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Advanced Control Mechanism for grid-connected small-scale wind turbines

Jagatjyoti Ranjan Das
College of Engineering Bhubaneswar, Odisha, India

Keywords: Grid connection, MPPT control, robust system, Small wind turbine.

Abstract

Because low power wind systems are clean, sustainable, renewable, and alternative sources of electric energy, they are now a hot research issue with significant socioeconomic appeal. Low power wind systems may provide electricity profitably over time in a variety of settings, including houses, schools, telecommunications towers, oil rigs, and rural hospitals. However, innovative approaches to create straightforward, reliable, and affordable systems are necessary for the low-scale popularization of renewable energy. With this situation in mind, this study suggests a system based on a push-pull inverter, DC-DC buck converter, and passive rectifier that allows tiny wind turbines to be connected to the mains. A 1kW tiny wind turbine was used in the analysis, design, and verification of the suggested system.

1 Introduction

Wind energy can already be considered a consolidated renewable source to produce electrical energy, due to its advances in recent decades in researches, publications, products and, mainly, practical applications [1,4]. Truth be told, this consolidation has happened based on the deployment of large wind farms, in which hundreds of megabytes have been processed. However, currently, many studies are being conducted to develop technologies for the greater use of small wind turbines to generate electricity [2,3]. One of the great advantages of small wind turbines is the possibility of employing them in urban centers [10], where the wind has lower speed and greater turbulence.

Low-power wind turbines are usually connected to battery banks or directly to the electricity grid. One of the biggest drawbacks to connect the wind generator to battery banks is the total volume of the system, very often leaving this type of connection unfeasible. Therefore, connection of small wind turbines into the electric grid has become a subject of much academic interest [11].

According to the literature [5], there are three usual electronic systems used to connect small wind turbines into the mains. The first and most simple configuration can be seen in Figure 1. The system consists of a passive rectifier connected to an inverter. This topology presents the advantage of being extremely simple, although a very low efficiency [13].

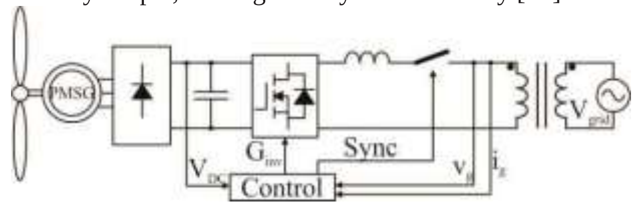

Figure 1: Passive Rectifier + Inverter.

The second most usual configuration [5] is composed of a rectifier diode, a DC-DC converter and an inverter. The greater advantage is the cost benefit between ease of implementation and the final system performance. Usually in such systems the MPPT control is done by the DC-DC converter switch and the inverter has the function of protection and synchronization with the grid [12]. The topology can be seen in Figure 2.

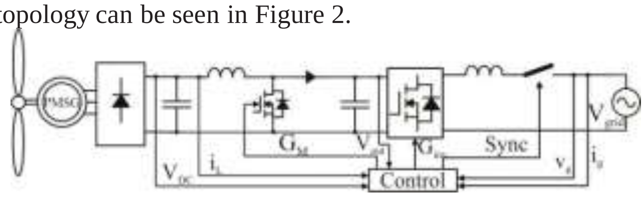

Figure 2: Passive Rectifier + DC-DC Converter + Inverter.

The third most common setting is shown in Figure 3. The system consists of a back-to-back converter. The biggest advantage of using this topology is the low distortion output current of the generator. However, this configuration is much more complex than the others presented. Generally this topology is used for higher powers.

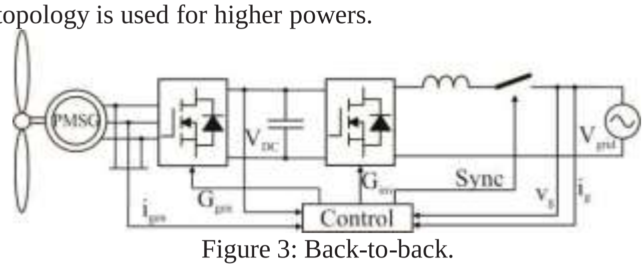

Figure 3: Back-to-back.

This paper proposes a power electronic system for grid connected small wind turbines, 1kW 220V@60Hz, which is simple, robust and cheap. It can be used in telecommunication systems, houses, farms, energy storage system and others applications, where renewable energy generation in small scale is interesting.

2 Proposed System

The paper proposed system can be seen in Figure 4. The topology consists of a passive rectifier, a converter DC-DC buck and a push pull inverter. A commercial low frequency transformer is present for galvanic isolation.

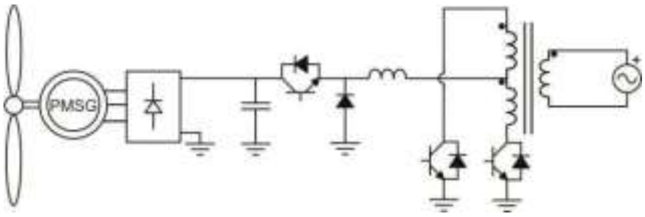

Figure 4: Proposed System.

The system is being designed to process 1 kW in rated power. The turbine studied has been constructed for use in urban settings, in which the wind has greater turbulence.

Passive rectifier

A passive rectifier was placed at the output of the generator in order to convert the ac output voltage of the turbine in a dc voltage. Thus the generator can work at variable frequency and operate in a range close to the maximum efficiency. This strategy is suitable for small wind turbines.
The passive rectifiere employed in the project is better known as the Graetz Bridge. The choice was given because it is an extremely simple and robust component [6], [7], [14]. It should also be noted that due the high inductance of the generator, the current distortion is low even with the use of the diode rectifier.

Buck converter DC-DC

The buck converter has two functions: the first one is to control the dc (rectifier output) bus and extract the maximum power from the generator; the second is to control the current injected into the inverter, which must be a current in a sinusoidal wave rectified format.
The choice of a DC-DC buck converter, lies in the fact that for low power applications some advantages are presents as: (*i*) it works at lower voltage across the semiconductors; (*ii*) it can be used a simple control technique; (*iii*) the switch in a direct path between the generator and the grid enables the safer circuit disconnection; (*iv*) its voltage input characteristic facilitates the MPPT control; (v) its current output characteristics provides simplicity for the inverter and (*vi*) only one capacitor bank is necessary in the whole system.

Push-Pull inverter

The inverter functions are defined as: (*i*) to invert the current of the buck converter and; (*ii*) to isolate the system and inject a current into the grid. As the current already has the form of a rectified sine wave, the converter's function is to invert the current every half period of the mains. Thus, it operates in open loop, with switching synchronized with the grid and frequency of 60 Hz.
Regarding the push pull inverter, its advantages are: (*i*) low switching frequency, which reduces the switching loss in the semiconductors; (*ii*) one switch is turned ON in the positive period of electrical grid and another the negative period, thus the synchronism with electrical grid is easy [8]; (*iii*) the transformer also provides isolation to the system; (*iv*) the transformer is designed to operate at 60Hz guarantying robustness to the system.

Control

The MPPT technique is made through the buck converter switch, regulating the voltage on the DC bus. The MPPT technique ensures that the generator works at maximum power or close to it. At the same switch there is a current loop control, which controls the inductor current and thus the power factor could be delivered as close to the unit.

3 Principle of Operation

Initially, the analysis of the topological stages will be presented with the operating system when the grid is in the positive half cycle and, after, with the negative half cycle. During both cycles, the DC-DC buck converter operates in continuous conduction mode with a switching frequency in the order of kilohertz. The push-pull inverter also works in continuous conduction mode, but with a frequency equal to the mains, 60 Hz.
Therefore, two-topological states for each half cycle of the grid will be displayed.

DC-DC Buck converter operation – positive halfcycle.

Topological Stage with Switch s1 ON

In this mode the switch of DC-DC buck converter is conducting, current flows from the turbine to the inductor, characterizing the energy storage phase. Being the grid in positive half cycle the switch s2a is conducting, while s2b is not. This state has its end when the switch is switched off, interrupting the current that passed through this, turning the free wheel diode on.

Topological Stage with Switch s1 OFF

In the end of the previous stage, start this new stage, in which the input source (Wind Generator Rectifier + Capacitive Bank) is disconnected from the mains power. Meanwhile the energy stored in the inductor is delivered to the grid through the free wheel diode. The switch s2a is current on, because it is still the positive half cycle. This stage ends when the operation switch s1 is turned on again. The two operating stages are shown in Figure 5.

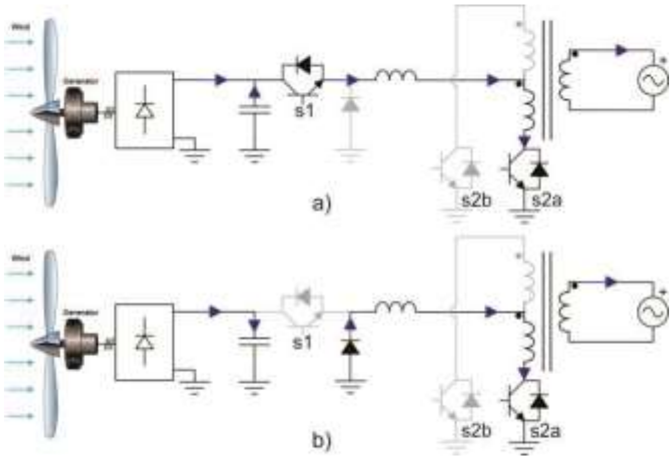

Figure 5: Topological stages in positive half cycle.
a) buck switch, s1, on; b) buck switch, s1, off.

DC-DC Buck converter operation – negative halfcycle.

During the negative half cycle of the mains, again two topological stages are obtained. One in which the input source is sending power to the grid (switch s1 on) and another where the wind turbine will be disconnected from the grid (switch s1 off). The only difference between the negative and positive half cycle is the push-pull switch that is turned on. In this half switch s2b is on. Figure 6 shows the two stages.

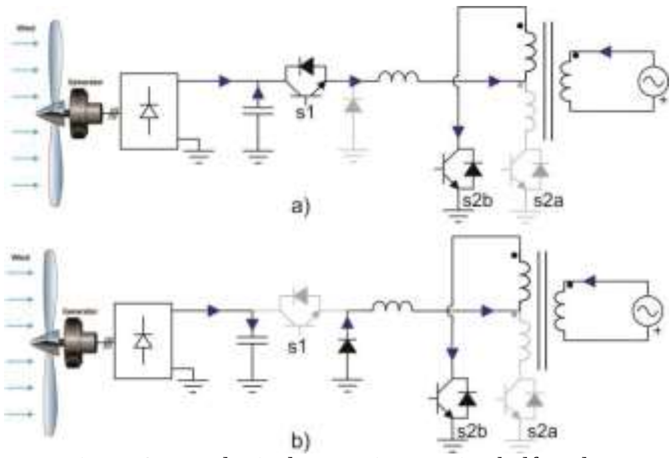

Figure 6: Topological stages in negative half cycle.
a) buck switch, s1, on; b) buck switch, s1, off.

4 Quantitative Analysis of Operating

Duty Cycle

The duty cycle of the buck converter can be calculated by varying the inductor current for a switching period. Figure 7 shows the equivalent circuit, which can be used to calculate the static gain.

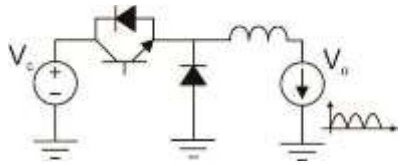

Figure 7: Equivalent Circuit.

In Figure 7, when the switch is conducting the voltage over the inductor multiplied by the conduction time is given by:

$$V_L = (V_c - V_o) \cdot D \cdot T_s \, , \qquad (1)$$

and when the switch is locked it has:

$$V_L = V_o \cdot (1 - D) \cdot T_s \, . \qquad (2)$$

For a period of switching the average voltage across the inductor is zero, then:

$$(V_c - V_o) \cdot D \cdot T_s = V_o \cdot (1 - D) \cdot T_s \, , \qquad (3)$$

however, the output voltage is sinusoidal, ie:

$$V_o = V_p sen\theta \, , \qquad (4)$$

substituting (4) into (3) and isolating D,

$$D(\theta) = \frac{V_p sen\theta}{V_c} \qquad (5)$$

4.2 Stress in semiconductors

The theoretical waveform of the current in the inductor is shown in Figure 8.Thus, the equation of the inductor current is given by:

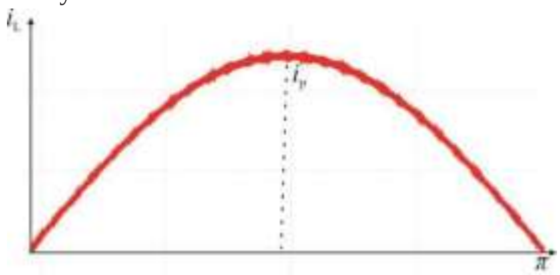

Figure 8: Inductor current waveform.

$$i_L(\theta) = I_p \cdot sen\theta \qquad (6)$$

Since i_p is calculated as follows:

$$P_o = \frac{V_p \cdot I_p}{2} \rightarrow I_p = \frac{2P_o}{V_p} \, , \qquad (7)$$

where, P_o is the output power and V_p is the peak voltage on the transformer primary.
Knowing the inductor current, the rms current in the buck switch and the average current in the freewheeling diode are expressed by:

$$Is_{rms} = \frac{I_p \cdot \sqrt{V_p}}{\sqrt{V_c} \cdot \sqrt{\pi}} \sqrt{\int_0^{\pi} \sin(\theta)^3 \, d\theta} \qquad (8)$$

$$Id_{avg} = \frac{1}{\pi} \int_0^{\pi} [I_p \cdot \sin(\theta) - \frac{I_p \cdot V_p}{V_c} \cdot \sin(\theta)^2] d\theta \qquad (9)$$

4.3 DC-Link

The choice of the dc-link capacitance is fundamental for the system to operate at a great level. The 120 Hz component coming from the rectifier power grid has great influence on the whole system and the DC-link must absorb as much as possible from the component. So the total capacitance required is defined by (10).

$$C_o = \frac{P_o}{4\pi \cdot f_{grid} \cdot \Delta V_c \cdot V_c} , \qquad (10)$$

where, ΔV_c is the voltage ripple and f_{grid} is the grid frequency.

4.4 Control

The control system designed as previously stated, has two control loops. Figure 9 shows the block diagram.

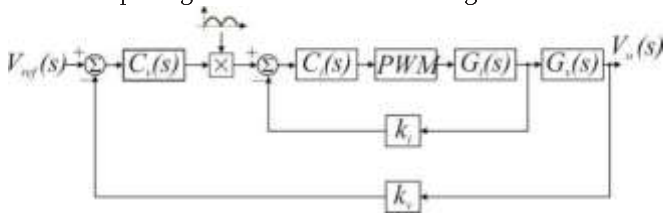

Figure 9: Block diagram.

The transfer function of the inductor current is defined by,

$$\frac{\Delta_{iL}}{\Delta_d} = \frac{V_c}{s \cdot L} \qquad (11)$$

and transfer function of the capacitor voltage is given by,

$$\frac{\Delta_{Vc}}{\Delta_{iL}} = \frac{-D}{s \cdot C} \qquad (12)$$

5 Design example

Design specification

Design specification for the verification of proposed system can be seen in Table 1.

Parameter	Value
Nominal Power	1000 W
Output Voltage (rms)	220 V
Voltage on the Transformer Primary (rms)	33 V
DC-Link Voltage	70 V
Grid Frequency	60 Hz
Current Ripple	5%

Table 1: Design specification

Turbine

The turbine used in this work is the GERAR 246, manufactured by Enersud (a Brazilian company). The wind turbine has a nominal power of 1000 W, with the wind speed at 12 m/s. The turbine has a horizontal axis and three blades. The cut-in speed is 2.2 m/s. Further information can be found in [9].

5.3 Duty Cycle

The duty cycle used for the system was calculated with (5) and is shown in Figure 10.

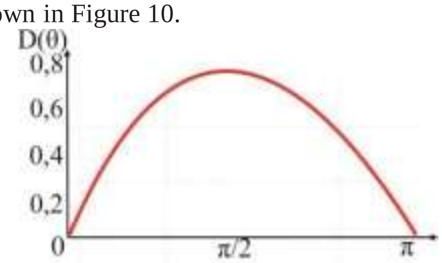

Figure 10: Duty Cycle.

The transformer conversion ratio was chosen in order that the buck converter could operate safely with a 70 V input. To choose a suitable value of the transformation ratio, first was defined a maximum ripple in the input voltage and then was chosed the primary voltage of the transformer.

By setting the maximum ripple on the input voltage, and through (10) the capacitance required for the DC link was calculated.

5.4 MPPT Control

The studied turbine has a particular behavior that makes the system very robust. For different wind speeds, one bus voltage from 60 V to 80 V ensures that the system is operating at maximum power or close to it. Then it was decided to use a control with fixed reference, 70 V. The Figure 11 shows the behavior of the turbine for different wind speeds.

The MPPT technique is made through the buck converter switch, regulating the voltage on the DC bus.

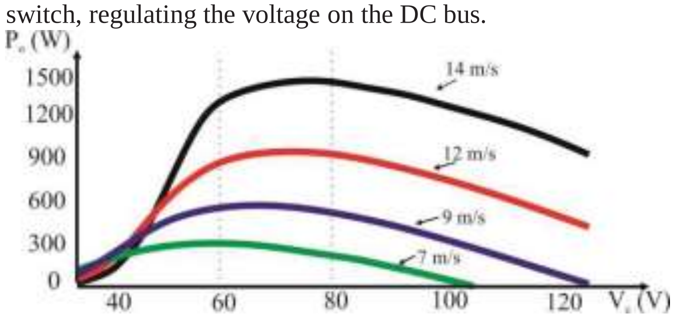

Figure 11: Output power x DC-Link voltage.

Table 2 and Table 3 show the components used to implement prototype and a comparison between the values of calculated and simulated parameters respectively.

Component	Part-Number
Passive Rectifier	36MT20
Diodes – Buck	V80170PW-M3/4W
Diodes - Push Pull	DSA90C200HB
Switches	FQA62N25C
Transformer	220V/33V/60Hz
Inductor	0.5 mH
DC-Link	2068 uF
Controller	UC3854
Driver Bootstrap	IR2127SPBF

Table 2: Components used in the prototype.

6 Simulation results

Complete system

The system has been fully implemented and simulated in PSIM software. Those simulations were made with constant and variable wind speed. **Erro! Fonte de referência não encontrada.** shows the simulated topology.

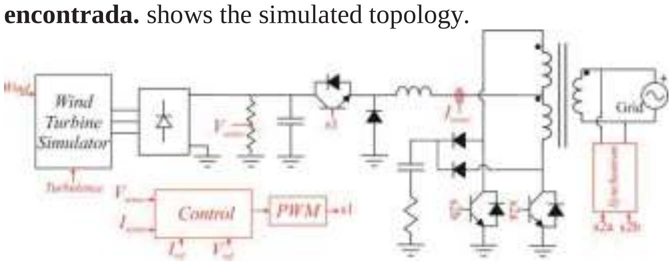

Figure 12: Simulated System.

	Theoretical	Simulated
Vc	70 V	72 V
ΔVc	10 V	10.5 V
Il_{pk}	42 A	43 A
D_{max}	0.667	0.65
I_{grid}	6.4 A	6.5 A
Po_{nom}	1000 W	1010 W

Table 3: Theoretical and simulated parameters.

Steady-state

Figure 13 shows the dc-link voltage for a fixed wind speed. It shows the existence of a component of 120 Hz in the waveform. This component was only limited to the converter always runs smoothly for the most critical levels of the grid. In Figure 14 the waveform of the current and voltage at the output of the system are plotted. The power factor is close to unity, validating the control used. The simulated wind speed was 10,5 m/s.

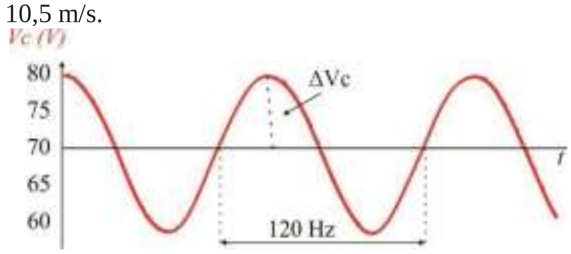

Figure 13: Simulation results:
DC-Link voltage.

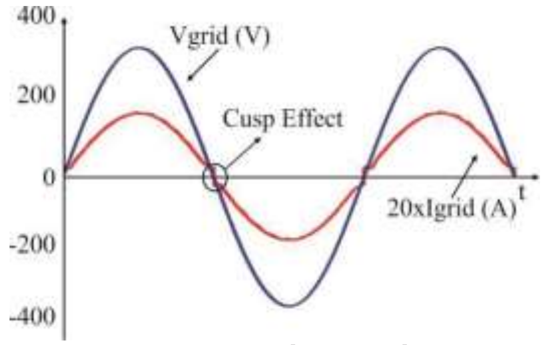

Figure 14: Simulation results:
output current and voltage.

The control signals of both the current loop and the voltage loop can be seen in Figure 15 and Figure 16, respectively.

Figure 15: Simulation results:
current control.

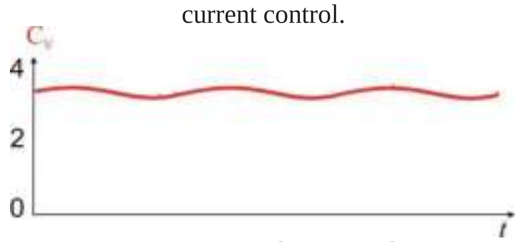

Figure 16: Simulation results:
voltage control.

Dynamic simulation

A simulation with changing wind speed was also made. In the simulation the wind speed increases according to a ramp, as can be seen in Figure 17. The Figure 18 shows the dc-link voltage is regulated in 70 V, with a component of alternating current with 120 Hz around 7% when the output power is 700 W and 10% when the system power is nominal, as designed. Figure 19 presents the current injected into the grid, which increase when wind turbine supplies more active power. Its THD is low (less than 5%), throughout operation range.

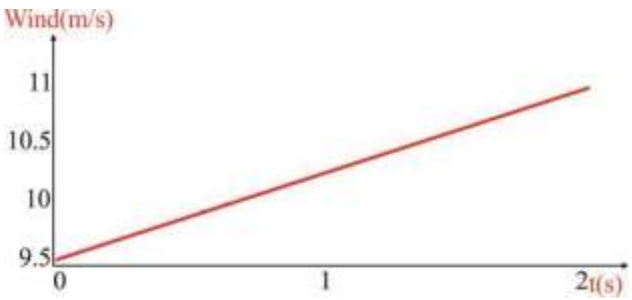

Figure 17: Wind speed.

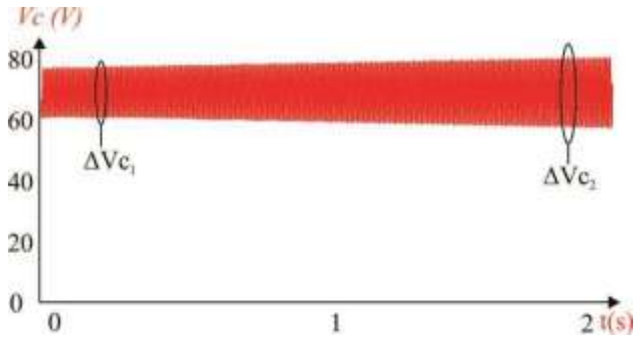

Figure 18: DC-Link voltage.

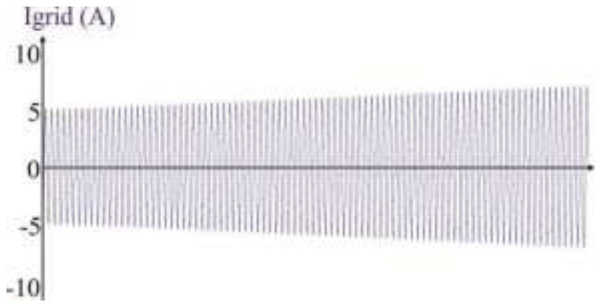

Figure 19: Output current.

7 Conclusions

A new system for connecting small wind turbines was proposed in this paper. The system consists of a passive rectifier, a DC-DC buck converter, a push-pull inverter with current input and two control loops: one that ensures the MPPT voltage and another that ensures the injection of a sinusoidal current into the power grid.

The proposed system has the following advantages: the buck DC-DC converter that facilitates both the control input voltage and control of the current in the inductor; the push-pull inverter fed in current, switching at 60 Hz and isolating the system; it is only used one capacitor bank; and the control system can be done with a commercial IC 3854.

With all these features the system is simple and suitable for the connection of small wind turbines to the electricity grid, which is a booming area in Brazil and worldwide.

Protection issues, especially on islanding, are fundamentally important for systems of this magnitude. However, this work will not be covered.

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