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Rotor Installed Corona Probe: Further Refinement Toward a Final Product

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14. ABSTRACT
In previous research, a method of slow-roll testing that could map partial discharge activity in large diameter rotating machines was shown to be feasible and a prototype was built. In other work, the Electromagnetic Rotor Turner (EMRT) was developed as a prototypical device for electrically turning rotating machines offline for routine maintenance and slow-roll testing. The subject research, along with one other research project, extended the EMRT capability to a more functional system called the Rotor Turning Test Suite (RTTS). The RTTS is designed to incorporate all types of slow-roll testing, including the method described here: rotor installed partial discharge mapping of large diameter hydro generators. This project builds on this concept by acquiring dedicated equipment for partial discharge mapping and developing an efficient path forward for adoption of this technology throughout Reclamation.

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Partial discharge, partial discharge mapping, rotor installed corona probe, slow-roll testing, hydropower diagnostics, rotor turning

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Cover Image – Hydropower generators (also known as rotating machines) at Glen Canyon Dam.

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Acronyms and Abbreviations

EMRT	Electromagnetic Rotor Turner
MCU	Multi-device Control Unit
NFC	near field communication
O&M	operation and maintenance
PD	partial discharge
S&T	Science and Technology
Reclamation	Bureau of Reclamation
RTTS	Rotor Turning Test Suite

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Executive Summary

Feasibility of remotely sensing partial discharge (PD) with near field communication (NFC) antennas was shown in Science and Technology (S&T) project number 1711 (Lapenna 2018). A prototypical system was developed to show proof of concept in S&T project number 19078 (Lapenna 2021). The present research leveraged these previous projects to develop a path forward for deploying this technology across Reclamation (and possibly industry wide).

Economic analysis indicates that widespread adoption of this technology across Reclamation will yield around a 10x return on investment. These benefits include reduced outages, better operation and maintenance (O&M) decision support, and an overall increase in hydropower fleet reliability. However, there are many technological hurdles to overcome before this technology can be widely adopted.

The prototypical system developed in project 19078 was cumbersome to deploy, relied on equipment dedicated to other tasks, and required extensive specialized knowledge and post-processing to perform and interpret the data. The primary goal of this project was to determine the best way of streamlining this technology so that it can be more easily deployed across the myriad environments and disciplines seen throughout Reclamation facilities.

The subject technology relies on an NFC antenna mounted on the rotor. The rotor is turned while the antenna detects and maps partial discharge activity throughout the stator winding. One of the largest technical hurdles to widely adopting this technology is a means of slowly and precisely turning rotors. For this reason, a large portion of this project's efforts were spent on extending the capability of the Electromagnetic Rotor Turner (EMRT). In collaboration with S&T project 21006 (Lapenna 2024), this effort led to the development of the Rotor Turning Test Suite (RTTS) system. The RTTS extends the functionality of the EMRT, enabling it to potentially automate all slow-roll testing, including PD detection using an NFC antenna.

This project covers two main aspects: 1) the acquisition of dedicated hardware to incorporate into the RTTS for partial discharge mapping, and 2) the development of extensible systems within the RTTS to accept this test technique (and many others) into the portfolio of possible RTTS-controlled hydropower diagnostic testing. This project did not provide sufficient time and funding to incorporate the hardware into the extensible RTTS systems as a final product, and this is left to future work. The bulk of the technical details of this work are reported in other works, as cited, and this report primarily serves as a bridge to these technical documents and documentation.

1.0 Background

Partial discharge (PD) is electrical discharge within insulation that only partially bridges the insulation thickness. It most often occurs in micro-voids within the insulation. These micro-voids create a spatial discontinuity in the electric field across the insulation. Sufficient voltages will cause these micro-voids to ionize and discharge, moving electric charge across them. This ionization inside the insulation can present a deterioration mechanism over time.

These discharge events, like any accelerating electric charge, release electromagnetic radiation into the space around them. As discovered in S&T project 1711, this radiation can be remotely sensed with NFC antennas (Lapenna 2018). As further shown in S&T project 19078, the NFC antenna can be mounted on a rotor pole face to detect PD events in the stator winding across the air gap of a rotating machine (Lapenna 2021). If a rotor pole-mounted NFC antenna encircles the entire stator winding as the rotor turns, PD events can be accurately mapped to their specific locations in the stator winding.

The developed technology is contrasted with the present state-of-the-art PD detection, which uses a coupling capacitor connected to the stator winding to detect PD occurrence. An output plot from this detection technique is shown in Figure 1. Present technology is good at detecting PD occurrence and trending its magnitude over time but cannot reliably determine its location of origin within the machine; it has very high temporal resolution but limited spatial resolution. This is shown in Figure 1 where individual PD events (points in the plot) are resolved within the 60 Hz sine wave (thin green line) of an operating generator. However, any PD events in this plot cannot be spatially distinguished from any other in the context of where they originated within the machine. Moreover, in large diameter machines, most of the PD events go undetected as their signal attenuates before it reaches the galvanically connected coupling sensor (Lapenna; Eastment 2018). In contrast, the plot shown in Figure 2, generated by the PD mapping prototype, displays the count of detected PD events corresponding to the specific stator slot from which they were detected.

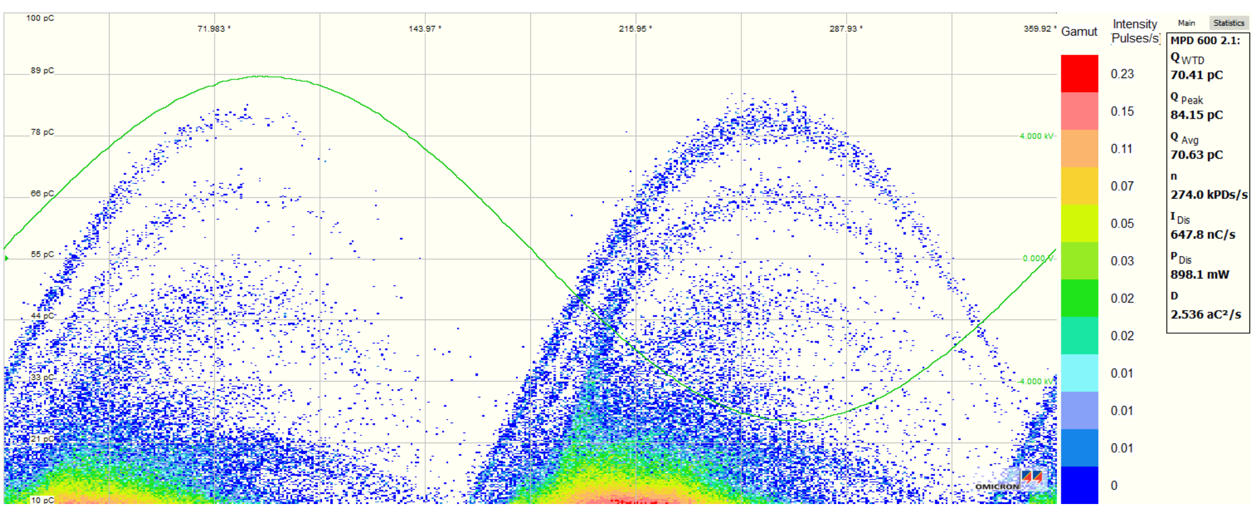

Figure 1.—Example plot of partial discharge activity as detected from a galvanically connected coupling capacitor.

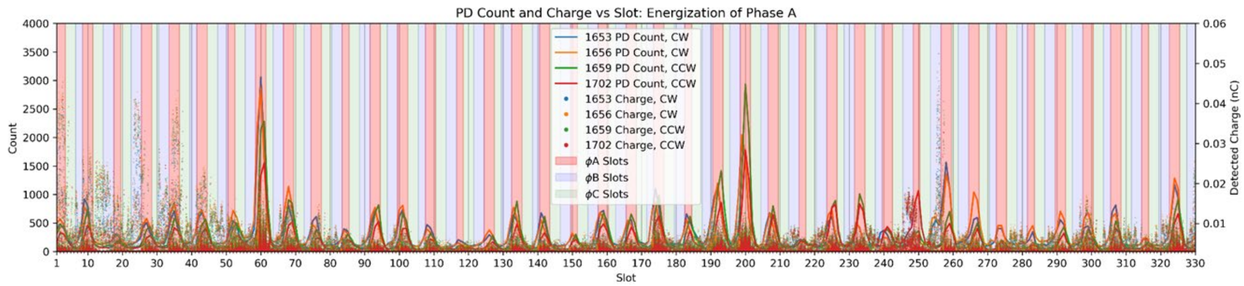

Figure 2.—Plot produced by the partial discharge mapping prototype showing partial discharge detection event count versus stator slot position (Lapenna 2021).

The developed technology's increase in spatial resolution can help determine whether insulation deterioration is a localized or bulk issue within a machine, which has significant impact on mitigation strategies. This directly affects outage times and repair costs. For this reason, the new technology may present a major improvement in asset management efficiency in the context of generator operation, maintenance, and eventual repair and replacement.

2.0 Work Performed

Presently, the invented technology utilizes the data acquisition equipment from a commercially available PD monitoring system. The NFC antenna is simply connected to the input that is typically connected to a capacitive coupler galvanically connected to the asset winding (Lapenna 2021). The equipment used in the prototypical system (S&T 19078) is required for other hydropower diagnostics tasks, so this project sought to acquire a dedicated device for this application. In addition to this commercially available monitoring hardware, a dedicated computer was acquired to facilitate the collection and processing of the PD mapping data.

A purchase request for the PD monitoring device was made in late 2021, and this equipment was received in 2022. Due to supply chain issues and internal processes for acquiring non-standard computers, it took two years to acquire the computer for this system. This dedicated hardware is available for immediate use in bringing this PD mapping technology into the RTTS platform in the future. Hardware procurement management and the cost of the hardware itself consumed approximately one-third of this project's budget. The remaining two-thirds of the budget was spent developing scalable and extensible systems and accurate rotor position tracking for the RTTS (Lapenna 2024).

The PD mapping prototype developed in S&T 19078 utilized a capacitive proximity probe mounted on the rotor next to the NFC antenna to track antenna position throughout the machine. This proximity probe produces an oscillating signal as the machine rotates and this sensor moves past core teeth and winding slots. In effect, counting the probe's signal oscillations amounted to counting the slots the NFC antenna passed as the rotor was turned (Lapenna 2021). However,

this analysis could only be performed in post processing, and, even then, it is cumbersome and prone to error due to signal noise and improper test setup. A more robust approach would be to monitor rotor position (and thereby antenna position) in real time. In this way, PD activity and its position could be presented to the test operator as it is measured and would be less prone to post-processing errors. For this reason, a portion of this research was spent integrating a rotary encoder into the RTTS (Lapenna 2024).

The RTTS rotary encoder's resolution varies based on machine size and encoder drive ratio, though an encoder bit depth was chosen such that every machine within Reclamation's fleet will have sub-slot position resolution (Lapenna 2024). The bulk of the encoder work was developing a means of monitoring it in a separate computing process. Specifically, the RTTS user interface is displayed via a real-time browser application. The backend for this application is written in Python. The main Python process serves this browser application, and, when needed, other processes are tasked via a distributed task queue to perform tasks such as monitoring the encoder position. Presently, Celery (Ask Solem; contributors 2024) is used for the task queue and Flask (Pallets 2024) is used for the backend (Lapenna 2024). Redis (Redis 2024) is the present message broker of choice underlying the task queue and WebSocket handling (Lapenna 2024). In the future, efforts to migrate to the simpler, more modern, more performant platforms Dramatiq (Cleartype 2024) and FastAPI (Tiangolo 2024) should be made for the distributed task queue and backend, respectively. Migration to RabbitMQ (Broadcom 2024) should also be sought for the message broker for documented Windows support if needed.

The distributed task architecture of the RTTS application was made possible by this research project and allows for PD mapping tasks to easily be brought into RTTS task orchestration (Lapenna 2024). A depiction of the distributed nature of the RTTS is shown in Figure 3.

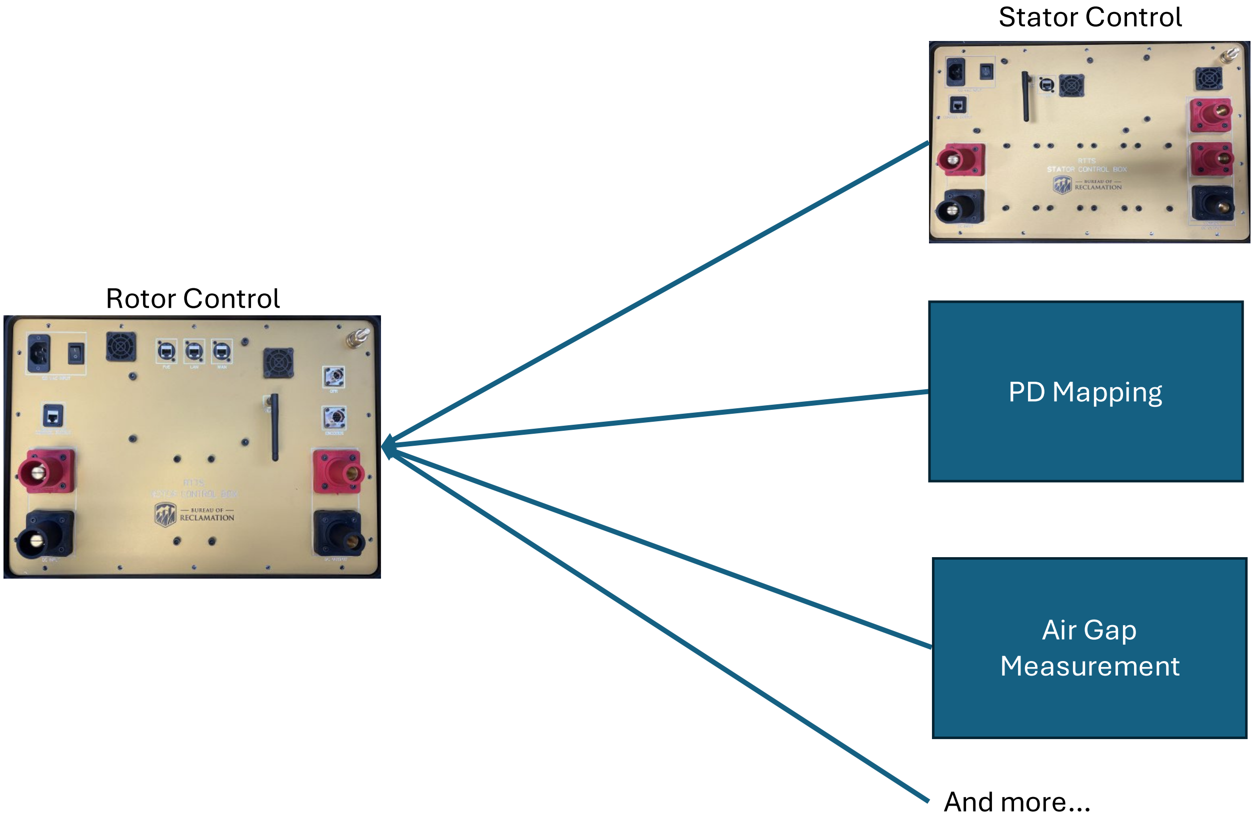

Figure 3.—Depiction of the RTTS distributed computing architecture and modular hardware design (Lapenna 2024).

The RTTS has two main components: the rotor controller and the stator controller. Each is housed in a dedicated Pelican case (termed "box") and physically connected to the rotor field winding and stator winding respectively. These control boxes make the rotor turning possible (Lapenna 2024). The rotor control box runs the main process and orchestrates everything in the RTTS system. It serves the browser application, processes user interaction, monitors the encoder, and distributes current switching tasks to the stator control box over the network. This means that all other control boxes in the RTTS system only need to run task queue worker processes and connect to the message broker over the network to receive tasks (Lapenna 2024). Their specific task definitions are coded into their respective code bases on each box.

With this architecture, adding functionality, like PD mapping, is a matter of building a PD mapping control box to house the dedicated hardware discussed earlier, and defining the compute tasks required to carry out PD mapping. Most of these software-defined tasks can be migrated from the prototype's code base. In addition, instead of post processing NFC antenna position from a proximity probe, the PD-mapping tasks will be able to access rotor position directly, as the encoder monitoring tasks store position inside the message broker's in-memory cache (Lapenna 2024).

This research and the extensibility of using a distributed task queue and message broker makes any future functionality easy to incorporate. In addition to partial discharge mapping, air gap measurement and any other slow-roll testing could be potentially brought into the RTTS portfolio of diagnostic testing capabilities.

3.0 Future Work

Hardware needed to carry out PD mapping includes an Omicron MPD 600 partial discharge data acquisition system, an Omicron Multi-device Control Unit (MCU), and an industrial Windows computer to run the Omicron software that connects with and controls these devices. This hardware was purchased in this project. Future work will develop a dedicated Pelican case for this hardware with a faceplate that will match the RTTS system and only expose the user-required interfaces (Lapenna 2024).

The fact that Windows is required to run the MPD 600 Omicron software means that some software changes will be required. Specifically, the distributed task queue (Celery) and the message broker (Redis) are not officially supported on Windows. Migration to Dramatiq and RabbitMQ, for the distributed task queue and message broker respectively, will be required to reliably allow a Windows-based control box on the RTTS network. It may also be possible to circumvent the Omicron software altogether and allow a Linux based control box, though this would require deeper investigation to determine.

Additional future software engineering work will involve defining the tasks that the PD mapping control box will require. Specifically, each control box has tasks defined in their code base for running the tasks they need to achieve their functionality within the RTTS. For example, the stator control box has current switching tasks defined on it (Lapenna 2024). The code written in these task definitions interacts with the data and hardware to switch current on and off and control its direction through the stator winding (Lapenna 2024). Similarly, code will have to be written for the PD mapping tasks. Such tasks would include starting and processing the data acquisition from the MPD 600 device and monitoring the encoder to track antenna position throughout the rotor turning process. Much of this code can be adapted from the prototype system developed in S&T 19078. Some of this code will have to be developed from scratch, as the prototype did not utilize a rotary encoder or a message broker.

Outside this research project, facilitated adoption funding was secured to build and deliver several RTTS test sets to key facilities and regions throughout Reclamation over the next three years. These systems will likely be delivered to the field locations before the PD mapping functionality can be added to the RTTS. However, the modular nature of the RTTS system means that to add this functionality to already deployed systems is a simple matter of updating the software and shipping the PD mapping control box to the RTTS owner for incorporation into the test set.

4.0 Conclusions

This research has opened the door for future advancements in slow-roll testing. By engineering software extensibility and hardware modularity into the RTTS system, virtually any type of slow-roll testing can be controlled through the RTTS user interface in the future. This extensibility not only paves the way for PD mapping, but also air gap measurement, bearing alignment, and potentially yet-to-be-invented methods of machine diagnostics. The extensibility of the RTTS means that present owners of the system can get future features like PD mapping with a simple software update and purchase of the appropriate RTTS control box. Presently, a project is underway to facilitate adoption of the RTTS technology Reclamation-wide, paving the way for efficient adoption of this and future technologies moving forward.

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