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Development of a Voltage Measuring System for the Pusan-Hamada Submarine Cable
釜山 － 浜田間 海底케이블 電壓測定 裝置의 開發

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Abstract□A voltage measuring system specified for the voltage fluctuation of the Pusan-Hamada submarine cable is developed by adding circuits of differential amplification and analog-to-digital conversion to a microprocessor-based data logger with a data modem. This system is charaterized by its small size, no power failure, fully unmanned operation, and precise instrumental drift correction. In addition to the cable voltage and current, it measures an ambient temperature and a mercury cell voltage in order to calibrate temperature effect and check its long-term stability. The data acquired by this system show that the voltage signal, comprising fast random noises with a constant width of about 0.2V, fluctuates within a range of about 1V and the fluctuation frequency is similar to that of tidal motion. The source voltage of power feeding equipment (PFE) for the cable system seems to be affected when the room temperature changes rapidly.

要　旨：差動增幅과 A/D(analog-to-digital) 變換 回路를 마이크로프로세서(microprocessor)로 作動되는 데이타로거(data logger)에 連結하여 釜山-하마다間의 海底케이블 電壓變動을 記錄하는 裝置를 開發하였다. 이 裝置는 低價格, 小型, 低電力消耗가 特徵이며 計器의 電壓드리프트(drift)가 精密修正되고, 無人自動으로 多量의 資料貯藏과 모뎀(modem)에 의한 資料傳達이 可能하다. 케이블 電壓 및 電流以外에 室內溫度와 水銀電池電壓을 測定하는데, 이는 溫度影響에 따른 誤差補正과 長期間 計器安定度를 確認하기 위한 것이다. 이 計器에 의한 觀測資料에 의하면 釜山海底中繼局에서의 電壓信號는, 約 0.2볼트의 一定한 幅의 높은 周波數의 雜音帶로 이루어져 있는데, 潮汐과 비슷한 느린 週期로 約 1볼트 範圍내에서 變動한다. 또한, 케이블 電源供給裝置는 室內溫度가 빠르게 변할 때 많은 影響을 받는 것으로 나타났다.

1. INTRODUCTION

The Korea-side voltage of a submarine telephone cable installed in 1978 between Pusan (Korea) and Hamada (Japan) has been observed using a high-resolution data logger since March, 1990 (Kim *et al.* 1991). Spectrum of the one year data shows peaks at tidal frequencies and energy in the frequency lower than 0.01 cph dominates the voltage fluctuation. It is suspected that the low frequency fluctuation may be contaminated by the voltage drift due to changes of room temperature, as an independent laboratory test.

In order to obtain reliable long-term cable data, the data logger should be improved or replaced with more accurate and stable system that can reduce temperature effect. This study focuses on the development of a new recording instrument which measures ambient temperature (room temperature) variations to check and correct temperature-dependent components in the cable system as well as those in the recording instrument.

2. PUSAN SUBMARINE CABLE STATION

The Pusan-Hamada submarine cable, a 286-km-long coaxial cable with 50 repeaters equally spaced, is powered by both Pusan and Hamada

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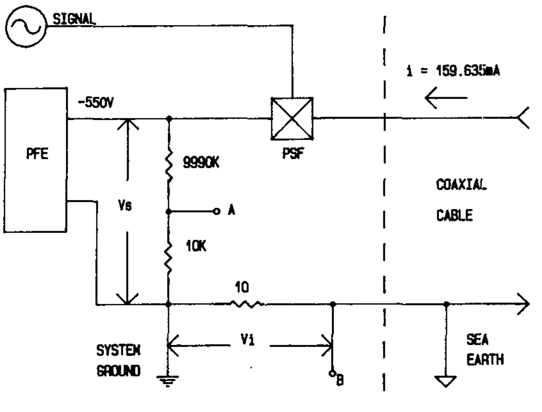

Fig. 1. Circuit diagram of the Pusan submarine cable relay station. Power feeding equipment (PFE) supplies −551 V and −156.935 mA. The Japan-side circuit is symmetrical, but its power voltage is +551 V. High-frequency telephone signals from/to a coaxial cable are filtered through power separation filter (PSF).

cable stations. Fig. 1 is a circuit diagram of the Korea-side station which is symmetrical to that of the Japan-side station except the polarity of power voltage. Both power feeding systems work reciprocally and regulate the cable current to be constant.

The voltage of a power supply V_S, $-551\text{V}\pm 2\text{V}$, is measured from a 1000 : 1 voltage divider (point A in Fig. 1): $V_A = V_S\ 10\text{k}\Omega/(9990\text{k}\Omega + 10\text{k}\Omega)$. The current i, $-156.935\text{mA}\pm 0.01\text{mA}$, is determined from the voltage across a 10 ohm resistor (point B): $i = V_i/10\Omega$.

The room containing the power supply system is air-conditioned to be kept about 22℃. But there are daily and seasonal variations of more than ±4 ℃.

3. OLD RECORDING SYSTEM

Since the cable voltage is −551V and varies within ±2V, the desired resolution is at least 10 mV, 10 μV at test point A in Fig. 1, which can be achieved using a 16-bit analog-to-digital (A/D) conversion (full scale of 65536) in which 551V corresponds to 55100 counts.

A commercial 16-bit recording system may be a personal computer interfaced with a high-precision digital voltmeter. However, the system requires not only the high cost and the large space but also the uninterrupted AC power supply, which is less suitable for long-term measurement.

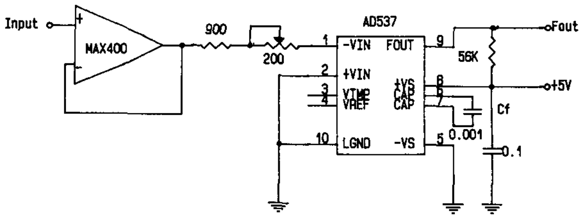

Fig. 2. Circuit of voltage-to-frequency (V/F) converter. An analog input of 1000 mV makes a full scale output of 100 kHz.

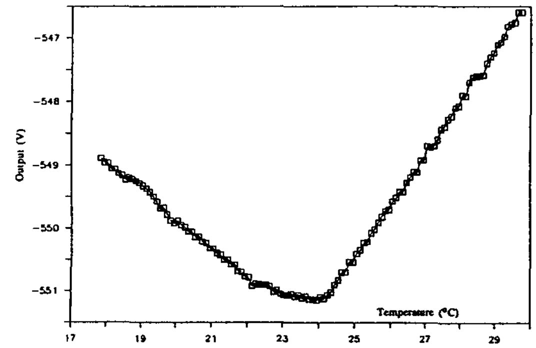

Fig. 3. Temperature versus data-logger output. A constant input −550 mV is sourced from MAX671, an ultra-precision voltage reference with drift of 1 ppm/℃ (Maxim Inc. 1989).

The recording system designed uses a microprocessor-based data logger (Bahk *et al.*, 1989; KORDI 1991) and voltage-to-frequency (V/F) converters. It is characterized by small size ($20\times 30\times 8\ \text{cm}^3$), low power consumption (<60 mW), and fully unmanned data recording and transmission.

It is easy to get high resolution with long-time integration using a V/F converter. In Fig. 2, an input voltage is buffered by an operational amplifier (OP amp), MAX400 of Maxim Inc., and drives a V/F converter, AD537 of Analog Devices Inc. The cable current is also converted using a similar circuit. The data logger counts the frequency outputs every second and stores data to static random access memory (SRAM). The stored data are transmitted via an internal modem when a user calls. In this method, the analog input of −551 mV makes the out-

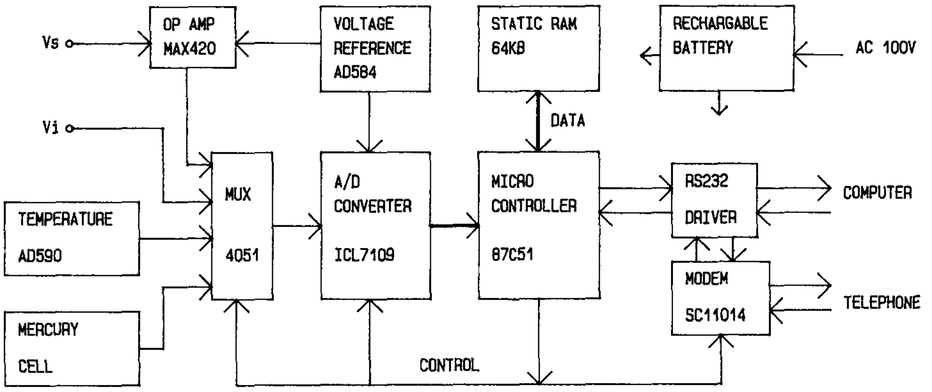

Fig. 4. Function diagram of the cable voltage measuring system. V_S and V_i are voltage at test points A and B in Fig. 1, respectively. MUX = analog multiflexer.

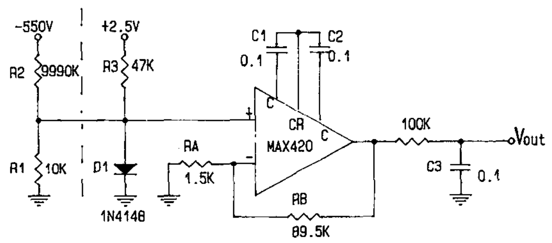

Fig. 5. Chopper-stabilized OP amp with minimum components. R_1 and R_2 are resistors inside the PFE. Diode D_1 is for overvoltage protection. Capacitor C_3 removes chopper clock pulses. The +2.5 V is from the AD584 voltage reference in the recording system.

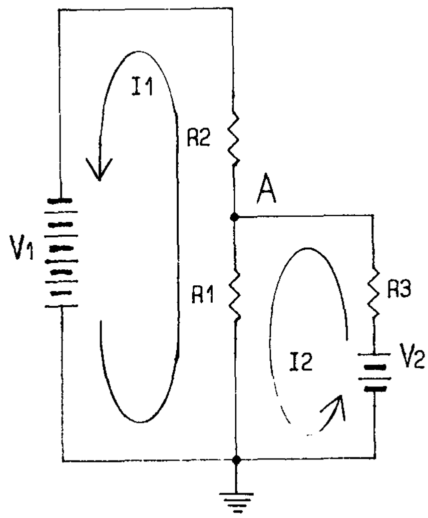

Fig. 6. Two loop currents in the input circuit of Fig. 5.

put of 55100 counts per second.

From one year measurement a large seasonal variation of voltage in a range of 5 volts was found by Kim *et al.*(1991). However a laboratory test of data logger indicates that voltage output is temperature-dependent as shown in Fig. 3. This nonlinear drift causes a complicated problem which is hard to resolve, because there are several components of more than one count error within the room temperature change of about ±4°C, such as V/F converter, counter, and oscillator for time base of the counter.

4. IMPROVED RECORDING SYSTEM

Another low-cost method to get high resolution is to apply differential amplification of input voltage and use a general 12-bit A/D converter. The voltage variation (ΔV_S) can be obtained by subtracting or adding a constant reference voltage (V_R) from the cable voltage (V_S). Then, ΔV_S is amplified to the input range of the A/D converter.

Fig. 4 shows the newly installed recording system which scans four input channels, comprising cable voltage, cable current, ambient temperature to calibrate temperature drift, and mercury-cell voltage to check long-term stability of the recording system. The major improvement of the old recording system is the replacement of the old V/F converter circuit by circuits of differential amplification and A/D conversion. It also includes a precision temperature sensor with a resolution of 0.1°C. This measuring system is located near the bottom outside the power feeding equipment (PFE).

The amplifier circuit designed is shown in Fig. 5. Since it handles at least 10 μV input variation, the number of components should be minimized to avoid the problem of long-term drift occurred commonly in a micro-volt level DC (direct current) circuitry. Although it is not a normal differential amplifier, it performs true differential amplification by substracting a constant positive voltage at the test point A. The circuit in Fig. 6 is identical to the input circuit of the designed system, in which two loop currents are identified. The two loop equations are written as follows:

$$V_1 = -i_1R_2 + (i_2 - i_1)\ R_1$$
$$V_2 = i_2R_3 + (i_2 - i_1)\ R_1$$

Solving for i_1, i_2 and calculating V_A, one has

$$V_A = (i_2 - i_1)R_1 = V_1R_2R_3(R_1R_2 + R_2R_3 + R_3R_1) + V_2R_1R_2(R_1R_2 + R_2R_3 + R_3R_1).$$

The OP amp in Fig. 5 is configured as a non-inverting amplifier whose gain is given as $1 + R_B/R_A$. Thus,

$$V_{out} = (1 + R_B/R_A)\ V_A$$

Since $R_1 = 10\text{k}\Omega$, $R_2 = 9990\text{k}\Omega$, $R_3 = 47\text{k}\Omega$, $R_4 = 1.5\ \text{k}\Omega$ and $R_B = 89.5\text{k}\Omega$, it is given by

$$V_{out} = 0.0500\ V_1 + 10.6345\ V_2$$
$$= 50\ (V_1/1000 + 0.021269\ V_2)$$

This equation shows that the circuit acts as a differential amplifier with a gain of 50. If $V_2 = +2.5\text{V}$, $V_{out} = 50\ (V_1/1000 + 0.5314)$. The output V_{out} is -1.080 V when $V_1 = -553\text{V}$. The cable voltage change of 10 mV, 10 μV at test point A in Fig. 1, corresponds to the output of 0.5 mV (500 μV). According to these values, the A/D converter circuit is designed with a resolution of 500 μV and a full scale input range of −2V.

5. ACCURACY

In this kind of instrument which measures low-level DC signals, measurement accuracy relies mostly on the voltage reference source and offset drift of operational amplifier. Any reference inaccuracy and amplifier drift will degrade the accuracy of the overall system.

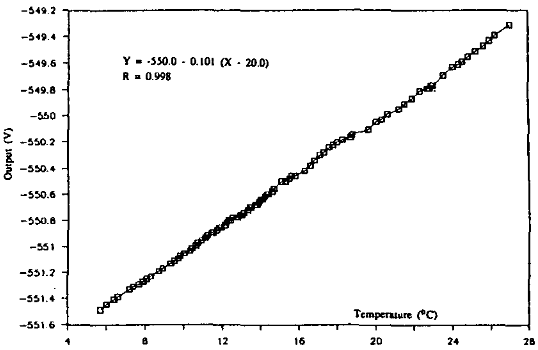

Fig. 7. Temperature characteristics of the measuring system. A constant input is sourced from MAX671 voltage reference with drift of only 1 ppm/℃ (Maxim Inc. 1989).

5.1 Voltage Reference Source

The voltage reference in this system is AD584LH of Analog Devices Inc. Its temperature coefficient is less than 10 ppm/℃ at +2.5V output (0.025 mV/℃) with +15V supply (Analog Devices Inc. 1989/1990). When used with a supply voltage of +5V a much larger coefficent is expected. Its temperature drift curve, however, draws a straight line within a temperature range 5~35℃, enabling precise data calibration.

5.2 Operational Amplifier Circuit

In order to achieve ultimate precision DC amplification and long-term stability, a chopper-stabilized OP amp, MAX420, is selected. This device offers input offset and drift specification superior to previous "precision" amplifiers. The maximum temperature input-offset drift is 0.05 μV/℃ (Maxim Inc. 1989) and all resistors in this circuit are precision metal foil ones with nominal temperature coefficient of 0.4 ppm/℃ from 0 to 50℃, contributing actually no error within the room temperature range. V_{out} varies only 3 μV per 1℃ in the circuit of Fig. 6.

5.3 A/D converter circuit

ICL7109 in Fig. 4 is a 12-bit integrating A/D converter. Although the ICL7109 itself yields no count

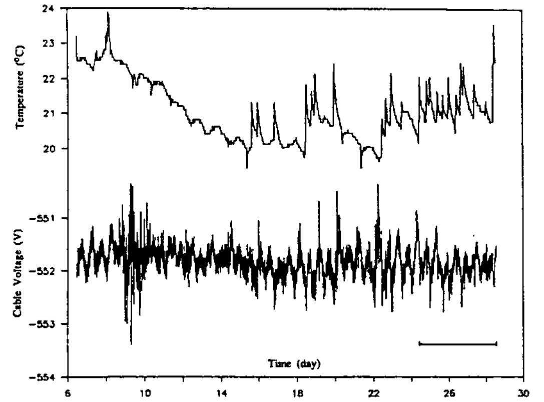

Fig. 8. Cable voltage and room temperature between 6 and 29, November, 1991. Sample interval was 5 minutes.

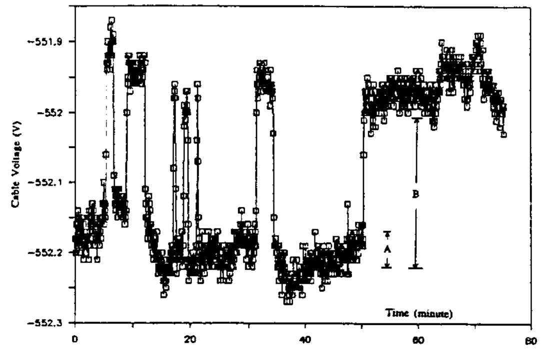

Fig. 9. Cable voltage from 80 minutes, starting at 15 : 00, November 4, 1991. Sample interval was 4 seconds.

error with 30 μV accuracy, the combined circuit also has a temperature coefficient because its reference source is the AD584LH.

Experimental data (Fig. 6) show that the total temperature coefficient of the newly designed recording system within the range 5~27℃ is −0.101 V/℃ with a linearity of 0.998 for the cable voltage (−180 ppm/℃). Since the room temperature is measured together with the cable voltage, the cable voltage drift caused by the recording instrument can be eliminated through data processing.

6. CABLE VOLTAGE CHARACTERISTICS

Fig. 8 shows the cable voltage and room temperature data from the newly installed recording system, during the period from 6 to 29, November, 1991. The voltage changes can be divided into three categories based on the change rate; (1) fast random changes of less than 60 minutes, (2) daily change, and (3) long-term variations, such as seasonal or longer-period changes.

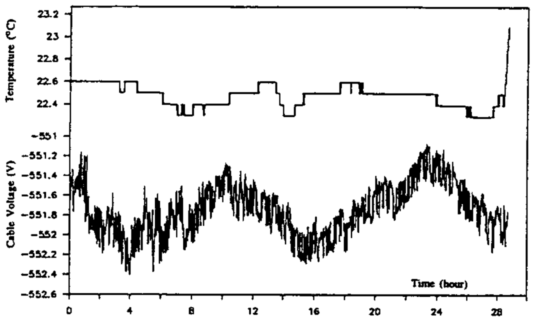

Fig. 10. Cable voltage from 28 hours, suggestive of a tidal signal. Sample interval was 16 seconds. Starting at 06 : 30, November, 5, 1991.

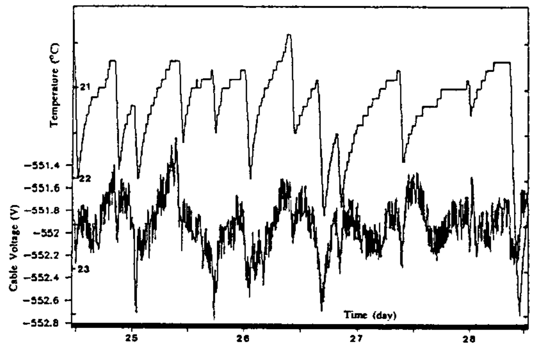

Fig. 11. Zoomed data during the period with remarkable temperature variations. For location, see Fig. 8. Note inverse temperature scale.

The fast random changes include A and B type changes shown in Fig. 9. The A type change, ranging about 0.05 V, about 10 ppm of the cable voltage, is composed of high frequency random signals, most likely caused by noises occurred from the cable system. The B type voltage rises and falls rapidly within a nearly constant width of about 0.2 V. This change is caused probably by a switched voltage adjustment of the power feeding equipment (PFE) to keep the cable supply current constant. In this recording instrument, the resolution for cable current, presently 50 μA or 500 μV (see Fig. 1 and

4), should be decreased to at least 1 μA in order to check the correlation between voltage and current.

The changes both A and B types make the major signal band of the cable voltage. This band also changes daily (Figs. 8 and 10). Without noisy peaks, daily variations of voltage and temperature are about 1 V and 2℃, respectively. The daily change is yieleded primarily by tidal current cutting the vertical lines of the earth's magnetic field (Hughes 1969; Prandle and Harrison 1975). The long-term variations for the Korea-side voltage cannot be analyzed yet due to the insufficient data.

There exists, however, still a temperature drift depicted in Fig. 11. The trend of voltage change does not exactly coincide with that of temperature change, suggesting that this drift is originated not from the measuring instrument but from the PFE itself. Since the temperature is measured outside the PFE, it can be somewhat different from the temperature inside, and this drift is explained probably to be caused by temperature-dependent components in the PFE. The voltage is influenced strongly by the room temperature gradient in time. To compensate this influence, temperature measurement inside the PFE and more data are required. It is under investigation to correct the voltage signals.

7. CONCLUSIONS

Although high-precision components are selected for the circuits of input amplifier and A/D converter, the measuring system has the temperature coefficient caused mainly by temperature characteristics of the voltage reference. To minimize the temperature effect, ambient temperature should be measured continuously. This measuring system turns out to be very accurate, stable and low-cost in monitoring the fluctuation of low-level DC voltage changes.

More precise correction of voltage fluctuation derived by ocean current is probably possible if: (1) long-term data are collected, (2) the recording system simultaneously monitors an additional temperature inside the power feeding equipment (PFE) at the Pusan cable station with a resolution of 0℃, and (3) the current of the power supply is recorded with a resolution of at least 1 μA.

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