Stability Analysis of Island Grid with Wind Energy and Energy Storage to Support Large Scale Deployment of Renewable Energy in Indonesia

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Abstract—**This study performs transient stability analysis for integrating wind power into an existing diesel-based remote/mini grid. A model was created of the eastern grid in Sumba Island, Indonesia, which has a network of diesel generators, three 20-kV buses, and primarily lighting load with a peak load of approximately 5.7 MW. The impact of integrating one 850-kW Type 3 wind turbine generator (WTG) is studied. During the high wind and low load scenario, the loss of the WTG or the loss of the largest conventional generator at a bus caused instability in the grid. The addition of a 500-kW storage unit, hybrid power plant controller, and the designation of an existing 550-kW diesel generator with 10-second cold-start time as the backup were used to stabilize the grid. This solution was shown to improve the reliability of the energy supply, enhance the stability of the system, and reduce greenhouse gas emissions. With the potential for minigrids/microgrids to provide power to 620 million people in Africa, the proposed solution has significant applicability.**

Keywords—**Wind energy, energy storage, load flow, short circuit, transient stability, grid stability, island grid, microgrid.**

I. INTRODUCTION

In India, more than 300 million people do not have access to electricity. One reason is because extending the grid to remote communities is very expensive. With the falling prices of wind power, solar photovoltaic, and energy storage, there is an economic case for providing electricity to remote communities with the use of a hybrid solution that includes diesel, renewable energy, and energy storage. This solution can be cheaper and more reliable than grid connected power for the remote communities. In addition, this solution has the potential to significantly reduce greenhouse gas emissions.

This paper deals with a hybrid solution for an island grid in Indonesia. The population of Indonesia is more than 240 million people. Renewable energy currently accounts for just about 5% of Indonesia's primary energy supply. However, tremendous potential for expansion exists – especially in the case of geothermal, hydropower, wind power, solar photovoltaic (PV) and biomass resources. Meanwhile, Indonesia's energy sector is complex, with widely varying energy demands throughout an archipelago of 17,000 islands, of which about 6,000 are inhabited at different levels of population density and feature diverse economic activities.

This paper describes the management of transient stability issues using energy storage and a backup generator in a diesel grid that has a high penetration of wind. The example of Sumba Island, Indonesia, is used to model the grid and study the transient behavior. Sumba Island was chosen as the iconic island for a renewable energy initiative by the Government of Indonesia in collaboration with donor agencies such as Hivos International and Asian Development Bank with the goal of achieving close to 100% electricity from renewable energy.

The map of wind resources is given in Fig. 1. As shown, the wind resource is generally good in the north-central and northeastern parts of Sumba Island, reaching up to 7.5 m/s at a height of 60 m in regions approximately 25 km from load centers.

Toward the goal of achieving 100% renewable energy, the first wind project consists of deploying one 850-kW Type 3 wind turbine generator (WTG) in the eastern power network of Sumba Island to be followed by up to four additional WTGs of the same size in the same geographical area.

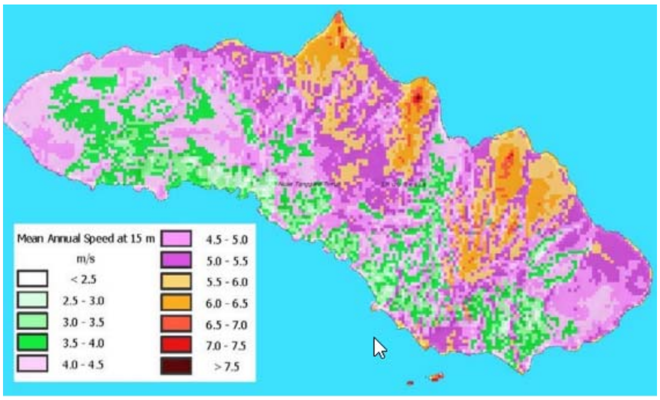

Fig. 1. Annual average wind resources in Sumba Island [1]

To support the first grid-connected wind project, load flow, short-circuit, and transient stability studies were performed. The objectives of the load flow study and short-circuit analyses were to identify: a) transmission bottlenecks, b) buses with voltages that are not within limits, c) the amount of wind energy that can be injected at the point of common coupling (PCC) without causing the PCC voltage to exceed the limits specified in the grid code, and d) if the switch-gear equipment can withstand the additional short-circuit current from the wind power plant. Transient analyses were performed to determine the stability of the system under a variety of fault conditions. DIgSILENT's PowerFactory 15.2.4 was used for this study.

A. Literature Review

One of the early studies of power quality and stability analysis was done for wind-diesel hybrids [2]. Another study was conducted with the objective of achieving the best load-shedding mechanism to maintain system stability and synchronism under several cases, such as the loss of a utility grid connection, the loss of a wind power connection, and the loss of both a distributed generation connection and a short circuit on one of the load busses [3]. Several papers presented analyses of wind-diesel energy storage systems. For example, an optimal power flow model to determine the size of the energy storage in a grid with wind energy was presented in [4]. A transient stability analysis for a wind pumped-storage hydropower system for the Canary Islands, a small isolated grid, was presented in [5]; the results showed that a wind system with a hydropower unit connected as a synchronous compensator can maintain stability in a grid that has only wind and hydropower plants. A more recent paper on the Canary Islands reported on the use of three storage technologies to achieve frequency stability: ultracapacitors, flywheels, and Lithium-ion (Li-ion) batteries [6].

This paper focuses on the stability analysis of integrating an 850-kW wind turbine into an island grid consisting of diesel generators and a peak load of 5.7 MW. To overcome the observed instability under two contingencies, an energy storage solution along with a backup diesel generator is proposed. The stability of the proposed system is then analyzed and reported.

II. SYSTEM CONFIGURATION

A. Network Configuration

A single-line diagram of the eastern power system network of Sumba Island is shown in Fig. 2. This system consists of three 20-kV buses: Kambajawa, Waingapu, and Haharu. An 850-kW Type 3 WTG is connected at the Haharu Bus. The baseline power flow analyzed the power system during light load (2.751 MW) and heavy load (5.682 MW) conditions before the wind generator was installed. Details about the loads on each bus during the maximum and minimum load conditions are given in Table I.

The diesel generators connected at Kambajawa and Waingapu have a total available generation capacity of 4.58 MW and 1.79 MW, respectively; Haharu Bus has no generation. During off-peak hours, only the Kambajawa generators operate; and during peak load hours, specific Waingapu generators are dispatched based on their specific values of fuel consumption.

The dynamic model of the generators, governors, and exciters used in the study were based on the available data from the library provided by the power system software program. The control model of the 850-kW doubly-fed induction generator with low-voltage ride through was provided by Vestas under a nondisclosure agreement. This model was used in the simulation compared to a "generic model" to study the impact under realistic conditions.

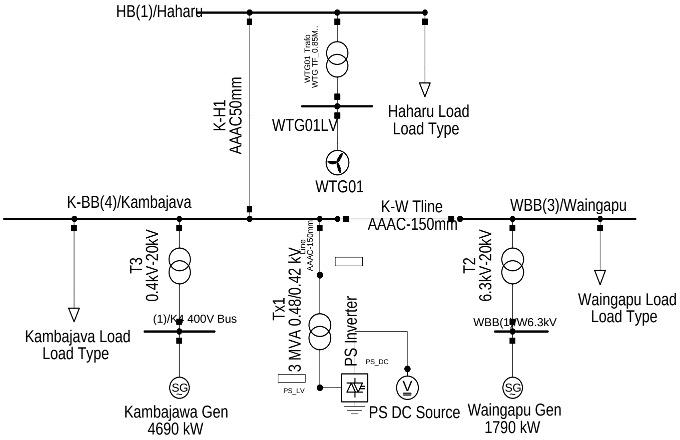

Fig. 2. Single-line diagram of the eastern grid of Sumba Island

TABLE I
Power Demand and Power Factor of Loads at Three Substations

Name of Substation	**Max. Load (MW)**	**PF, Peak Load**	**Minimum Load (MW)**	**PF, Off-Peak Load**
Haharu	0.104	0.85	0.051	0.85
Kambajawa	3.494	0.90	1.691	0.95
Waingapu	2.084	0.90	1.0086	0.95
Total	5.682		2.751	

B. Storage Unit Controller

A control model [6] provided by ABB for the storage unit was used; see Fig. 3. It was modeled as a current source, and it independently and instantaneously controls the active (I_R) and reactive (I_I) components of the current. The active power-frequency (P-f) controller and reactive power-voltage (Q-V) controller take as input grid frequency and terminal voltage and produce active and reactive current components. The active power-frequency controller provides inertial (rate of change of frequency) and droop (change of frequency) supports. Next, limits were placed on the current components based on the state of charge (SoC), allowable absolute value of current, frequency, and voltage. The power electronics converter then generated the active and reactive components of the current. These components were constrained by I_{tot} $(= \sqrt{I_R^2 + I_I^2})$, the current-carrying capacity of the power switches (e.g., insulated-gate bipolar transistor), as shown in Fig. 3b. The deliverable output power depends on the allowable ramp rates, and the duration of energy delivery depends on the state of charge of the energy storage. Two energy storage technologies were considered: flywheel and Li-ion battery. Because the response of the storage unit was fast, it was able to compensate for the 10-plus seconds required to cold-start the diesel generators.

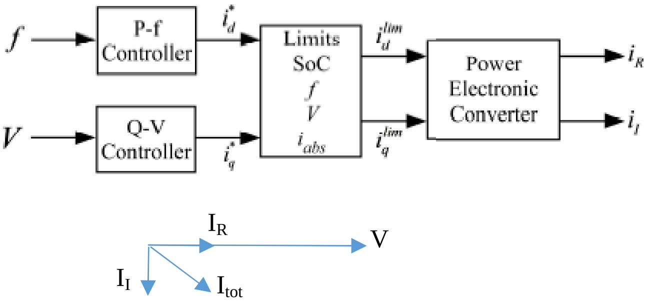

Fig. 3. Storage unit high-level control model, a) Control block diagram, b) Phasor representation current components (I_R, I_I, I_{tot})

III. SIMULATION RESULTS

The power system study was conducted using DIgSILENT's PowerFactory 15.2.4. Overall, three cases were analyzed: a baseline using 2015 demand and generation data, a baseline with an 850-kW WTG, and a baseline with an 850-kW WTG and 500 kW of energy storage. The focus of the paper is on transient stability analysis, and therefore the load flow analysis and short-circuit analyses are covered briefly.

A. *Load Flow Study*

The results of the load flow study of all three cases indicated that the voltages at all buses were within the limits of the grid code, and the loads on the transmission lines were within the thermal limits of the conductor.

B. *Short-Circuit Current Study*

The short-circuit power ratio (SCPR) was computed to be 16.82 p.u. during high load and 13.41 p.u. during low load. This was well above the SCPR requirement for connecting a wind turbine; in most grid codes, the SCPR requirement is 10 p.u. or higher to avoid large fluctuations in voltage at the PCC.

C. *Transient Stability Study*

The 2014 network trip report (provided by the State Electricity Company of Indonesia, PLN) for Sumba Island indicated that the number of blackouts and trips are high (approximately one per day). The baseline network, therefore, has stability issues. Initial analysis suggests that this is because:

A. The faults are not cleared within the specified setting time of the circuit breakers,
B. Generators are dispatched with low headroom (low spinning reserves),
C. A lack of vegetation management causes overhang on transmission lines, and
D. The diesel generators are old, which leads to a large number of unscheduled maintenance.

The stability analysis of the baseline model was conducted for two scenarios (high and low load) and three study cases (generation, load, and transmission loss), and the results confirmed the stability issues listed above. For brevity, the results are not presented here; see [7].

TABLE II
Matrix of Scenarios and Study Cases That Were Run for This Model

Study cases ⇨ Scenarios ⇩	**Wind turbine Loss**	**Generation Loss**	**Load Loss**	**Transmission Fault**
High Wind at High Load	W-H-LWTG	W-H-LG	W-H-LL	W-H-LTL
High Wind with Storage Unit at High Load	WS-H-LWTG	WS-H-LG	WS-H-LL	WS-H-LTL
High Wind at Low Load	W-L-LWTG	W-L-LG	W-L-LL	W-L-LTL
High Wind with Storage Unit at Low Load	WS-L-LWTG	WS-L-LG	WS-L-LL	WS-L-LTL

The stability analysis of the two cases—baseline with a WTG and baseline with a WTG plus storage—was conducted for all combinations of the four scenarios and four study cases, as described in Table II. The focus of this paper is on transient analysis due to the loss of a WTG; the results of the other study cases are presented in [7]. In the WTG loss study case, it was assumed that after the fault the WTG does not reconnect within 40 seconds (the duration of the simulation).

1) *Study Case Setup*

In the simulations, all faults occurred at 0.5 seconds. As a result of the fault, if a backup generator was required, then it synchronized and started delivering power at 10.5 seconds. The backup generator was a 550-kW diesel generator set with a cold-start time of 10 seconds. To mimic current operations on Sumba Island, all of the scheduled diesel generators except the largest generator were running at 100% capacity. For high-load scenarios, the largest diesel generator had a capacity of 650 kW; for low-load scenarios, the largest diesel generator had a capacity of 420 kW. In the scenario with a WTG and storage, a fast-response energy storage unit was connected in parallel to a WTG at the Haharu Bus. Because the primary purpose of energy storage is frequency response, it was shut down after 30.5 seconds of simulation. The total simulation run time was 40 seconds. Note that the number of diesel generator sets connected at any time varied with load, and thus the available inertia also varied.

2) *Study Case 1: Loss of a WTG*

In this study case, the loss of a WTG (850 kW) was simulated at high load (Fig. 4) and low load (Fig. 5). The plots give the comparison results of faults with and without storage.

a) *High-Load Scenario*

In the scenario without storage, there was a rapid drop in frequency (it dropped below 0.9 p.u. between 0.5 and 10.5 seconds) because the inertia and headroom were insufficient to compensate for the large loss of generation; see Fig. 4A. Per grid code, frequency must remain above 0.90 p.u. At 10.5 seconds, the standby/backup 550-kW generator started delivering power, resulting in the change in the rate of change of frequency from negative to positive. Whereas in the scenario with storage, the storage unit provided energy between 0.5 and 10.5 seconds, thus arresting the rapid fall of frequency that was previously observed.

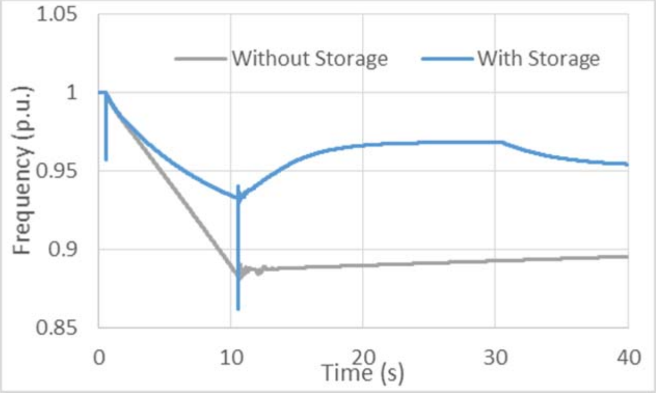

Fig 4A. Bus frequency during the loss of a WTG at high load for scenarios without storage and with storage

The sum of the active power of the diesel generators for the scenarios with and without storage is compared in Fig. 4B. The loss of a WTG at 0.5 seconds resulted in an inertial transfer of energy from the diesel generator sets starting from 0.5 to 10.5 seconds, which led to a drop in frequency. When storage was present in the grid, it ramped up delivery of energy from 0.5 to 10.5 seconds (Fig. 4C), thereby reducing the inertial transfer of energy from the diesel generator sets, which reduced the rate of the frequency drop.

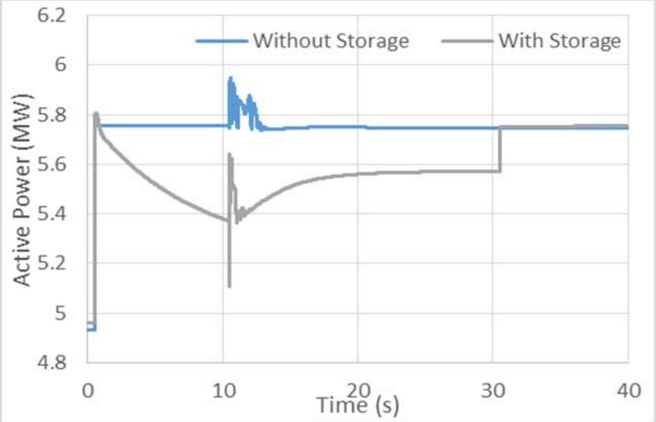

Fig 4B. Total sum of diesel generators during the loss of a WTG at high load for scenarios without storage and with storage

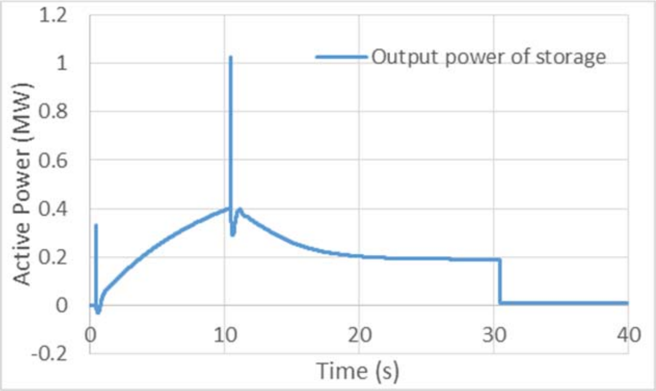

Fig 4C. Active power output of storage unit during the loss of a WTG at high load for scenarios with storage

b) Low-Load Scenario

At low load without the storage unit, the simulation showed a rapid drop in frequency to 0.6 p.u. between 0.5 and 10.5 seconds because the inertia and headroom were insufficient to compensate for the large loss of generation, which caused a loss of synchronism; see Fig. 5A. There was no loss of synchronism when the storage unit was present. The storage unit ramped up quickly and provided 500 kW of power; see Fig. 5C. This caused the sum of the active power output of the diesel generator sets to drop rapidly between 0.5 and 10.5 seconds (Fig. 5B)—that is, during this interval, the amount of transfer of inertial energy was reduced, which slowed the drop in frequency.

In the low-load scenario, the system had low inertia, so the power output of the storage unit gave the maximum power rating for the storage unit. Fig. 5C shows that the power output of the unit was approximately 500 kW, and it supplied for 30 seconds. Without storage the system lost synchronism; see Fig. 5B to compare the total diesel generator set outputs for both scenarios.

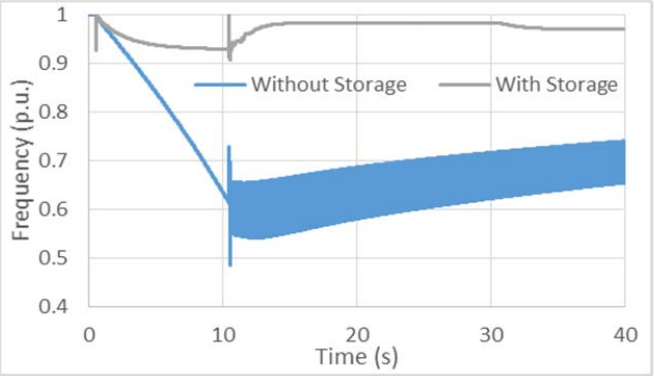

Fig 5A. Bus frequency during the loss of a WTG at low load for scenarios without storage and with storage

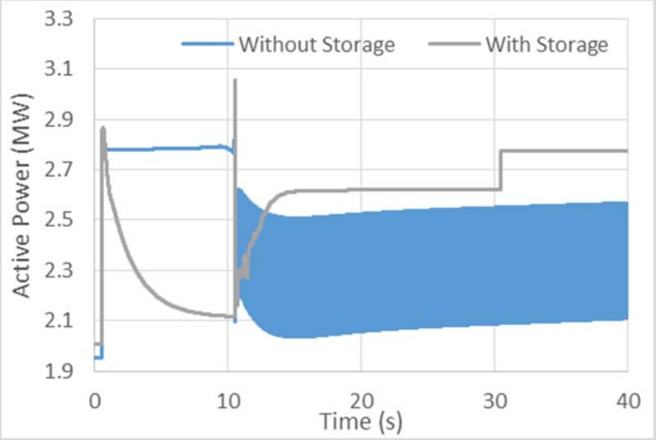

Fig 5B. Total sum of diesel generators during the loss of a WTG at low load for scenarios without storage and with storage

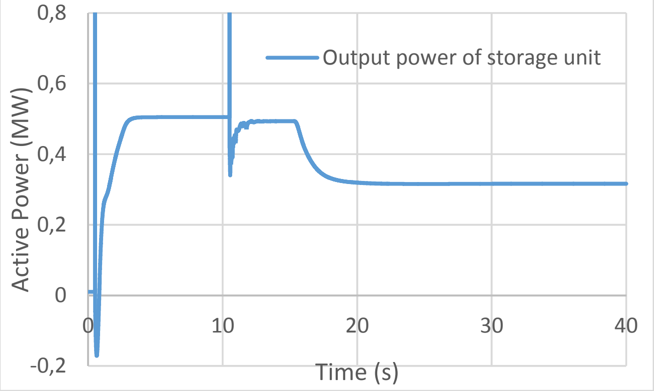

Fig 5C. Active power output of storage unit during the loss of a WTG at low load for scenarios with storage

To determine the size of the storage unit, the following information was used: a) amount of power required to replace the loss of generation during a major fault in the system and the available rotating inertia in the system, and b) the length of time that power should be supplied until the backup generation came online.

1. The critical fault considered in this study was the loss of a WTG (850 kW). The inertia plus headroom available from the scheduled generators during the high- and low-load scenarios was 597.8 kW and 377.3 kW, respectively—that is, the dispatched generators were able to increase power output by this amount. Therefore, there was a gap of 252.1 kW and 472 kW in the high- and low-load scenarios, respectively, that must be supplied by the storage unit to stabilize the system. Hence, a storage unit with a power capacity of 500 kW was chosen.
2. To determine how long the unit would need to supply this power, the cold-start time of the backup generator needed to be considered. As indicated, a backup generator with a "rated" cold-start time of 10 seconds was used. Because this generator was 15 years old, the cold-start time was stretched to 30 seconds, which included the times for cold-start, synchronization, and ramping up to full capacity. The energy capacity of the storage unit was:

$$500 \text{ kW x } (30/3600) \text{ hours} = 4.17 \text{ kWh} \qquad (1)$$

Therefore, an energy storage unit with a power and energy capacity of 500 kW and 4.17 kWh was chosen.

IV. PROPOSED SOLUTIONS FOR DYNAMIC STABILITY PROBLEMS

As a result of the analysis, the changes proposed to the eastern grid of Sumba Island to maintain stability for the studied scenarios and study cases are as follows: Add a 500-kW (4.17-kWh) energy storage unit; designate a 550-kW diesel generator with a cold-start time of 10 seconds as a backup generator; and use the control system to auto-start the backup diesel unit. The following sequence of events is required to maintain system stability:

1. The storage unit provides energy from the time of the disturbance for duration of 10 seconds, thereby reducing the rate of the decrease in grid frequency and improving the frequency nadir during the loss of generation.
2. The controller sends an auto-start signal to the 550-kW backup diesel generator when the frequency dip is detected.
3. The backup diesel unit starts within 10 seconds.
4. The storage unit continues to provide power for 30 seconds and then disconnects.
5. After 30 seconds, other generators are started or existing generators in the system increase production by tapping into headroom to deliver the additional power required.

Locating the storage unit at Kambajawa instead of Haharu (the location of the WTG) provides stability for the cases when there is a fault that is not cleared in 30 seconds at the Haharu Bus or on the Haharu-Kambajawa transmission line. The proposed solution should improve the reliability of the energy supply, enhance the stability of the system, and reduce greenhouse gas emissions.

V. CONCLUSIONS

This paper described the management of transient stability issues using energy storage and a backup generator in a diesel grid that has a high penetration of wind. A case study of the eastern grid of Sumba Island, Indonesia, was used. This is an isolated diesel grid with 5.7 MW of peak load that is seeking to integrate 850 kW of wind power. Africa has a large number of small isolated diesel grids of similar size. With falling prices of wind and solar, renewable energy sources are a cheaper alternative to diesel-based electricity generation. This integration study is applicable to all such grid integration studies.

The case study focused on managing the transient stability of the grid under a variety of disturbances. A transient stability study was conducted for different load scenarios and fault study cases to determine the impact of the introduction of a WTG on the stability of the system. The investigation showed instability during the loss of a WTG. A solution was proposed and analyzed for these stability issues. The solution is to: a) add a 500-kW (4.17-kWh) energy storage unit, b) designate a 550-kW diesel generator with a cold-start time of 10 seconds as a backup generator, and c) use a hybrid plant controller along with high-speed communications among the controller, the storage unit, and the backup diesel generator.

ACKNOWLEDGMENTS

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