國家原子能科技研究院

委託研究計畫研究報告

變電所輸變電設備損傷診斷專家系統研究

Research on Expert System for Diagnosis of Damaged Transmission and Transformation Equipment in Substations

計畫編號：112A016

受委託機關(構)：國立臺灣科技大學電機工程系

計畫主持人：郭政謙

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目　錄

中文摘要

輸變電設備一旦故障即損失極大的經濟效益,所以預防更勝於治療,高壓絕緣劣化檢測的有效方法之一就是觀察設備局部放電的現象,且為最初期的特徵,即早發現設備問題就可以提前做預防,而趨勢性觀察更優於週期性的檢查,長時間的觀察有效降低誤判的機率。

本計畫擬自行開發高速資料擷取裝置擷取局部放電原始放電波形數據進行雜訊抑制。為了能使診斷系統提升診斷效率與準確性,需對量測數據進行雜訊抑制,使得對於放電類型進行故障辨識,本計畫擬採用原始放電波形與雜訊抑制技術來快速對輸變電設備進行放電類型鑑別與識別。透過此方法可以讓系統實際運行數據紀錄原始放電波形,了解此輸變電設備於多次的局部放電量測中之原始放電波形狀況有哪幾種,再進行雜訊抑制後,作為局部放電類型鑑別。

Abstract

If the power transmission and transformation equipment fails, it will lose great economic benefits, so prevention is better than treatment. One of the effective methods for high-voltage insulation degradation detection is to observe the phenomenon of partial discharge of equipment, and it is the earliest characteristic. Prevention can be done in advance, and trend observation is better than periodic inspection. Long-term observation can effectively reduce the probability of misjudgment.

This project intends to develop a high-speed data acquisition device to acquire the original discharge waveform data of partial discharge for noise suppression. In order to improve the diagnostic efficiency and accuracy of the diagnostic system, it is necessary to suppress the noise of the measurement data, so that the fault identification of the discharge type is carried out. Carry out discharge type identification and identification. Through this method, the actual operating data of the system can be recorded as the original discharge waveform, so as to understand the original discharge waveform conditions of the power transmission and transformation equipment in multiple partial discharge measurements, and then after noise suppression, it can be regarded as the type of partial discharge identification.

壹、計畫緣起與目的

一、 計畫背景

變電所輸變電設備發生損傷大多是絕緣劣化的原因，而絕緣劣化通常是經由電應力、熱應力或機械應力造成的老化現象，這些老化現象會再因為局部放電的關係加速劣化導致嚴重的事故發生，為避免造成重大事故，即時了解設備狀況就成了必備條件。

二、 計畫目的及重要性

變電所輸變電設備部分放電訊號，除了有低頻成分也有高頻成分，但低頻信號所受到的環境干擾較高頻信號多，故本計畫以高頻成分信號進行局部放電分析。藉由安裝 HFCT 感測器，並進行全時長期線上量測，則可達到趨勢性的定量檢測，並記錄原始放電波形及雜訊抑制技術做放電檢測判斷。

本系統的檢測改善了過去許多檢測方式的缺點，像是過去高壓設備局部放電診斷使用 PRPD 分析圖譜，此方法測試都只能測出高壓設備整體的絕緣劣化情形，但本系統透過檢測到的局部放電信號，利用原始放電波形的分析診斷出高壓設備的瑕疵放電，而且舊有的檢查方法需要透過斷電才能進行檢查，設備停電的時間將會帶來經濟成本損失，因此本計畫運用高頻電磁波間接量測法，不需要再擔心靠近高壓設備的風險，高壓設備也不需要停電就能做即時傳輸資訊的監控。

三、 國內外有關本計畫之執行情況

關於變電所輸變電設備局部放電的研究國內及國外皆有眾多報告、論文可以參考，PRPD 圖的分析至今還是此類項目非常重要的判斷依據，因此在參考的報告中有提供利用試片盤模擬的

放電測試[1]，模擬了電暈放電、外部放電及內部放電，此報告中相關的放電頻段、放電數值、PRPD 圖都成為本系統相關數據的依據。

有關局部放電的雜訊處理也參考了相關的各項研究，時頻分析法利用放電訊號的時間長短可以有效地分析出雜訊和實際局部放電值[2]，另外也有參考人工智慧分類 PRPD 圖的報告、論文。

貳、研究方法與過程

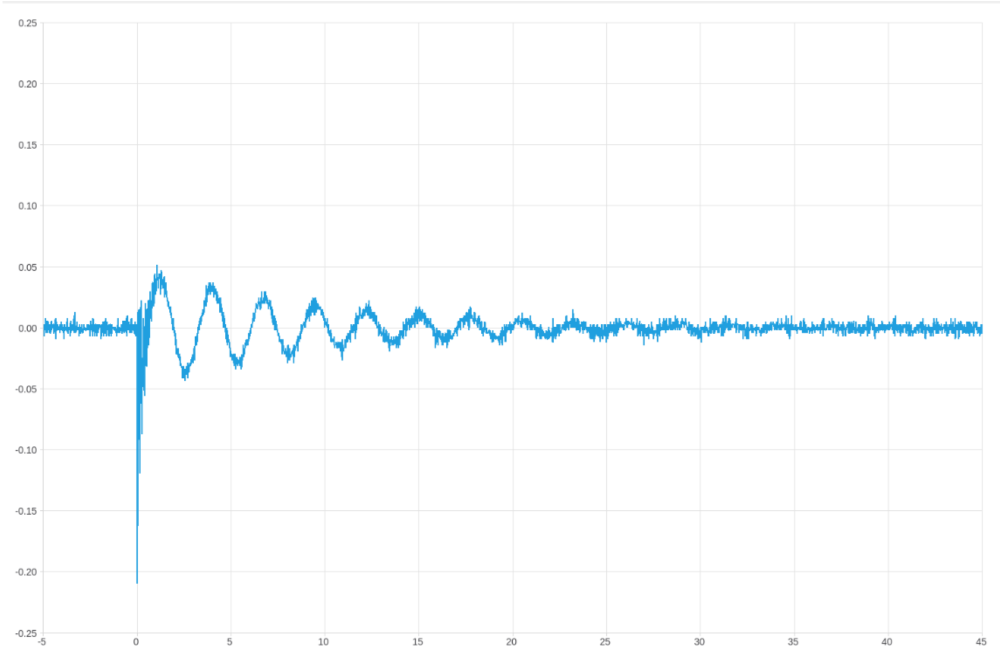
一、 採用之方法與原因

輸變電設備在投入使用以後，由於長期的運轉在高電壓、高電流及高溫度的情況下，導致了設備內各元件逐漸地發生各種老化現象，並隨著時間，元件的絕緣等級會隨之下降，且直接影響相關電力設備的運轉能力，亦可能導致設備發生非預期的突發性事故，造成停電困擾。目前商用環境下多半使用局部放電量測技術，以期提早發現高壓設備的瑕疵，惟局部放電的量測後的圖譜故障型態判別，非常受限於經驗豐富的專家或學者，因此若能利用人工智慧技術來輔以進行故障類型的評估，將能更大量的提高局部放電量測系統的建置，並獲致故障預知的效果，減少因高壓設備於未知下的傷害及其所造成的損失。基於此，本計畫擬針對油浸式變壓器進行線上之局部放電量測，並將之轉為可用來評估變壓器故障類型的原始放電波形，輔以人工智慧深度學習的技術，確保電力設備可靠的運行，降低維護費用，並提高安全性與穩定供電，避免未知的故障所引起的用電中斷現象。

本系統提出運用高速資料擷取裝置擷取局部放電原始放電波形及述雜訊抑制技術進行改善局部放電類型鑑別之辨識率。為了能使診斷系統提升診斷效率與準確性，需對量測數據進行原始放電波形擷取，使得對於故障數據敏感性高的原始放電波形檢測數據進行故障辨識，本計畫採用高速資料擷取裝置與雜訊抑制技術來快速對輸變電設備進行放電類型鑑別之辨識。透過此方法可以將系統實際擷取原始放電波形，了解此輸變電設備於多次的局部放電量測中之原始放電波形狀況有哪幾種，再進行雜訊抑制後，

作為改善局部放電類型鑑別之辨識率。

如圖一局部放電原始放電波形圖，可以看到放電訊號會先有一個峰值，並產生震盪逐漸變小。以往通常都會直接抓取峰值電壓，但並不是所有峰值都是放電訊號，此系統可以擷取原始放電波形，並加以分析判斷，可有效提升局部放電訊號的準確。



圖一、局部放電原始放電波形

二、 預計可能遭遇之困難及解決途徑

高速資料擷取裝置、雜訊抑制技術這些方面的技術已經相當成熟，但使用類比數位轉換器與現場可程式化邏輯閘陣列需要經過時間監測不停的修正與改善才能使系統更符合案場需求，故前期可能會出現參數設定數值不當或是誤判局部放電的情形出現。

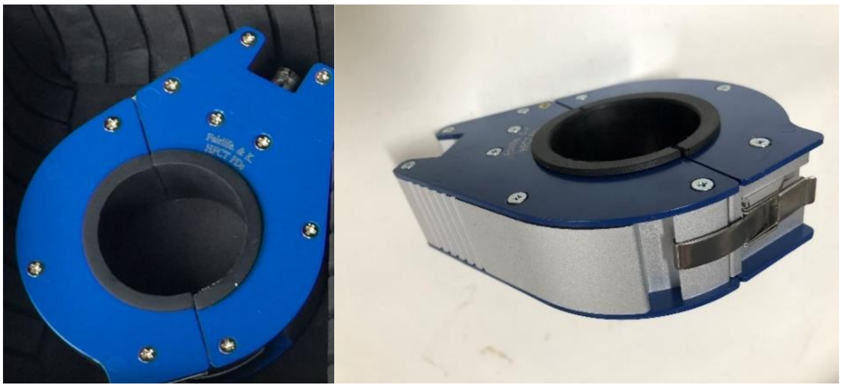
預計會遭遇的困難為每一案場各有不同的雜訊干擾，故解決方法可能為利用雜訊抑制技術來區分雜訊與真正的放電訊號。另一方面需要解決的困難為局部放電類型鑑別，因目前所能作為訓練判斷的原始放電波形數量不夠，可能會導致放電類型鑑別效果

不好而判斷錯誤，須利用長時間的監測及模擬局部放電情形來改善此狀況。

三、 重要儀器之配合使用情形

(一)HFCT（高頻 CT）

以 IEC62478 部份放電線上量測建議方法 HF／VHF 量測法(感測器)為 3MHz 至 300MHz，此 UHF 使用的 HFCT 頻寬為 1M~50MHz，採用鎳鋅高頻磁粉鐵心繞置之開合電感式比流器，可監測接地線之部份放電訊號。



圖四、HFCT 俯視圖(左) HFCT 側面圖(右)

頻寬	1M~50MHz
廠牌	Fairlife & k.
耐候等級	-10~65 華氏度，室內型
介面	輸出為 BNC 接頭
電源	被動式元件不需電源

(二)UHF（超高頻可繞式天線）

以 IEC62478 部份放電線上量測建議方法 UHF 量測法(感測器)為 300MHz 至 3GHz，此 UHF 頻寬範圍為 300MHz~1.2GHz，工作環境的干擾頻率通常在 300MHz 以下，雜訊相對很少，不需太複雜的雜訊消除技術。

可量測距離小，適合於變壓器之高壓電纜端或套管端，電力電纜中間與終端接頭，高壓開關盤內。

圖五、UHF 俯視圖(左) UHF 側面圖(右)

頻寬	300M~1.2GHz
廠牌	Fairlife & k.
耐候等級	-40~90 華氏度，室外型
介面	輸出為 N-Type 高頻接頭
電源	被動式元件不需電源

(三)現場可程式化邏輯閘陣列

由於訊號輸入必需即時連續的取樣資料，避免擷取波形時導致波形失真，由於微處理器工作是由軟體進行排成，無法達到即時的處理工作，因此必須採用現場可程式化邏輯閘陣列，使用硬體電路設計邏輯閘達到即時高速取樣。

圖四、現場可程式化邏輯閘陣列

製造商	Xilinx
系列	XC6SLX16
邏輯元件數目	14579 LE
輸入/輸出數	232 I/O
電源電壓	1.14 V ~ 1.26 V
工作溫度	- 40 C ~ + 100 C
封裝/外殼	CSBGA-324
分佈式 RAM	136 kbit
內嵌區塊 RAM - EBR	576 kbit
最大工作頻率	1080 MHz
邏輯陣列區塊數目 - LAB	1139 LAB
工作電源電壓	1.2 V

(四)高速類比數位轉換器

高速類比數位轉換器可將類比訊號轉換為數位信號，當類比信號頻率高時，需要高速的取樣率，以高速類比數位轉換擷取類比資料。採用亞德諾半導體(Analog Devices)所生產的AD9226 類比數位轉換器。

圖五、Analog Devices AD9226

製造商	Analog Devices Inc.
封裝	SMD/SMT
電源供應	5 V
解析度	12 bit
取樣率	65 MS/s
通道數	1
最低工作溫度	- 40 C
最高工作溫度	+ 85 C
中央處理器	Intel® Atom x7-E3950
記憶體	4 GB DDR3L 1600 MHz SODIMM module (Up to 8 GB support)
儲存裝置	128 GB mSATA SSD
有線網路介面	2 個 GbE ports (2 個 Intel I210IT)
通道數	4 個同步通道(可擴充成 16 通道)
解析度	16 it

參、主要發現與結論

一、 計畫目標

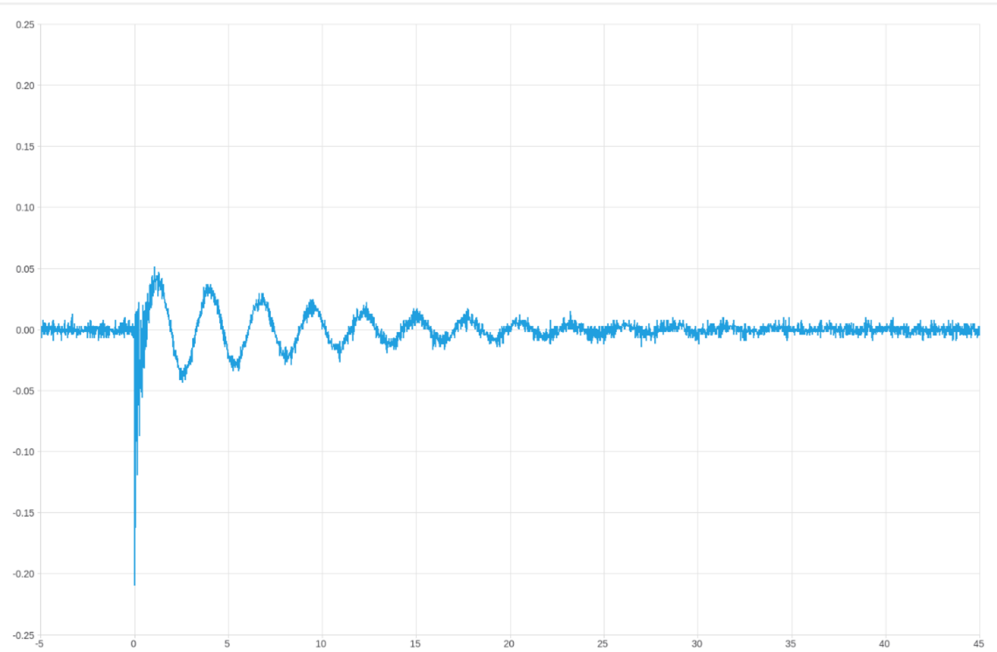
為執行「大數據監測與智慧診斷技術」計畫，擬進行「變電所輸變電設備損傷診斷專家系統研究」，包含建置變電所輸變電設備之原始放電波形局部放電訊號高速資料擷取裝置、軟體功能規劃、人機介面設計以及整合雜訊抑制技術與大數據分析資料庫，以掌握變電所輸變電設備運轉狀態，進而可針對變電所輸變電設備之健康狀態進行智慧診斷技術之開發研究。

二、 工作項目/內容

本研究計畫預計完成變電所輸變電設備之局部放電原始波形高速資料擷取裝置系統建置，工作項目如下：

(一) 進行輸電設備之局部放電記錄原始放電波形

1. 於測試環境進行局部放電原始波形監測記錄。
2. 資料擷取即轉換速率可達到 60 MHz 以上的取樣頻率，如圖六所示。

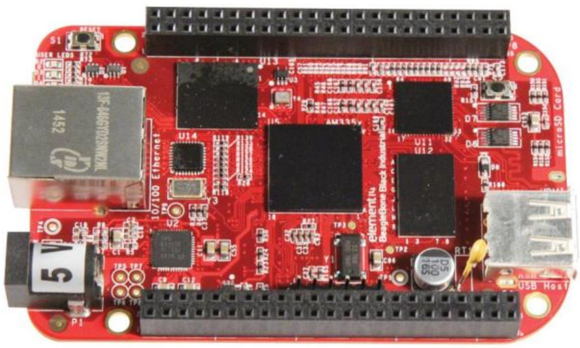


圖六、測得的波形

(二) 高速資料擷取裝置開發功能規劃

1. 嵌入式 ARM 處理器

本研究局部放電原始放電波形擷取系統採用德州儀器 TI Sitara Processor AM3358 處理器，此處理器採用 ARM Cortex-A8 架構設計，其處理器規格與開發板如圖七。



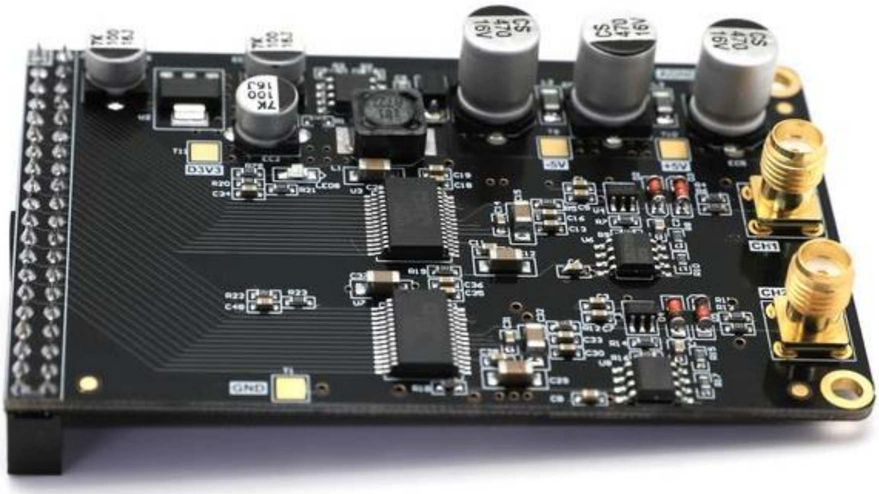
圖七、AM3358 開發板

項目	規格
製造商	Texas Instruments

零件編號	AM3358BZCZ100
核心處理器	ARM® Cortex®-A8
速度	1.0 GHz
協同處理器	PRU-ICSS
介面	CAN, I2C, SPI, UART, USB
記憶體控制器	LPDDR, DDR2, DDR3, DDR3L
圖形加速	1 3D
乙太網路	10/100/1000 Mbps
工作溫度範圍	-40°C ~ 105°C

2. 類比數位轉換器

局部放電原始放電波形量測系統因原始放電波形頻率約 10 MHz，故採用亞德諾半導體(Analog Devices Inc., ADI) AD9226 高速類比數位轉換器，AD9226 類比數位轉換模組如圖八。AD9226 供電方式採用單一電源供應，並具備高性能放大器和基準電壓源，其電壓解析度可達 12 位元，取樣率則可高達 65 MS/s，能夠應用於超聲波、影像和通信系統等應用，適用於高頻連續訊號中檢測範圍電壓的多路複用系統，亦可以進行奈奎斯特速率(Nyquist Rate)進行單通道輸入取樣，額定溫度範圍為-40˚C 至+85˚C。



圖八、AD9226 類比數位轉換模組

3. 現場可程式化邏輯閘陣列

現場可程式化邏輯閘陣列(Field Programmable Gate Array, FPGA)採用 Xilinx Spartan-6，可運用邏輯區塊進行可程式設置的路由，再由設定晶片去建立客制化的硬體功能，FPGA 擁有可重複設置的性質，再依據使用的需求做不同的修改。

FPGA 整合特定應用積體電路(Application-Specific Integrated Circuit, ASIC)與處理器架構系統，具有硬體時脈的速度與可靠性，降低客制化 ASIC 設計的費用，並可重新設計程式晶片，與軟體有相同的彈性，卻不受限於處理器核心的數量，另一方面 FPGA 為平行架構，因此不同的處理作業並不會佔用相同資源，每個獨立的處理作業都會指派至專屬的晶片區塊，不會影響其他邏輯區塊即可自動產生功能，因此當新增其他處理作業時，應用部份的效能亦不會受到影響。

FPGA 是一個強大而靈活的硬體平台，尤其適用於需要高度自定義和高性能計算的場合。然而，由於其開發過程相

對複雜，通常需要專業的硬體設計和電子工程知識。

圖九、Xilinx XC6SLX16-2CSG324 開發板

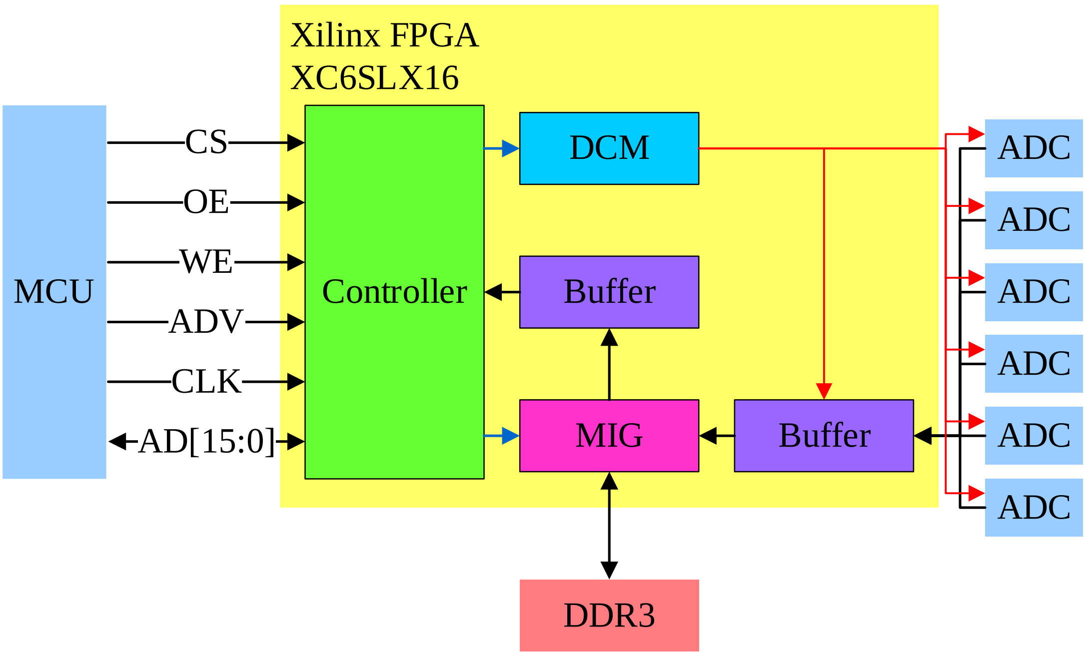
項目	規格
製造商	Xilinx Inc.
系列	Spartan-6
零件編號	XC6SLX16-2CSG324
邏輯元件數	14,579
LAB 數	1,139
記憶體	576 kbit
輸入/輸出數量	232
工作溫度範圍	0°C ~ 85°C

(三) 高速資料擷取裝置系統技術架構規劃

局部放電原始放電波形擷取系統之類比數位轉換器，採用 FPGA 作為類比數位轉換器(Analog-to-Digital Converter, ADC)的控制器，使其有較高的取樣率，以達成傳輸速度的要求。

本研究設計的 FPGA 電路功能如圖十所示，有一個控制器 (Controller)，設計採用並列方式讓微控制器 (Microcontroller Unit, MCU)可以與控制器傳遞資料，並列埠

的連接線路有晶片選擇(Chip Select, CS)、輸出致能(Output Enable, OE)、寫入致能(Write Enable, WE)、位址有效(Address Valid, ADV)、時鐘信號(Clock, CLK)、位址資料(Address Data, AD)，其次有數位時鐘管理器(Digital Clock Manager, DCM)用於設定及控制類比數位轉換器的取樣率，以及記憶體介面產生器(Memory Interface Generator, MIG)進行 DDR3 記憶體的寫入與讀取的控制，最後在資料傳輸過程中若有資料寬度或是傳輸速率不同，則須在傳輸中間加入緩衝區(Buffer)。



圖十、FPGA 電路功能設計方塊圖

(四) 高速資料擷取軟體系統功能規劃

局部放電原始放電波形檢測系統之高速資料擷取軟體系統功能採用 ARM 處理器設計開發，其高速資料擷取軟體系統功能包跨 FPGA 驅動程式、ADC 取樣擷取控制程式、以及資料傳輸介面。

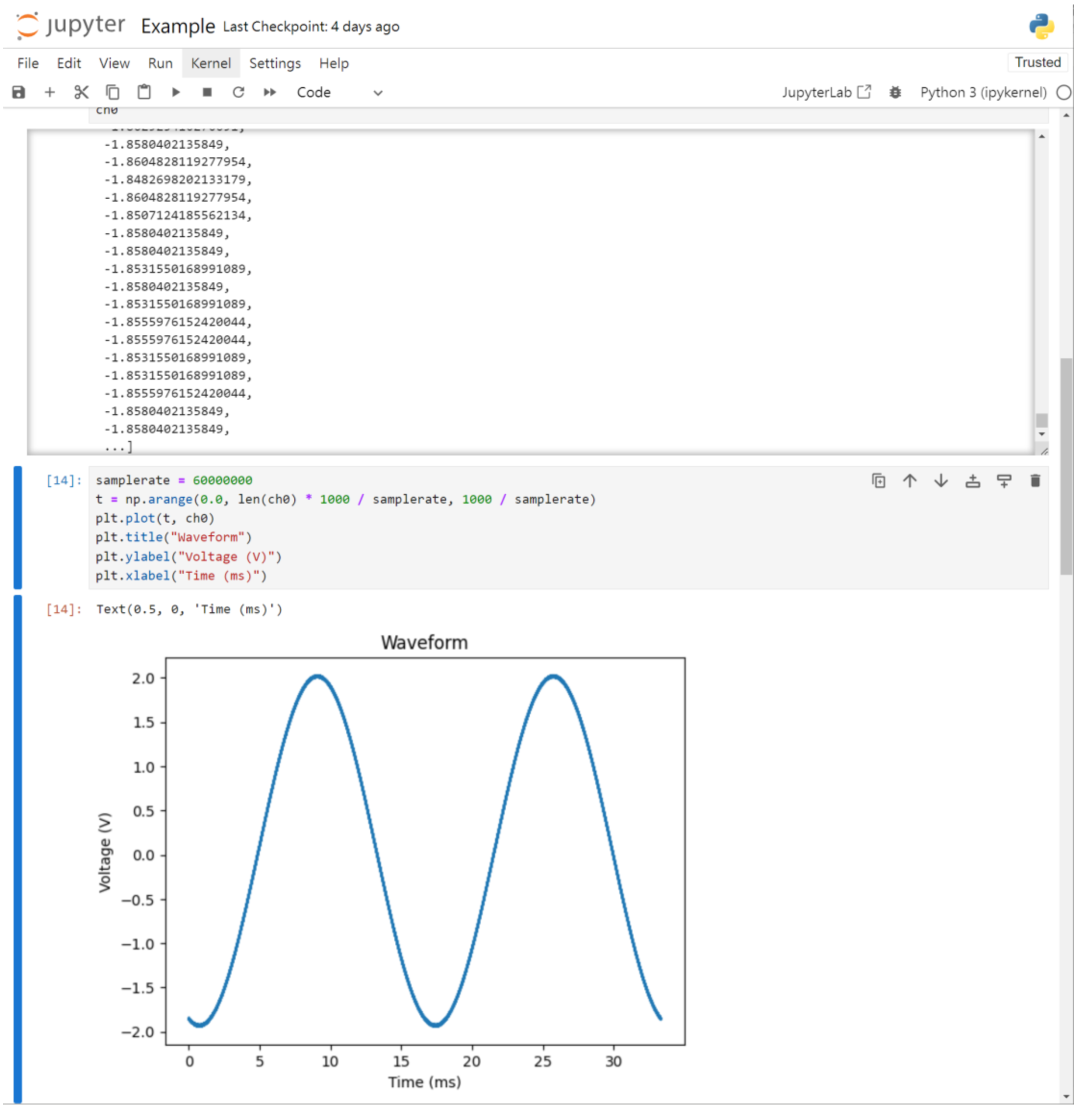
流程控制需要先運用 FPGA 通訊之驅動程式載入系統核心，在 Linux 中，驅動程式（Driver）是一種特殊的核心模組，用於實現和硬體設備之間的通訊。通過驅動程式，操作系統和應用程式能夠與硬體設備進行交互。Linux 核心模組（Kernel Module）是一種可在系統運行時動態加載和卸載的程式碼塊。這些模組基本上是擴展 Linux 核心功能的插件，允許開發者在不更改整個核心源碼或重新編譯核心的情況下添加新功能或更新現有功能。

設定 ADC 取樣率長度及門檻值，取樣率長度及門檻值的設定可以藉由 REST API 進行設定，即可開始擷取類比數據。當轉換完成後，可以透過傳輸指令控制高速資料擷取之局部放電原始波形傳送到嵌入式系統，最後即可藉由 REST API 取得局部放電原始波形之數據。

(五) 高速資料擷取裝置軟體系統人機介面設計

局部放電原始放電波形檢測系統之圖形化介面採用 Jupyter 介接設計，Jupyter 是一個互動式環境，可用於數據分析、機器學習、統計建模和其他數學計算。最常見的形式是 Jupyter Notebook，可以包含程式碼、文件、數學公式和可視化工具的網頁應用。局部放電原始放電波形檢測之高速資料擷取裝置運用 REST API 之通訊技術架構，代表性狀態傳輸（Representational State Transfer, REST API）應用程式介面是一種用於開發網路服務的軟體架構風格。它使客戶端和伺服器能夠通過 HTTP 協定交換資料。REST API 通常用於構建和提供資源導向的服務，並應用資源或是數據模型實體例如

URI。故高速資料擷取裝置軟體系統人機介面設計採用 Python 程式進行接收，可於 Jupyter 之介面編寫 Python 程式，並可以立即運行並顯示運算之結果於 Jupyter 之顯示介面。



圖十一、Jupyter Notebook 高速資料擷取裝置軟體系統人機介面

(六) 輸變電設備故障診斷系統實作與分析

輸變電設備故障診斷系統實作與分析是一個非常專門和高度實用的主題，通常涉及多學科的知識，包括電力工程、

信號處理、機器學習和數據分析等。變電所輸變電設備損傷診斷專家系統，針對油浸式變壓器進行線上之原始放電波形紀錄，並且利用雜訊抑制技，輔以改善局部放電鑑別之辨識率的技術，確保輸變電設備可靠的運行，降低維護費用，並提高安全性與穩定供電，避免未知的故障所引起的用電中斷現象。

輸變電設備故障是一個非常嚴重的問題，不僅可能影響電力供應，而且還可能對周邊環境和人員安全造成威脅。常見故障類型如短路電流突然增加，可能因為絕緣失效或外部物體接觸。設備運行在高溫狀態，通常由於負載過大或冷卻系統故障。機械損壞包誇斷路器彈簧損壞、變壓器油漏等。絕緣可能因為材料老化、外部污染或高壓所導致的劣化等。

(七) 輸變電設備之原始放電波形蒐集與彙整

變電所輸變電設備損傷診斷專家系統，針對油浸式變壓器進行線上之原始放電波形紀錄，接者利用雜訊抑制技，輔以改善局部放電鑑別之辨識率的技術，確保輸變電設備可靠的運行，降低維護費用，並提高安全性與穩定供電，避免未知的故障所引起的用電中斷現象。局部放電是評估輸變電設備絕緣健康狀態的一個重要指標。持續的局部放電可能導致絕緣材料的進一步老化或損壞，進而增加設備故障的風險。

(八) 雜訊抑制技術資料蒐集與彙整

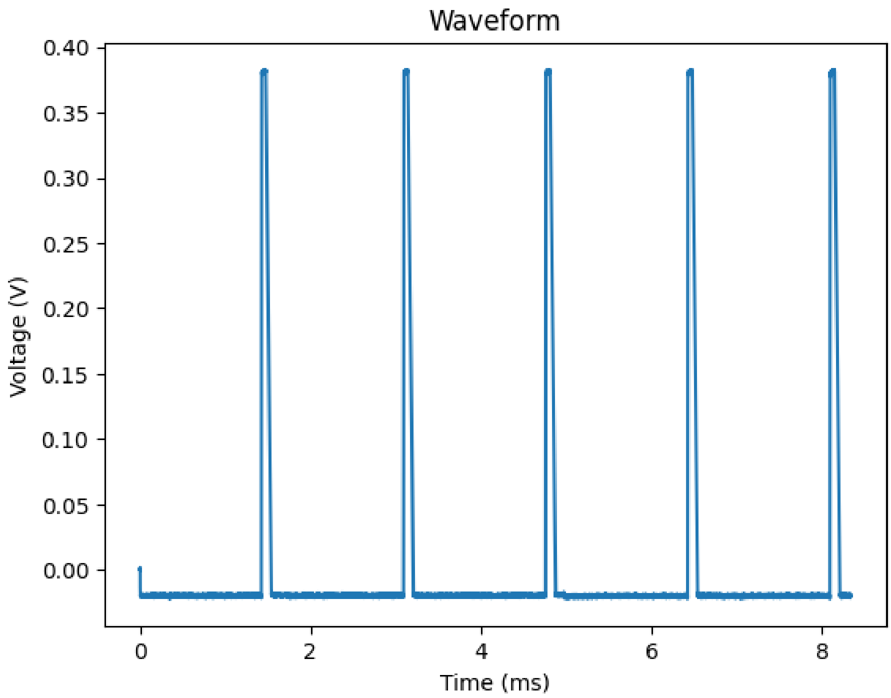
雜訊抑制技術運用於局部放電原始放電波形檢測系統之設計規劃，用於減少或消除不必要信號、干擾或背景噪音

的方法和技術。過濾類比數位轉換器（ADC，Analog-to-Digital Converter）輸入的雜訊是一個常見但重要的問題。這樣的轉換器用於將類比信號轉換為數位信號，但在這一過程中可能會引入各種類型的雜訊。

以截止頻率為-3dB 及帶阻頻率 fN 是帶通和帶阻濾波器的兩個主要指定要求。其中濾波器中帶寬和帶阻頻率的可變性將改變濾波器特性的行為。可以改變帶寬和帶阻頻率的濾波器被稱為可變濾波器或可調濾波器，在數位信號處理應用中發揮著非常重要的作用。可變數位帶通和帶阻濾波器有多種設計，文獻中大多數設計提出的先前設計之一建議用二階數位全通濾波器替換數位低通原型濾波器中的幾乎所有延遲元件，並且然後修改係數，然而計算非常複雜。為了可以有效的減少計算複雜度的方法，即對傳遞函數的係數使用泰勒級數展開，然而截斷的近似線性項會降低濾波器的幅頻響應。另一種簡單計算的方法[6]，僅調整中心頻率 f0，但帶寬保持不變，並且設計僅針對窄帶數位濾波器是近似的。通過改變數位低通原型濾波器中的截止頻率 fc 來調整帶寬的方法。採用這種方法可變數位濾波器的帶寬 bw 取決於數位低通濾波器的截止頻率，這會導致一些有限的頻率範圍，對於濾波器的高階，係數過濾器增加，導致計算更加複雜。另一個值得嚴重關注的問題是大多數的數位帶通和帶阻濾波器的設計都使用中心頻率 f0，它是較低頻率 fL 和 fU 的幾何平均值，並且僅適用於模擬濾波器的設計。眾所周知，在設計數位帶通和帶阻濾波器時使用中心頻率 f0 存在局限性，

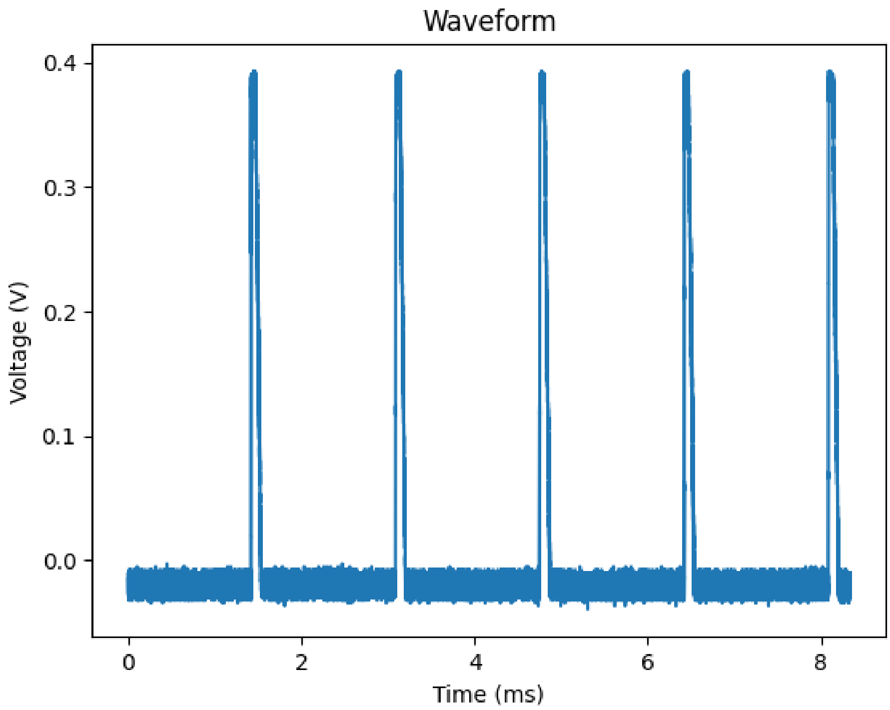
因為中心頻率 f0 不是帶阻頻率 fN，並且僅對於窄帶濾波器的設計是近似的數位濾波器。

有限脈衝響應（FIR，Finite Impulse Response）濾波器的特點是其脈衝響應是有限長度的，輸入信號與一組固定的係數以得到輸出信號。此濾波器通常可以設計成線性相位，信號的各個頻率成分會以相同的速度通過濾波器，有效減少相位失真。設計可變 IIR 數位帶通帶阻濾波器的方法。將-3dB 帶寬 bw 和帶阻頻率 fN 由兩個可調參數獨立控制α和β。參數α源自低通到低通濾波器的域頻率變換，用於控制-3dB 帶寬。參數β用於控制帶阻頻率 fN，是從低通到高通濾波器的數位域頻率變換導出的。數位帶通和帶阻濾波器是利用數位域頻率變換將半帶數位低通濾波器變換而來。可變數位濾波器的係數較少，這意味著與以前的設計相比，實現電路中的乘法器、加法器和延遲較少。 本文提出的方法的設計步驟對於計算來說非常簡單，因為只有兩個可調參數。帶有α和β的阻尼因子ζ的新公式，並分析了帶有阻尼因子的二階可變數位巴特沃斯帶通帶阻濾波器的根軌跡。如圖十三為使用 FIR 濾波器之結果。

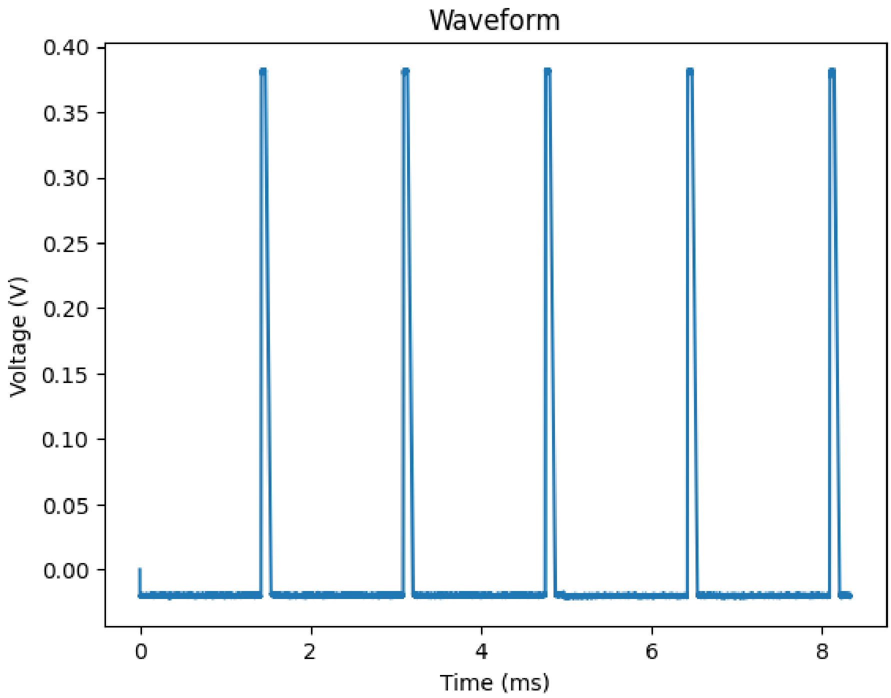


圖十三、局部放電波形雜訊抑制使用 FIR 之結果

局部放電原始放電波形擷取高頻信號之結果如圖十四所示，圖中可以明顯看出信號準位含有高頻雜訊，濾波器可在不同輸出處形成低通濾波器，主要用於允許低頻成分通過而削減或屏蔽高頻成分，低通濾波器能夠過濾高於某一特定截止頻率的所有頻率成分，只讓低於這一頻率的成分通過。包含在各種用途的類比數位轉換器的輸入。此外亦可用於構建具有獨立可控下限和上限截止頻率的各種寬帶濾波器，以及以可調諧帶通濾波器的形式確保在中實現倍頻程和三分之一倍頻程濾波器組。基於典型的濾波器部分的可調諧主要缺點是它們不允許在高頻下實現高穩定性。圖十五為 RC 濾波器之結果。



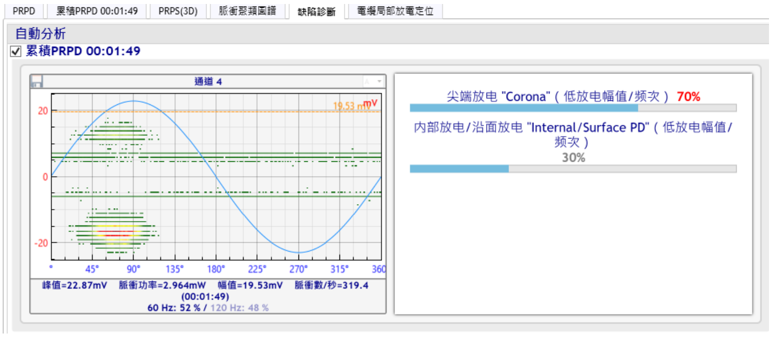
圖十四、局部放電原始放電模擬波形



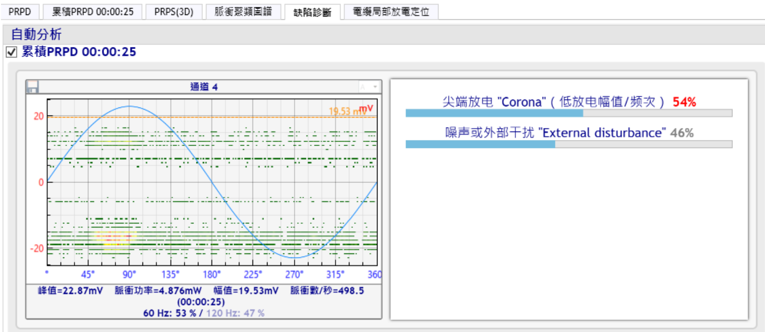
圖十五、局部放電波形雜訊抑制使用 RC 濾波之結果

(九) 輸變電設備之原始放電波形與雜訊抑制技術之整合測試

雜訊抑制技術是一項廣泛應用於不同領域的技術，用於減少或消除雜訊的干擾，以提高信號的品質和可靠性。本研究採用有限脈衝響應（FIR）濾波器，FIR 濾波器是一種有效的雜訊抑制技術，可以提高局部放電辨識率。通過使用 FIR 濾波器，我們可以在時間域內調整信號，去除不需要的頻率成分，從而提高局部放電信號的清晰度，使其更容易被檢測和辨識。如圖十六為局部放電模擬器產生之局部放電信號，可以明顯看出此放電為尖端放電。如圖十七為局部放電模擬器產生之局部放電信號加上白雜訊信號之局部放電檢測結果，可以從圖中看出在 45 度至 90 度之間有明顯的放電現象，其他綠色的部分則是背景雜訊。



圖十六、局部放電模擬訊號分析



圖十七、局部放電模擬雜訊分析

因此 FIR 雜訊抑制技術在提高局部放電辨識率方面具有

重要作用。它允許我們將局部放電信號從背景雜訊中提取出來，並改善信號的清晰度，有助於及早檢測和識別潛在的電力設備問題，提高電力系統的安全性和可靠性。

輸變電設備的局部放電檢測結果是非常重要的，因為局部放電是一種潛在的設備故障現象，可能會導致設備損壞或故障。局部放電檢測通常涉及使用特殊的儀器和技術來檢測和評估設備中是否存在局部放電現象。輸變電設備的局部放電檢測結果通常會與雜訊有關。局部放電是一種放電現象，通常伴隨著高頻的電場變化，因此會在電路中產生雜訊。以下是有關局部放電檢測結果和雜訊的一些相關信息

局部放電檢測結果與雜訊密切相關，通常通過監測和分析雜訊來檢測和評估局部放電的存在和程度。這是確保輸變電設備安全運行的關鍵步驟之一，有助於及早發現潛在的故障或問題，以減少設備損壞和運行中斷的風險。

總結來說，雜訊抑制技術在各種應用中都扮演著重要的角色。它們有助於減少或消除雜訊對信號的干擾，提高了許多技術和系統的性能和可靠性。通過適當的雜訊抑制技術，我們能夠確保信號的品質和穩定性，使各種應用能夠更好地運作。

肆、參考文獻

[1] 程于真,「局部放電訊號偵測裝置之研製」,碩士論文,國立臺灣科技大學,2016 年。

[2] Feng-Chang Gu, Hong-Chan Chang, **Yu-Min Hsueh**, Cheng-Chien Kuo, Bo-Rui Chen, "Development of a High-Speed Data Acquisition Card for Partial Discharge Measurement," *IEEE Access*, Vol. 7, pp. 140312-140318, September 2019.

[3] Hong-Chan Chang, Yu-Ming Jheng, Cheng-Chien Kuo, **Yu-Min Hsueh**, and Yu-Jhen Cheng, "Development of a Reconfigurable FPGA-Based Partial Discharge Detection Device," *2017 IEEE International Conference on Applied System Innovation*, Sapporo, Japan, 2017, pp. 22-24.

[4] 陳柏睿,「多通道局部放電監測裝置之研製」,碩士論文,國立臺灣科技大學,2018 年。

[5] 薛聿明,「多功能電氣即時波形檢測系統之研製」,博士論文,國立臺灣科技大學,2021 年。

[6] 邱敏彥、李長興、黃智賢、吳明學、曾威能,「應用 UHF 技術檢測高壓設備局部放電」,中華民國第二十七屆電力工程研討會,台灣新竹,2006 年 12 月

[7] N. S. Phuoc, "Variable IIR Digital Band-Pass and Band-Stop Filters", *2018 2nd International Conference on Imaging Signal Processing and Communication (ICISPC)*, pp. 132-137, 2018.

[8] L. Samoylov, N. Prokopenko and D. Denisenko, "Dynamic Errors of Butterworth Band-Pass Filters in Analog-digital Control and Monitoring Systems," *2022 International Russian Automation Conference (RusAutoCon)*, Sochi, Russian Federation, 2022, pp. 128-133, doi: 10.1109/RusAutoCon54946.2022.9896341.

伍、附錄

Title: Operation Strategy for Charging Station Considering Solar and Storage System

Authors: Bo-Hong Li, Chang-Kuo Chen, and Cheng-Chien Kuo

Abstract: In alignment with net-zero ambitions, the reconfiguration of existing urban infrastructures, such as retail store rooftops and parking zones into electric vehicle (EV) charging stations represents a strategic step towards the advancement of transport electrification in densely inhabited island regions. This conversion facilitates facility operators in not only exemplifying their dedication to carbon footprint reduction through the adoption of self-generated renewable energy but also in capitalizing on EV charging services. The focus of this paper is on an innovative, adaptive energy management system (EMS) that unifies solar power with an energy storage solution for EV charging stations. This system adeptly adjusts to various factors including the demand for EV charging, solar power generation, the status of the energy storage system (ESS), contract capacity, and the fluctuating rates of electricity for EV charging, tailored to a real-life setting in Taiwan. The study highlights the considerable advantages of integrating an energy storage system, which encompasses efficient contracted capacity management, optimization of peak demand, valley filling, and exploiting electricity price variations. The incorporation of this flexible EMS with a solar and storage-integrated charging station is shown to substantially minimize electricity costs and reduce the necessity for extensive electricity contract capacities. This enhancement leads to a significant boost in the operational profitability of the station, which derives not only from the direct sale of electricity but also from the additional revenue generated from excess solar energy. An extensive cost-benefit analysis indicates that the implementation of this integrated EMS could potentially increase the net earnings of facility owners by approximately 125% in comparison to simply equipping a basic charging infrastructure.

applied sciences

Article

Research on Partial Discharge Expert System for Diagnosis of Damaged Transformation Equipment

Ping-Chang Tsai [1], Yu-Min Hsueh [1], Chang-Kuo Chen [2] and Cheng-Chien Kuo [1,*]

[1] Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei 10607, Taiwan; D11007007@mail.ntust.edu.tw (P.-C.T.); D10307009@mail.ntust.edu.tw (Y.-M.H.);
[2] National Atomic Research Institute, Taoyuan City 32546, Taiwan; changkuochen@nari.org.tw (C.-K.C.);
* Correspondence: cckuo@mail.ntust.edu.tw

Abstract: If the power transmission and transformation equipment fails, it will lose great economic benefits, so prevention is better than treatment. One of the effective methods for high-voltage insulation degradation detection is to observe the phenomenon of partial discharge of equipment, and it is the earliest characteristic. Prevention can be done in advance, and trend observation is better than periodic inspection. Long-term observation can effectively reduce the probability of misjudgment. This project intends to develop a high-speed data acquisition device to acquire the original discharge waveform data of partial discharge for noise suppression. In order to improve the diagnostic efficiency and accuracy of the diagnostic system, it is necessary to suppress the noise of the measurement data, so that the fault identification of the discharge type is carried out. Carry out discharge type identification and identification. Through this method, the actual operating data of the system can be recorded as the original discharge waveform, to understand the original discharge waveform conditions of the power transmission and transformation equipment in multiple partial discharge measurements, and then after noise suppression, it can be regarded as the type of partial discharge identification.

Keywords: partial discharge; equipment fails

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1. Introduction

The majority of damages to substation transmission and transformation equipment are due to insulation degradation, which is usually an aging phenomenon caused by electrical stress, thermal stress, or mechanical stress. These aging phenomena are further accelerated by partial discharge, leading to serious accidents. To prevent major accidents, it is essential to have real-time knowledge of the equipment's condition. In the operation of the power system, the high-voltage power equipment is responsible for the supply, transmission, and distribution of electricity [1–4]. Given the increasing complexity of the power system and the demand for power going up. Therefore, insulation defects of high-voltage power equipment will cause serious power outages, equipment damage, economic loss, and inconvenience to the industry, even equipment and people casualties. To prevent such incidents from happening, for the reason that the prediction and preventive measurement of insulation defects have become the main subject of research. Partial Discharge (PD) measurement has been identified as a reliable insulation evaluation diagnostic tool for high-voltage equipment. As voids, cracks, and gaps are significant defects in dielectric materials, whatever, Solid, liquid, or gas. When subjected to high-pressure stress that will cause physical and chemical degradation of the insulation interface, it is significant to the characterization of the insulation state of electrical equipment [5-6]. Partial discharge measurement methods include pulse current, ultrasonic, and ultra-high frequency [7-8]. To satisfy the requirements, one of the measurement systems uses a high-speed A/D acquisition card or oscilloscope [9]. For example, a high-speed data acquisition unit is used to get complete discharge waveform information in a power frequency cycle. Partial discharge (PD) in this study is a tiny signal that occurs at the insulation defect of the power supply equipment that is usually accompanied by physical phenomena such as light, sound, and heat to develop a self-made portable partial discharge analyzer. Partial discharge (PD) inspection is an effective technology to evaluate the condition of the insulation components of power equipment. It can replace defective insulation components in advance to ensure a stable power supply [10–12]. Under the influence of a strong electric field, some of the defects in the internal insulation of the equipment, such as bubble gaps, impurities, and spikes or points all cause uneven electric field distribution inside the equipment insulation [13]. The partial discharge is the electric field intensity of the defective increases, which is easy to cause the discharge and does not penetrate the overall insulation [14]. On the other hand, Partial discharge inside the insulation of high-voltage electrical equipment will affect the service life of the insulation. These partial discharge phenomena include needle plate discharge, creeping discharge, air gap discharge, and metal particle discharge [15]. Partial discharge (PD) occurs in degraded high-voltage insulation. The specification of IEC60270 defines partial discharge as Partial discharge (PD), Only the partially bridge the insulation between conductors and may or may not happen near the conductor. Partial discharge is usually the result of local electric stress concentration in or on the surface of an insulator. Usually, this discharge is a pulse lasting much less than 1 microsecond. These discharges will cause the insulation resistance to decrease and ultimately lead to catastrophic failure. Each discharge represents a current pulse. The monitoring of these pulses is a mature technology for evaluating the insulation status of high-voltage equipment [16]. Traditional techniques for detecting partial discharge current pulses include high-frequency current sensors (HFCT), transient ground voltage sensors (TEV), and UHF sensors (UHF)[17]. The classification of partial discharge modes is the basic criterion for evaluating and diagnosing the performance of insulation systems. Because it provides a significant indicator of the severity of the discharge. In order to evaluate the insulation status of the equipment, this uniqueness must be used to correlate the discharge pattern with the defect type. Partial discharge (PD) diagnosis is completed by visual inspection in the initial stage. Due to the difficulty of detecting partial discharge, only experts with rich personal experience can distinguish various discharge phenomena and evaluate the severity of the fault [18].

2. Materials and Methods

2.1 Hardware architecture

The hardware architecture of the homemade partial discharge analyzer, as shown in Figure 1, is divided into two main components: the data acquisition module and the embedded system.

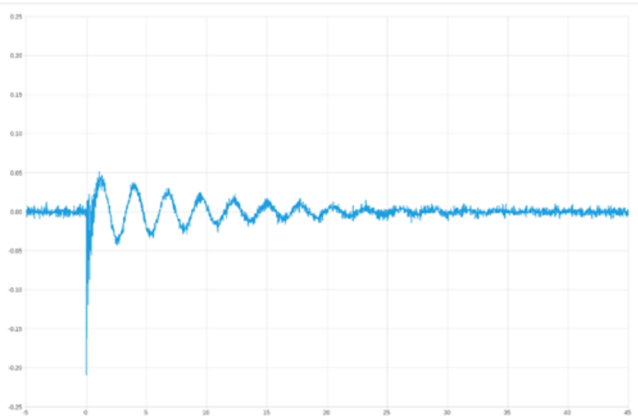

Figure 1. Original partial discharge waveform.

The data acquisition module is based on the literature [19] to design and improve it. As Figure 2 points out there are six analog synchronization input channels, the resolution of each channel is 12 bits, the maximum sampling rate is up to 65 MS/s, with 256 MB DDR3 memory, and each data is calculated by 16 bits, up to 67,108,864 data can be stored. Adjustable input voltage range: ±5V, ±2V, ±1V, ±0.5V. Design with FPGA includes a communication controller, memory controller, ADC controller, and frequency controller. Change the transmission mode from Asynchronous Nonmultiplexed Device to Synchronous Address/Data-Multiplexed Device to increase the transmission speed. Asynchronous and Synchronous have different ways of judging. Asynchronous based on a WE or OE signal to judge. Synchronous is based on GPMC_CLK to judge. In the Synchronous model, only send the address once before starting the transfer and subsequent to automatically increase by 1 each time according to CLK, so address line errors can be avoided. The difference is whether the transmission position is continuous, and it is the continuous position in this case. Therefore, a Synchronous Address/Data-Multiplexed Device is more suitable. At the same time, the Address/Data-Multiplexed address line and data line can be multiplexed, and the hardware circuit is omitted.

In the literature [2], the FPGA parallel port design uses GPMC Asynchronous 16-bit Address/Data-NonMultiplexed without DMA to transmit data with ARM. The data line and the address line are independent, so there is no need for CLK or CS trigger to transmit data. A CS trigger can send 4 words time in around 500 ns, equivalent to the transmission speed of 128 Mbps. As shown in the transmission interface GPMC Synchronous 16-bit Address/Data-Multiplexed with DMA in this study, DMA is enabled to increase transmission continuity, and there is no need to switch jobs due to the multi-threading of the ARM system to achieve the increase in transmission speed. In this transmission mode, the address is transmitted first, and then the address must be incremented --Burst mode, up to 16 words of data can be transmitted each time, the transmission time is 400 ns, and the transmission speed is equivalent to 640 Mbps. In actual transmission, it takes some time, such as Linux execution program, system thread conversion and hardware settings, etc. The original transmission time is about 30 seconds reduced to less than 5 seconds to achieve the purpose of increasing the transmission speed.

2.1.1. Embedded ARM processor

The partial discharge raw discharge waveform acquisition system in this study utilizes the Texas Instruments TI Sitara Processor AM3358 processor, which is based on the ARM Cortex-A8 architecture. The processor specifications and development board are depicted in Figure 2.

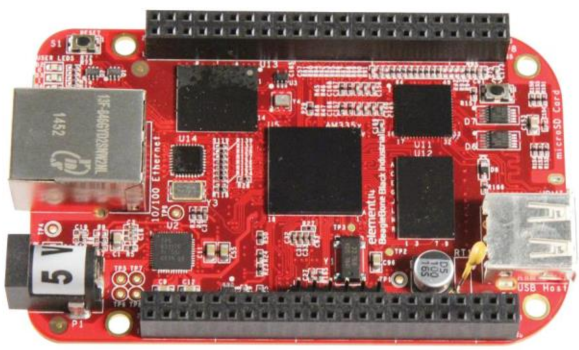

Figure 2. AM3358 Board.

2.1.2. Analog-to-Digital Converter

The local discharge raw discharge waveform measurement system employs the Analog Devices Inc. (ADI) AD9226 high-speed analog-to-digital converter (ADC) due to the approximate 10 MHz frequency of the raw discharge waveform. The AD9226 analog-to-digital conversion module is depicted in Figure 3. The AD9226 operates with a single power supply and features a high-performance amplifier and reference voltage source, offering a voltage resolution of up to 12 bits and a sampling rate of up to 65 MS/s. It can be applied in various applications such as ultrasound, imaging, and communication systems, making it suitable for multi-channel multiplexing systems for detecting voltage ranges in high-frequency continuous signals. It can also perform single-channel sampling at the Nyquist Rate and has a rated temperature range of -40°C to +85°C.

Figure 3. AD9226Analog-to-Digital Converter.

2.1.3. Field Programmable Gate Array

The on-site Field Programmable Gate Array (FPGA) utilizes the Xilinx Spartan-6, which allows for programmable routing using logic blocks, creating custom hardware functions from configured chips. FPGA possesses the property of reconfigurability and can be modified according to specific usage requirements.

FPGA integrates Application-Specific Integrated Circuit (ASIC) and processor architecture systems, offering hardware clock speed and reliability, reducing the cost of custom ASIC design, and allowing for chip reprogramming similar to software flexibility. It is not limited by the number of processor cores. Additionally, FPGA is a parallel architecture, so different processing tasks do not occupy the same resources. Each independent processing task is assigned to a dedicated chip block, which does not affect other logic blocks and can automatically generate functions. Therefore, when adding other processing tasks, the performance of the application section is not affected.

FPGA is a powerful and flexible hardware platform, as shown in Figure 4, particularly suitable for scenarios that require high customization and high-performance computing. However, due to its relatively complex development process, it typically requires specialized hardware design and electronic engineering knowledge.

Figure 4. Xilinx XC6SLX16-2CSG324.

2.1.4. Technical Architecture of High-Speed Data Acquisition Device System

The analog-to-digital converter (ADC) in the system for capturing the raw discharge waveform of partial discharge employs an FPGA as the controller for the ADC to achieve a higher sampling rate, meeting the requirements for transmission speed.

The FPGA circuit functions designed in this study, as depicted in Figure 5, include a controller. The design adopts a parallel approach to allow data transmission between the Microcontroller Unit (MCU) and the controller. The parallel port connection lines include Chip Select (CS), Output Enable (OE), Write Enable (WE), Address Valid (ADV), Clock (CLK), and Address Data (AD). Additionally, there is a Digital Clock Manager (DCM) used for configuring and controlling the sampling rate of the analog-to-digital converter, as well as a Memory Interface Generator (MIG) for controlling the write and read operations of DDR3 memory. Finally, if there are differences in data width or transmission rates during data transmission, a buffer must be added in the middle of the transmission.

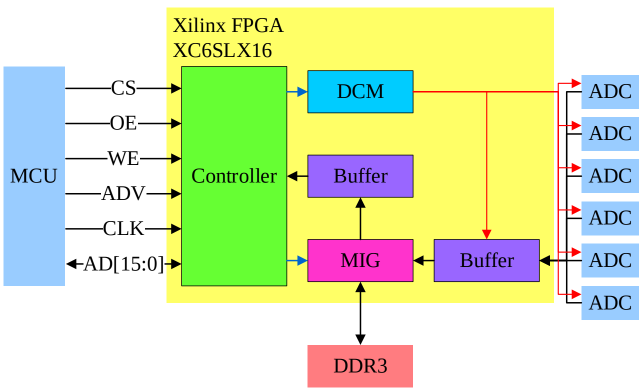

Figure 5. Embedded System.

2.2. Functions and Processes of System Software and Data Acquisition Systems

The high-speed data acquisition software system functions of the raw discharge waveform detection system for partial discharge utilize ARM processor design and development. The high-speed data acquisition software system functions encompass FPGA driver programs, ADC sampling and acquisition control programs, and data transmission interfaces.

The process control requires loading the driver program for FPGA communication into the system core. In Linux, a driver is a special kernel module used for communication with hardware devices. Through the driver, the operating system and applications can interact with hardware devices. Kernel modules in Linux are code blocks that can be dynamically loaded and unloaded at runtime. These modules essentially act as plugins that extend the functionality of the Linux kernel, allowing developers to add new features or update existing ones without altering the entire kernel source code or recompiling the kernel.

Setting the ADC sampling rate length and threshold values can be configured through the REST API, allowing for the initiation of analog data acquisition. After the conversion is completed, the high-speed data acquisition of the local discharge raw waveform can be transmitted to the embedded system via transmission commands. Finally, the data of the local discharge raw waveform can be obtained through the REST API.

2.2.1. Software system user interface design

The graphical user interface (GUI) of the raw discharge waveform detection system for partial discharge is designed to interface with Jupyter. Jupyter is an interactive environment used for data analysis, machine learning, statistical modeling, and other mathematical computations. The most common form is Jupyter Notebook, which is a web application that can contain code, documents, mathematical formulas, and visualization tools.

The high-speed data acquisition device used for local discharge raw waveform detection employs a communication technology framework based on REST API (Representational State Transfer Application Programming Interface). REST API is a software architectural style used for developing web services. It enables the exchange of data between clients and servers over the HTTP protocol. REST API is typically used to build and provide resource-oriented services, and it models resources or data entities using URIs (Uniform Resource Identifiers).

The human-machine interface design of the high-speed data acquisition device software system is implemented using Python programs. Python code can be written within the Jupyter interface and executed immediately, displaying the computational results in the Jupyter display interface, as shown in Figure 6.

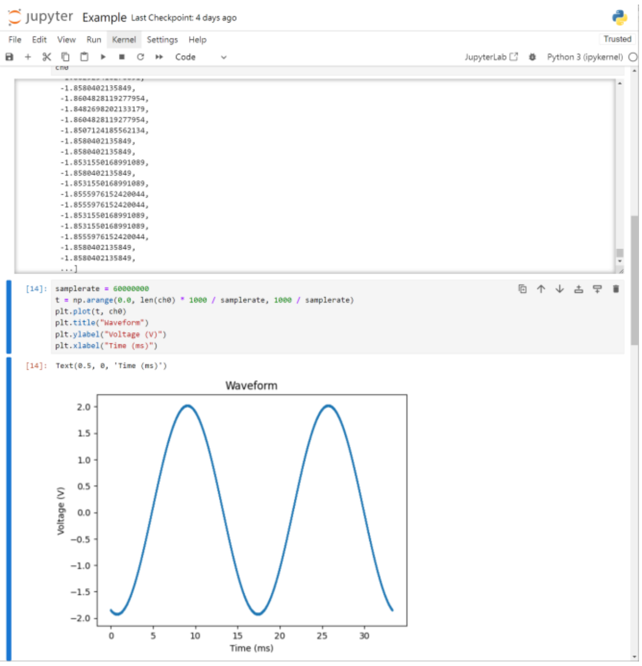

Figure 6. Jupyter Notebook UI.

2.2.2. Discharge waveform measurement

The expert system for diagnosing damage to substation transmission and transformation equipment focuses on online recording of raw discharge waveforms for oil-immersed transformers, as shown in Figure 7. It utilizes noise suppression techniques and improves the identification rate of partial discharge to ensure the reliable operation of the transmission and transformation equipment, reduce maintenance costs, enhance safety and stable power supply, and prevent power interruptions caused by unknown faults. Partial discharge is an important indicator for assessing the insulation health of substation transmission and transformation equipment. Continuous partial discharge may lead to further aging or damage of insulation materials, thereby increasing the risk of equipment failure.

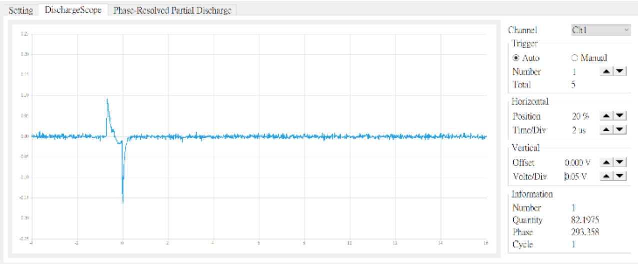

Figure 7. Simulated discharge waveform of power transmission transformation equipment.

2.2.3. Noise suppression technology

The noise suppression technique is applied in the design planning of the raw discharge waveform detection system for partial discharge. It is a method and technology used to reduce or eliminate unnecessary signals, interference, or background noise. Filtering noise in the input of the Analog-to-Digital Converter (ADC) is a common but important problem. Such converters are used to convert analog signals into digital signals, but they may introduce various types of noise in the process.

Two main specified requirements for bandpass and bandstop filters are the cutoff frequency at -3dB and the stopband frequency fN. The variability of bandwidth and stopband frequency in the filter will change the behavior of the filter. Filters with adjustable bandwidth and stopband frequency are known as variable filters or adjustable filters, and they play a very important role in digital signal processing applications. There are various designs for variable bandpass and bandstop filters, with one of the previously proposed designs in the literature suggesting replacing almost all delay elements in the digital low-pass prototype filter with second-order digital all-pass filters and then modifying the coefficients, which can be computationally complex.

To efficiently reduce computational complexity, one method is to use a Taylor series expansion of the transfer function coefficients, but truncating the approximated linear terms can degrade the filter's amplitude-frequency response. Another computationally simpler method adjusts only the center frequency f0 while keeping the bandwidth constant and is designed primarily for narrowband digital filters. This method adjusts the bandwidth of variable filters based on the cutoff frequency fc of the digital low-pass prototype filter, resulting in a limited range of frequencies and increased complexity for higher-order filters.

Another significant issue to consider is that the design of most digital bandpass and bandstop filters using the center frequency f0, which is the geometric mean of the lower frequency fL and the upper frequency fU, applies primarily to analog filter design. It is well-known that using the center frequency f0 for designing digital bandpass and bandstop filters has limitations because f0 is not the stopband frequency fN and is only an approximation for the design of narrowband digital filters.

Finite Impulse Response (FIR) filters are characterized by having a finite-length impulse response, where the input signal is convolved with a set of fixed coefficients to obtain the output signal. These filters can typically be designed with linear phase characteristics, where all frequency components of the signal pass through the filter at the same rate, effectively reducing phase distortion.

The method presented in this paper designs variable IIR digital bandpass and bandstop filters by independently controlling α and β, two adjustable parameters, to achieve -3dB bandwidth bw and stopband frequency fN. The parameter α originates from frequency domain transformation from low-pass to low-pass filter and controls the -3dB bandwidth. The parameter β controls the stopband frequency fN and is derived from frequency domain transformation from low-pass to high-pass filter. Digital bandpass and bandstop filters are obtained by transforming a half-band digital low-pass filter using digital domain frequency transformations. Variable digital filters have fewer coefficients, which means fewer multipliers, adders, and delays in the implemented circuit compared to previous designs. The design steps of the method proposed in this paper are very simple in terms of computation, as it involves only two adjustable parameters. A new formula for the damping factor ζ with α and β is introduced, and the root locus of the second-order variable digital Butterworth bandpass and bandstop filters with damping factor is analyzed. Figure 8 shows the results using an FIR filter.

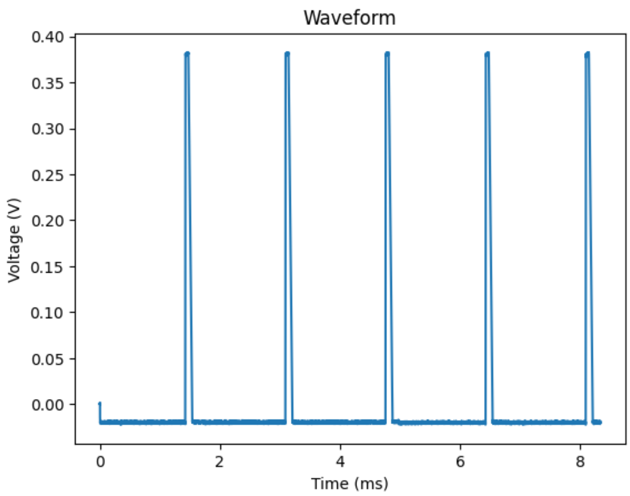

Figure 8. Partial discharge waveform noise suppression results using RC filtering.

The results of capturing high-frequency signals from the raw discharge waveform of partial discharge are shown in Figure 9. It is evident from the figure that the signal levels contain high-frequency noise. Filters can be used to create low-pass filters at different output points, primarily designed to allow low-frequency components to pass through while reducing or blocking high-frequency components. A low-pass filter can filter out all frequency components above a certain specific cutoff frequency, allowing only components below that frequency to pass. This is included in various applications of analog-to-digital converters. Additionally, it can be used to construct various broadband filters with independently controllable lower and upper cutoff frequencies, as well as to ensure frequency doubling and one-third octave filter sets in the form of tunable bandpass filters. The main drawback of tunable filters based on typical filter sections is that they do not allow for high stability at high frequencies. Figure 10 shows the results of an RC filter.

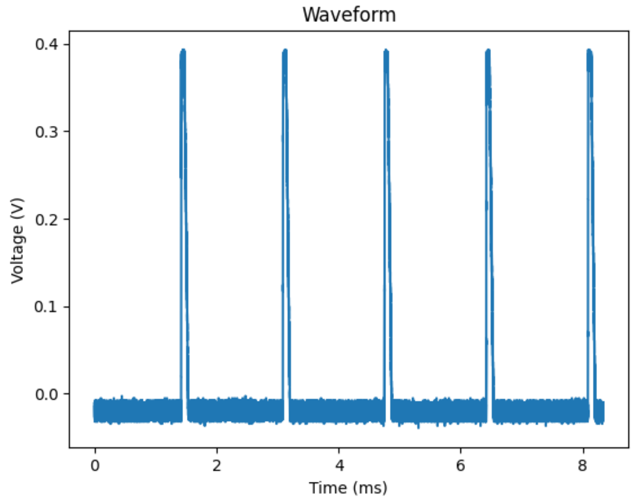

Figure 9. Partial discharge original discharge simulation waveform.

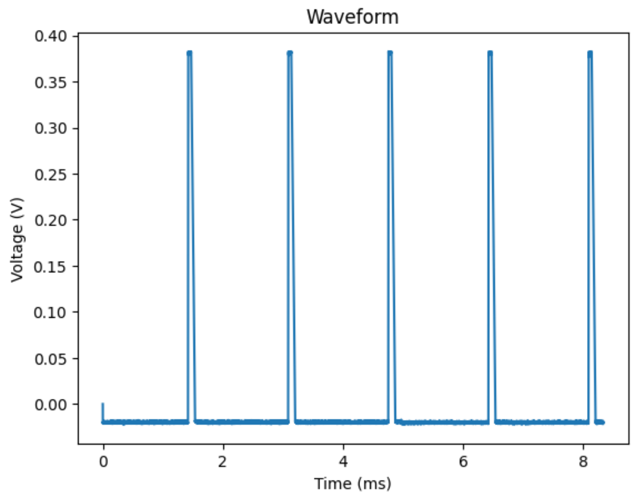

Figure 10. Partial discharge waveform noise suppression results using FIR.

3. Conclusion

In this study, experiments were conducted using a partial discharge signal simulator with three different levels of noise. Besides, signal analysis and noise suppression techniques were employed, utilizing a homemade data acquisition module and digital signal processor (DSP) for analysis and computation. This approach not only reduces costs but also enhances computational performance. Compared to commercial partial discharge detection systems like the PD700, the signal analysis and noise suppression techniques effectively reduce noise and improve recognition rates. Experimental results demonstrate that the locally designed partial discharge detection and analysis system can capture the discharge characteristics of partial discharge and can be expanded as needed. Furthermore, the methods proposed in this study can also be applied to the recognition of partial discharge in other types of high-voltage power equipment, thereby enhancing its functionality and contributions in industrial and commercial applications.

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References

1. X. Chen, Y. Qian, Y. Xu, G. Sheng, and X. Jiang, " Energy estimation of partial discharge pulse signals based on noise parameters," IEEE Access, vol. 4, pp. 10270-10279, 2016.
2. F. Petzold, H. Schlapp, E. Gulski, P. P. Seitz, and B. Quak, "Advanced solution for on-site diagnosis of distribution power cables," IEEE Trans. Dielectr. Electr. Insul., vol. 15, no. 6, pp. 1584-1589, Dec. 2008.
3. H. Ma, J. C. Chan, T. K. Saha, and C. Ekanayake, "Pattern recognition techniques and their applications for automatic classification of artificial partial discharge sources," IEEE Trans. Dielectr. Electr. Insul., vol. 20, no. 2, pp. 468-478, May. 2013.
4. F. Zeng, S. Wu, X. Y, Z. Wan, J. Tang, M. Zhang, and Q. Yao, "Fault diagnosis and condition division criterion of DC gas insulating equipment based on SF6 partial discharge decomposition characteristics," IEEE Access, vol. 7, pp. 29869-29881, Mar. 2019.
5. D. Wang, L. Du, C. Yao, and J. Yan, "UHF PD measurement system with scanning and comparing method," IEEE Trans. Dielectr. Electr. Insul., vol. 25, pp. 199–206, 2018.
6. J. Benzing, I. Blokhintsev, C. Patterson and A. Loesch, "Continuous OnLine Partial Discharge monitoring of medium voltage substations", Pulp and Paper Industry Technical Conf., Portland, OR, USA, pp. 1-7, 2012.
7. H. J. Koch, Gas Insulated Substations, Vol. 4. New Jersey: John Wiley & Sons Ltd Press, pp. 206-234, 2014.
8. R. Piccin, A. R. Mor, P. Morshuis, A. Girodet and J. Smit, "Partial Discharge Analysis of Gas Insulated Systems at High Voltage AC and DC", IEEE Trans. Dielectr. Electr. Insul., Vol. 22, No.1, pp. 218-228, 2015.
9. D. Ding, W. Gao and W. Liu, "Influence of the Structure Dimension of GIS on the Partial Discharge", IEEE Int'l. Conf. Condition Monitoring and Diagnosis. Bali, Indonesia, pp.958-962, 2012.
10. M. Wu, H. Cao, J. Cao, H. L. Nguyen, J. B. Gomes, and S. P. Krishnaswamy, "An overview of state-of-the-art partial discharge analysis techniques for condition monitoring,". IEEE Electr. Insul. M., vol. 31, no. 6, pp. 23-35, Oct. 2015.
11. M. Ghorat, G. B. Gharehpetian, H. Latifi, and M. A. Hejazi, " A new partial discharge signal denoising algorithm based on adaptive dual-tree complex wavelet transform," IEEE Trans. Instrum. Meas., vol. 67, no. 10, pp. 2262-2272, Oct. 2018.
12. Z. Guozhi, X. Zhang, H. Xingrong, Y. Jia, J. Tang, Z. Yue, T. Yuan, and L. Zhenze, "On-line monitoring of partial discharge of less-oil immersed electric equipment based on pressure and UHF," IEEE Access, vol. 7, pp. 11178-11186, Jan. 2019.
13. J. J. Zhang, The Technology and Application of High Voltage Discharge Ultraviolet Detection. Beijing, China: China Electric Power Press. 2009.
14. P. Yao, H. Zheng, X. S. Yao, and Z. Ding, "A method of monitoring partial discharge in switchgear based on ozone concentration," IEEE Trans. Plasma Sci., vol. 47, no. 1, pp. 654-660, 2019.
15. CIGRE WG D1.33, "Guide for Electrical Partial Discharge Measurements in compliance to IEC 60270," Technical Brochure 366, Electra, vol. 60, no. 241, 2008.
16. D. W. Upton et al., "Low power radiometric partial discharge sensor using composite transistor-reset integrator," IEEE Trans. Dielectr. Electr. Insul., vol. 25, no. 3, pp. 984–992, Jun. 2018.
17. Y. Z. Adzis W. A. Izzati, and Z. Adzis, "Modeling of partial discharge mechanisms in solid dielectric material," Int. J. Eng. Innov. Tech., vol. 1, no. 4, pp. 315–320, 2012.
18. S. Govindarajan, J. A. Ardila-Rey, K. Krithivasan, J. Subbaiah, N. Sannidhi and M. Balasubramanian, "Development of Hypergraph Based Improved Random Forest Algorithm for Partial Discharge Pattern Classification," in IEEE Access, vol. 9, pp. 96-109, 2021, doi: 10.1109/ACCESS.2020.3047125.
19. F.-C. Gu, H.-C. Chang, Y.-M. Hsueh, C.-C. Kuo, and B.-R. Chen, ''Development of a high-speed data acquisition card for partial discharge measurement,'' IEEE Access, vol. 7, pp. 140312–140318, 2019.
20. N. S. Phuoc, "Variable IIR Digital Band-Pass and Band-Stop Filters", 2018 2nd International Conference on Imaging Signal Processing and Communication (ICISPC), pp. 132-137, 2018.
21. L. Samoylov, N. Prokopenko and D. Denisenko, "Dynamic Errors of Butterworth Band-Pass Filters in Analog-digital Control and Monitoring Systems," 2022 International Russian Automation Conference (RusAutoCon), Sochi, Russian Federation, 2022, pp. 128-133, doi: 10.1109/RusAutoCon54946.2022.9896341.