A Comparison of Battery Charge Controller Technologies for Wave Energy Converters

Preprint

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National Renewable Energy Laboratory

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A Comparison of Battery Charge Controller Technologies for Wave Energy Converters

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***Abstract*—Wave energy is a uniquely challenging field for electrical system designers. High peak and low average power potential with a constantly varying energy input is difficult to harness and control through conventional means. To power the blue economy, low-powered wave energy converters (WECs) need batteries for energy storage. Safely and effectively charging batteries from waves requires a charge controller to properly monitor and control voltage and current going to the battery. Currently, off-the-shelf charge controllers exist for other renewable generation such as wind, hydro, and solar. Two topologies were validated: a buck converter and a pulse width modulation (PWM) charge controller. Using an in-lab dry testbed, wave energy power inputs were simulated to properly validate the effectiveness of existing charge controller technologies, identifying the shortcomings and improvements needed to effectively harness wave energy.**

***Index Terms*—wave energy, dc/dc converter, charge controller, battery storage, wave energy converter**

I. Introduction

Renewable energy sources are inconsistent and constantly varying depending on the season, time of day, and weather. In electrical power take-off systems (the means by which the renewable resource is converted into usable electrical energy), energy storage is critical for capturing excess energy at times of overproduction and supporting load demand at times of underproduction. Electrochemical storage found in batteries is a common method of storing electrical energy due to its energy density and widespread adoption [1] [2] [3] [4]. Charge controllers are power electronic modules that control the voltage and current delivered to a battery from a DC source via semiconductor switching elements to safely monitor and control the flow of energy into batteries.

Wave energy is a nascent renewable technology with promising applications in supporting emerging coastal communities, monitoring the ocean, producing green hydrogen, and powering disaster response [5]. To provide these applications with the smooth and continuous supply of electrical power they need, wave energy converters (WECs) are paired with battery storage [6] [7].

The nature of wave energy is inconsistent and instantaneously unpredictable, making it difficult to anticipate control adjustments. Additionally, wave energy is largely pulse-based, with surges of waves producing high energy potential that shortly are followed by minimal states of energy [8]. High peak-to-average power ratios force designers to size electrical components for high voltage and current conditions. Wide ranges of generator speeds require compatibility with a large range of frequencies [7]. This increases the cost and decreases the efficiency of the electrical system at average and low power conditions. While research into DC/DC converters for wave energy is abundant [1] [3] [6] [7] [8] [9], no off-the-shelf charge controllers are available for commercial use. Existing charge controllers are designed for more constant and predictable energy inputs such as wind, solar, and non-renewable generation. Although they may be rated for and work with wave inputs, they are far from optimal in harnessing the most potential energy.

The purpose of this paper is to experimentally analyze the performance of existing charge controllers in the context of wave energy, identify the best existing technology, determine shortcomings of validated charge controllers, and identify improvements to be made for future charge controller designs in the wave energy space.

II. Charge Controller Topologies Under Review

A. Buck Converter

Buck converters step down DC voltage in an adaptable and instantaneously controllable manner and can keep a DC bus constant with a variable source [11]. In solar systems, buck converters are used to achieve maximum power point tracking (MPPT), extracting the most power from solar irradiance [12]. In wind applications, buck converters control the appropriate amount of current going into the battery, provided there is enough wind energy to support the battery load, and adjust the input current and voltage to fulfill the damping requirements of the system [13].

B. Pulse Width Modulation

Pulse width modulation (PWM) charge controllers, named after the same technique utilized in buck converters, directly couple the battery to the input source via a controlled semiconductor switch. Based on the charging state and current needs of the battery, the gate signal is pulsed to precisely control energy flow [14]. PWM charge controllers are typically designed for solar inputs where the nominal voltages of the solar panel and battery are similar. PWM devices are typically cheaper per kW and implement simpler, more robust hardware and control. Improved efficiency makes MPPT buck converter type charge controllers more cost-effective over time. However, these come with an increased upfront cost [15].

III. Testbed Setup

Thorough validation of the charge controllers under test required an adaptable testbed to properly simulate wave conditions. The focus of this test was not to validate a whole WEC, but rather to focus on a specific aspect of the design. A dry in-lab testbed was developed to quickly change between charge controller setups, simulate a variety of run conditions, and adjust battery parameters quickly and without recharge.

A. Testbed Design

The designed testbed pictured in Fig. 1 consists of three major sections: generation, charge controller under test, and battery simulation. Fig. 2 shows a block diagram of the testbed.

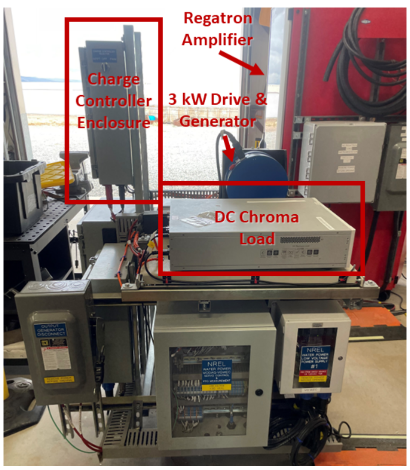

Fig. 1. Picture of testbed for charge controller validation.

1) Generation: The scope of this project is intended for off-grid applications requiring battery storage such as water desalination, ocean monitoring, and power for emergency response equipment. A servo motor was coupled to a 3-kW custom generator. The nameplate ratings are found in Table I. Artificial wave profiles were programmed into the servo motor controller and provided the generator with constant speed, sinusoidal, and realistic irregular wave cases. The three-phase output of the generator was fed through a passive diode rectifier. The resulting DC bus was supported by a 4300 μF capacitor to reduce voltage ripple into the charge controller.

2) Charge Controller: A buck converter charge controller and a PWM charge controller were validated using the designed testbed.

a) Buck Converter Charge Controller: The ratings of the buck charge controller can be found in Table II. This charge controller is designed for use with solar, wind, and hydro inputs with a variety of control strategies including MPPT for solar, dump load control, and power curve tracking. Power

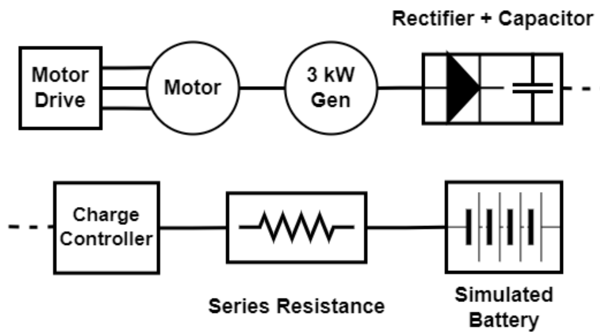

Fig. 2. Simplified block diagram of testbed for charge controller validation.

TABLE I
INNOTEC 3-KW GENERATOR NAMEPLATE RATINGS.

Nominal Power	3 kW
Speed	1000 rpm
Pole Pairs	9
Rated Voltage	120 V
Rated Current	25 A
Phases	3

curve tracking is best suited for wave energy to properly damp the system. In this mode, the charge controller follows a user-defined curve made up of 16 corresponding voltage and current points. Based on the measured output current flowing in the battery, the duty cycle is adjusted to correct the input voltage from the DC bus. Four custom wind power curves were used for experimentation in a 24-V nominal system: a gentle curve that slowly increased current and voltage, an aggressive curve that quickly increased current and voltage, a medium curve that lies between the gentle and aggressive curves, and a linear curve that increases voltage and current at a constant rate. The custom wind curves programmed into the charge controller are plotted in Fig. 3.

TABLE II
RATINGS FOR BUCK CONVERTER AND PWM CHARGE CONTROLLERS.

	Buck	PWM
Input Voltage	150 V + Battery Voltage	68 V
Output Current	94 A	60 A
Rated Power	700 W	4080 W

b) PWM Charge Controller: The ratings of the PWM charge controller can be found in Table II. Intended for use in solar systems, this charge controller controls the charging of batteries, supply to load, or diversion load control. The specifications of this charge controller are found in Table II. To focus on comparing the battery charging capabilities of the controllers, only the charging mode was validated.

3) Battery Simulation: Batteries introduce variability in an experiment due to inconsistent state of charge, temperature, and age. To reduce safety risks and data inconsistency, battery emulation was used in place of real batteries.

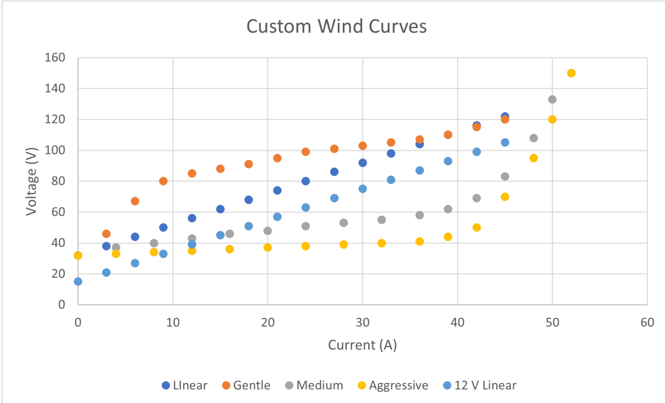

Fig. 3. Plots of custom wind curves programmed into the buck converter charge controller.

To realize a battery emulator, a Typhoon hardware-in-the-loop real-time digital simulator was paired to a Regatron power amplifier. The Regatron and Typhoon combination is able to act as a current or voltage source/sink. Ideally, the Regatron would act as a current sink, drawing the correct amperage based on measured input voltage from the charge controller. At idle state, there would be no battery voltage feedback and the charge controller would refuse to start operation. Using the Regatron as a voltage sink, the charge controller and Regatron voltages would track each other and result in no current flow. To create a current sink with voltage feedback, a series resistance of 0.25 Ω was added in line with the charge controller and Regatron using a variable DC load. As shown in Fig. 4, the battery model outputs a current command. A PI controller compares the model current to the physical current and commands a voltage to the Regatron to create a potential difference across the series resistance and drive current. At system idle, the PI controller commands battery voltage to achieve zero current.

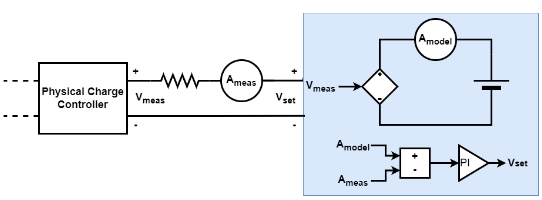

Fig. 4. Battery emulator line diagram.

A 24-V battery was simulated with a capacity of 80 A-h, internal resistance of 0.0075 Ω, and full charge voltage of 116%. Only a lithium-ion battery chemistry was considered for its superiority in pulse-based wave energy applications.

B. Wave Cases

Two broad categories of energy inputs were used to validate the charge controllers: sinusoidal waves and irregular waves. A matrix of sinusoidal wave inputs in Table III characterized the performance of the charge controllers in a predictable sea state. Irregular wave cases were created with a sum of sinusoidal inputs to represent realistic sea states with varying peak generator speeds and frequencies. Table IV lists the irregular wave cases tested by period and the significant peak speed of the generator.

TABLE III
SINUSOIDAL WAVE CASES CHARACTERIZED BY THE WAVE PERIOD AND PEAK SPEED OF THE GENERATOR.

Buck		PWM	
Wave Period (s)	**Peak Speed (rpm)**	**Wave Period (s)**	**Peak Speed (rpm)**
5	150	5	150
9	350	9	200
12	550	12	230
15	750	15	260
20	950	20	290

TABLE IV
IRREGULAR WAVE CASES CHARACTERIZED BY THE WAVE PERIOD AND SIGNIFICANT PEAK SPEED OF THE GENERATOR.

Wave Periods (s)	Peak Speed (rpm)
5	300
10	600
15	750
20	

IV. Test Results

A. Sinusoidal Wave Cases

Sinusoidal wave cases characterize the response of the charge controller over the cycle of a predictable, smooth changing wave. Crucially, sinusoidal cycles record the system response during state transients as the wave rises and falls.

1) Buck Converter Charge Controller: Fig. 5 displays key waveforms of the charging system using the buck converter charge controller programmed with the linear custom wind power curve. A sinusoidal wave input with an maximum generator speed of 750 rpm and period of 12 seconds was used in this run.

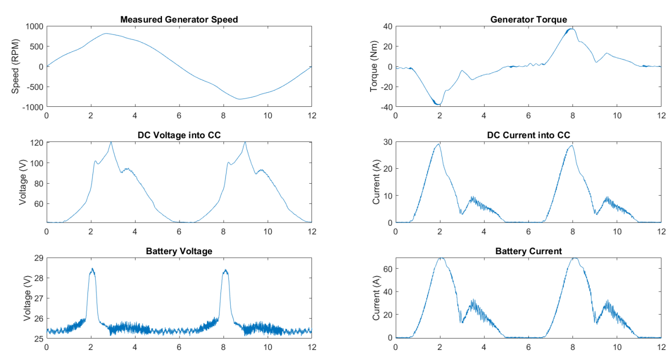

Fig. 5. Key parameters using a linear custom power curve programmed into the buck converter charge controller during a sinusoidal wave case of 750 rpm amplitude and 12-second period.

a) Cut-In Voltage: Because the buck converter charge controller can only step down voltage, it is only able to provide current to the battery when the input voltage is greater than that of the battery charge voltage. This cut-in-voltage is 30% higher than the battery voltage, or 31.2 V for 24-V systems. This eliminates power production when sea states are below the threshold voltage.

When the DC bus voltage into the buck converter charge controller exceeds the threshold voltage, the charge controller activates and pushes charge into the battery. When the DC voltage falls to the threshold voltage, current is cut to the battery and the bus capacitor holds the voltage at threshold level. The band of operation is dictated by this threshold voltage, as no power can be produced below. Fig. 6 displays the commanded wave profile with the power flowing into the battery. The battery is charging between 0.11π to 0.82π and 1.11π to 1.84π radians of the sin wave, or 72% of the time.

b) Current Overshoot: An unexpected phenomenon experienced with the buck charge controller was a large current overshoot seen after the controller first reached the threshold voltage. Seen in Fig. 5, the current flowing into the battery rapidly climbed to a peak value of 68 A, despite the input DC bus voltage to the charge controller increasing from 41 V to 70 V during this time. Per the programmed curve, the corresponding current at this point was expected to be 18 to 21 A. Effects of the current spike were observed throughout the system, causing a similar dual-peak shape in the mechanical torque on the shaft and momentary departure from the commanded speed of the generator.

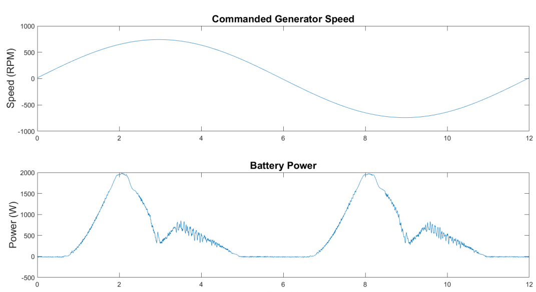

Fig. 6. Power to the battery over one period of sinusoid with 750 rpm amplitude and 12-second period using custom linear power curve.

The effect of current overshoot differed based on the wave conditions. Fig. 7 plots the linear wind curve in three instances for a fixed wave amplitude of 550 rpm: 15, 12, and 9 seconds. When the wave period is long, the charge controller is able to track the wave and produce current to the battery without overshoot. When the wave period is short, the current is unable to correct in time before the wave cycle is complete, causing the entire profile to be comprised of overshoot. Similar results were found with wave cases of higher amplitude.

The buck charge controller was designed to be used in wind applications where large variations in generator torque occur more slowly and are less frequent than those in wave. When given a comparatively quick-changing voltage, control mechanisms that are tuned for slow rates of change are unable to make timely adjustments to the gate signal duty cycle. The set duty cycle lags behind an increasing voltage, causing the large overshoots. The greater the rate of change from shortened periods or greater amplitudes, the more drastic the effects of control lag are. This is not necessarily a limitation of buck converters, but is a limitation of available charge controllers using this topology.

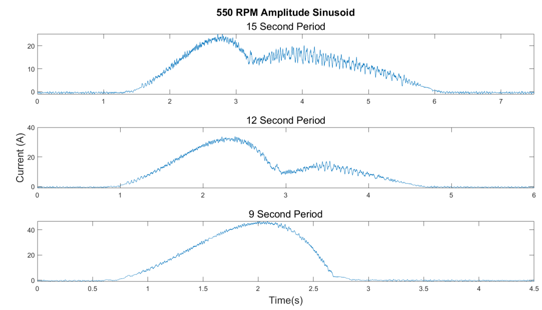

Fig. 7. Battery current with buck charge controller with sinusoidal waves at 550 rpm and varying periods.

c) Charge Controller Failure: Introducing the buck charge controller to increasingly more energetic wave conditions proved fatal for the hardware. At a sinusoidal wave condition with a peak of 1000 rpm and period of 15 seconds, the charge controller experienced a catastrophic failure and was rendered inoperable. The cause of the failure can be seen in Fig. 8. As generator speed increased, the same current overshoot from the previous section was experienced. At this rate of change and peak amplitude, the over current protection of the Regatron, set at 80 A, tripped. This caused the battery current to suddenly drop to zero. This sudden drop of the load corresponded to a drop in motor torque that caused a sudden ramp in generator speed. Before the motor drive was able to adjust and return to the correct speed, the DC bus voltage reached 231 V. Because the charge controller was not drawing current, the bus capacitor after the rectifier held the voltage at this level. Exposed to extended voltage higher than its rating, the charge controller failed.

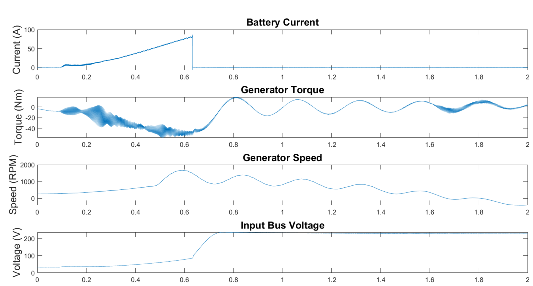

Fig. 8. Failure of buck charge controller at an energetic wave condition.

During a water deployment of a WEC, the same sequence of events can happen. The over current protection of the Regatron is similar to battery fuses. If the battery is charged above its rated current, a fuse will suddenly blow, stopping current. As the system instantaneously becomes under-damped, the WEC will become more buoyant and overspeed the generator, causing the same cascade of events seen in lab testing.

d) Wave Case Comparison: Fig. 9 gives a matrix of average power to the battery in watts over a variety of sinusoidal wave cases using the buck charge controller programmed with the gentle, medium, aggressive, and linear power curves, respectively. When the curve is programmed more aggressively, the charge controller is unable to survive in more energetic conditions due to large current overshoots described in the previous section. In survivable cases, these aggressive curves produce more power and are generally active for a greater portion of the wave.

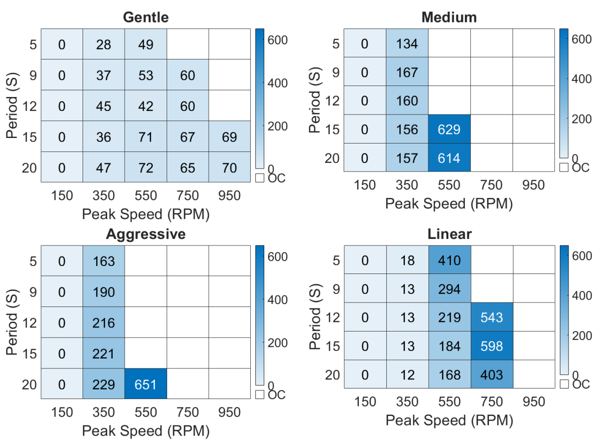

Fig. 9. Average power into the battery with the buck converter charge controller programmed curve over various sinusoidal wave amplitudes and periods.

2) PWM Charge Controller: Fig. 10 displays the key waveforms for the PWM charge controller over one fundamental cycle of a sinusoidal waveform with peak speed of 290 rpm and period of 12 seconds. The topology of the PWM charge controller couples the output of the generator and battery directly, forcing the battery and DC bus voltage to be the same. Over a wave period, the only fluctuation in DC bus voltage is what the charge controller commands to raise the battery voltage for charging. The threshold voltage of the PWM charge controller is equal to the battery voltage, as opposed to 30% above the nominal value, as it is for the buck converter.

The current going into and out of the charge controller is identical due to the direct connection of source and load. As the generator speed increases, the controller draws more current to hold the voltage at the desired level to charge the battery. The current overshoot seen with the buck charge controller is absent with the PMW charge controller. The PWM charge controller is not as controllable as with using custom wind curves with the buck charge controller. However, it is more predictable and stable than its buck converter counterpart.

a) Limitations on Operation Range: A major limitation of the PWM charge controller is the narrow operating band.

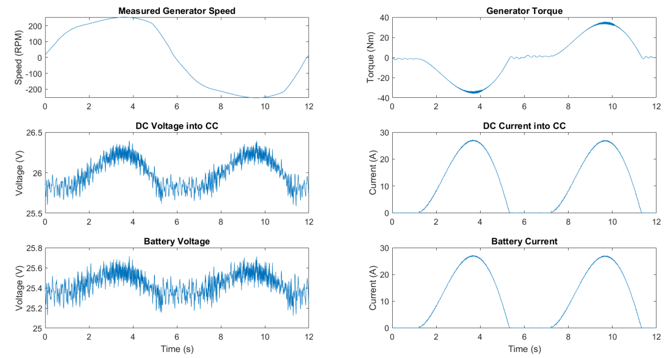

Fig. 10. Key parameters using the PWM charge controller during a sinusoidal wave case of 290 rpm amplitude and 12 second period.

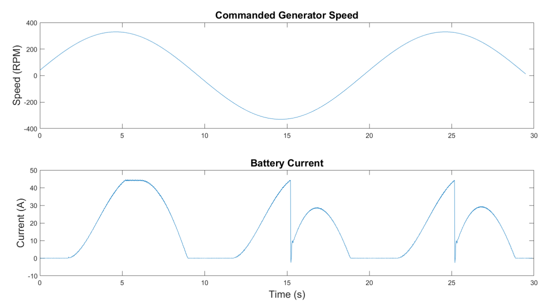

Fig. 11. Battery current collapse of PWM charge controller at 330 rpm.

When the charge controller current reaches its 45 A rating, it is unable to properly limit the voltage created from additional generator speed. Fig. 11 is the battery current corresponding to a sinusoidal waveform with an amplitude of 330 rpm and 20-second period. The current waveform becomes unstable and momentarily drops to zero. The torque, speed of the generator, and DC bus voltage correspondingly drop, restoring a stable operating range. A hard ceiling limit in the charge controller operation is created as a result. Paired with the battery voltage as a floor of operation, this limit results in a narrow range of potential power production.

b) Wave Case Comparison: Fig. 12 gives a matrix of average power into the battery over a wave cycle as well as the percentage of time the charge controller was active. The PWM charge controller was able to produce more power in comparable wave conditions than the buck converter charge controller and could operate in less energetic wave conditions, due to its lower cut-in voltage.

B. Irregular

While sinusoidal wave inputs are able to characterize the system response to a changing input, the likelihood of a perfectly sinusoidal wave state in the ocean is exceedingly low. Irregular inputs as described in section III-B is run on the drive connected to the generator.

1) Buck Converter Charge Controller: Considering an irregular wave case with a fundamental period of 10 seconds

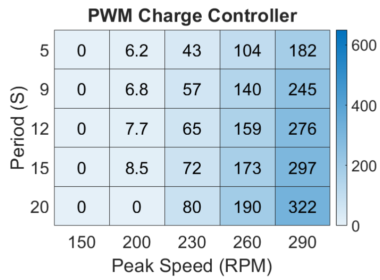

Fig. 12. Average power into the battery with the PWM charge controller over various sinusoidal wave amplitudes and periods.

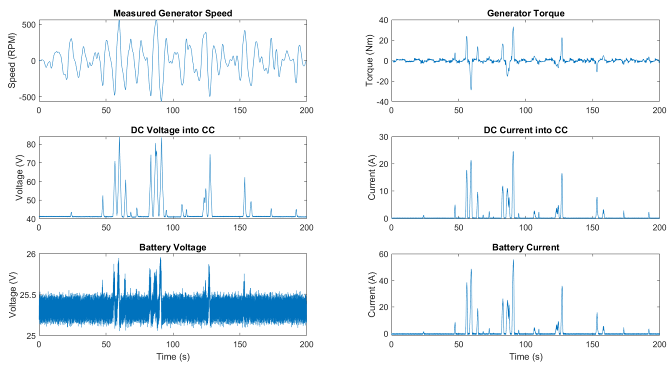

Fig. 13. Key parameters using a linear custom power curve programmed into the buck converter charge controller during an irregular wave case with significant peak of 600 rpm and 10-second period.

and significant wave height corresponding to 600 rpm seen on the generator and using the linear custom power curve, Fig. 13 depicts key variables measured in the system over 200 seconds. Over the measured interval, approximately 1.65 Wh was added to the battery averaging 30 W production. Power was produced for 35 seconds, or 17.5% of the interval.

Fig. 14 zooms in on a section of the measured interval and plots the commanded generator speed with power flowing into the battery. Despite the wave having energy-producing potential, the charge controller is only able to activate during the most energetic peaks and is idle for most waves that pass through. The current overshoot that is present in section IV-A is seen during energetic waves with relatively high peaks and short periods.

Fig. 15 outlays the average power delivered to the batteries using the buck charge controller with the four custom curves. As with the sinusoidal cases, more aggressive curves are able to extract a greater amount of power, but they are unable to survive energetic wave conditions without experiencing excessive current overshoot. The average power delivered to the battery in every wave case is orders of magnitude less than the rated power of the system.

2) PWM Charge Controller: An irregular wave with a fundamental period of 10 seconds and significant wave height corresponding to 300 rpm is run with the PWM charge controller and plotted in Fig. 16. As seen in sinusoidal testing,

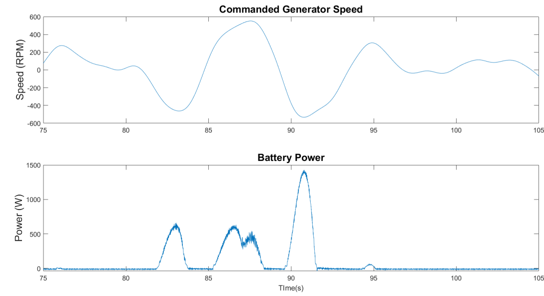

Fig. 14. Power delivered to the battery with linear custom power curve programmed into the buck converter charge controller during irregular wave condition.

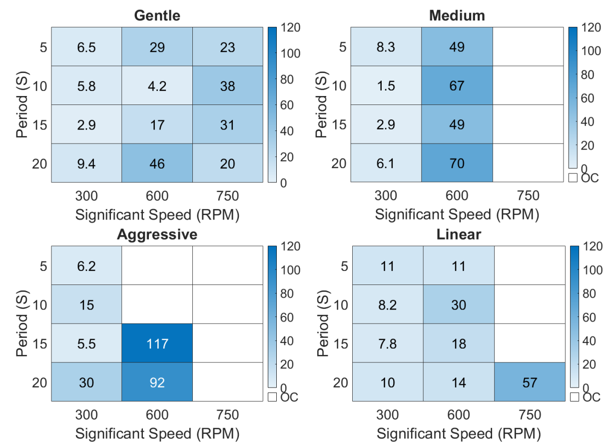

Fig. 15. Average power delivered to the battery in varying irregular wave cases using the buck converter charge controller.

the DC bus voltage going into the charge controller is held at battery voltage by the controller by controlling current into the battery. This current is smooth and corresponds to a smooth torque waveform seen on the generator shaft. This relationship can be seen more clearly in Fig. 17, showing the plot of variables over a 20-second interval. Over the course of the 200-second wave condition, an average of 69 W power was added to the battery.

a) Comparison to Buck Converter Charge Controller: The average power produced using the PWM charge controller over a variety of irregular wave cases is shown in Fig. 18. The charge controller was able to survive only during wave cases with significant peak of 300 rpm, unlike the buck charge controller that was able to operate at more energetic cases. However, at the same 300 rpm conditions, the PWM charge controller was able to produce more power.

For each wave case, the PWM charge controller was able to charge the battery for a longer amount of time over the period and added more power to the battery. The PWM charge controller was unable to survive at more energetic wave states like the buck converter converter could, severely limiting its operation for deployments in a variety of sea states.

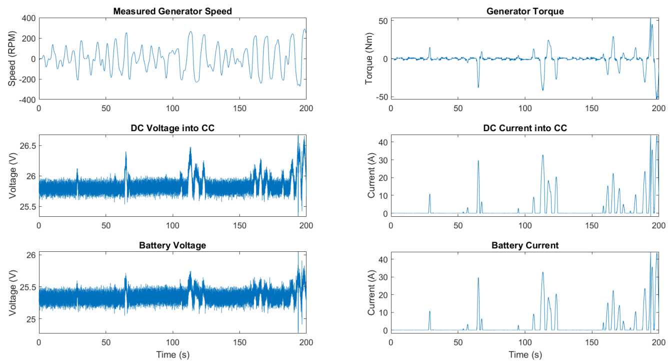

Fig. 16. Key parameters using the PWM charge controller during an irregular wave case with significant peak of 300 rpm and 10-second period.

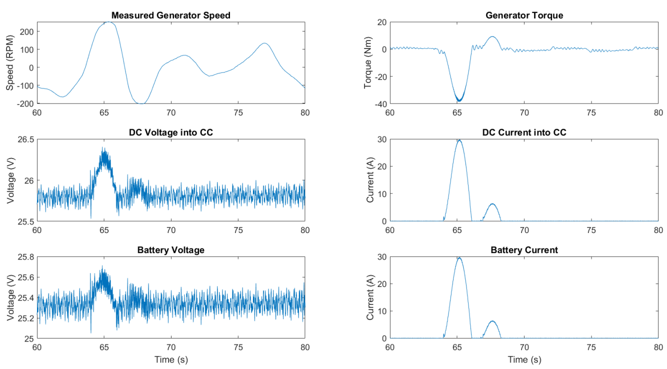

Fig. 17. Zoomed plots of key parameters using the PWM charge controller during an irregular wave case with significant peak of 300 rpm and 10-second period.

V. Discussion

A. Buck Converter Charge Controller

The buck charge controller is an effective charge controller in the spaces that it was designed for—namely, solar, wind, and hydro power. These energy sources share the common characteristic of having a relatively stable input, unlike that seen in wave energy. The buck charge controller accommodates a large range of input voltage, allowing designers of electrical wave energy power take-off systems to use this controller without much control to the DC bus outside of correct generator and rectifier sizing. The buck charge controller offers sophisticated control and protection mechanisms. Custom power curves give designers regulation of system damping, adjusting current draw based on the input voltage. Versatile hardware topology and control strategies give it the ability to work with different energy sources adjustable by the user.

Many of the benefits of the buck converter topology and control strategies of the controller are forfeited when faced with the challenges of wave energy. The wide operational input voltage is beneficial during consistently energetic waves. However, a buck converter is only able to reduce voltage, rendering the charge controller inoperable until a wave is strong

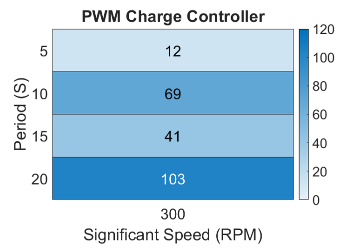

Fig. 18. Average power delivered to the battery over varying irregular wave cases with the PWM charge controller.

enough to increase the bus voltage past this point. As seen in the realistic irregular wave cases, this limitation severely reduced the controller's operation time. The customizability and sophisticated control of the controller works for longer, less energetic waves, but it is too slow for quicker waves. Wave energy requires instantaneous measurement and adjustment to keep up with the ever-changing wave. Large current overshoot and repeated voltage stress can significantly reduce the lifespan of the controller. Slow control and sudden cut-in of the controller causes unpredictable and choppy damping of the system. A well-damped WEC will see smooth torque to the generator and keep the buoyancy of the device steady. The choppy torque seen in testing would constantly change the buoyancy of the WEC, causing a jerky motion that is not ideal.

To use the buck converter charge controller effectively in wave energy, an active boost stage is needed to raise the bus voltage to cut-in. Increasing the AC output of the generator via increased windings or a transformer stage will cause the DC voltage to reach the minimum threshold more often but will result in higher peak conditions that exceed the charge controller ratings. To counter the effects of current overshoot and over-voltage, a surge protector is needed to dump excess energy. Fast-blow fuses and/or breakers are required to protect high current spikes but will require replacement and maintenance.

B. PWM Charge Controller

The PWM charge controller is a simpler controller than the buck converter controller, both in hardware topology and control. The PWM controller offers a smooth, predictable current draw from the generator. Additionally, the charge controller is active at exactly the battery voltage, allowing for a lower cut-in than with the buck controller.

Designed for use with solar cells that have matching nominal voltages with the battery, the PWM charge controller has a very limited operating band. The controller is able to adjust slight differences between the actual voltages. When the input voltage is highly variable, such as with wave energy, the survivable range past cut-in voltage is very slim. Due to the direct connection, the generation source is held at the battery voltage. When generation is via rotary generator, current is increased to limit voltage, increasing torque significantly to the generator. The drive used in lab testing is able to provide this torque, but in ocean deployment this will result in overdamping and submersion of the WEC.

To use the PWM charge controller effectively, a buck stage is needed before the controller to keep the input voltage within the slim operational band. Additionally, increasing the AC voltage or boosting the DC bus at low energy wave conditions will bring the input voltage within range and increase operation time. The additional conversion stages would result in an unrealistic design due to unnecessary redundancy, increasing cost and decreasing reliability and efficiency.

C. Comparison

The buck charge controller is not ideal for wave energy, and the PWM charge controller is likely not viable for wave energy. Although the PWM controller was able to function in lab conditions, it would be unable to survive in deployment or with realistic waves without excessive support from conversion stages and control, at which point it becomes a redundant step before the battery. The buck charge controller is able to work and survive physical deployment and realistic wave conditions, but it is ineffective without an additional boost stage due to its high cut-in voltage and slow control.

D. Future Improvements

For a charge controller to be effective and viable for a WEC, it must overcome two main challenges: decreasing cut-in threshold and increasing efficiency at average power while still surviving at peak power. Many existing controllers on the market use buck converters, tailored for solar and wind where output from the generator can be designed to exceed the battery voltage. Some DC/DC converters explored in literature designed for wave energy use boost DC/DC converters [7] [10]. These converters improve the threshold voltage and are able to capture low-energy wave power, but they are required to dump load to remain within the operation region of the power electronics during high-energy wave conditions. A buck/boost DC/DC converter such as the one seen in [16] can boost voltage during times of low energy and buck voltage at high energy, but it loses efficiency at maximum gain. Further complexity in converter design should be done iteratively to progress the technology available for wave energy.

VI. Conclusions & Recommendations

Wave energy presents unique and difficult challenges for power electronics designers. Existing off-the-shelf components are designed for other renewable sources and are ill-suited to the quick-changing, stochastic nature and wide operating range of waves. Both the buck converter charge controller and the PWM charge controller have advantages and disadvantages, but the PWM controller is unable to survive realistic wave conditions due to its critically slim operation band. The buck charge controller is able to work with a wave input, but it is ineffective and unable to absorb energy unless conditions are highly energetic. Further effort is required to produce a viable charge controller for wave energy and meet the challenges of wave energy. Iterative research into known and novel DC/DC converters will increase the power potential of the ocean.

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