the test instruments of this system are shown in figure 5.2.

Figure 5.1 110 kV high voltage combined electronic transformer
5.1 **System operating environment and configuration**

The hardware that used in the experiment include the pressure sensor, temperature sensor, switch, PC, MSP430 microcontroller, external A/D converter, Serial to Ethernet converter, optical fiber with conditioning circuit, receiving circuit and transmission circuit. Which is the PC operating system is Windows XP.
5.2 System operation results and analysis

5.2.1 Measurement result

The test was accomplished on 15 November 2011. At that time, the ambient temperature is 10°C. System collected data once every ten minutes, but the data in this analysis is based on half hour unit and extracted from the collected data. Figure 5.3 illustrate the pressure measured values of the system and figure 5.4 illustrate the temperature measured values of the system.

![Figure 5.3 The pressure measured values of the system](image1)

![Figure 5.4 The temperature measured values of the system](image2)
According to the characteristic of SF₆ gas, internal pressure of electronic transformer in general engineering applications is about 0.3 Mpa to 0.5 Mpa. Temperature rising at bus pole is not more than 50°C. From the recorded data we can see that, all of the physical quantities of monitored transformer are in the normal operating range.

5.2.2 Uncertainty analysis

According to the presence of measurement error, there is difficult to determine the true value of measurement, because the measurement results have uncertainty. Measurement uncertainty is an important index that can be evaluated the quality of measurement results and it point out the uncertainty of change in measurement result. It is a sign that the true value is measured in a certain range of estimation and represent the distribution of measured value\[^4\]. Evaluation of standard uncertainty can be classified into type A and type B. Type A evaluation is accomplished by statistical analysis method. By using error analysis in the on-line monitoring system devices, A type standard uncertainty of the system mainly originated from the following:

1. Uncertainty error component cause by signal acquisition devices.
2. Uncertainty error component cause by microprocessor and A/D converter.
3. Uncertainty error component cause by various random factors.

We will divide each component to calculation as follow:

1. Measurement uncertainty that cause by signal acquisition devices \( U_1 \)

The output of temperature sensor is digital quantity. It has to connect with microprocessor in order to get data. So, we just test on the analog output pressure sensor only. The test is carried out in a constant condition and in a number of measurements (10 times). Each test results are independent. Standard deviation of pressure sensor is \( 1.895 \times 10^{-3} \). So, the uncertainty component is:

\[
U_{a1} = \frac{1.895 \times 10^{-3}}{\sqrt{10}} = 5.992 \times 10^{-4}, \text{ degree of freedom } r_1 = 9, \text{ normal distribution;}
\]

2. Measurement uncertainty that cause by microprocessor and A/D converter \( U_2 \)

Because of the limitations of accuracy of microprocessor and A/D converter, so they can generate uncertainty to their measured data. We consider the microprocessor and A/D converter as an integrated body and were measured as a high stable voltage source. Then
perform repeated measurement in a constant external environment (tested 8 times). Each test results are independent. Standard deviation of microprocessor and A/D converter is $9.519 \times 10^{-3}$. So, the uncertainty component is:

$$U_{A2} = \frac{9.519 \times 10^{-3}}{\sqrt{8}} = 3.366 \times 10^{-3}$$

degree of freedom $r_2 = 7$, normal distribution;

(3) Measurement uncertainty that cause by various random factors $U_3$

Various random factors can generate uncertainty to every physical quantity that was measured and sent to PC until the process is complete. Measurements proceeded 7 times under normal atmospheric condition. Each test results are independent. Standard deviation of pressure value under the influence of random factors is $1.472 \times 10^{-2}$. So, the uncertainty component is:

$$U_{A3} = \frac{1.472 \times 10^{-2}}{\sqrt{7}} = 5.564 \times 10^{-3}$$

degree of freedom $r_3 = 6$, normal distribution;

Measurements proceeded 7 times under normal atmospheric condition. Each test results are independent. Standard deviation of temperature value is $3.379 \times 10^{-3}$. So, the uncertainty component is:

$$U_{A4} = \frac{3.379 \times 10^{-3}}{\sqrt{7}} = 1.277 \times 10^{-3}$$

degree of freedom $r_3 = 6$, normal distribution;

B type standard uncertainty is not used statistical analysis method, but used other method to estimate probability distribution or the distribution was assumed to evaluate the standard deviation and get the standard uncertainty. Generally from the product specification, verification certification, technical standard or practical experience etc. Uncertainty generated by the system mainly came from the sensor, A/D converter and optical/electrical, electrical/optical converter. For the sensor, the temperature sensor manual pointed out that temperature accuracy is $\pm 0.3°C$. According to Measurement Uncertainty Evaluation and Expression Guide, uncertainty generally use uniform distribution to calculating standard uncertainty component which cause by temperature digital sensor indicating value tolerance $U_{B1} = \frac{0.3}{\sqrt{3}} = 0.173$, standard uncertainty
component which cause by pressure sensor tolerance  \( U_{b2} = \frac{0.01}{\sqrt{3}} = 5.774 \times 10^{-3} \). The system used 16 bit A/D converter, which accuracy level is 0.02%. Standard uncertainty component that cause by its tolerance is  \( U_{b3} = \frac{2 \times 10^{-4}}{\sqrt{3}} = 1.155 \times 10^{-4} \). Electrical/optical, optical/electrical converter accuracy is 0.2%. Standard uncertainty component that cause by its tolerance is  \( U_{b4} = \frac{0.002}{\sqrt{3}} = 1.155 \times 10^{-3} \).

5.3 Summary

This chapter explained in detail about the test of system. Include the condition of measured equipment and test environmental conditions. Furthermore, the chapter summarized the result of the test measurement and calculated A type and B type uncertainty analysis of collected data. By testing we obtained the overall accuracy level 2 that reached the electronic transformer on-line monitoring basic requirements.
6 Summary and Prospect

6.1 Summary of the whole dissertation

When an electronic transformer which filled with SF$_6$ gas insulated is running, the SF$_6$ gas temperature and pressure can be affected by many factors. This will lead to changing in the density of SF$_6$ gas. During the operation of electronic transformer, it inevitably leaks of SF$_6$ gas that leading to decline of SF$_6$ gas density. SF$_6$ gas density changes can affect the value of the relative dielectric constant ($E_r$) and make coaxial capacitance value (C) fluctuate. Finally affect secondary voltage measurement result. Moreover, SF$_6$ gas leaks will quickly reduce the electronic transformer insulation and external moisture will penetrate into the transformer. Lead to the water content of SF$_6$ gas exceeds standard, so it make the transformer unsafe.

Because of the leak will rapidly reduce the performance of SF$_6$ gas transformer insulation. So, it is necessary to monitor the SF$_6$ gas leakage of transformer. SF$_6$ gas leakage is one of the important matters of monitoring of electrical equipment, especially for electronic transformer.

With the promotion of intelligent substation, electronic transformer has got more and more attention. This makes the safe operation of electronic transformer and equipment maintenance studies to become an urgent matter. However, the current maintenance of electrical equipment, most of them are in the offline maintenance state. This is not only affects the normal operation of the power grid, it even more degrade the efficiency. Under this condition, SF$_6$ gas density on-line monitoring system is more proper. This paper proposed a kind of SF$_6$ gas density on-line monitoring system of electronic transformer, the system is based on virtual instrument and worked properly in transformer. It constantly monitored the SF$_6$ gas density within the electronic transformer and in a timely manner for reporting the insulation performance. The system used virtual technology and digital technology to avoid large current and strong magnetic field that interfere the signal. So that it improve the reliability of the system. This paper describes in detail about the principle and design scheme of virtual instrument of SF$_6$ gas density monitoring system and describe about each component part. According to the three aspects of application of
MSP430 microcontroller, the communication of LabVIEW program and processing correction algorithm of different data give detailed instruction design of system software platform. For the above, this paper made the following research

(1) Introduced the prospects of the development of SF₆ gas density on-line monitoring system and the necessity, combined the virtual instrument that made the scheme of on-line monitoring device within the operating state.

(2) According to the measurement requirements of SF₆ gas density on-line condition monitoring system, described the selection of appropriate temperature sensor and pressure sensor for this measurement system.

(3) Used C language controlled microcontroller to received sensor signals and converted analog signal into digital signal. Then followed a certain order to sending data through the serial port for sent it to PC

(4) Used different correction algorithm to corrected the received data and accomplished the overall data treatment by the method of virtual instrument

(5) Analyzed A type uncertainty and B type uncertainty of the pressure data and temperature data of the experiment, and got the degree of accuracy of system to level 2, that met the requirement of this topic.

6.2 Prospect

Due to the time constraint and limited ability of the author, the SF₆ on-line monitoring system is still some further researches to do.

(1) Network transmission design is more conservative. Although the Ethernet method can be adapted to the general scale of the substation, fiber-optic wiring can provide more complex transmission system to a complex substation. In the precondition of guaranteeing transmission quality, we can consider using wireless communication method to simplify the traditional wiring pattern, such as bluetooth or microwave.

(2) The system generated an SF₆ gas density database which used some space in hard disk of PC. If there is not necessary in your application, you can save the space by cancel this database and just only use Beattie-Bridgman empirical formula to manually calculate for the gas density when necessary.

I'm sure my poor scholarship has missed others and my experience is very limited, If
you find any errors or have any questions, comments or suggestions, please report them directly to the author.
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Reference

[1] 刘延冰, 李红斌, 余春雨, 叶国雄, 王晓琪. 电子式互感器原理、技术及应用. 一
北京: 科学出版社, 2009


华中科技大学硕士学位论文

司, 2005
[16] 常涛, 刘永, 方玉林, 姚强. SF₆气体绝缘变压器故障诊断分析. 重庆: 重庆电力科学试验研究院, 2009
[26] 吴亚珍. SF₆气体泄漏检测方法及报警技术. 福建、龙岩: 龙岩电业局, 2006
[27] 刘文浩. SF₆气体压力换算方法. 湘北: 湖北省超高压受电电局, 1992
[40] 张桐, 陈国顺, 王正林. 精通 LabVIEW 程序设计. 北京: 电子工业出版社, 2008: 532-536
[43] 杨乐平, 李海涛, 赵勇等. LabVIEW 高级程序设计. 北京: 清华大学出版社,
2002: 258-259


[47] Thomas L. Floyd. ELECTRONIC DEVICES. PRENTICE HALL, 1999

[48] 国家质量技术监督局计量司. 测量不确定度评定与表示指南. 北京: 中国计量出版社, 2005