Design and Development of a Microgrid Control System for Integration of Induction Generation With Storage Capability at Saint Paul Island, Alaska

Abdel Rahman Khatib, Bharath Nayak, and Bowen Dai
Schweitzer Engineering Laboratories, Inc.

Jito Coleman, Steve Hoskins, and Jan Tierson
TDX Power, Inc.

This paper was presented at the 2017 IEEE PES Innovative Smart Grid Technologies Conference and can be accessed at: https://doi.org/10.1109/ISGT.2017.8086051.

For the complete history of this paper, refer to the next page.

Published in
Wide-Area Protection and Control Systems: A Collection of Technical Papers Representing Modern Solutions, 2017

Originally presented at the
2017 IEEE PES Innovative Smart Grid Technologies Conference, April 2017

Design and Development of a Microgrid Control System for Integration of Induction Generation With Storage Capability at Saint Paul Island, Alaska

Abdel Rahman Khatib, PhD, PE
Bharath Nayak
Bowen Dai
Schweitzer Engineering Laboratories, Inc.
Pullman, WA, USA

Jito Coleman
Steve Hoskins, PE
Jan Tierson, PE
TDX Power, Inc.
Anchorage, AK, USA

Abstract—**This paper presents a centralized microgrid control system for effective operation of wind turbines and diesel engines coupled to a flywheel electrical storage component on Saint Paul Island. The wind turbines have sufficient capacity to support the entire island without using the diesel engines, allowing the formation of an islanded power system completely powered by renewables.**

The proposed strategy includes use of the flywheel, wind turbines, and diesel generators to attain survivability and resilience. The strategy is challenged and validated against different low to turbulent wind gust profiles and low to peak loading. Multiple permissive-based decoupling schemes, tie-flow controls, and heat load trading features are implemented. The tie-line flow control/heat load trading is operated in tandem with local diesel generators and wind turbines to maintain a minimum flow from the utility. The control system was tested using hardware-in-the-loop (HIL) with a simplified electrical model of Saint Paul Island.

Index Terms—**Centralized control, distributed energy resources, microgrid, storage, and wind turbines.**

I. Introduction

Increasing renewable market penetration, rising fuel costs, increased renewable generation coupled with congested and aging power grids, the demand for carbon dioxide reductions, and the impact on energy resilience from extreme weather and unintended outages have led to the birth of a semi-autonomous, decentralized grid structure referred to as a microgrid. Technical advances have made it possible to integrate distributed energy resources (DERs) within remote communities to serve their load and generation demands. Controlling the energy balance in the microgrid is one of the most difficult challenges of a reliable microgrid operation. Seamless transition to island mode, automatic generation, tie flow, intelligent response to intermittent changes in power source, load management, coordinated operation with protection relays, and resynchronization are crucial capabilities of microgrid controllers. Reference [1] discusses the control strategy implemented in the industry and [2] discusses a typical microgrid control system (MGCS) layout. This paper focuses on the design philosophy and developments of a centralized MGCS for Saint Paul Island. A centralized control strategy was developed based on the key functionality requirements of the Saint Paul microgrid in tandem with the requirements of IEEE 1547 [3].

A reliable control network is developed based on existing intelligent electronic devices (IEDs) and local DER controller protocol properties. For this project, high-speed industry protocols, such as IEC 61850 Generic Object-Oriented Substation Event (GOOSE), and existing protocols, such as Modbus®, were implemented. Relays protecting the point of common coupling (PCC) were also integrated into the architecture. The designed control strategy and communications network were then tested in a closed-loop configuration with a real-time digital simulator (RTDS) test bed to demonstrate the MGCS functionality in response to actual events such as excessive wind energy influx, loss of the diesel generator, and turbulent wind speeds.

II. System Overview

On Saint Paul Island, which is located in the Bering Sea, electrical power is generated by six synchronous diesel generators, with a total generation capacity of 3.7 MW. The city of St. Paul's power plant is a municipally owned utility. All loads can be managed by the city power plant (referred to as "the utility"), except the internal loads of the Trident plant and the Pribilof Offshore Support Services (POSS) camp. The city power plant is the dedicated utility connection to the Saint Paul Island distribution system.

The island has two other significant generation assets: the POSS camp generation station and the Trident power plant. The POSS camp consists of two 175 kW diesel generators (DG1/DG2) and three 225 kW wind turbines (WTs). In addition, there is a 160 kW flywheel (FW) to mitigate power fluctuations from the WTs. The camp also consists of a frequency regulator (SSR1) rated at 446 kW, a resistive dump load (SSR2) rated at 333 kW, and a synchronous condenser (SC) rated at 300 kVA.

The Trident power plant is intended to power the required loads for its plant operations. It functions with four diesel-powered generator sets with a combined capacity of 2.4 MW feeding a common 480 V bus. For the study, an aggregate representation of Trident plant was implemented. The electrical distribution grid on the island is connected by underground cables operating at 7.2/12.5 kV. The utility feeds a medium-voltage switch that powers three feeders. Fig. 1 shows a simplified one-line diagram of the Saint Paul Island electrical system. For the study, remote heat loads rated at 200 kW were modeled at locations M, N, O and P.

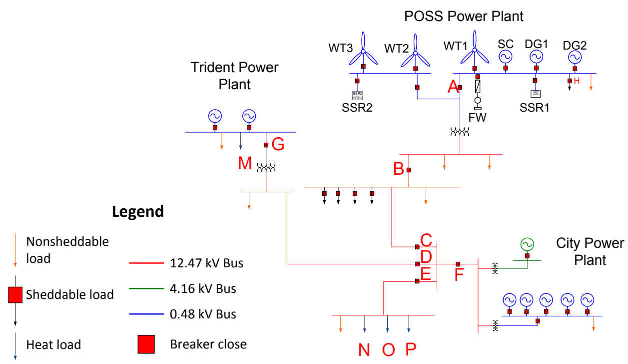

Figure 1. Simplified diagram of the Saint Paul Island electrical system

III. Existing Electrical Configuration

The city of St. Paul is responsible for operating its power plant and is the local electric utility.

POSS camp is an industrial facility owned by TDX Power, Inc. It is located approximately 2.5 miles from the city power plant. Presently, the POSS power plant operates as a separate grid feeding the local POSS camp load with one wind turbine and two diesel generators. POSS camp Breaker A is in the Open position. The Trident power plant operates as a separate grid feeding loads to the Trident plant with Breaker G is in the Open position.

Presently, the utility is connected to the POSS camp wind farm bus that feeds most of the city loads.

IV. MGCS Objectives

The MGCS objectives are as follows:

- Unit commitment, tie-flow control (TF), and heat trading (HT).
- Detecting islands and performing automatic synchronization (A25A).
- Assessing load and generation capacity.
- Maintaining power balance by fast load-shedding control and load restoration.
- Controlling WT, FW, and heat loads.
- Determining enable criteria to the SSR1 frequency regulator.
- Providing access to an operator via the human-machine interface (HMI).

The MGCS has different operating philosophies depending on whether the microgrid is operating with the utility connected, without utility-connected modes, or with or without Trident connected. Table I summarizes modes of operation. The synchronous condenser (SC) is not included in the table because it will dispatch reactive power as required.

A. *Forming the Microgrid Operation Philosophy*

Enabling the breakers for decoupling is based on two inputs, the city operator permissive and MGCS capacity calculations.

The city operator can only enable the following configurations: Breaker A; Breakers A and B; or Breakers A, B, and C.

TABLE I. Modes of Operation

Initial Condition	**Wind Profile**	**Decoupling Permissive**	**Event**	**Assets**					
				DG1/DG2	***FW***	***SSR1***	***SSR2***	***WT***	***Remote Heat Load***
Utility connected to POSS and Trident	Low	Enable_Breaker A	No Event	ON	NA	NA	NA	NA	NA
		Enable_Breaker B		ON	Q Dispatch	NA	NA	NA	NA
		Enable_Breaker C		ON	Q Dispatch	NA	NA	NA	NA
	High	Enable_Breaker A	No Event	OFF	NA	NA	TF/HT	NA	TF/HT
		Enable_Breaker B		OFF/ON	Q Dispatch	NA	TF/HT	Pref[**]-Curtail	TF/HT
		Enable_Breaker C		OFF/ON	Q Dispatch	NA	TF/HT	Pref-Curtail	TF/HT
	Low	Enable_Breaker A	Breaker A_Decouple	OFF/ON	P Dispatch	Freq-Reg[*]	NA	NA	TF/HT
		Enable_Breaker B	Breaker B_Decouple	OFF/ON	P, Q Dispatch	Freq-Reg	NA	NA	NA
		Enable_Breaker C	Breaker C_Decouple	OFF/ON	P, Q Dispatch	Freq-Reg	NA	NA	NA
	High	Enable_Breaker A	Breaker A_Decouple	OFF/ON	P Dispatch	Freq-Reg	TF/HT	NA	TF/HT
		Enable_Breaker B	Breaker B_Decouple	OFF/ON	P, Q Dispatch	Freq-Reg	NA	NA	NA
		Enable_Breaker C	Breaker C_Decouple	OFF/ON	P, Q Dispatch	Freq-Reg	NA	NA	NA

[*]Freq-Reg is frequency regulation. [**]Pref is power reference.

Based on inputs from the city operator, the MGCS determines the decoupling PCC breaker in such a way that it respects the selection of the city operator, uses the spinning reserve, and feeds the essential loads within the microgrid. The MGCS can perform the following actions:

- If the city operator selects Breaker A, the MGCS will always select Breaker A.
- If the city operator selects Breakers A and B, the MGCS will enable either Breaker A or B, depending upon the spinning reserve in the island.
- If the city operator selects Breakers A, B, and C, the MGCS will enable either Breaker A, B, or C depending on the spinning reserve in the island.

The POSS camp operator can select the spinning reserve capacity to turn on or turn off the diesel generators. The POSS camp operator selects the breakers based on capacity levels. These levels can only be enabled one at a time:

- Level 0 implies capacity supporting loads to Breaker A.
- Level 1 implies capacity supporting loads to Breaker B.
- Level 2 implies capacity supporting loads to Breaker C.

Based on inputs from the POSS camp operator-selected levels, the MGCS determines whether to turn the diesel generators on or off as follows:

- Level 0 – The MGCS turns on the diesel generators as required to cover the loads up to Breaker A; otherwise, it turns off the diesel generators.
- Level 1 – The MGCS turns on the diesel generators as required to cover the loads up to Breaker B; otherwise, it turns off the diesel generators.
- Level 2 – The MGCS turns on the diesel generators as required to cover the loads up to Breaker C; otherwise, it turns off the diesel generators.

B. *Utility-Connected Operation Philosophy*

For this configuration, the MGCS has four critical control functionalities:

- Maintain tie-flow control across the utility tie (Breaker F) to regulate a minimum percentage loading of diesel-powered generator sets (30 percent of rated power) at the utility by dispatching excess wind power to the resistive loads and remote heat loads.
- Control OFF/ON of the generators at POSS camp.
- Charge or discharge the FW and provide active and reactive power (P and Q) support.
- Curtail the WT power reference in case of a high-wind profile if Breakers B or C are enabled for decoupling. This logic is implemented to prevent an overfrequency condition after decoupling.

C. *Island Operation Philosophy*

If microgrids are formed because of disconnection from the utility by opening either Breaker A, B, C, or F, the MGCS will perform as follows:

- For frequency and voltage control, the MGCS will switch Trident to isochronous (ISOC) mode if Trident is connected to the newly formed microgrid.
- If Trident is not connected to the microgrid, the MGCS will function to maintain the voltage and frequency as follows:
  - Enable the SSR1 to regulate frequency and allow the SC to regulate the terminal voltage.
  - Provide resilience by transitioning the POSS camp diesel generators from Base mode to ISOC mode for a fixed period before switching the generators back to Base mode. This function is only enabled under special circumstances when the island is operating in peak load and SSR1 is limited by its capability thresholds.
  - Command the FW to dispatch reactive and active support and simultaneously send a Start command to the diesel generator (with a startup time of 20 seconds). The delay in startup time is coordinated with the FW dispatch. This condition occurs when the wind profile is less than 5 m/s cut in and greater than 22 m/s cut off.
- The MGCS determines normal and abnormal conditions based on voltage and frequency measurements. If the utility is normal, A25A can be performed through Breakers A and B.
- The operator may enable or disable A25A through Breakers A and B. Breaker C is not equipped with A25A functionality.
- Manual close operation to Breaker C is performed as follows:
  - The operator opens Breaker B and then issues a Dead-bus Close command on Breaker C.
  - The operator initiates A25A to Breaker B and restores loads based on priority.
- If a microgrid is formed with the utility in an abnormal state, the MGCS determines whether enough spinning reserve exists with the newly formed microgrid. If so, the MGCS indicates this state to the operator. The operator can then issue a Breaker Open command to Breaker B or C. The MGCS will issue a Dead-bus Close command on either Breaker A or B, and will restore power.
- Loads can be shed if necessary to mitigate frequency excursions after disconnection.

D. *Contingency-Based Load-Shedding Philosophy*

After the islanding event, the main objective for the MGCS is to stabilize the new island. Because the MGCS determined the decoupling point based on the essential loads within the microgrid, the MGCS will decide whether load shedding is required to maintain balance between the generation and loads.

The contingency-based scheme sheds load based on a predicted power deficit when a contingency occurs. Contingencies are defined as breaker openings that cause the loss of one or more power sources. This scheme reduces the total plant load to less than the calculated available capacity based on the measured capacity. The calculation occurs before a contingency and includes the spinning reserve of the power sources [4].

E. Heat Load Trading Philosophy

The MGCS will dispatch excessive wind power to resistive load SSR2 and charge the FW, if necessary. The MGCS will constantly record the SSR2 power value and calculate an average power. If the average power is set to a specific kW value for a specified period, the MGCS will trade a certain percent of this average excessive wind power value from SSR2 to the remote heat loads. This trade value will be distributed evenly to all heat loads based on topology and heat loads status (M, N, O, and P). If the SSR2 active power value is less than the average power set kW value for a specified period, the MGCS will declare the heat load trading complete. If excessive wind power drops to zero, the MGCS will immediately shut off the heat loads. The time settings in the trade philosophy are adjustable on the MGCS HMI.

V. Closed-Loop Test Interface

Fig. 2 shows the communications architecture that was designed to simulate a field setup. The system modeled in the RTDS is a replication of the power system for Saint Paul Island shown in Fig. 1. The existing DER protocol (Modbus) and IEC 61850 GOOSE protocol were programmed to communicate status and control signals between the RTDS and the MGCS to mimic the interaction between the MGCS and the diesel generators, PCC breakers, WTs, FW, SC, sheddable loads, dump loads, and heat loads.

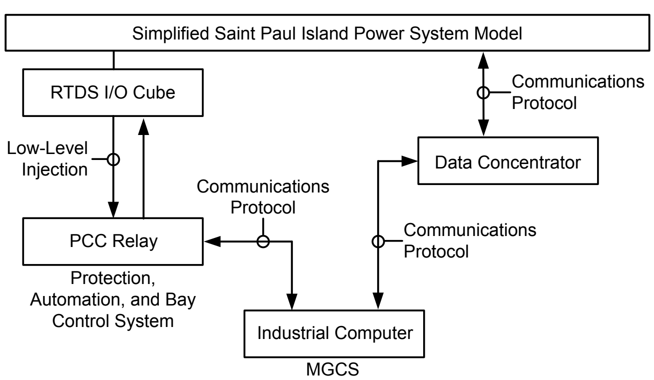

Figure 2. Closed-loop test interface

The protection relays at the PCC were connected in a closed loop with the RTDS to test the A25A logic [5] and the decoupling strategy.

An interface controller was programmed to serve as a data concentrator and function as a bridge between the power system model and the MGCS communications architecture to simulate communication between the data concentrator and the field IEDs. The critical step in the process was to develop an extensive input/output (I/O) list to analyze the data type (e.g., active or reactive power, bus frequency or voltage, breaker status, trip commands, analog control set points).

VI. Closed-Loop Test Results

More than 70 tests were performed as part of the factory acceptance test (FAT). Two of those tests are explained in this paper.

A. Decoupling Event With Steady-State High Wind

In this test, the city generator was operating in ISOC mode, the POSS camp diesel generators were operating in Droop mode, and the wind speed at POSS camp was set at 14 m/s. A decoupling event was simulated by applying a single-line-to-ground fault for 300 ms at Breaker C.

As the POSS camp operator selected Level 2, the city operator selected Breakers A, B, and C. Also, the MGCS enabled Breaker C based on sufficient spinning reserve. In response to the fault, a new microgrid was formed at Breaker C. The MGCS enabled SSR1 and dumped 300 kW to regulate frequency (see Fig. 3). The MGCS used the FW to dispatch 100 kVAR of reactive power to support the bus voltage. Fig. 4 shows the frequency response to the decoupling event at Breaker C and the unintentional opening of that breaker. The authors superimposed both events to indicate the formation of a resilient and stable microgrid.

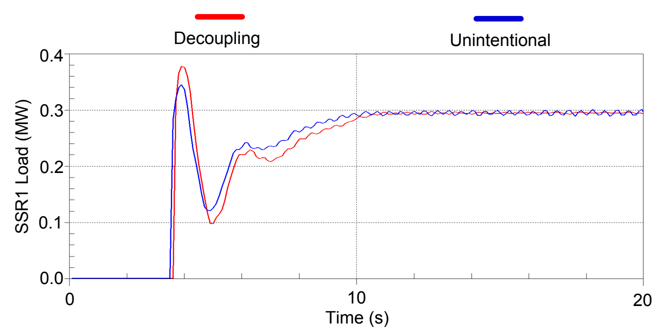

Figure 3. SSR1 response for high-wind decoupling

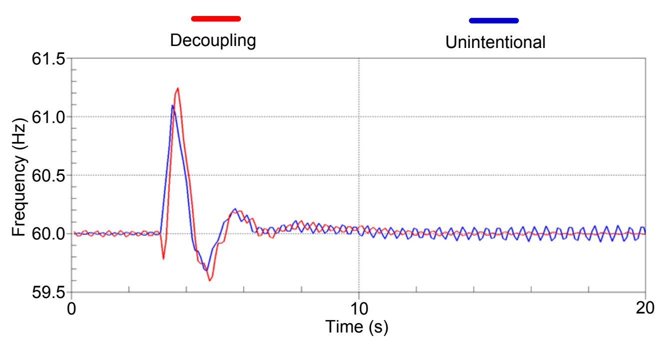

Figure 4. Frequency response for high-wind decoupling

B. Actual High-Wind Condition With the Utility Connected

In this test, an actual wind profile extracted from the site WT tower anemometer was programmed into the model as shown in Fig. 5. Fig. 6 shows the interaction of city generator operating in ISOC and the wind power influx into the system. Based on Table I, the MGCS regulated the minimum set point across Breaker F by controlling the SSR2 power, as shown in Fig. 7. As MGCS selected Breaker C, it commanded the FW to dispatch 100 kVAR for reactive power. The MGCS also implemented WT power reference curtailment to avoid any overfrequency trips if a decoupling event occurred, as shown in Fig. 8.

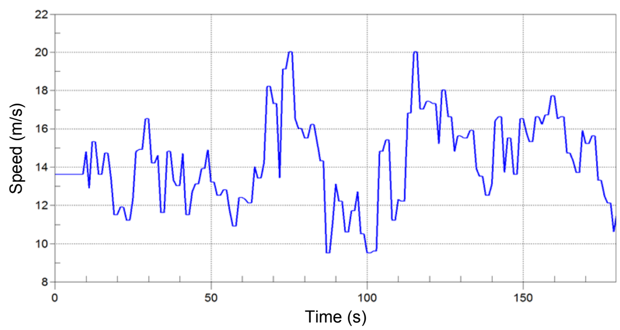

Figure 5. Actual high wind profile

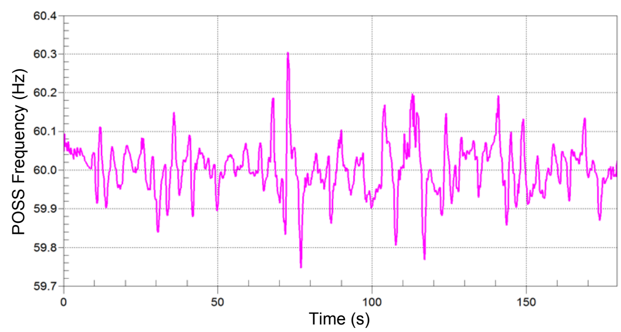

Figure 6. System frequency response to actual high wind profile

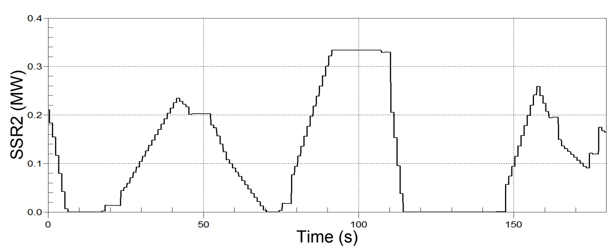

Figure 7. SSR2 response for controling the tie flow

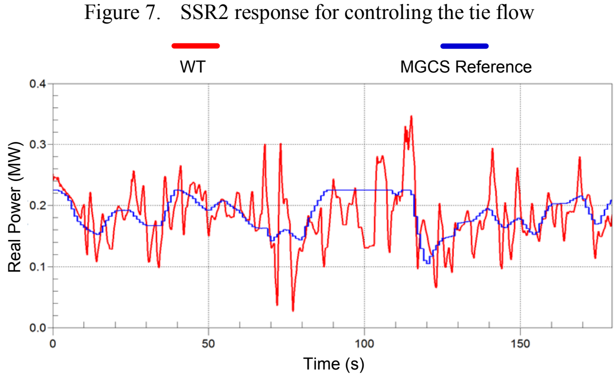

Figure 8. Wind power reference curtailment with utility connected

VII. Advantages of Closed-Loop Testing

The effects of connecting the St. Paul city power plant, POSS camp, and Trident plant together as one island were studied. The following insights were identified:

- Although an active power balance was attained, the microgrid collapsed because of a shortage of reactive power, especially during high-wind conditions.
- Preliminary solutions were discussed with TDX Power, Inc. to solve the reactive power shortage during decoupling events. These solutions included placing static capacitors at different local buses, increasing WT tower capacitance, and using the FW as a reactive source. Further studies are required to determine a final solution.
- The MGCS actions were studied with the existing protection settings of the DERs in the island. The conclusion was that the existing settings must be coordinated to achieve survivability.
- The existing SSR1 frequency regulator must be retuned when all three WTs are on one islanded system.
- Implementing fast communications protocol for enabling/disabling the SSR1 frequency controller is important for system instability.

VIII. Conclusion

This project was conducted in collaboration with TDX Power, Inc. with the prime objective of establishing a proof of concept of the MGCS functionality against critical criteria such as disconnection, resynchronization, steady state, protection, and dispatch. In the process, a robust MGCS was developed to provide resilience, survivability, and stability. Multiple permissive-based decoupling schemes, tie-flow controls, and heat load trading features were implemented and tested using hardware-in-the-loop (HIL) simulation with a simplified electrical model of Saint Paul Island. In the process of closed-loop testing, several insights were identified, lessons learned from the HIL are also discussed in this paper.

References

[1] A. H. Etemadi, E. J. Davison, and R. Iravani, "A Decentralized robust control strategy for multi-DER microgrids—part I: fundamental concepts," IEEE Trans. Power Delivery, vol. 27, no. 4, pp. 1843–1853, Oct. 2012.

[2] M. R. D. Zadeh, A. Hajimiragha, M. Adamiak, A. Palizban, and S. Allan, "Design and implementation of a microgrid controller," in *Proc. 2011 64th Annual Conference for Protective Relay Engineers*, pp. 137–145.

[3] "*Draft Guide for IEEE Standard 1547, Interconnecting Distributed Resources with Electric Power Systems*," in IEEE Unapproved Draft Std. P1547.2/D11, 2008.

[4] B. Cho, H. Kim, M. Almulla, and N. Seeley, "The Application of a redundant load-shedding system for islanded power plants," in *Proc. 35th Annual Western Protective Relay Conference*, 2008.

[5] A. Upreti, S. Manson, and M. Thompson, "Case Study: Smart Automatic Synchronization in Islanded Power Systems," proceedings of the Power and Energy Automation Conference, Spokane, WA, March 2013.

Previously presented at the 2017 IEEE PES Innovative Smart Grid Technologies Conference, Arlington, VA, April 2017.