Clean High-Energy-Density Mini-Scale Renewable Power Generation and Energy Harvesting Systems

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ABSTRACT

We perform various tasks in design, optimization, analysis, evaluations and characterization of *clean* energy renewable power generation systems. These scalable systems can be used as mini-scale and *light-duty* auxiliary, portable and self-sustained power systems in various applications, such as, aerospace, automotive, biotechnology, medical, communication, marine, robotics, etc. Our objectives are to: (1) Guarantee highly efficient mechanical-to-electrical, electrical-to-electrical and electrical-to-chemical energy conversions; (2) Ensure superior wind and hydro energy harvesting capabilities; (3) Advance energy sources capacities; (4) Enable electric machinery and power electronics solutions, etc. We design highly efficient *clean* high-energy-density power generation systems.

Keywords: *Clean* energy, energy conversion, power generation, renewable energy

1. INTRODUCTION

Advanced solutions must be applied to design *clean* power generation, energy harvesting and energy storage systems which guarantee high power and energy densities, efficiency, robustness, safety, reliability, scalability and sustainability [1]. A modular system organization, applicable to a wide class of auxiliary and portable power systems, must be designed. The major efforts should be focused on guaranteeing overall consistency and coherency of various design tasks, solutions and technologies.

The proposed high-energy-density systems, findings and solutions are substantiated by performing experimental studies, verification, testing and characterization. By using relevant application-specific adjustments, the designed systems guarantee superior performance, enabled capabilities, affordability and sustainability in various applications. The prototypes of integrated power generation systems are evaluated in expanded operating envelopes. We achieved; (i) High power and energy densities; (ii) High efficiency; (iii) Robustness; (iv) Safety and affordability. The proposed solutions are scalable from mini- (starting from μW) to light- and medium-duty auxiliary and portable power and energy systems.

2. POWER GENERATION SYSTEMS

The proposed *clean* power generation system consists of energy harvesting, energy conversion and energy storage subsystems. The system is comprised from the following modules:

1. Turbine or other prime mover;
2. High power density permanent-magnet brushless synchronous generator;
3. Power electronic module;
4. High-performance energy storage unit.

This power generation system utilizes a minimal-complexity modular organization as reported in Figure 1. Advanced solutions, enabling technologies and best practice are used to design and select optimal-performance subsystems, units and components. For example, a practical power electronic module should include the following major components:

- Controlled or uncontrolled rectifier;
- Soft-switching dc/dc PWM converter;
- Controllers, sensors and filters;
- Chargers;
- Signal conditioning and monitoring circuitry; etc.

The electrical energy can be stored by high-energy-density rechargeable batteries, super-capacitors (double-layer capacitors), etc.

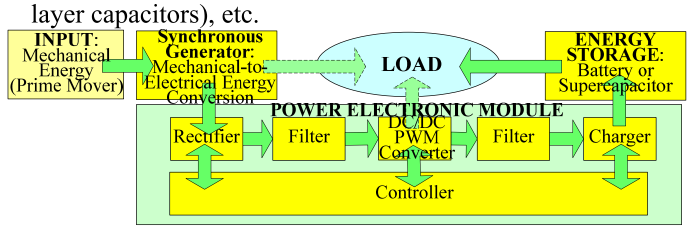

Figure 1.Modular organization of a power generation system

As illustrated, the induced phase voltages of a permanent-magnet synchronous generator are supplied to a rectifier. The rectifier converts *ac* voltage to *dc* voltage. The angular velocity of turbine and generator varies. The varying induced voltage is stabilized by using a controllable rectifier and converter. The *LC* filters are aimed to attenuate undesirable voltage and current ripple and chattering. The stabilized *dc* voltage is supplied to a charger which charges the battery or super-capacitor using a specified mode within a battery-specific allowed or optimal current-voltage profiles [2]. Controlled rectifiers,

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PWM converters and chargers are designed with build-in proportional and proportional-integral analog controllers, decision-making, health-monitoring and indicator circuits.

3. SYNCHRONOUS GENERATOR

The consistent analysis is performed for many-pole commercial and newly designed generators. Synchronous generators with high number of poles P guarantee high power and energy densities due to high torque and electrical angular velocity.

The permanent-magnet synchronous generators induce phase voltages as *motional emf*. Using the electromagnetic field intensities (**E** and **B**), *effective* length **l** and area **s**, one has [3, 4]

$$emf = \oint_l \mathbf{E} \cdot d\mathbf{l} = \oint_l (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{l} - \oint_s \frac{\partial \mathbf{B}}{\partial t} d\mathbf{s} \, .$$

High-fidelity analysis, nonlinear design and optimization of synchronous machines are performed. Permanent-magnet synchronous generators (which are available from μW to sub-megawatt) guarantee better performance as compared to other DC or AC electric machines. The images of some examined high-performance axial and radial topology generators with the outer diameter from ~2 mm to ~10 cm are documented in Figure 2. These medium- and high-speed generators (mechanical angular velocity ω_{rm} varies from ~100 to 20,000 rad/sec, ~1 mW to ~100 W) induce two- and three-phase *ac* voltages from 5 to 100 V. The aforementioned generators are characterized by:

1. Optimal electromagnetic and mechanical designs;
2. Enabled permanent magnets arrays;
3. Use of rare-earth magnets (SmCo and NdFeB) which ensure very high energy densities $BH_{\max}$.

These generators guarantee:

1. Significant overloading capabilities with the achievable $P_{\text{peak}}/P_{\text{rated}}$ ratio from 5 to ~10 during a short-period (few minutes);
2. Ideally-sinusoidal induced *ac* voltage in the full operating envelope, including peak load operation.

The experimental results for a three-phase 40 W (rated) permanent-magnet synchronous generator at the rated and peak loads are reported in Figure 3. The angular velocity of a prime mover significantly reduces as peak loads are applied. As illustrated, ω_{rm} is reduced from ~500 to 300 rad/sec). The sinusoidal *ac* voltage guarantees: (i) High efficiency; (ii) Significant losses reduction; (iii) Harmonic distortions avoidance; (iv) Low noise, vibration and heat; (v) Optimal rectifier operation due to ideal solid-state device loading with minimal stresses; etc.

We performed a comprehensive analysis for a class of *light-duty* portable power generation systems. The applied high-performance permanent-magnet brushless synchronous generators are uniquely suited and a preferable choice for high power energy densities, power generation, and energy harvesting systems. Additional requirements (power, prime mover velocity, load profile, etc.), rationale, considerations (safety, affordability and other), performance (efficiency, stability, etc.) and capabilities are specified and must be applied. The aforementioned factors define a type of generator used (ac or dc), motion (rotational or *linear*/translational), generator topology (radial or axial), as well as other features. The consistent, cohesive and coherent analysis must be performed.

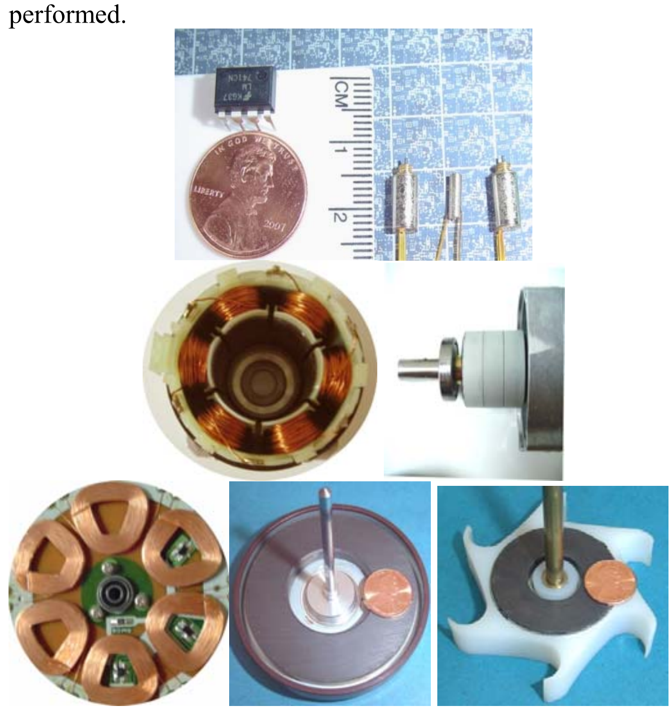


Figure 2. High-performance permanent-magnet radial and axial topology synchronous generators

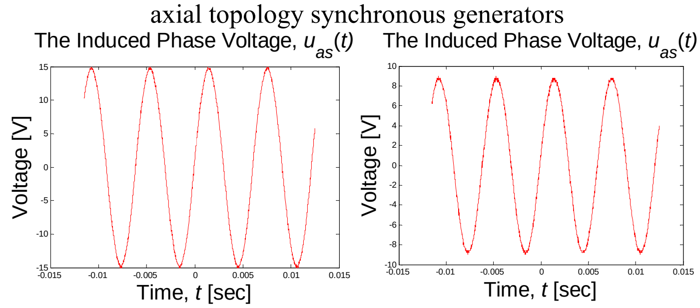


Figure 3. The induced phase voltages in a three-phase synchronous generator ($i_{\text{Load rated}}$=2 A and $i_{\text{Load peak}}$=4 A)

4. EXPERIMENTAL RESULTS FOR *CLEAN* POWER GENERATION SYSTEMS

Using a modular organization and systematic syntheses, various mini-scale and *light-duty* renewable power generation systems are designed. All system components and modules were selected using a consistent analysis.

Consider a power generation system prototype which includes the following major modules: A three-phase brushless synchronous generator (40 W rated, 600 rad/sec, 40 V), a three-phase rectifier, two band-pass *LC* filters, LT1070 *buck-boost* converter, and, battery-specific chargers. For example, the LT1510 PWM battery charger (2 to 20 V, 1.5 A) supports *constant-current* and *constant-voltage* modes ensuring fast charging of various rechargeable batteries such as lithium-ion, nickel-metal-hydride and nickel-cadmium.

We examined an expanded operating envelope due to different loads (predefined by the battery state-of-charge and charging mode), angular velocity, temperature, etc.

The operating envelope is mainly defined by:

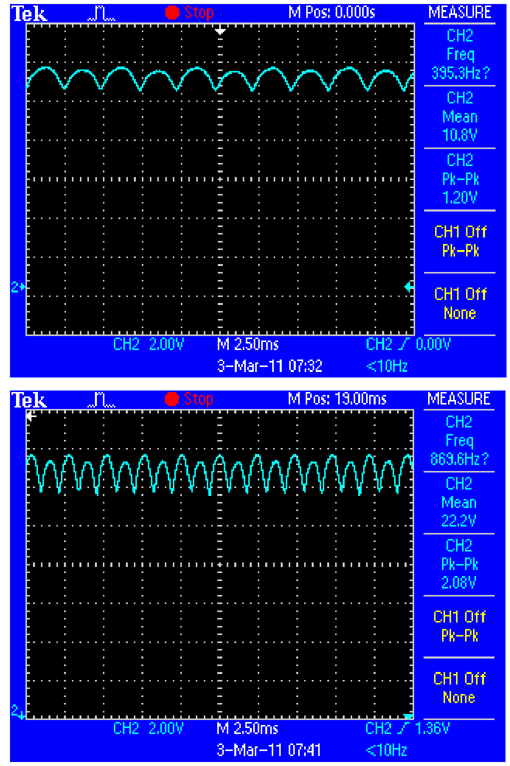
1. Voltage manifolds $V_j \in [V_{j\,\min} \;\; V_{j\,\max}]$;
2. Current manifolds $i_j \in [i_{j\,\min} \;\; i_{j\,\max}]$;
3. State-of-charge manifold $\mathrm{SoC} \in [\mathrm{SoC}_{\min} \;\; \mathrm{SoC}_{\max}]$;
4. Angular velocity manifold $\omega_{rm} \in [\omega_{rm\,\min} \;\; \omega_{rm\,\max}]$;
5. Temperature manifold $T_j \in [T_{j\,\min} \;\; T_{j\,\max}]$.

Here, the subscript j corresponds to the voltages, currents and temperatures of the generator, rectifier, converter, battery charger and battery.

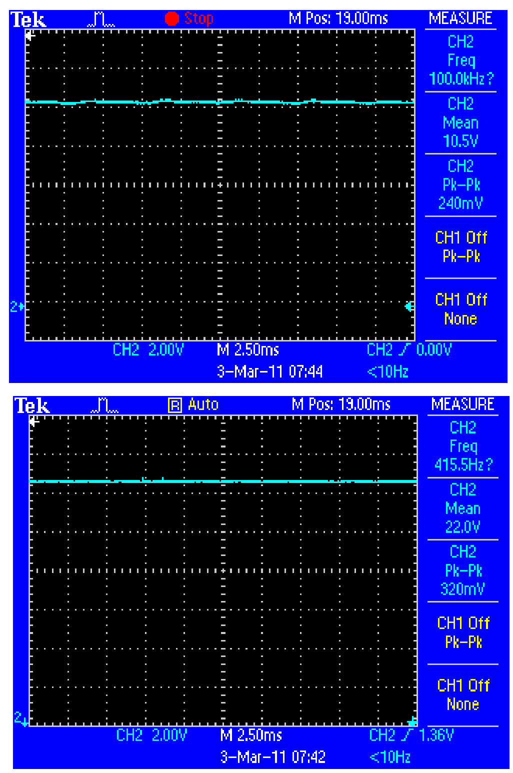
At the rated and peak loads, the experimental results are documented in Figures 4 to 7. Figure 4.a reports the rectified voltage at the output of the rectifier terminal. To eliminate the voltage variations and ensure a constant *dc* voltage supplied to the *buck-boost* converter, a band-pass *LC* filter is inserted. The resulting *dc* voltage across the capacitor of the *LC* filter is illustrated in Figure 4.b.

The dc/dc PWM *buck-boost* converter provides an ability to regulate and stabilize the output voltage to the desired value. Due to the voltage and current spikes and chattering, the output band-pass *LC* filter is inserted after the *buck-boost* converter. The voltage waveforms without and with the output band-pass *LC* filter are documented in Figure 5. Depending on the angular velocity of rotation in the operating envelope $\omega_{rm} \in [50 \;\; 1000]$ rad/sec, the induced phase voltages of the generator, and, the output voltage of the rectifier vary from 5 V to 100 V. Figure 6 reports the voltage stabilization to the desired value $V_{\text{converter}}$=15.5 V if the rated and peak loads are applied. The voltage is stabilized by utilizing a *buck-boost* converter. As illustrated in Figure 6, up to the rated loads ($i_{\text{converter}}$=1 A) and for $\omega_{rm} \in [200 \;\; 1000]$ rad/sec, we guarantee $V_{\text{converter}}$=15.5 V. If the load varies within the rated envelope, and, the angular velocity of a prime mover changes within $\omega_{rm} \in [200 \;\; 1000]$, we achieve $V_{\text{converter}}$=15.5±0.05 V as reported in Figure 6.

Allowable, optimal or near-optimal charging regimes are ensured by using the *constant-current*, *constant-voltage* and *varying voltage/current* modes. We examined different loads, distinct charging phases, and, various charging profiles in an expanded operating envelope. Various lithium-ion batteries in different configurations were successfully charged guarantying robustness, high efficiency, optimal performance and superior capabilities.



(a)



(b)

Figure 4. Battery charging mode, SoC is 50%:
(a) Voltage variations at the rectifier terminal, ω_{rm} is 200 and 400 rad/sec;
(b) Voltage variations at the *LC* bandpass filter terminal, ω_{rm} is 200 and 400 rad/sec.

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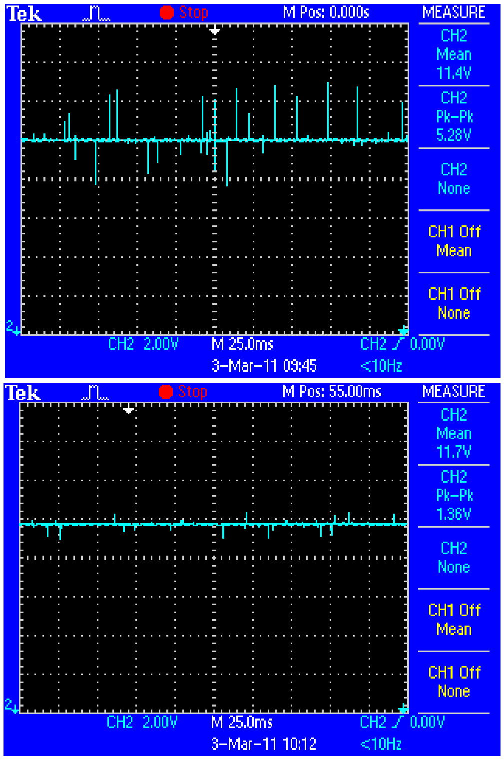

Figure 5. Battery charging mode, SoC is 50%:
(a) Voltage spikes at the output a *buck-boost* converter terminal at the rated load, $i_{\text{converter}}$=1 A and ω_{rm}=300 rad/sec; (b) Voltage variations at the output of the *buck-boost* converter *LC* bandpass filter terminal at the rated load

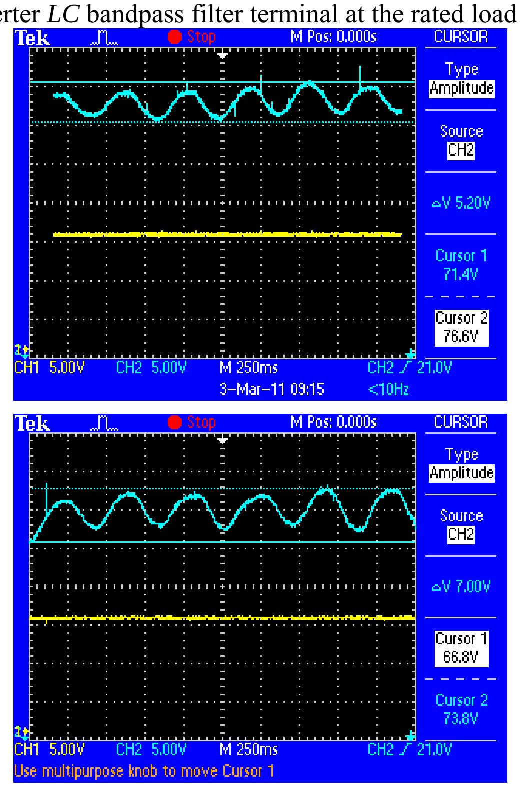

Figure 6. Battery charging mode (SoC is 50%): Voltage stabilization by a PWM *buck-boost* converter at the varying changes of angular velocity, $V_{\text{converter}}$=15.5±0.05 V

5. Conclusions

We designed, optimized, analyzed, evaluated and characterized *clean* energy renewable power generation systems. Highly efficient energy conversion was guaranteed by using high-performance permanent-magnet brushless synchronous generators, rectifiers, adaptive filters, soft-switching converters. As energy storage solutions, we examined super-capacitors and advanced rechargeable batteries. Efficient battery-specific chargers ensured near-optimal or optimal charging.

The system design and developments included various fundamental tasks such as:

1. Design and optimization of system organization;
2. Component-, module- and system-level matching, utilization, integration and accompaniment;
3. Control and optimization of energy generation and conversion;
4. Effective and efficient energy storage;
5. Design of high-performance generators;
6. Synthesis of enabling rectifiers and converters;
7. Optimization of charging profiles;
8. High-fidelity analysis, nonlinear design and multi-objective optimization;
9. Verification, testing, characterization and evaluation.

This paper further enabled engineering and technology forefronts by applying most advanced recent theoretical findings and engineering solutions. We advanced knowledge, engineering practice and technology for *clean* and renewable energy systems.

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