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Grid Simulator for Testing a Wind Turbine on Offshore Floating Platform

V. Gevorgian

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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Prepared under Task No. WTY7.1000

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Contents

1. Introduction

The DeepCwind Consortium's mission is to establish the State of Maine as a national leader in deepwater offshore wind technology through a research initiative funded by the U.S. Department of Energy, the National Science Foundation, and others. The University of Maine-led consortium includes universities, nonprofits, and utilities; a wide range of industry leaders in offshore design, offshore construction, and marine structures manufacturing; firms with expertise in wind project siting, environmental analysis, environmental law, composites materials to assist in corrosion-resistant material design and selection, and energy investment; and industry organizations to assist with education and tech transfer activities. One of the tasks in the DeepCwind research is to develop a complete design of a floating turbine platform, capable of supporting a wind turbine rated for up to 250 kW for deployment at the University of Maine Deepwater Offshore Wind Test Bed.

An important aspect of such offshore testing of a wind turbine floating platform is electrical loading of the wind turbine generator. An option of interconnecting the floating wind turbine with the onshore grid via submarine power cable is limited by many factors such as costs and associated environmental aspects (i.e., an expensive and lengthy sea floor study is needed for cable routing, burial, etc). It appears to be a more cost effective solution to implement a standalone grid simulator on a floating platform itself for electrical loading of the test wind turbine. Such a grid simulator must create a stable fault-resilient voltage and frequency bus (a micro grid) for continuous operation of the test wind turbine. Such an onboard grid simulator has its own technical and design challenges due to space, weight, and environmental limitations.

In March 2011, the National Renewable Energy Laboratory (NREL) entered into contractual agreement with University of Maine (TSA-22-361) to perform a modeling task and develop a design specification for such a grid simulator for operating a V-27 225-kW wind turbine to be installed on a floating platform off the coast of Maine.

Authors would like to thank Steve Drouilhet of Sustainable Power Systems, LLC for his valuable input to this work.

2. Grid Simulator Design Challenges

The University of Maine proposed deployment of a V-27 floating wind turbine to meet the primary objective of testing the one-third scale floating system, and to obtain motion and structural response data to compare and validate numerical models developed by NREL that predict how turbines and supporting platforms would perform under various meteorological and oceanographic conditions. To achieve these research goals, the wind turbine electrical loading must be provided to replicate characteristics of the onshore power grid under varying wind speed conditions. Such characteristics include amplitude and frequency of voltage on turbine terminals, as well as power quality issues.

In such a standalone offshore application, there are essentially two main grid-simulator configuration options that can be considered:

- Battery and inverter-based grid simulator topology
- Diesel generator-based grid simulator topology

Both topologies are possible from an engineering point of view. The main challenge is to select a topology that provides stable, unattended turbine operation during the whole deployment period at minimum hardware costs and least weights. Weight minimization is of most importance since heavy hardware will affect weight distributions, and therefore the dynamic performance of the floating wind turbine platform.

A key condition for stable operation of any power system is to maintain a constant balance between generation and load. In this standalone floating mode of operation, continuous load matching is necessary to dissipate the real power produced by the wind turbine at any wind speed. This condition sets a requirement for using a controllable load bank as part of the grid simulator setup. Such a load bank must be part of the system independent of the grid simulator electrical topology (battery/inverter or diesel). The difference is that in diesel topology the load bank, along with the diesel generator governor controller, are the primary means of maintaining voltage frequency (unlike the battery/inverter system, where grid frequency is set by the inverter controls). Another important aspect is the capability of the system to provide a sufficient amount of reactive power for voltage support and transient stability of the system. There are significant technical, cost, and operational differences in reactive power and frequency support approaches that are specific to battery/inverter or diesel topologies.

3. V27 Wind Turbine Characteristics

Selection of V-27 wind turbine was based on the needs of the testing program, including the following: power control method (variable pitching or stall controlled blades), lead time, costs, suitability for use on a one-third scale platform (i.e., mass, geometry, and power output), structural capacity, availability of design information for numerical modeling, and the ability to publish turbine information as part of research publications.

The Vestas V-27 wind turbine has been selected by the University of Maine for the testing program and the analysis presented in this report, and is based on specifications of the onshore Vestas V-27. The

Vestas V-27 turbine has a generating capacity of 225 kilowatts. The turbine rotor diameter is 88.6 feet, and the tower height would be approximately 100 feet for a maximum height of approximately 144 feet for the proposed project. The turbine is designed with a wind cut-in speed of 8 miles-per–hour, and when the wind speed exceeds 55 miles per hour, the turbine automatically cuts out by slowing the rotor speed using the control system and feathering the turbine blades. The turbine also includes an emergency disk brake. The turbine is designed to withstand wind gusts up to 120 miles-per-hour. The maximum rotational speed of the turbine rotor is 44 revolutions-per-minute.

Figure 1: Vestas V-27 wind turbine

The V-27 wind turbine is a pitch-regulated constant-rotational speed wind turbine. The blade pitch angles are controlled continuously to provide optimum power production. The active pitch brings additional operational benefits, such as:

- Output power limited at 225 kW;
- No need for motoring starts;
- Generator cut-in at synchronous speeds;
- Possibility of stopping the turbine without engaging the mechanical brakes.

The turbine power (for sea level) and aerodynamic power coefficient Cp curves are shown in Figure 2.

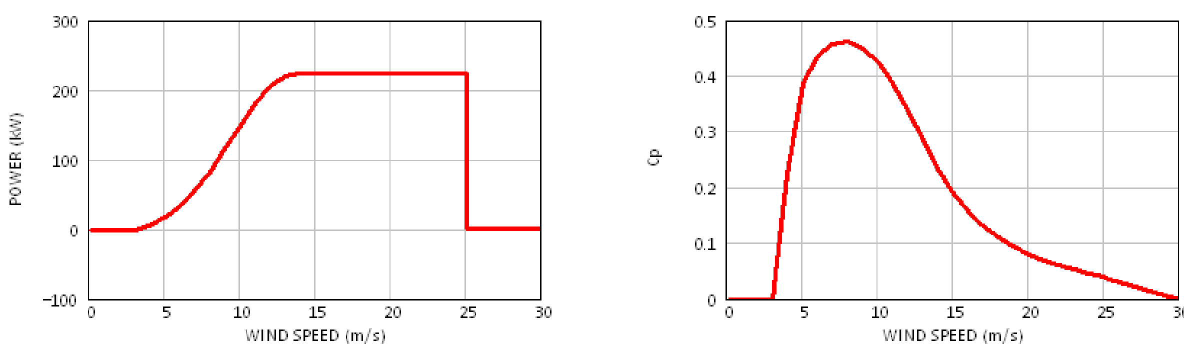


Figure 2: V-27 power and Cp curves

The electrical topology of the V-27 (480 VAC/60Hz) wind turbine is based on a two-winding squirrel-cage induction generator. Each winding uses a different number of poles, so two-speed operation becomes possible. The electrical characteristics of the generator are shown in Table 1:

Table 1: Generator electrical characteristics

	Winding 2	Winding 1
Number of poles	6	8
Synchronous speed (rpm)	1200	900
Rated speed (rpm)	1209	906
Winding configuration	Δ	Δ
Power rating (kW)	225	50
Full load current (A)	335	85
No load current (A)	143	49

The wind turbine uses a thryristor-based soft starter for in-rush current limiting during generator start ups. Two sets of capacitor banks are used for power factor correction (PFC). The PFC capacitors are switched off during start up transients when the soft starter is active. The reactive power / power factor characteristics for the generator and the total wind turbine power factors are show in Table 2:

Table 2: Reactive power / power factor characteristics

	Winding 2	Winding 1
Generator power factor: 100% load 75% load 50% load 25% load	 0.81 0.75 0.65 0.41	 0.71 0.65 0.54 0.30
Generator reactive power, no load (kVAR)	118.9	40.7
PFC capacitor rating (kVAR)	112.5	37.5
Total wind turbine power factor: 100% load 75% load 50% load 25% load	 0.98 0.98 0.98 0.96	 0.97 0.99 1.00 0.98
Total wind turbine current at full load current (A)	277	62

Calculated steady-state power vs. rpm characteristics of V-27 turbine are shown in Figure 3:

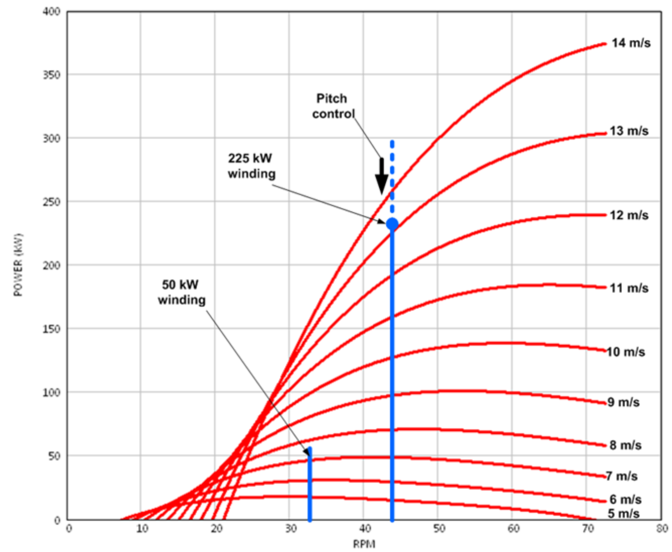


Figure 3: V-27 steady state operation

The general layout of V-27 components is shown in Figure 4. A two-stage 443-kW gearbox is used in the V-27 wind turbine to step up the wind rotor speed. There are two 0.66-kW motors used in turbine's yaw system. A disk brake unit is capable of emergency stopping of the wind turbine in case of grid loss.

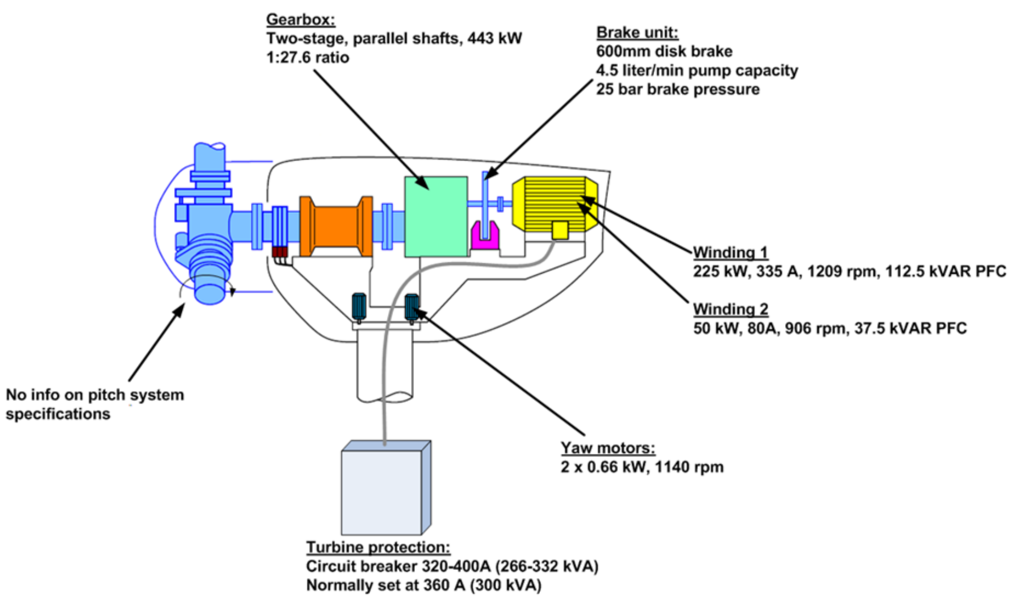


Figure 4: V-27 major components

4. Overview of Grid Simulator Topologies

It was pointed out earlier in this document that two main grid-simulator configurations are the inverter/battery and diesel generator-based solutions. The third possible option is a modification of the diesel generator option that uses a synchronous condenser for voltage control. This solution also requires a controlled load bank for frequency regulation. Functional and control aspects of each topology are described in this section.

4.1 Battery/inverter topology

Latest advances in energy storage technologies led to lower cost and improved performance battery solutions designed specifically for renewable energy and electric vehicle applications. The improvements include higher energy capacities at lower weights, faster charge/discharge rates, and increased reliability and battery life. Battery technologies such as advanced lead-acid, lithium, Ni-Cd and others are being adapted in many renewable energy projects including operations with wind generation. The main application of such batteries in wind related projects is a short-term balancing of wind power variability, participation in frequency regulation, and providing voltage support. All these functions are also made possible by employing advances in the inverter technologies.

A general diagram of a possible battery/inverter solution for a floating platform grid simulator is shown in Figure 5. It consists of a battery bank and voltage source grid-forming inverter. The main purpose of the inverter is to set both the voltage and frequency in the system's 480VAC/60Hz bus, making possible for the wind turbine to operate. The V-27 wind turbine is represented by two generators (equivalent of 2-winding topology) with individual capacitor banks for power factor correction, and a soft starter.

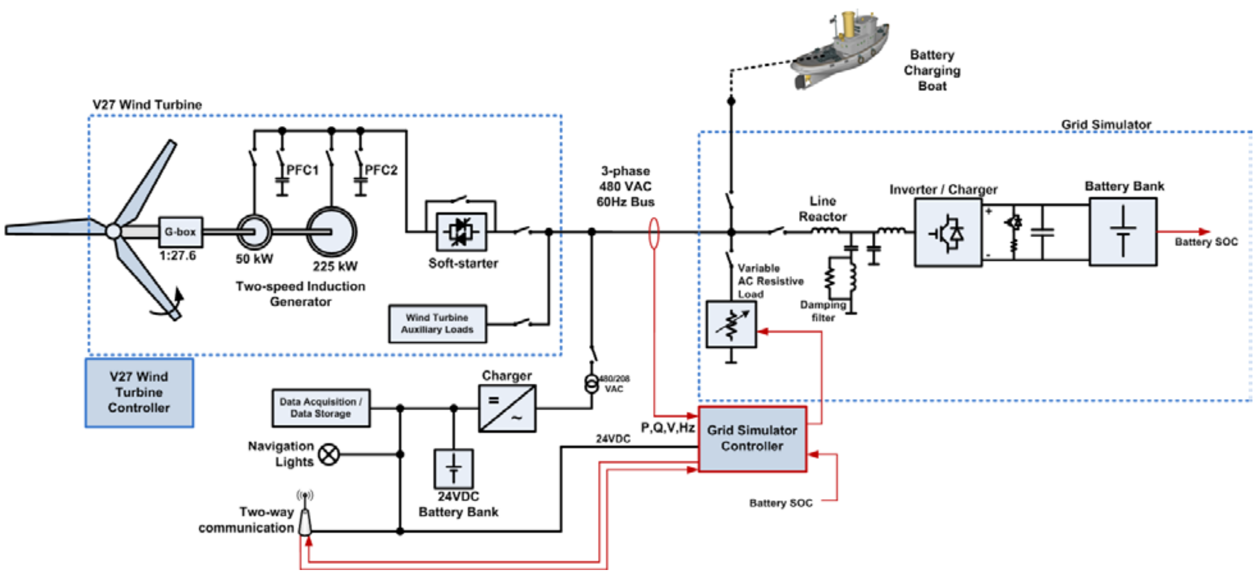


Figure 5: General diagram of battery/inverter option

Platform secondary loads and the instrumentation battery charging system are separate from the grid simulator battery and inverter.

The dynamic operation and control of the grid simulator is possible by means of employing a fast-response resistive-load bank. Such load banks with controllers have been used in many wind-diesel and mini-hydro power systems for load and frequency controls. Element switching in such load banks can be achieved using several methods. It appears that element switching using a thyristor solid-state (SSR) zero-switching technique is the most feasible, especially in a standalone offshore application. All SSR switching is done at zero voltage, which eliminates the current waveform distortion and the poor power factor associated with phase-controlled SCR power controllers. In SSR zero-switching controllers, all of the thyristors can be directly bonded to integral heat sinks rated to handle their respective electrical loading. By switching on various combinations of the heating elements, any power level from zero to full load may be achieved, with a resolution close to 1% of full load. Also, element switching can be updated at fast rates, allowing smooth continuous control of electric power.

Such smooth and fast power control is essential for reliable continuous operation of the battery/inverter-based grid simulator. The electrical power flowing to/from the battery bank is essentially the difference between the turbine power production and the ability of the load bank to absorb the same amount of power. Ideally, there will not be any power flow into/out of the battery (except for to compensate for losses) if load bank consumption is fully matched with turbine power production. Also, power flow to battery (battery charging) can be controlled by adjusting the load bank power at any desired level.

The inverter system shown in Figure 5 has a harmonic filter and line reactor for improved voltage/current waveforms. An isolation transformer can also be used instead of a line reactor to eliminate possible ground loops, create a local ground-bonded neutral, and reduce harmonic currents.

Another important function of the inverter is to allow battery charging from an external power source such as portable diesel generator that can be transported to the platform on a service boat. This would be for situations when battery bank is completely discharged due to contingencies.

The inverter power rating must be sufficient to provide the reactive power needed by the wind turbine generator during start-up transients and switching between generator windings.

The grid simulator supervisory controller dispatches the overall system operation and performs the following tasks:

- Determines the required amount of power sent to the load bank at any given instance in time;
- Allows / inhibits wind turbine operation as necessary;
- Determines state of the charge (SOC) of the battery bank, and determine required amount of power to be sent to the battery for maintaining target SOC during whole period of operation;
- Sets inverter into battery charging mode when connected to portable diesel generator;
- Shuts down the inverter to preserve battery charge during the periods of no wind, or in case of wind turbine or other component failure;
- Performs data logging;
- Detects faults and provides protection; and
- Provides for remote access via wireless connection.

The supervisory controllers are generally based on an industrial-type panel-mount PC computer or programmable logic controller (PLC). The operator interface should have flexibility to change the operating strategy through the variety of user-settable parameters.

Detailed results for battery/inverter option are described in the modeling sections of this document.

4.2 Diesel generator topology

Wind-diesel hybrid systems have been used worldwide in remote standalone power-system applications. Many successful wind-diesel projects were deployed in various parts of the world (including offshore marine applications), so both control and operational aspects of such systems are well understood. The dynamic behavior of a wind-diesel micro-grid in a floating offshore-platform grid- simulator application is similar to a typical wind-diesel hybrid system. However, it has specific challenges mainly from the operational and fuel supply perspectives due to its location on a floating offshore platform.

A general diagram of possible diesel generator solution for a floating platform grid-simulator is shown in Figure 6. It consists of a diesel generator and resistive AC load bank. The purpose of the load bank (similar to above described battery/inverter case) is to provide smooth load matching for wind turbine power. However, in this case the load bank is controlled based on measured electrical frequency rather than wind turbine power production.

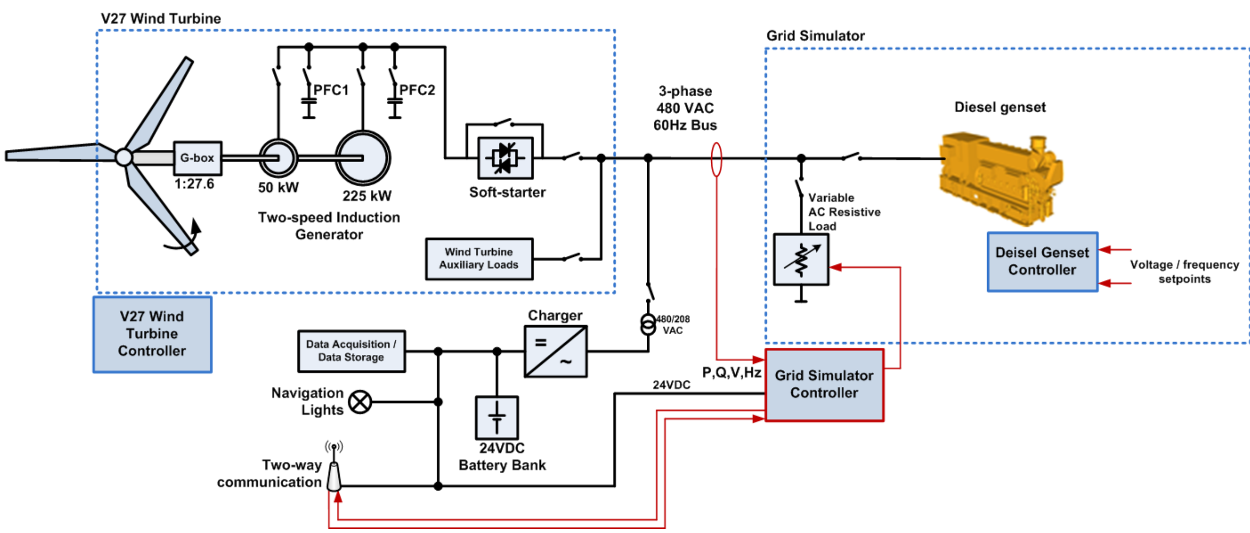


Figure 6: General diagram of diesel generator option

Fast load bank controllability is also critical to operational stability of this system. The purpose of the diesel generator is to set up the voltage and frequency in the 480 VAC bus. It must run continuously during the whole period of wind turbine operation. The power rating of the diesel generator must be sufficient to provide reactive power needed by the wind turbine generator during start-up transients. The supervisory controller performs similar tasks as in the battery/inverter option except for battery related functions:

- Determines the required amount of power sent to the load bank at any given instance in time
- Allows / inhibits wind turbine operation as necessary;
- Starts and stops diesel engine;

- Performs data logging;
- Detects faults and provides protection; and
- Provides for remote access via wireless connection.

The main disadvantage of this system is the need for periodic refueling of the diesel generator tank, and excessive weight associated with a storing large amount of fuel onboard the floating platform.

4.3 Diesel generator/synchronous condenser topology

Continuous diesel operation can be avoided if a synchronous condenser is added to the grid simulator topology. Significant reduction in fuel consumption can be achieved this way also. A general diagram of synchronous condenser grid-simulator topology is shown in Figure 7.

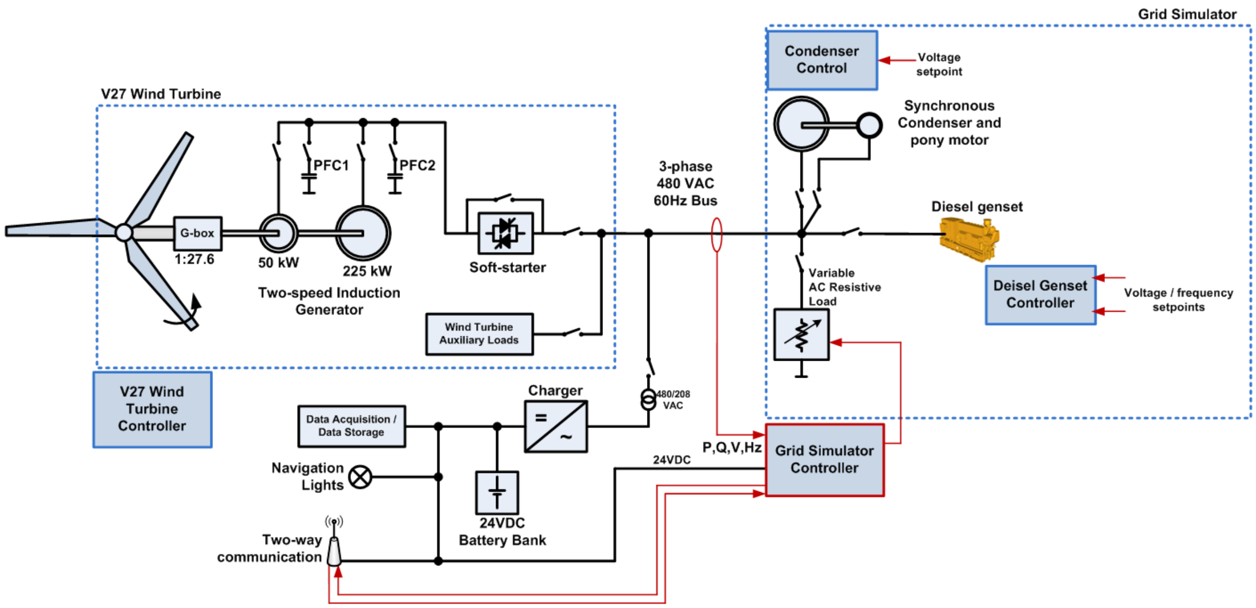


Figure 7: General diagram of diesel generator/ synchronous condenser option

The synchronous condenser allows a high level of control over the reactive power in the micro grid. It can generate or absorb reactive power to support the system's voltage level (or to maintain a specified power factor). The synchronous condenser has its own custom controls and is started using a small induction motor (pony motor). First, the diesel generator is started to set up the system voltage and frequency. Then the synchronous condenser is brought up to speed and synchronized with the diesel generator. Upon synchronization, the condenser is connected to the main bus. The diesel generator can be turned off after turbine starts, and resistive load is controlled to maintain stable system frequency.

The main advantage of this topology is that a smaller diesel generator with significantly reduced run-time can be used. Therefore, lower fuel consumption and smaller fuel tank weights can be achieved this way. The main disadvantages are more complex control and single speed operation. Unlike previous topologies, this topology won't allow switching between large and small generator windings. Both voltage and electrical frequency will collapse immediately after the generator winding is disconnected from the main bus.

5. Transient Modeling of Grid Simulator Topologies

Transient modeling results for all three grid-simulator topologies are described in this section. The purpose of transient modeling is to determine the power ratings of grid simulator components, identify potential controllability issues and ways of improving system transient performance. The most severe transient case for any grid simulator topology is a start up of the wind turbine using the large generator winding. The criteria for transient performance were based on V-27 wind turbine protection settings as shown in Table 3:

Table 3: V-27 protection settings

Action	Condition
Both generator and PFC will be cut off if:	Voltage above 528 VAC for 60 sec Voltage below 432 VAC for 60 sec Frequency above 62 Hz for 0.2 sec Frequency below 57 Hz for 0.2 sec
Only PFC will be cut off if:	Voltage above 540 VAC for 0.2 sec
Only generator will be cut off if:	Voltage is above 540 VAC for 0.5 sec

All transient modeling was done using PSCAD simulation software.

5.1 Transient modeling of battery/inverter option

The one-line diagram of the model is shown in Figure 8 (simplified version of Figure 5). The platform auxiliary loads are simulated by a single 3-kW (0.8 power factor) load. Wind turbine auxiliary loads (mainly yaw motors) are simulated by a single 2-kW induction motor.

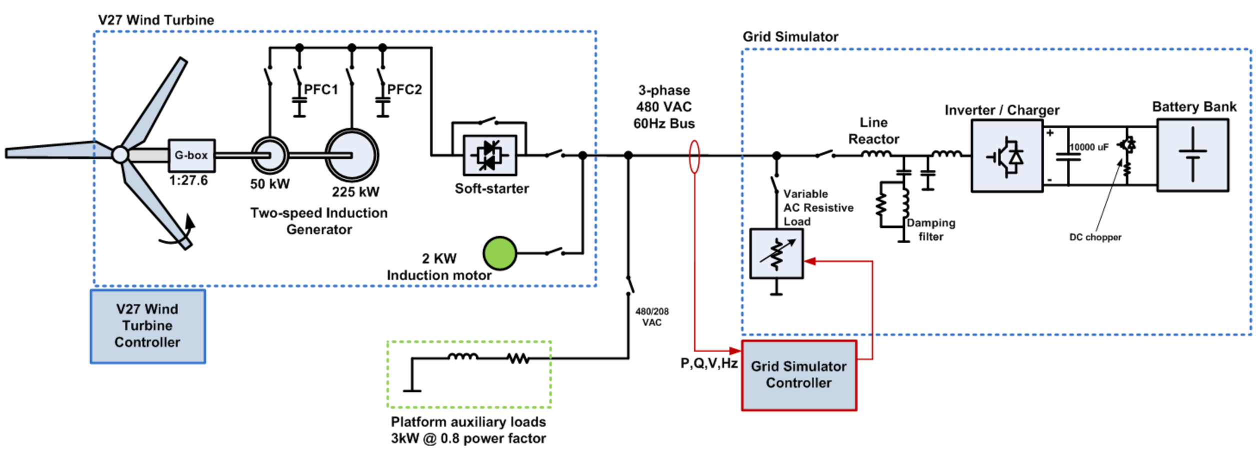


Figure 8: Simplified one-line diagram of battery/inverter option

Transient simulations were conducted during large generator cut in at constant wind speed. The resistive load bank with different response times (5, 15 and 50 ms) was controlled to match the wind turbine power output. It was mentioned earlier that the load bank response time is a critical parameter in providing stable operation and protecting battery from excessive currents.

Simulation results for the battery/inverter system with fast load-bank response time (5 ms) are shown in Figure 9. The initial turbine RPM in this simulation is at 0.9 pu. The inverter sets 480 AC voltage and frequency from the beginning of the simulation. The turbine accelerates for about 1 sec until the generator reaches synchronous speed of 1 pu. At this moment, the soft starter becomes active and starts conducting current to the generator winding. A lookup table is used for soft starter firing-angle control. The firing angle is controlled to gradually increase generator voltage, thus limiting in-rush start-up currents.

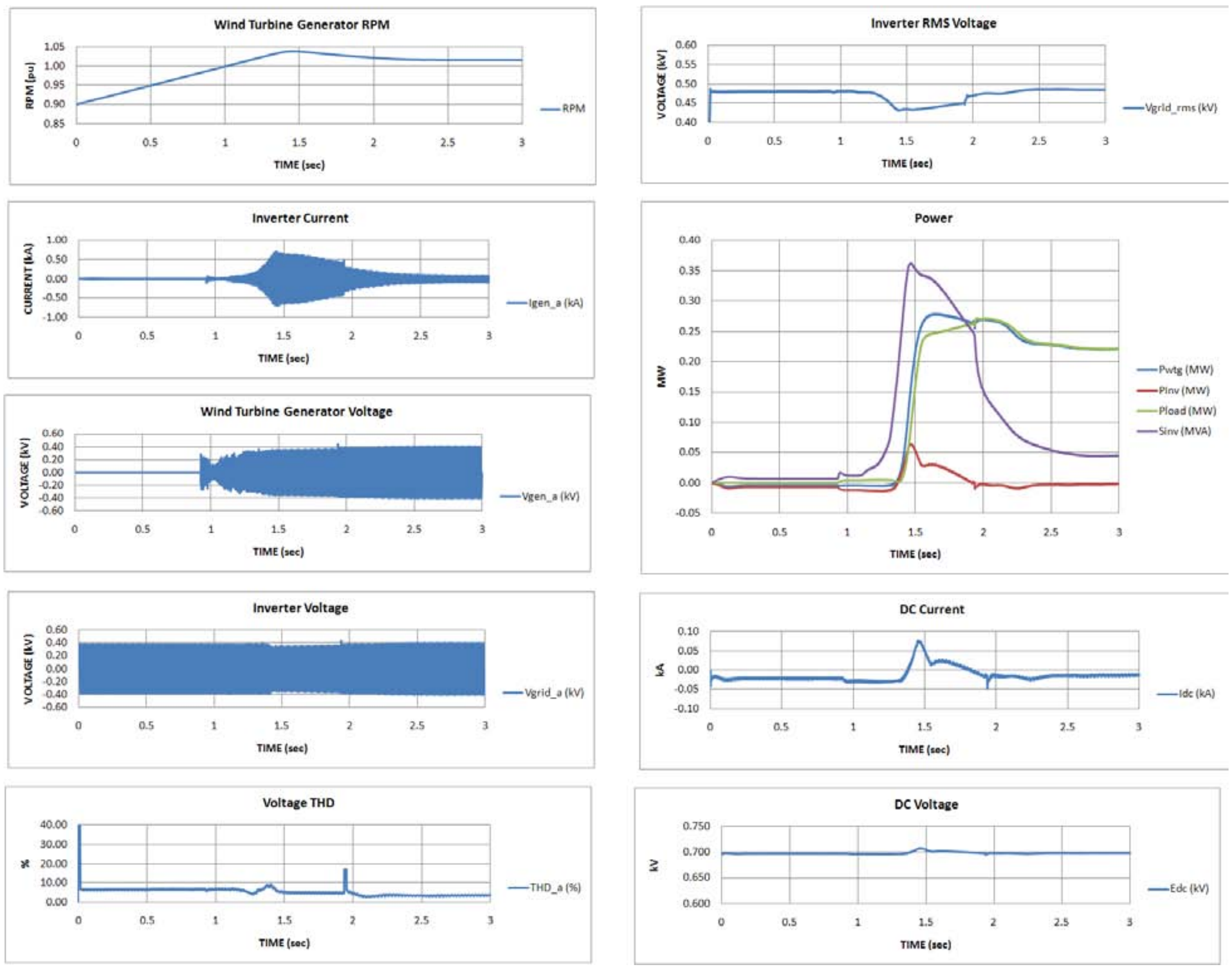


Figure 9: Large generator start up (load controller response – 5 ms)

Immediately after cut in, the wind turbine generator starts producing real power (labeled as Pwtg). At the same time, the load bank controller starts engaging the resistive elements to match the turbine power. The difference between wind turbine power (Pwtg) and load bank power (Pload) is the power that flows through the inverter into battery bank (Pinv). The peak DC current into the battery is at around 70 A.

The peak inverter apparent power (Sinv) is slightly over 350 kVA. This peak essentially determines the power rating of the inverter. It is important to note that inverters usually have short term over-current capability (for example, 150% for 3 sec, or similar). This means that there is a potential for using an inverter with a smaller power rating if all over-current (peak and duration) limitations are met.

It also can be seen from Figure 9 that the AC bus voltage drops to about 430 V during start-up transients, and then quickly recovers back to 480 VAC in about 1 sec. This recovery time will be different depending on inverter type, implemented controls, etc.

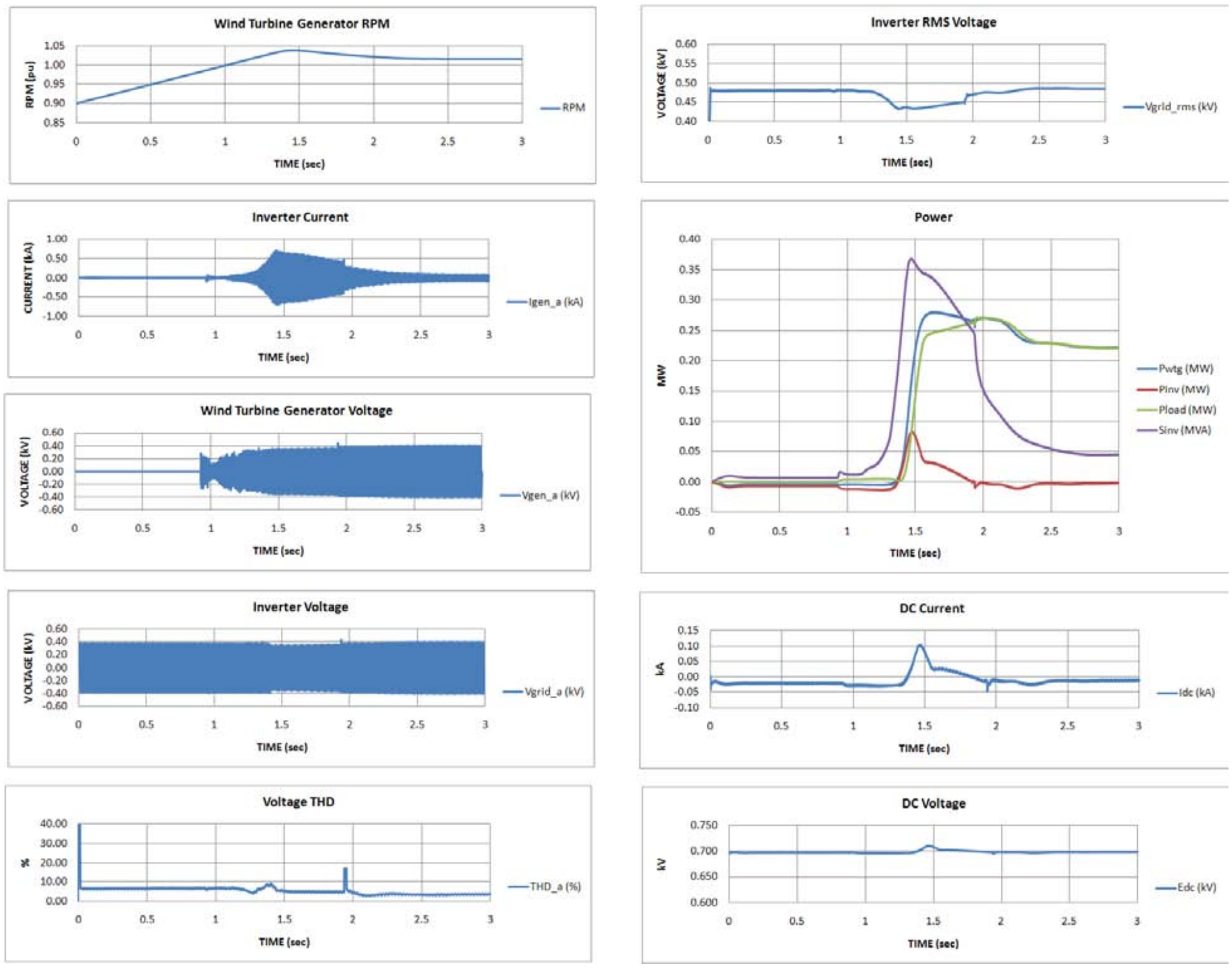


Figure 10: Large generator start up (load controller response - 15 ms)

A case with 15-ms load-bank controller response time is shown in Figure 10. In this case, a slower load bank controller creates a larger difference between Pwtg and Pload, which in turn causes a higher DC current spike in to the battery bank (up to 100A). The peak apparent power of the inverter is still about 350 kVA and is not affected by the slower load bank control.

A case with an even slower controller response (50 ms) is shown in Figure 11. In this case, there is a larger difference between Pwtg and Pload, so peak DC current is higher at about 150 A.

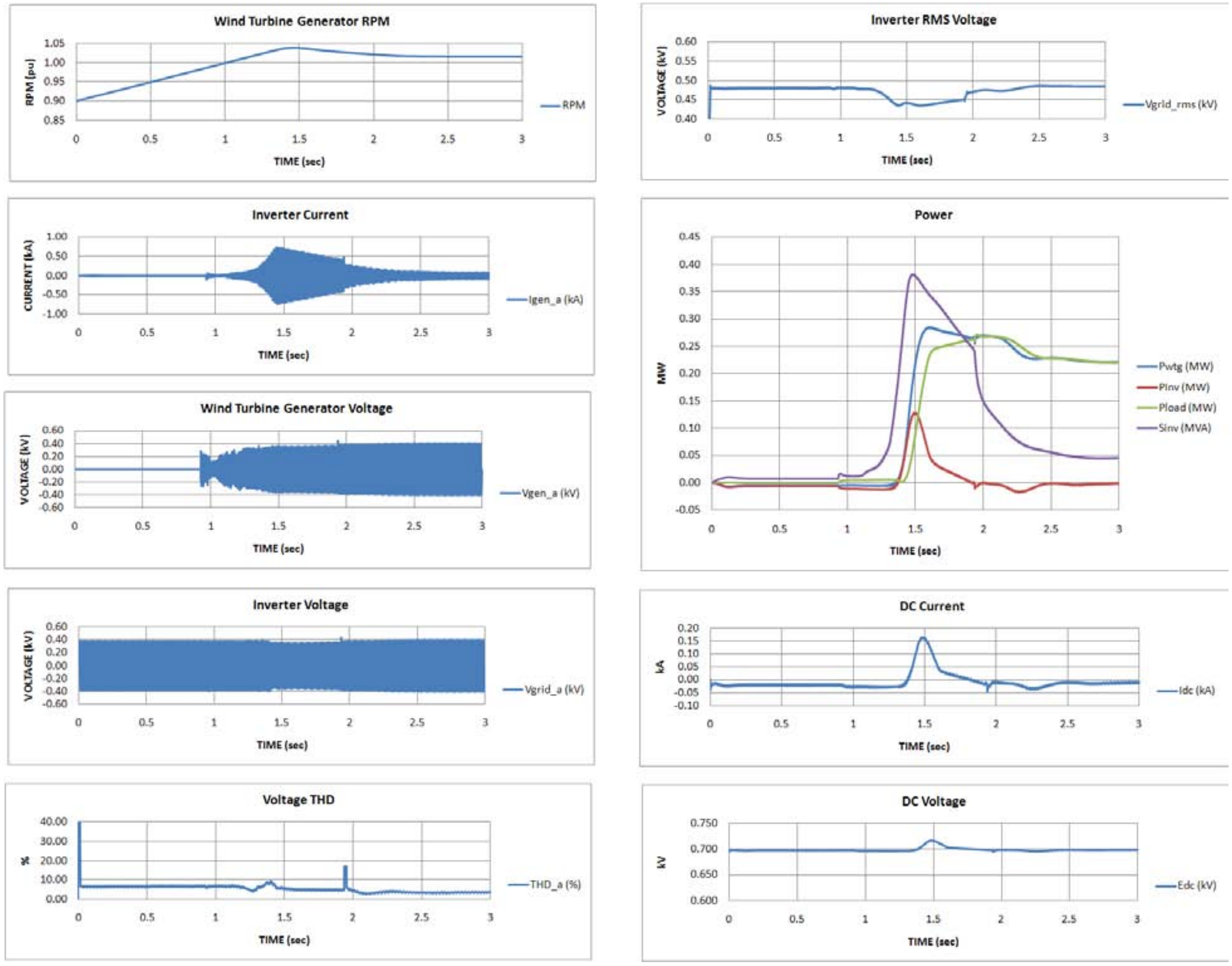


Figure 11: Large generator start up (load controller response - 50 ms)

For all three above cases, there was little impact of load controller response-time on peak apparent power (or rating) of the inverter. However, there was a significant impact on battery current. These simulations stress the importance of fast load controller response for performance of the battery bank.

A more detailed view of the generator voltage and current waveforms during start up transients are shown in Figure 12. The effect of a soft starter on voltage magnitude, and both current and voltage waveforms are shown. In general, as can be seen in Figure 9, Figure 10, and Figure 11, the voltage total harmonic distortion (THD) is far below 5% after the start up transients are over. Even during transients, the voltage THD is slightly above 5%.

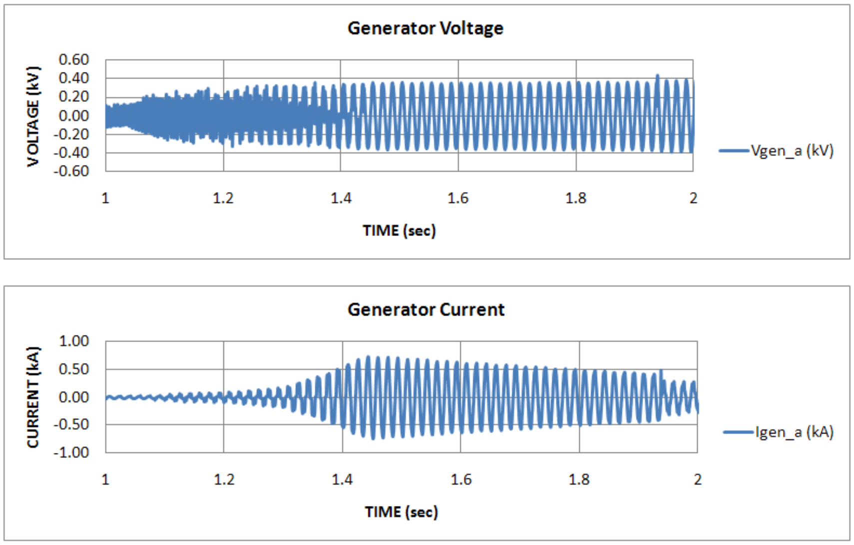


Figure 12: Wind turbine generator voltage and current

5.2 Transient modeling of diesel generator option

The one-line diagram of the model is shown in Figure 13 (simplified version of Figure 6). As in the previous case, the platform and turbine auxiliary loads are simulated by a single load and single induction motor respectively.

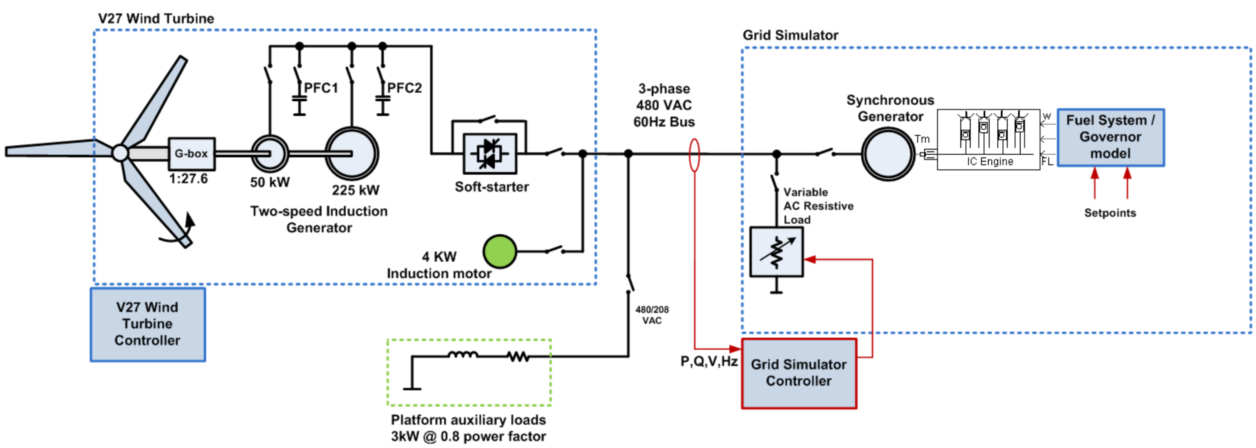


Figure 13: Simplified one-line diagram of modeled diesel generator option

Transient simulations were conducted during large generator cut in. The diesel generator sets both AC frequency and voltage. The resistive load bank was controlled to maintain the AC voltage frequency at 60 Hz. A 5-ms controller response time was used in these simulations.

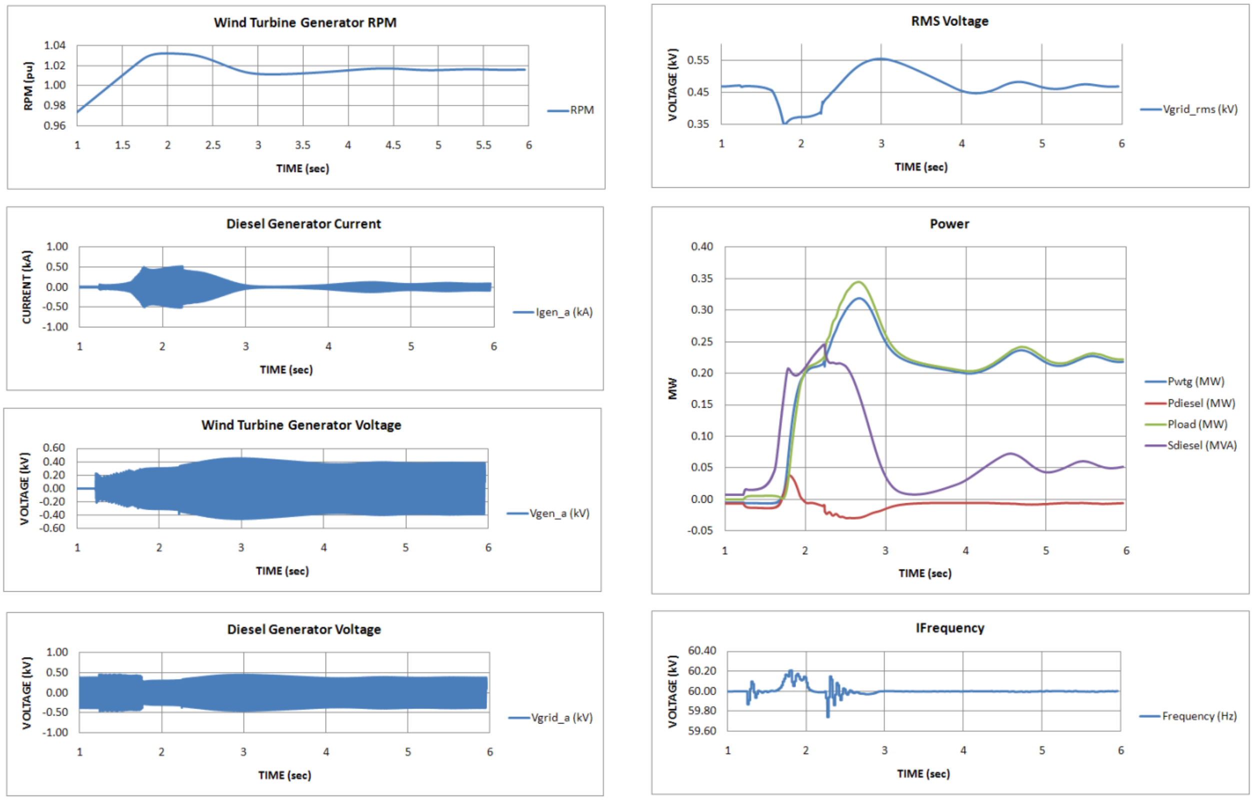


Figure 14: Simulation results with 400-kVA diesel generator

Simulation results of a large wind turbine generator start-up for a case with a 400-kVA diesel generator are shown in Figure 14. The wind turbine accelerates and generator cut in takes place as soon as synchronous speed is reached. The turbine soft starter is activated at the beginning of the transient. The load bank is engaged immediately by the load bank controller trying to stabilize the electrical frequency at 60 Hz. The voltage in 480 VAC bus first drops and then swells before it settles back to steady state, but it stays within allowed limits during the whole transient process. The frequency peaks at about 60.1 Hz before it is forced back to 60 Hz.

Many wind turbine generator start-up simulations were conducted for different kVA ratings of the diesel generator. It was found that 400 kVA was the minimum diesel rating that allowed reliable start up of the large wind turbine generator under various conditions. An example of a start-up simulation using a 300-kVA diesel generator is shown in Figure 15. In this case, the AC voltage exceeds protection limits of V-27 wind turbine, so both generator and PFC capacitor will be cut off under such conditions.

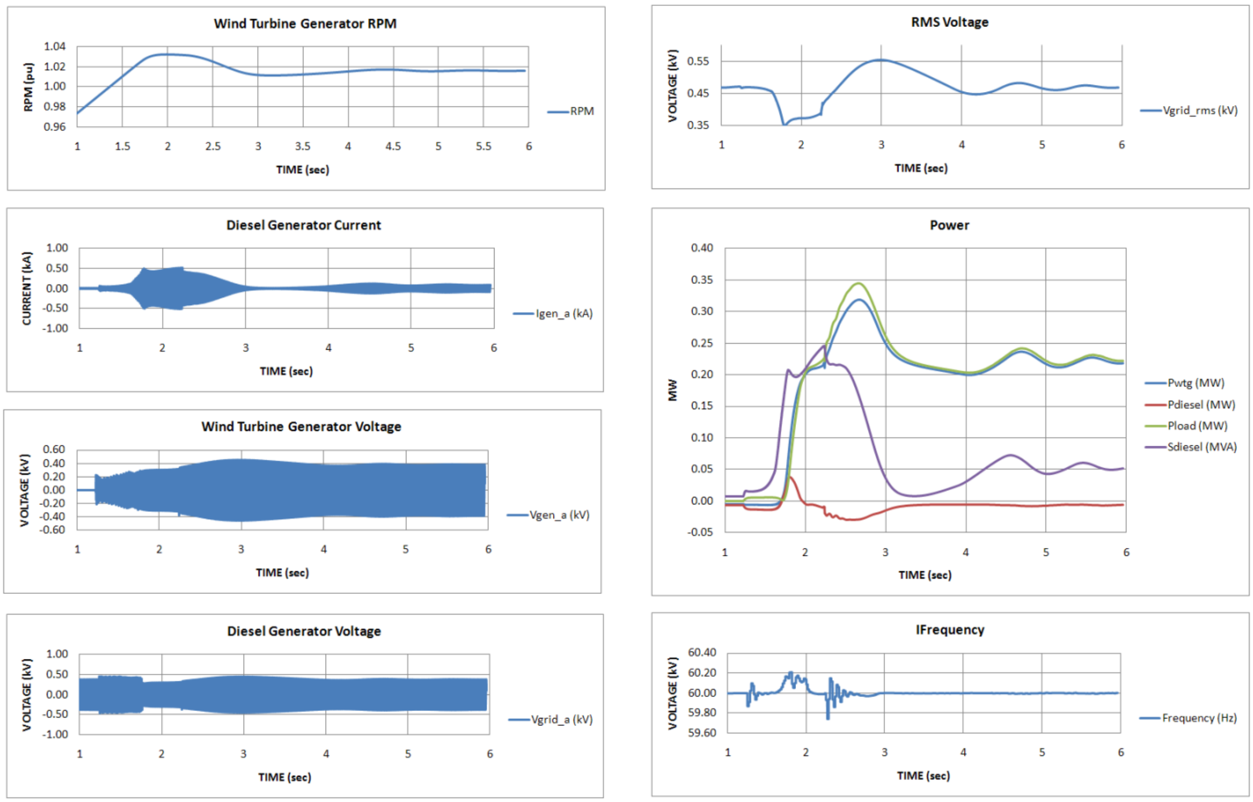


Figure 15: Simulation results with 300 kVA diesel generator

5.3 Synchronous condenser option

The one-line diagram of the model is shown in Figure 16. A 50-kVA diesel generator is used to start the system. A 400-kVA synchronous condenser with a 15-kW pony motor is used in the simulation.

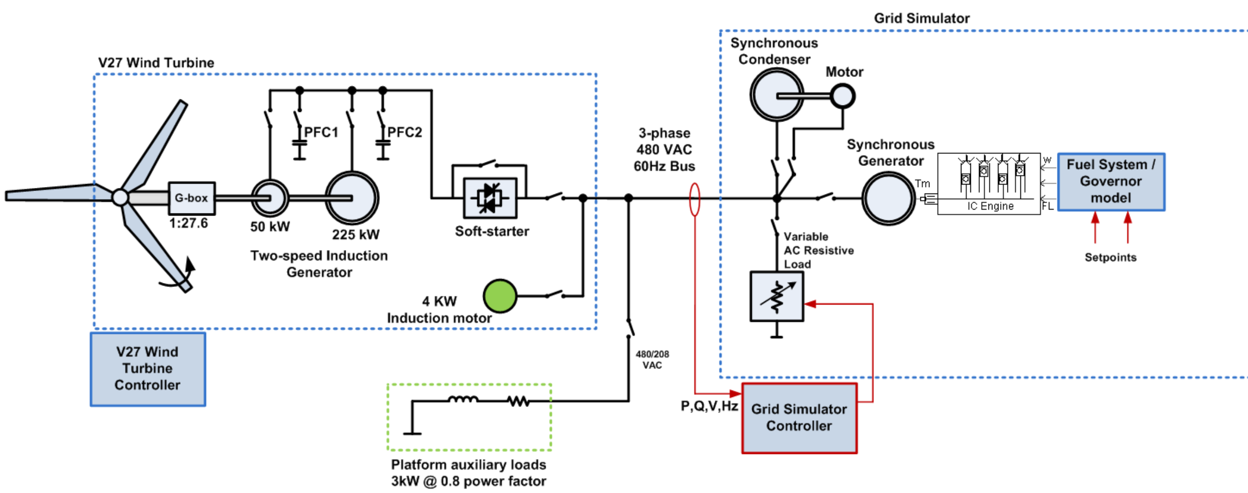


Figure 16: Simplified one-line diagram of modeled synchronous condenser option

Simulations were conducted or this option as well. It was found that the minimum rating of a synchronous condenser that allows reliable wind turbine generator starts at various conditions was 400 kVA. The simulated real and apparent power time-series for the 400-kVA synchronous condenser option is shown in Figure 17. Smaller kVA ratings ended up either in unstable conditions or exceeded voltage limits.

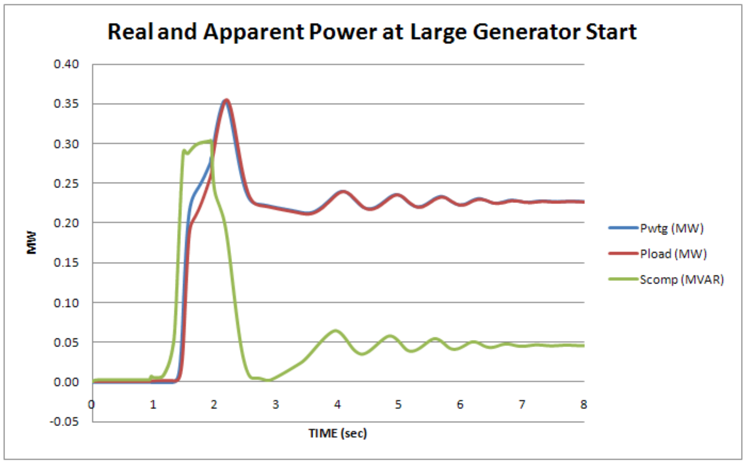


Figure 17: Wind turbine start with 400 kVA synchronous condenser

5.4 Transient simulation conclusions

The main findings of transient simulation stage of the project are summarized below:

1. Transient simulation showed that the V-27 turbine may consume up to 350-400 kVAR of reactive power (peak during 1-2 sec) during large generator start up. For a battery/inverter option, a 300-KVA inverter seems to be an adequate match for the V-27 wind turbine, assuming it has enough short-term over current capability (i.e. 150% for 2-3 sec). The approximate weight of a 300-kVA inverter is on the order of 1500 lbs (including cabinet). Additional weight should be added if an isolation transformer is used instead of line reactors. The maximum power rating of the load bank is at about 275 kW, according to simulations. With a safety margin, it appears that a 300 to 325-kW load bank will be sufficient for this grid simulator topology.
2. For a diesel generator option, a 400-kVA diesel generator seems to be an adequate match for the V-27 wind turbine. The approximate weight of 400-kVA diesel genset is around 9,000 lbs (with fuel weight). The load bank must be rated for at least 350 kW in this application.
3. For a synchronous condenser option, a 400-kVA synchronous generator will provide enough reactive power capability for V-27 wind turbine start up. The synchronous condenser by itself will weigh around 4,000 lbs. In addition, a 50-kW diesel genset and 350-kW load bank will be needed. Only one wind turbine generator winding (single speed operation) can be used with this topology.

Final comparison between the options can be done only after determining the capacity and weights of a battery bank for the battery/inverter grid simulator topology.

6. Continuous Steady State Simulations for Inverter/Battery Topology

6.1 Inverter efficiency

In the steady-state modeling case, the individual system components are modeled by their efficiencies and control strategies. In particular, inverter efficiency and losses are most important when modeling the long-term performance of battery/inverter option. A typical inverter efficiency curve is shown in Figure 18 and was used in this modeling stage.

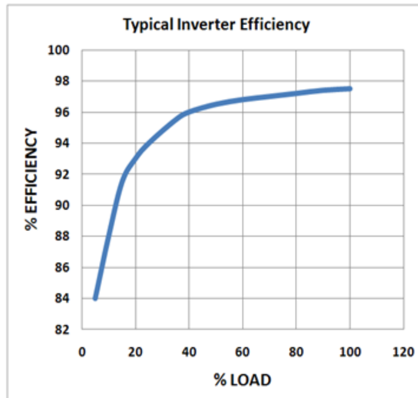


Figure 18: Typical inverter efficiency

6.2 Battery models

The following battery types were used in the simulations:

- Advanced valve-regulated lead-acid (VRLA) batteries of 600, 300, and 100 Ah capacities;
- Fast charge-discharge lithium-titanate batteries of 100 and 50 Ah capacities.

Examples of modeled nominal discharge characteristics for such batteries are shown in Figure 19 and Figure 20 respectively.

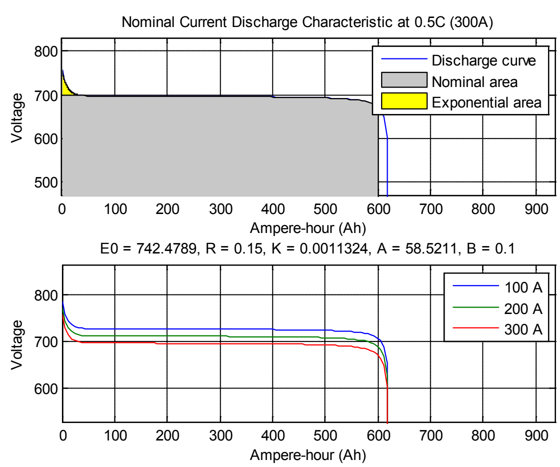


Figure 19: Discharge characteristics of 600-Ah lead-acid batteries

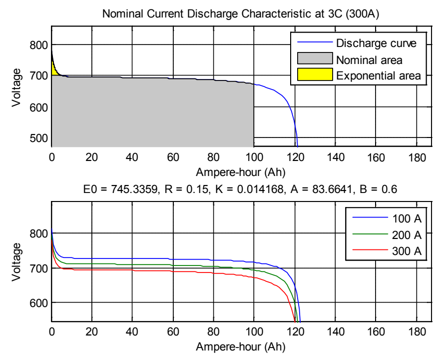


Figure 20: Discharge characteristic of 50-Ah lithium batteries

The steady state modeling was performed in the Matlab/Simulink environment. Generic Simulink battery models were used in the simulations. The main parameters used in these battery models are:

- Nominal voltage;
- Rated capacity;
- Initial state of charge (SOC);
- Fully charged voltage;
- Internal resistance;
- Exponential zone.

6.3 Wind turbine steady-state model

The V-27 turbine was modeled using its power curve as shown in Figure 2. Some results from transient simulations were used as an input for steady-state simulation. In particular, it was observed in transient simulations that up to 150-A short-term DC current spikes (worst case) will go into the battery during start-up transients due to load-bank control delay. The corresponding real power spikes were introduced into a steady-state model every time the wind turbine was starting up.

Also, a wind turbine may occasionally go into the transitional motoring/generating mode during the period of low winds. If motoring, the wind turbine will consume real power from the battery bank. The periods of motoring operation can be minimized by adjusting the appropriate settings in the V-27 wind turbine controller. In this simulation, the turbine control was programmed to minimize the motoring possibility and shut down the turbine after 60 seconds of operating in such a transition between generating and motoring. Also, grid simulator control was allowed to shut down the inverter during periods when the wind turbine is off to avoid parasitic losses. The inverter is turned back on only if average wind speed within the last 10 minutes is above a certain threshold, for example 7 m/s. The simulated 1-sec real power time-series for V-27 wind turbine is shown in

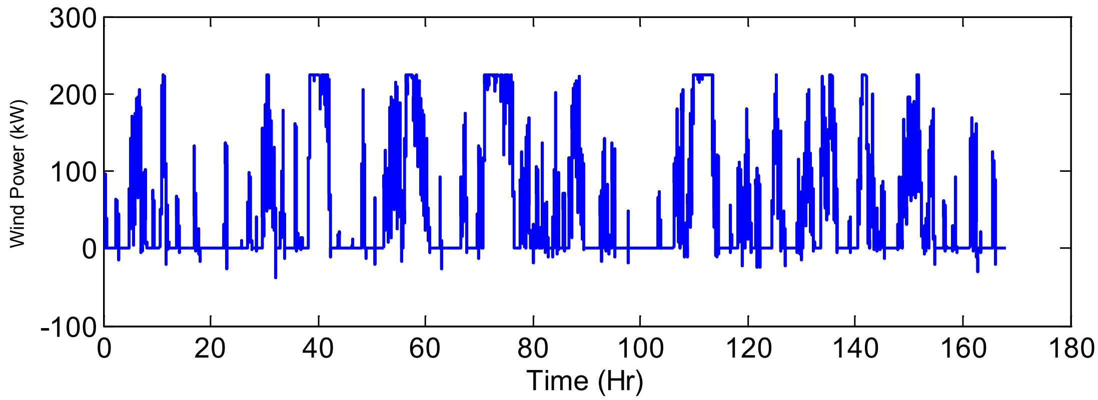


Figure **21** for 1 week of operation.

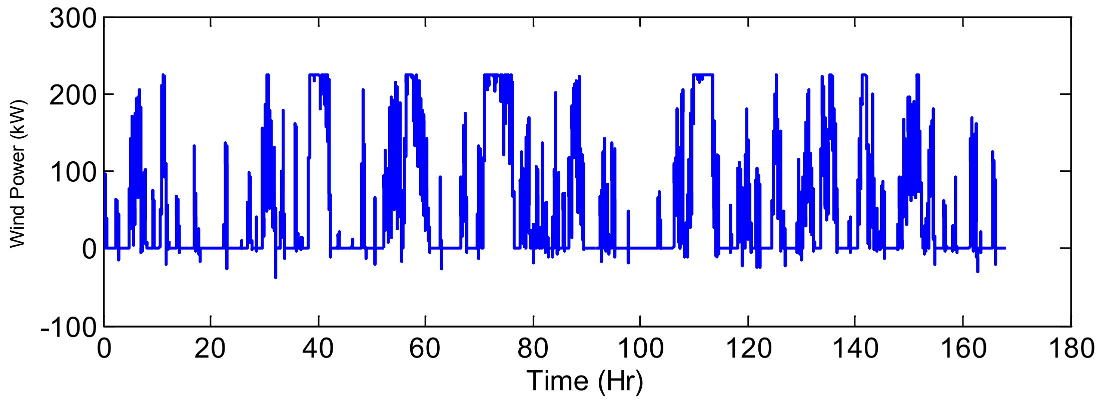


Figure 21: Simulated 1-sec wind power time series (1 week simulation period)

6.4 Battery Simulation Results

Simulation results for a VRLA battery bank for three different capacities (600, 300, and 100 Ah) are shown in Figure 22, Figure 23, and Figure 24 respectively. The secondary load controller adjusted power to the battery bank to maintain 70% SOC. The spikes in battery voltage were caused by current spikes during turbine start ups due to load-bank controller delay. The fully charged voltage for the selected battery configuration is 756 V (672-V nominal voltage).

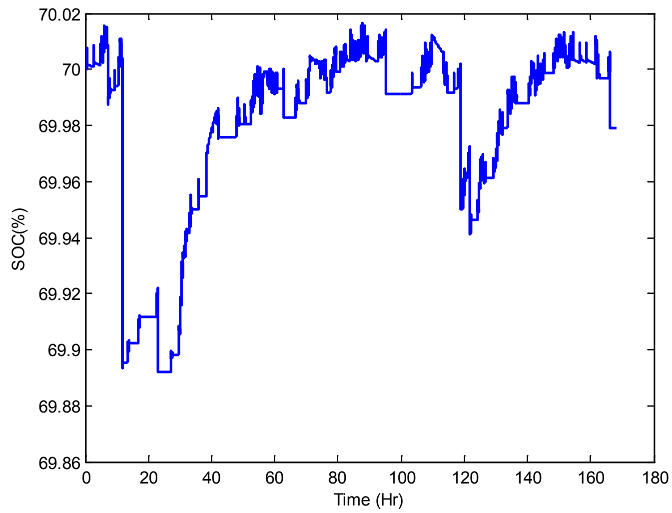


Figure 22: SOC for 600-Ah VRLA Battery

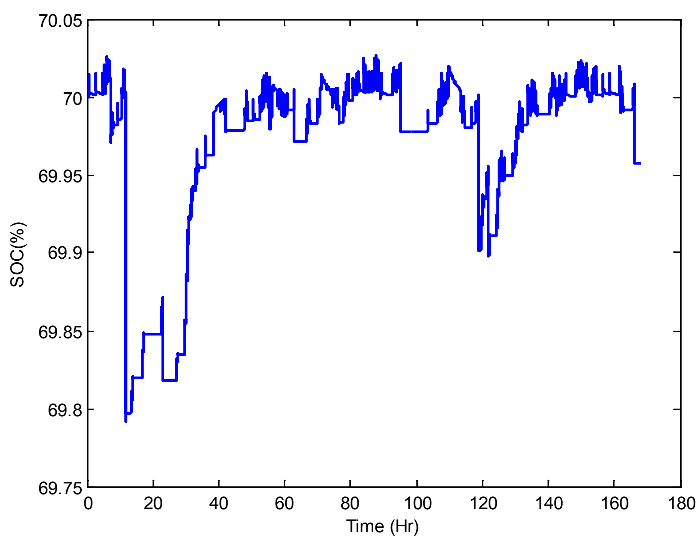


Figure 23: SOC for 300-Ah VRLA Battery

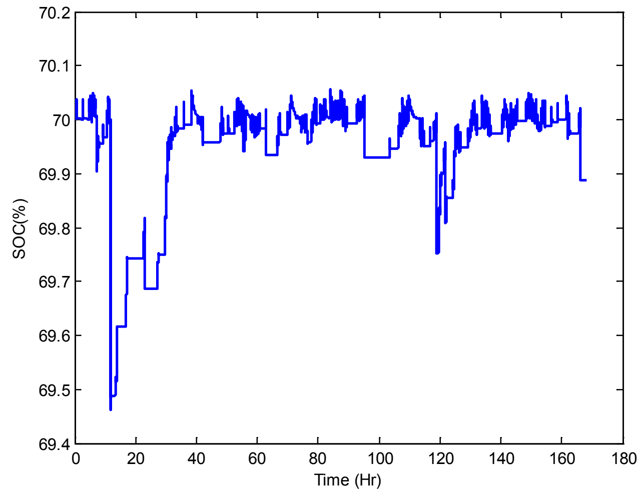


Figure 24: SOC for 100-Ah VRLA battery

The secondary load controller was able to control the battery SOC close to the target level during the whole period of operation. The modeling results showed that battery voltage was exceeding acceptable limits for the 100-Ah lead-acid battery during most of the simulation period. Both 600-Ah and 300-Ah batteries showed acceptable voltage performance. However, the 300-Ah battery's performance was at the margin of voltage limits. So, the 300-Ah capacity lead-acid battery is not recommended. The total weight of a 600-AH VRLA battery system is estimated at 37,000 lbs.

Modeling results for 100 and 50-Ah lithium-titanate batteries are shown in Figure 25 and Figure 26. A 50-Ah battery string (644-V nominal voltage) was used in the modeling. Two parallel strings were used for 100-Ah case. The fully charged voltage is 784 V. Both 100 and 50-Ah strings showed acceptable voltage performance. Based on lithium-titanate battery simulation results, a 50-Ah lithium battery is recommended for the grid simulator application. However, it is also recommended to have room for a second 50-Ah string as a precaution. The total weight of 50-Ah lithitum-titanate battery bank is estimated at 2,200 lbs (4,400 lbs for two parallel strings).

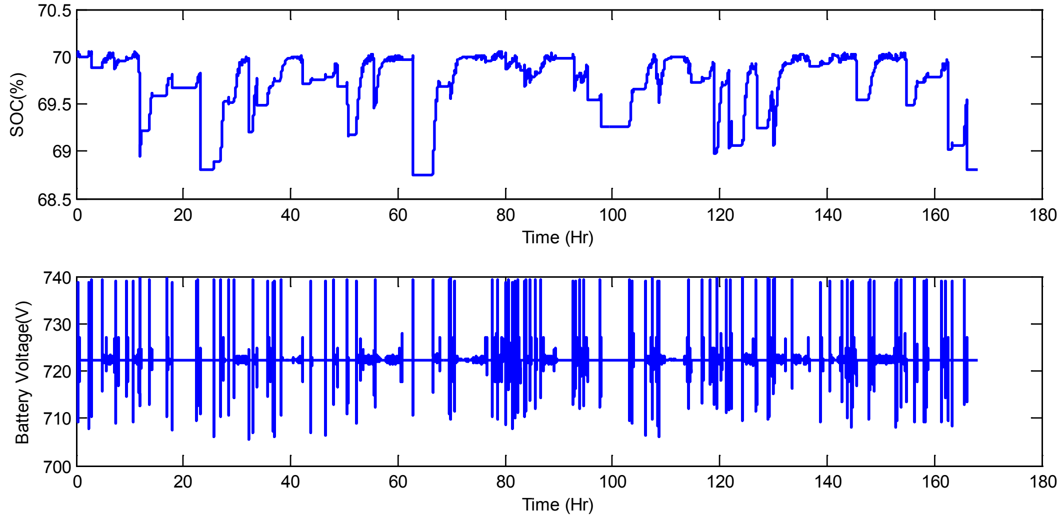


Figure 25: SOC and voltage for 100-Ah lithium battery

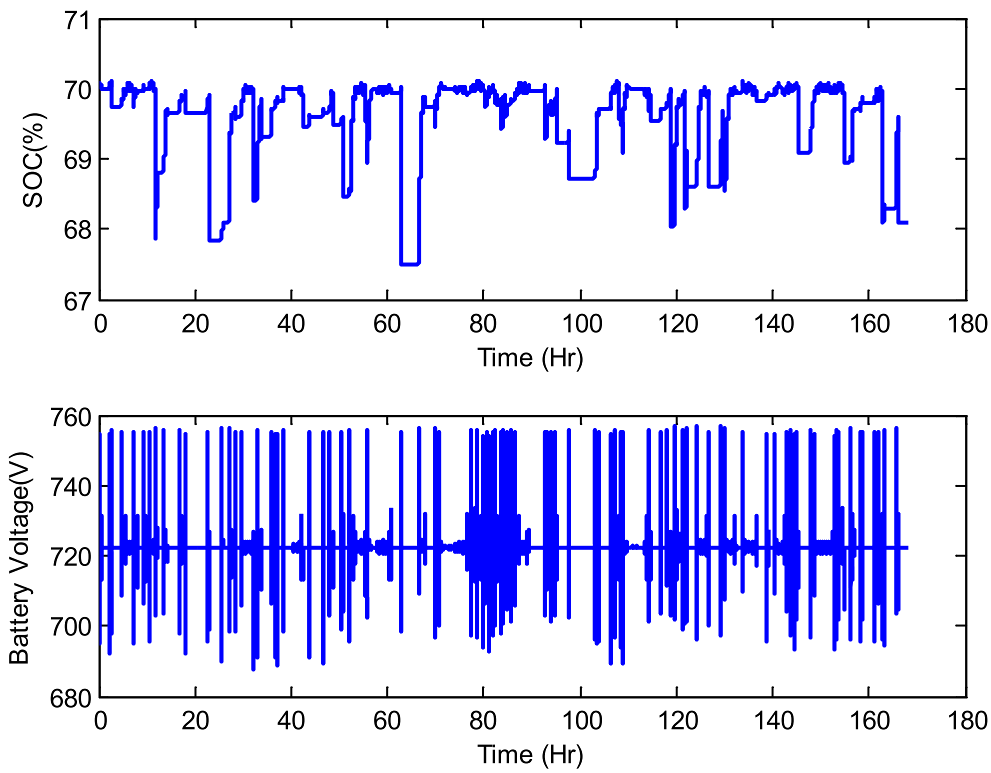


Figure 26: SOC and voltage for 50-Ah lithium battery

Appendix A

A.1 Technical Specifications

The technical specifications for the proposed battery/inverter-based grid simulator for V-27 225-kW wind turbine that will be installed on the DeepCwind floating platform were produced from transient and steady-state modeling described earlier in this report. It was also concluded earlier in this report that other possible grid-simulator solutions (such as a large diesel generator or small diesel genset with synchronous condenser) are not feasible for the application.

The list of technical requirements for various system components that are part of the battery/inverter grid-simulator option is given below:

Batteries

Lithium-based batteries were found to be the best fit in terms of both performance and weight/size limitations. Recommended lithium battery capacity is 50 Ah, based on modeling results. In case of unexpected performance problems, it would be desirable to have capability of accommodating a second parallel string of 50-Ah batteries.

Technology	Sealed lithium.
Nominal battery bank voltage	As required by the inverter.
Nominal capacity	Depends on battery type.
Maximum continuous charge / discharge current	300 A
Short-term (5 sec) pulse charge / discharge current	450 A
Operating and storage temperature range	-40…..+50^{0}C
Minimum battery cut off voltage	Up to bidder to determine.
Maximum battery cut off voltage	Up to bidder to determine.
Battery arrangement	Circular shelves around the perimeter of the column wall, see platform drawings for details.
Maximum weight of a single 50-Ah string	4400 lbs (including accessories)

Inverter

Technology	3-phase grid forming, 480-VAC voltage source, PWM modulated.
Minimum power rating	300 kVA continuous.
Maximum weight	1800 lbs
DC bus voltage range	Up to bidder to determine.
DC bus active overvoltage protection	DC chopper desirable.
Over current protection (both hardware and software), L-to-G and L-to-L trips	Circuit breakers on both AC and DC sides.
Frequency control accuracy	60 Hz ± 0.1% (±0.01% preferred)
Short-term over-current capacity	150% of full load for 5 sec every 5 min.
Enclosure	Force ventilated cabinet.
Inverter efficiency at rated load	97% minimum.
Power quality (with filters)	<5% voltage THD.

Isolation transformer/ line reactors	Transformer (480 VAC/325 kVA) or line reactors must be designed to comply with IEEE-519 on harmonic current injection (5% TDD max). In case of isolation transformer, a 1800-lbs max weight limit is applied.
Voltage imbalance	1% max.
Contingency battery charging	Possibility to charge batteries from an external portable diesel genset.

<u>Resistive (secondary) load bank</u>

Power/voltage rating	300 kVA/480 VAC– delta connected.
Maximum load step	1.5 kW (1kW preferred).
Cooling	Force ventilated cabinet.
Resistor switching method	Solid-state relays, zero crossing switching.
Maximum weight	1500 lbs.
Individual heating elements	Flange-mount tubular elements, salt water/corrosion resistant.

<u>Main Electrical Panel</u>

Main 480-AC bus, 600A	Connection point for all equipment: inverter, wind turbine, secondary load, auxiliary transformer and umbilical contingency battery-charging equipment (such as a portable diesel genset for charging the main battery bank).
Individual circuit breakers for each component	500-A molded case circuit breakers for a wind turbine, inverter, secondary load bank and umbilical (all remote trip capable) , TBD for auxiliary transformer and portable genset.
Enclosure	Industrial panel board cabinet, 1200 lbs.
Ground bus	In the case of an isolation transformer, the neutral point of wye winding must be grounded and tied up to the ground bus of the main electrical panel. In case of line reactors, the neutral point of the inverter filter can be the grounding point.

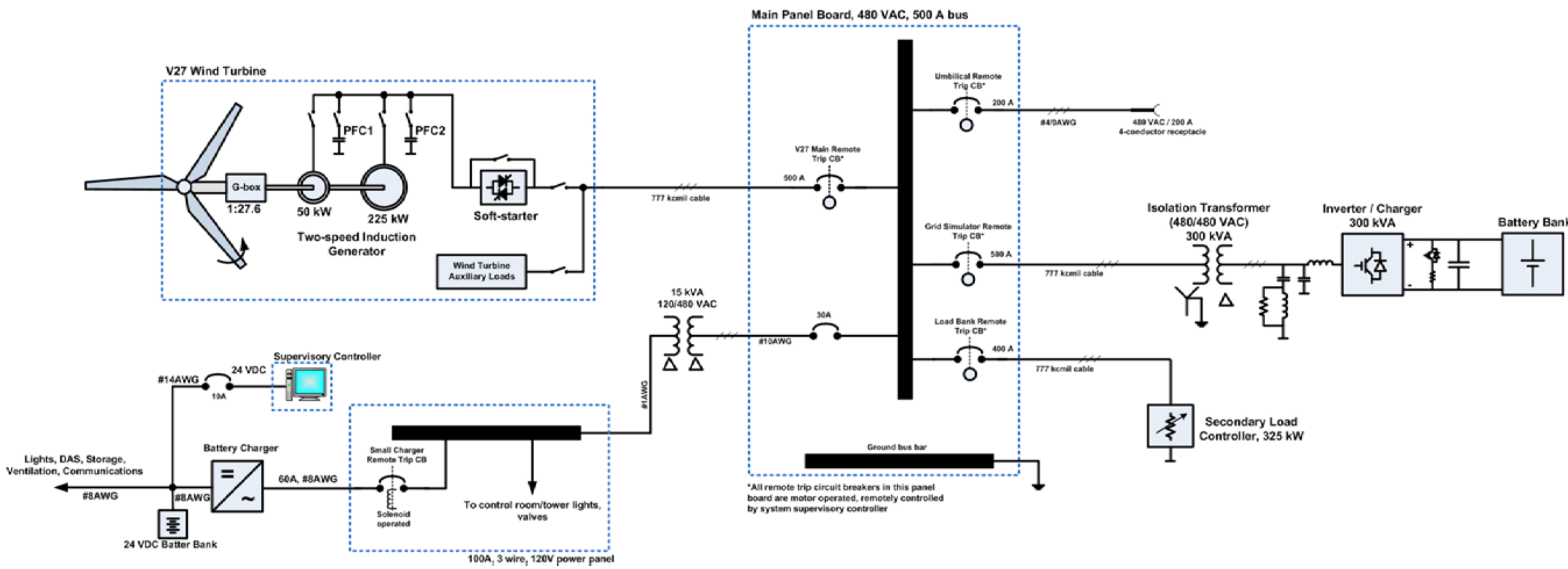
<u>Supervisory controller</u>

Secondary load bank control function (based on wind turbine power and battery SOC readings)	Control the secondary load bank to match the wind generation and simultaneous control of battery SOC by adjusting real power flow to/from battery. Maintains the battery SOC at optimum setpoint (TBD by bidder). Max response time of the controller in this mode is

	a 15 ms. Better response times are highly desirable for better performance and battery longevity. (In fact, this response time is the most critical technical parameter of the grid simulator).
Shut down the inverter during periods of no wind to preserve battery SOC (for example, shut down if turbine 10-min average power production is less than 10 kW – both time and kW thresholds must be selectable). Re-start inverter if 10-min average wind speed is greater than 7 m/s (both time and wind speed threshold must be selectable)	Signal from hub anemometer must be provided to the controller.
Monitor and log data on all power system components	List of channels TBD.
Remote wireless and two-way communication capability	Capability of two-way communication via existing satellite, Ethernet, or cell modem (part of platform DAS), time stamp synchronization capability with platform DAS, capability to send/receive data to/from platform DAS (using TCP/IP based communication protocol).
Command inverter to operate in contingency battery charging mode	Charge batteries from external portable diesel genset.
Communication with wind turbine controller	Send enable/disable command to wind turbine.
Capability to interrupt instrumentation battery charging process during periods of no wind (to preserve main battery state of charge)	Send enable/disable command to secondary charger circuit breaker.
Power supply	24 VDC preferred to match with secondary battery bank nominal voltage.

A.2 One-line Electrical Diagram

The one-line electrical diagram of proposed battery/inverter-based grid simulator is shown in this section. The main panel board is the point of interconnection of all major system components: V-27 wind turbine, inverter, secondary load, umbilical connection with portable diesel genset, and other platform loads. All these components are protected by the motor-operated remote-trip circuit breakers. All remote-trip circuits are controlled from the system supervisory controller. A choice of 777- kcmil AWG is based on flexible diesel locomotive (DLO) type RHH or RHW cables (777 kcmil allows about 545 A ampacity for three DLO conductors in a conduit at 30^0C ambient temperature; correction factors must be applied for higher temperatures). DLO cables are preferred for their flexibility and lighter weights.



V27 Wind Turbine
G-box
1:27.6
50 kW
225 kW
Two-speed Induction Generator
PFC1
PFC2
Soft-starter
Wind Turbine Auxiliary Loads
777 kcmil cable
Main Panel Board, 480 VAC, 500 A bus
V27 Main Remote Trip CB*
500 A
Umbilical Remote Trip CB*
200 A
#4/0AWG
480 VAC / 200 A 4-conductor receptacle
Grid Simulator Remote Trip CB*
500 A
777 kcmil cable
Load Bank Remote Trip CB*
400 A
777 kcmil cable
30A
#10AWG
Ground bus bar
*All remote trip circuit breakers in this panel board are motor operated, remotely controlled by system supervisory controller
Isolation Transformer (480/480 VAC) 300 kVA
Inverter / Charger 300 kVA
Battery Bank
Secondary Load Controller, 325 kW
15 kVA 120/480 VAC
#1AWG
Small Charger Remote Trip CB
Solenoid operated
To control room/tower lights, valves
100A, 3 wire, 120V power panel
Supervisory Controller
24 VDC
#14AWG
10A
Battery Charger
60A, #8AWG
#8AWG
Lights, DAS, Storage, Ventilation, Communications
#8AWG
24 VDC Batter Bank