RF front-end Module for On-Line UHF Partial-discharge Monitoring System

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Abstract: A RF front-end module is designed for GIS(Gas Insulated Substation) which is employed for effective and efficient very high voltage transmission. Major advantage of the unit is improved PD detection sensitivity through minimizing the effect of surrounding interference signals, which is achieved by controlling the gain and the selection of the frequency band, for the precise detection of any UHF PD(Partial Discharge) disturbance occurred in the GIS due to some unwanted problems. For the development of the module, various switches for providing selected signal paths, wideband LNA, 3 BPF for selecting detection frequency band, and video detector are designed, fabricated and measured on 1mm FR4 substrate with various RF components. The detection sensitivity of the unit was <-60 dBm that is sufficient to detect UHF PD signals as low as 1 pC. It is believed that the value is enough to detect the signal occurred in GIS.

Key Words : GIS(Gas Insulated Substation), RF(radio frequency) front-end Module, BPF(Band Pass Filter), LNA(Low Noise Amplifier), PD(Partial Discharge)

1. INTRODUCTION

The need of condition based maintenance and continuously monitoring diagnosing devices for GIS(Gas Insulated Switchgear) is being emphasized due to the enlargement of transformer installation caused by rapid increase of electricity demand lately. Among GIS diagnosis methods, UHF partial discharge detection, which measures electromagnetic signal of UHF band which results from partial discharges, can be easily applied to sites, measure even minute discharges thanks to higher signal-to-noise ratio than former IEC60270 based method, and thus precisely monitor the state of GIS[1,2]. The advantage to accommodate various analysis techniques also makes it popular as a means of condition based maintenance method for GIS.

The Fourier transformation of current signal during partial discharge under high pressure SF6 gas has a wide band of frequency spectrum higher than a few GHz[3]. Accordingly an appropriate sensor can detect PD signal inside GIS in UHF band. However, signals in cellular phone band (890 MHz) and PCS band (1.8 GHz) act as noise to existing UHF PD signal processors due to the broadband characteristic of PD signals and the limitation of devices which can process UHF band. Thus there rises the need for a high quality UHF signal processor which can remove the noise or minimize undesired interference of electromagnetic wave by just passing required band.

This paper describes the design and making of a UHF signal processor that can control system gain and frequency band. The characteristic of this device has been tested by various measuring instruments. The device here, which forms the core part of a partial discharge monitoring system for GIS, can be applied to highly reliable UHF PD detection by improving signal-to-noise ratio of the whole system.

2. ARCHITECTURE OF RF FRONT-END UNIT

RF front-end Unit plays the important role of connecting a UHF sensor and a data acquisition unit of GIS PD monitoring system, and the whole system's sensitivity and performance can be up to it. The device is required to have the characteristic to maximize Data Acquisition Unit's ability of distinguishing external noise from partial discharge signal, as well as to amplify feeble partial discharge signal in UHF band detected by the sensor.

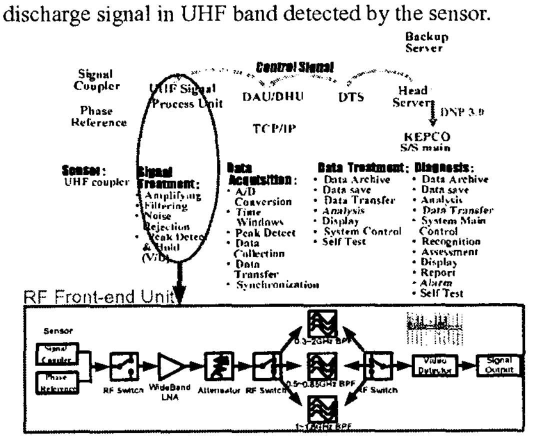

Fig. 1. Architecture of GIS Monitoring system and RF front-end Unit.

The key element of UHF signal processor consists of a wideband low noise amplifier(LNA), an attenuator, a band pass filter(BPF), a video detector(VD), etc., and a harmonious circuit design which considers the high frequency characteristic of all components is required. Advanced Design System, a nonlinear simulator of Agilent, is used as an analysis tool for the circuit design. The device amplifies weak partial discharge signal perceived by the UHF sensor using LNA, controls the gain with the attenuator, then minimizes the unwanted interference of electromagnetic wave at the BPF, and finally detects the magnitude of the signal. Thus the wideband UHF signal from the sensor comes out as a video signal of low frequency with proper level of noise reduction. Figure 1 is the structural diagram of the partial discharge monitoring system for GIS, and the detailed block diagram of UHF signal processor.

2.1. RF Switch

The input section of the device is composed of two SMA connectors in order to receive both the signal from the sensor and the reference signal for system test. The two input ports can be switched, using commercial SPDT RF switches of which the bandwidth is DC~2GHz and the channel separation is higher than 45dB in order that the interference between channels is minimized. Also, Using SP3T RF switches that can be select 3 BPF bank.

2.2. Wideband LNA

The part that affect the performance of the UHF signal processor most are the wideband LNA where the input signal is initially amplified, and the quality of BPF which minimizes the unwanted interference of electromagnetic wave. Therefore a wideband SiGe LNA of which the gain is 14dB, the bandwidth is DC~3GHz, and NF equals 2.4dB is applied to this device. Figure 2, the circuit diagram of wideband LNA and peripheral components, shows that C1, C2 and L1, L2 in the design makes a reference point which enables to control gain, gain flatness and impedance matching in the desired frequency band.

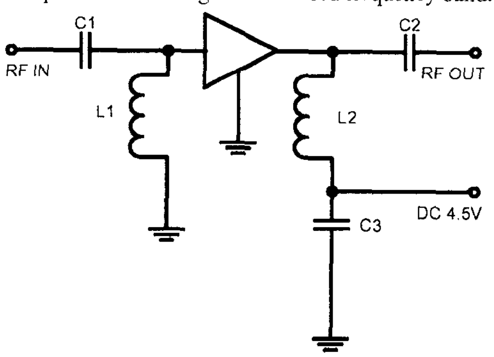

Fig. 2. Schematic of Wideband Low-Noise Amplifier

2.3. Attenuator

A wideband GaAs 5-bit digital attenuator, which can adjust the amount of attenuation from 1 to 31dB, and has +-0.5dB of bit error rate, is used to control gain after the amplification at the LNA.

2.4. Band Pass Filter Bank

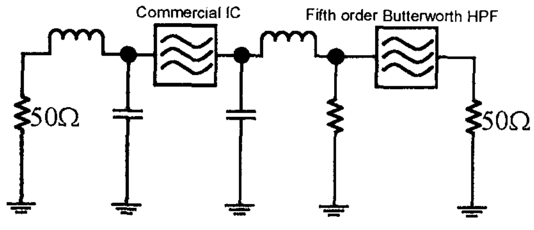

Fig. 3. Schematic of BPF 1, 2

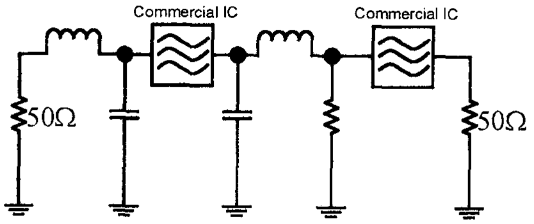

Fig. 4. Schematic of BPF 3

Figure 3 and 4 shows a BPF which can select frequency range was inserted to minimizes the unwanted interference of electromagnetic wave. Each BPF is composed of a combination of a high pass filter(HPF) and a low pass filter(LPF). The result of our measurement showed that insertion loss and skirt characteristics of filters which combines inductors and capacitors with commercial semiconductor were better than ones which were only consisted of passive elements in the high frequency range. Thus the LPF in this device was designed with the combination of L, C and commercialized semiconductor, while the HPF applied a serial connection of 5th order Butterworth alignment of passive elements. The input and output impedance of Each BPF have been designed to be 50Ohms.

BPF 1, of which the frequency bandwidth is 0.3~2GHz, has been made in order to eliminate signals under 300MHz and wireless LAN band while BPF2 has been designed to have the frequency range of 0.5~0.85GHz to avoid the interference in cellular and PCS phone band. Figure 3 is the structural diagram of BPF 1 and 2. the inductor and capacitor at the both end of the IC enables to adjust the -3dB cutoff frequency. As for the BPF3, of which the pass frequency band is 1~1.6GHz, it was designed by applying commercial LPF and HPF in serial connection (Figure 4). The inductors and capacitors in BPF3 are also for precise adjustment of the cutoff frequency.

2.5. Video Detector

The video detector, the last section of the device, has an effective frequency range of 0.2~2.5GHz. It uses MMIC elements of which the active range is higher than 60dB.

The video detector changes the UWB UHF signal, which has been input to the LNA and passed BPF, into low frequency video signal of less than 20MHz of bandwidth for easier signal processing. Then the voltage signal proportional to the power of the input signal is generated.

3. MEASUREMENT RESULTS OF MAJOR RF PARTS

Every part of UHF signal processor was mounted on a 1mm thick, micro-strip structure multi layer FR4 substrate, and the operating voltage is +-5V. Considering that the place of installation would be substations where surge and over-voltage occurs frequently, a circuitry that can protect elements from outer disturbance was added.

To measure the input and output characteristics of LNA, BPF 1, BPF 2, BPF 3 and VD, a vector network analyzer(HP8510C, 45 MHz~75 GHz, Agilent) and a noise figure (NF) analyzer(N8975A, 10 MHz~26.5 GHz, Agilent) was used. For the detection sensitivity of the whole module, we used a signal generator, a pulse modulator and an oscilloscope(TDS5104, 1 GHz, Tektronix).

3.1. Wideband LNA

To find out the characteristics of wideband LNA, we used a network analyzer and a noise figure analyzer. Table 1 and 2 shows measured noise figure and gain. Gain and gain flatness of the wideband LNA were optimized by adjusting the value of circuit elements. We can see from Figure 5 that the reflection loss of the input section in the frequency range of 0.3~2GHz was lower than -10db while the maximum gain was 14.4 dB.

Table 1 Specific of Wideband LNA

Parameter	Units	Min.	Typical	Max.
Freq. Range	MHz	60		3000
S21	dB	13	14	16
S11	dB		-9	
S22	dB		-15	
Output IP3	dBm	+33	+37	
Noise Figure	dB		2.4	

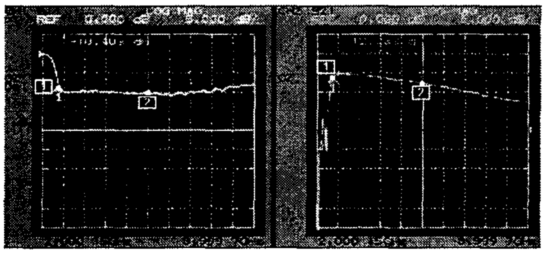

Fig. 5. Measurement of S11 and S21 for Wideband LNA(Marker 1 : 300MHz, Marker 2 : 2000MHz)

Table 2 Noise figure and Gain for Wideband LNA

Frequency	NF	Gain	reference
300 MHz	2.46	14.37	
800 MHz	2.47	14.10	PCS band
1.3 GHz	2.35	13.39	
1.8 GHz	2.42	12.83	Cellular band

3.2. Filter Bank

Measured values of input and output characteristics of BPF 1,2 and 3, which compose a filter bank, are shown in Table 3~5 and Figures 6~8. Although characteristics of each BPF somewhat varies, all 3 BPFs had Return loss of less than -10dB, maximum Insertion loss of approximately 2~2.1dB, and maximum pass band ripple of 0.5~1.5dB.

Table 3 Measure value of 0.3~2GHz BPF

Center Frequency	1150MHz
Pass band	0.3~2GHz, 1.7GHz BW
Pass band Ripple	$1.5dB_{Max}$
Insertion Loss	$2.0dB_{Max}$
Impedance	50 ohm

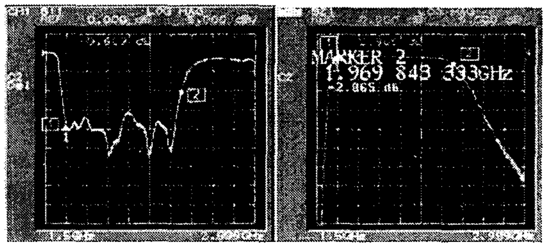

Figure. 6. Measurement of 0.3~2GHz BPF (Marker 1 : 300MHz, Marker 2 : 1970MHz)

Table 4 Measure value of 0.5~0.85GHz BPF

Center Frequency	675MHz
Pass band	0.5~0.85GHz, 350MHz BW
Pass band Ripple	$0.5dB_{Max}$
Insertion Loss	$2.1dB_{Max}$
Impedance	50 ohm

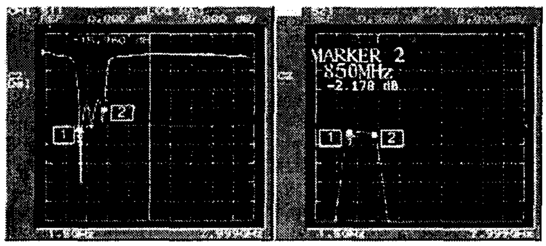

Fig. 7. Measurement of 0.5~0.85GHz BPF (Marker 1 : 500MHz, Marker 2 : 850MHz)

Table 5 Measure value of 1~1.6GHz BPF

Center Frequency	1300MHz
Pass band	1~1.6GHz, 0.6GHz BW
Pass band Ripple	$1.5dB_{Max}$
Insertion Loss	$2.0dB_{Max}$
Impedance	50 ohm

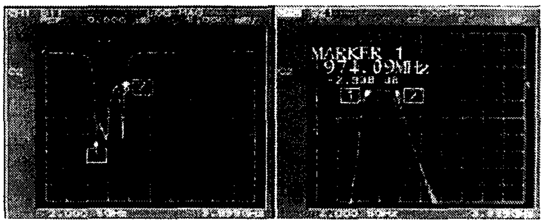

Fig. 8. Measurement of 1~1.6GHz BPF
(Marker 1 : 974MHz, Marker 2 : 1600MHz)

3.3. Video Dedector

Figure 9, 10 is the waveform of output signal from UHF signal processing Unit measured by an oscilloscope. A high precision measurement equipment confirmed that UHF signal processing Unit had the detection sensitivity of -60dBm. Figure 11 describes the input and output characteristics of the video detector used in the device. It shows relatively fair logarithmic characteristic of the input signal in the range of -60~0dBm, and it is satisfactory for the use for signals smaller than -70dBm or greater than +20dBm.

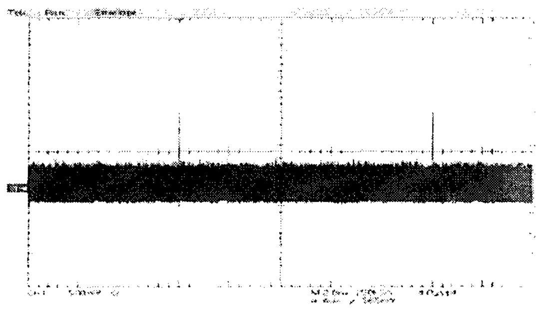

Fig. 9. Output waveform of UHF signal processing Unit
(pulse repetition rate = 200 Hz)
Horizontal scale: 2 ms/div, Vertical scale: 500 mV/div

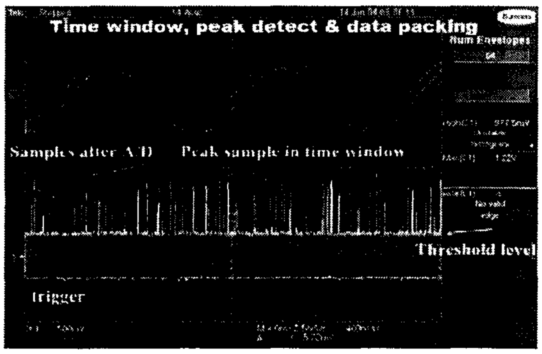

Fig. 10. Peak detect and Data packing for UHF signal processing Unit

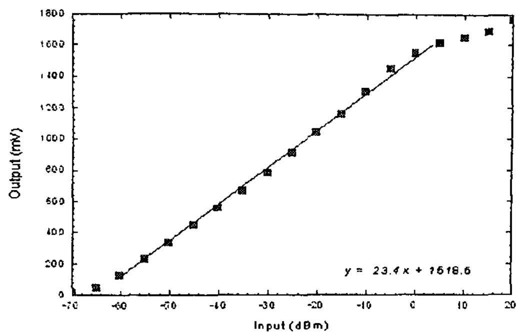

Fig. 11. Input and output characteristics of the video detector

4. CONCLUSION

The UHF signal processing Unit is the part that links a UHF sensor to the data acquisition unit of GIS PD monitoring system, and it has been developed to control the gain and selects frequency band for the purpose of optimizing PD detection sensitivity against external noise. High precision measuring instruments were used to evaluate high frequency characteristics, and sensitivity measuring experiments allowed us to know the following conclusions.

First, The reception sensitivity of the UHF signal processing Unit was lower than -60dBm, which is sufficient to detect partial discharge signals from GIS precisely[4].

Second, Applying adjustable band pass filters will increase S/N ratio and detection sensitivity at sites where external noise is excessive.

The GIS monitoring system employing the UHF signal processing Unit will raise the detection sensitivity of partial discharge signal by minimizing signal interference of cellular phone, PCS, IMT2000 and wireless LAN band. Along with plenty of field experience, UHF partial discharge monitoring system introducing this device will make it possible to operate electrical facilities with more reliability.

5. REFERENCE

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