Diagnosis of electric cable insulation by High Tc SQUID

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Abstract -- **We have developed the wide band electronics for SQUID and measured short pulse currents simulating a signal in a degraded power electric cable. The SQUID driving electronics had a bandwidth as wide as 1.4 MHz and it could successfully detect currents of 3 μA with the width of 120 nsec. These results suggested that SQUIDs can be applied to the partial discharge measurement of power cables.**

I. Introduction

An installed electric power cable such as a CV (Crosslinked polyethylene insulated polyVinylchloride sheathed) cable becomes degraded by continuous use for many years. The degradation occurs at a part of the cable insulation. This phenomena is initiated by a small defect such as a void [1]. Then the small defect extends and creates a current pass called "tree". Partial discharges in the tree expand the tree itself. Finally, it triggers a fatal breakdown. Therefore it is important to detect the defects at the initial stage. This kind of electric insulation diagnosis of power cable is one of non destructive evaluation. Generally, the partial discharge measurement by a radio receiver, a ultrasonic microphone and an impedance meter are commonly used for the diagnosis of the cable [2]. However, it is quite difficult to define the location where the small discharge occurs, because the discharge current is as small as several nano amperes and its pulse width is several 10 nano seconds.

High Tc SQUID magnetometer has a high sensitivity and a high space resolution. It is possible to apply the SQUID to the cable diagnosis. Unfortunately, you can not obtain a wide band SQUID driving electronics to detect such a small current with small pulse width on the market. Thus we have developed the wide band electronics for SQUID and measured simulated short pulse currents by using the system.

II. Experimental

A. Estimation of magnetic field associated with a discharge current

We estimated the magnetic field intensity as a function of spacing from a wire associated with a current to a sensor. The configuration of the SQUID sensor and a current is shown in Fig. 1. The intensity of the field generated by a current is calculated by a Biot-Savart Law,

$$Bz = \frac{\mu_0 Ix}{2\pi(x^2 + z^2)}$$

where μ_0 is permeability of vacuum and I is current associated with a discharge. Bz vs. spacing X between current and a sensor for several values of the currents is shown in Fig. 2. It shows that the magnetic field associated with the current of 10nA is about 0.1pTesla at a distance of 20mm from the current. It can be detected by a SQUID sensor.

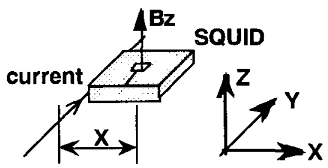

Fig. 1 Configuration of current direction and SQUID sensor. Direction of magnetic field which can be detected by the SQUID is B_z.

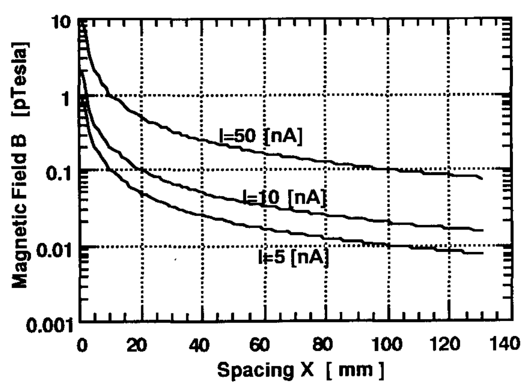

Fig. 2 Magnetic field vs. spacing for several currents. (Z: 0mm, X: 1 to 130mm) Magnetic field associated with the current of 10nA is about 0.1pTesla at a distance of 20mm from the current.

B. SQUID Driving Electronics Box

Pulse width of a discharge is about several 10nano seconds. The band width of the measurement system should be wide enough to detect the pulse. Modulation frequency of conventionally obtainable FLL (Flux Locked Loop) system on the market is about 1MHz. So we have made non-modulated FLL with APF (Additional Positive

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Feedback) technology [3], [4]. APF improves the effective flux-voltage transfer function and the noise properties. In an APF scheme, SQUID is connected to a resistance Ra and a inductance La as shown in Fig. 3. Effective flux-voltage transfer function $dV/d\phi_{ex}$ is given by

$$\frac{dV}{d\phi_{ex}} = \frac{\frac{dV}{d\phi}}{1-\beta_a}$$

where $dV/d\phi$ is transfer function of the SQUID without APF and

$$\beta_a = \frac{M_f}{R_a}\frac{dV}{d\phi} .$$

When the condition of $0<\beta a<1$ is satisfied, $dV/d\phi$ is improved. We used high Tc SQUIDs made by Sumitomo Electric industries and set parameters, 8 Ohms for Ra and 5 $\mu A/\phi_0$ for $1/M_f$ to maximize $dV/d\phi_{ex}$; this condition corresponds to $\beta a=0.38$. In our experiment, when βa was increased more than 0.4 by decreasing the value of Ra, output voltage of the SQUID decreased. Voltage-flux properties of the SQUID with and without APF are shown in Fig. 4(a) and (b) respectively. Flux to voltage transfer function is improved from $15\mu V/\phi_0$ to $19\mu V/\phi_0$ by using the APF though this improvement is somewhat lower than what we expected. To improve more, APF coil should be closer to the SQUID to increase mutual inductance. This problem is discussed in elsewhere [4].

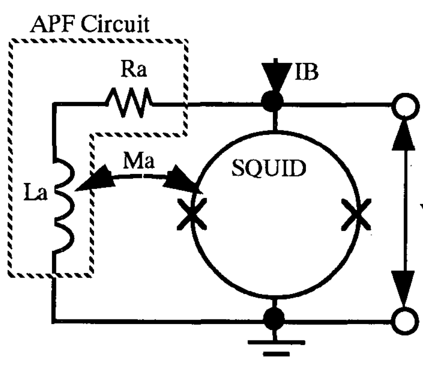
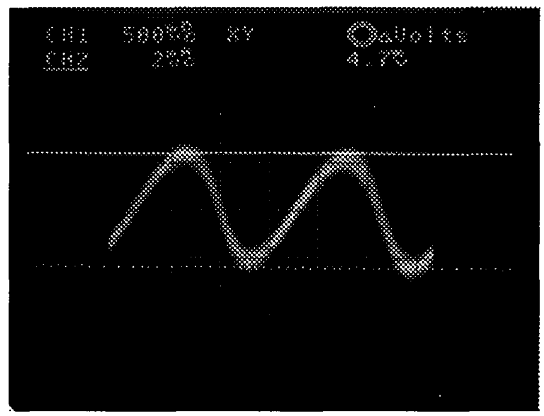
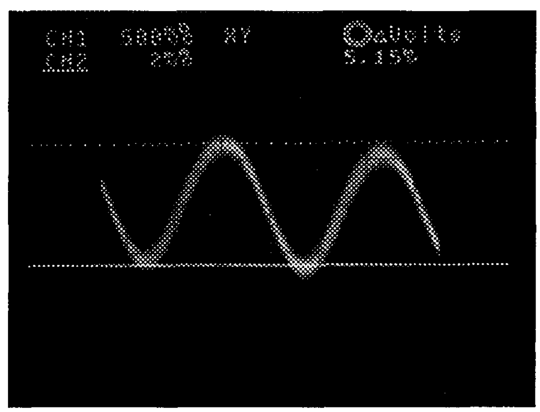


Fig.3 Schematic drawing of APF(Additional Positive feedback] circuit.

The SQUID driving circuit as shown in Fig.5 was designed. It is a non-modulation type [5], [6]. Ultra low noise operational amplifier AD797 (Analog Devices) was used as a pre-amplifier, which measured input noise voltage density was $1.3nV/Hz^{1/2}$. After the pre-amplifier the signal was amplified by second and third amplifiers. The band width of the amplifier including the pre-amplifier was 1.7MHz at the gain of 52000. Time constant τ of integrator was set at 0.9μsec. Feedback resistor was 5.1kOhms. The feedback range was $-40\phi_0$ to $40\phi_0$. A signal input coil (1 turn Cu wire) was magnetically coupled to the SQUID. The coil was connected to a digital pulse generator (BNC Model 7010) via a resistor for a signal current measurement. This system was powered by an acid battery. Noise properties of the flux locked SQUID was measured by HP35670A dynamic signal analyzer. To avoid ambient magnetic field the dewar is surrounded by three mu-metal shields. The flux noise was $50\mu\phi_0/Hz^{1/2}$ and almost flat in range from 100Hz to 100kHz. The field resolution was 1.0 $pT/Hz^{1/2}$ at white level. Sinusoidal input currents were pushed into the input coil to measure frequency response. Output voltage signal of buffer amplifier was measured.



(a) with APF circuit. (vertical scale: 2μV/div)



(b) without APF circuit. (vertical scale: 2μV/div)

Fig.4 Voltage-flux properties of SQUID (a) with and (b) without APF. Flux to voltage transfer function is improved from $15\mu V/\phi_0$ to $19\mu V/\phi_0$ by using an APF circuit.

The measured frequency response is shown in Fig. 6. Bandwidth was about 1.4MHz and there was a peak at 750kHz. Calculation by PSPICE (MicroSim) was performed. The calculated results are shown by dotted line in Fig.6. There is no such a large peak on the calculation. We think this peak is created by the buffer amplifier of the system because the buffer properties has not been reflected on the calculation.

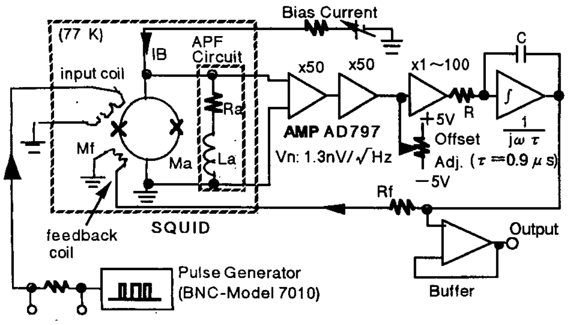


Fig.5 Schematic diagram of SQUID driving electronics. The band width of the amplifier including the pre-amplifier was 1.7MHz at a gain of 52000. Time constant τ of integrator was set at 0.9μsec. A signal input coil was magnetically coupled to the SQUID.

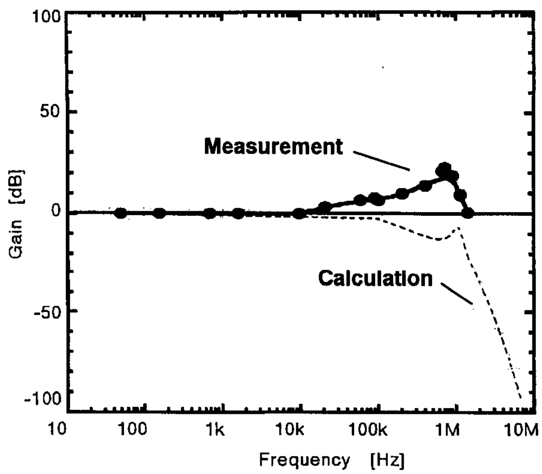
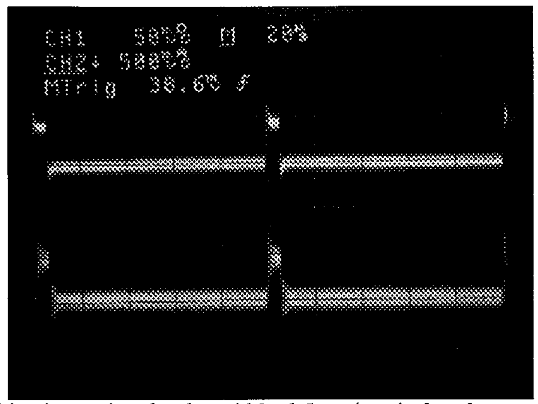


Fig. 6 Frequency response of flux locked SQUID. Filled circles are measured, and dotted line is calculated. Measured bandwidth was 1.4MHz and a peak was found at 750kHz.

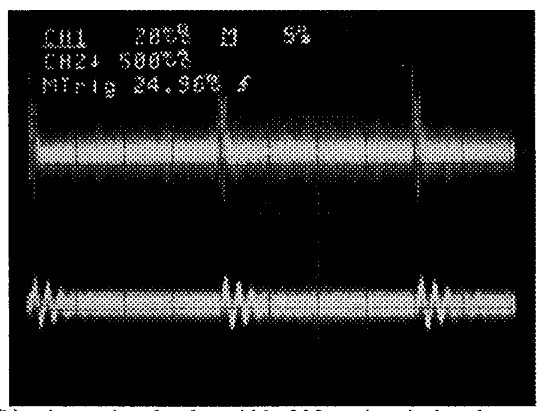
III. Results and Discussion

A. Response for short pulse currents

Short pulse response of the system was tested. Several different pulse currents were flown into the input coil by a pulse generator. Output signal of the system was measured by an analog oscilloscope. Typical input and output signal waveforms are shown in Fig.8. Although the output response for 6.5μsec and 50μA is square shape, the response for 900nsec and 20μA is distorted and it looks like a kind of oscillation. This may be because of restriction of bandwidth. Minimum detectable currents as a function of the pulse width, when the threshold level was 5mV on the oscilloscope screen, is shown in Fig.8. It shows that the detectable current values are 2μA and the same in the range from 560nsec to 6.5μsec. This value correspond to 0.25nT for SQUID. The minimum detectable current for width of 120nsec was 3μA. Use of a digital oscilloscope is recommended because this detectable currents are depend on the threshold of the oscilloscope. To reduce the threshold level, the field resolution of the SQUD should be improved. Recently high Tc SQUIDs with the resolution of 10-20 fT/Hz$^{1/2}$ are available. Using the high performance SQUID, the threshold will be improved by about two orders of magnitude. Another possibility to improve is applying an averaging signal processing. Since practical currents associated with partial discharge must be periodic with power line frequency, the averaging technology may be applicable. However, we have not done the feasibility study of the averaging processing yet.



(a) input signal pulse width: 6.5μs. (vertical scale: upper 50μA/div, lower 500mV/div, time scale: 20μsec/div.)



(b) input signal pulse width: 900ns. (vertical scale: upper 20μA/div, lower 500mV/div, time scale: 5μsec/div.)

Fig.7 Pulse response of the system. (a): for pulse width of 6.5μsec and (b): for pulse width of 900nsec. Upper is input signal and lower is output.

B. Cancellation of Magnetic Field from Power Line.

In an actual diagnosis, there are magnetic field noise from ac power line, which should be eliminated from the signal due to the defects. A cancellation technique by using two SQUIDs, one for detection of signals and noise, and the other for the noise, was tested. The experimental set up is shown in Fig.9. Power line currents were simulated by a sinusoidal 70Hz current generated by an oscillator. Two SQUIDs were used for this experiment The output signal of each system was electrically subtracted. Frequency of 70 Hz was selected to isolate the results clearly from 60 Hz noise associated with some other equipment in our lab. Pulse current was not flown in this experiment and only the 70Hz current was flown. Output signals from two systems and the subtracted signals from differential detector were measured by an oscilloscope and a spectrum analyzer. The results for different currents are shown in Fig.10. The 70Hz signal is reduced by a factor of 100. It is demonstrated that the 70Hz noise can be electrically canceled by using two SQUIDs.

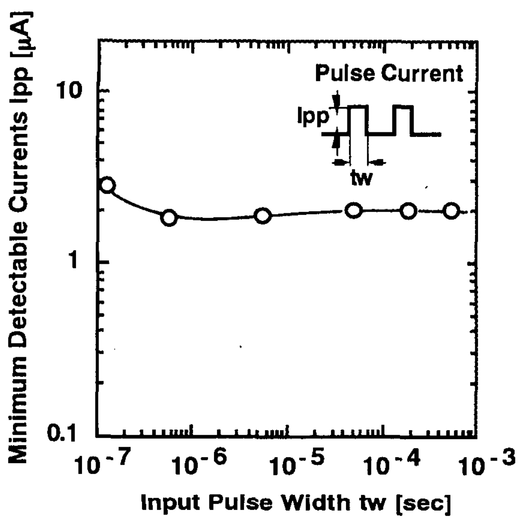


Fig.8 Minimum detectable currents as a function of the pulse width when the threshold level was 5mV on the oscilloscope screen.

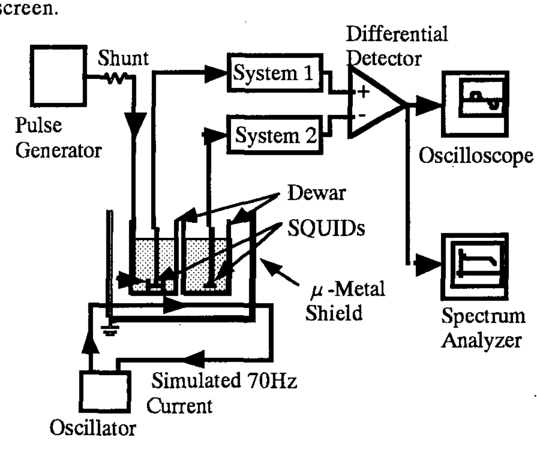


Fig.9 experimental set up diagram for power line cable cancellation test. Currents of power line were simulated by sinusoidal 70Hz current by an oscillator. Frequency of 70 Hz was selected to isolate the results clearly from 60 Hz noise associated with some other equipment.

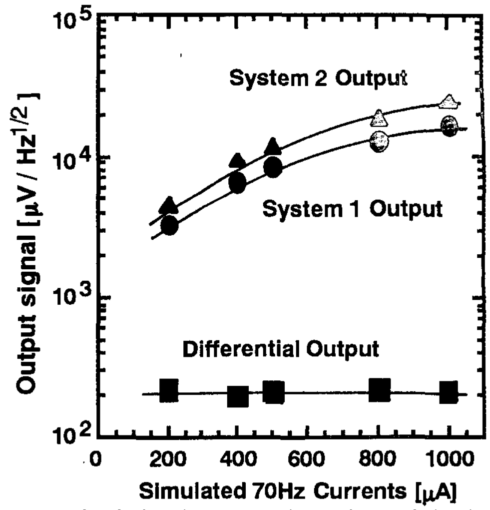


Fig.10 Output signal of each system and the subtracted signal. 70Hz signal is reduced by a factor of 100.

IV. Summary

A high Tc SQUID detection system for partial discharge in a electric power cable was designed. The SQUID driving electronics had a bandwidth as wide as 1.4 MHz. Pulse currents with the width of 120 nsec were detectable at the minimal 3μA. We think this value can be improved by using a higher performance SQUID. Cancellation of magnetic field from power line was tested by using two SQUIDs. The magnetic field was reduced by a factor of 100. Although our experiments were preliminary, these results suggested that the SQUID can be applied to the partial discharge measurement of power cables.

Acknowledgment

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