Nanoscaled Microelectronics and Nanotechnology-Enabled Energy Systems For Aerospace and Robotic Applications


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ABSTRACT

For autonomous and semi-autonomous micro air vehicles, minirobots, propulsion, remote sensing and other platforms, we study high-power and high-energy densities energy systems. These systems are designed using nanotechnology-enabled microelectronic, electronic, energy sources and energy storage components, devices and modules. Research and technology developments are performed for energy harvesting, management and storage. We apply and demonstrate key modules and components, such as: (1) Nanoscaled low-power microelectronics and sensors; (2) High-power-density semiconductor devices, circuit components and power electronics; (3) Nanotechnology-enabled solar cells; (4) Advanced energy storage devices; (5) Energy management system. The proposed solutions are substantiated by performing experimental studies. The compliance of the proposed technologies to radio-controlled mini air vehicles and robots is ensured. Proof-of-concept power systems are designed using specifications for all-electric autonomous aerospace, naval, robotic and security platforms.

Keywords: electronics, energy, nanotechnology

1. INTRODUCTION

Power adequacy, integrity and energy sustainability are essential to ensure functionality of propulsion, navigation, sensing, management and other systems in aerospace, land and underwater platforms. It is important to design, test and evaluate integrated self-sustained power systems for different platforms meeting application-specific requirements and specifications. Safety, affordability, energy density and other features can be ensured by using: (i) Nanotechnology-enabled components, devices and modules [1, 2]; (ii) Compliant modular organization; (iii) Advanced control schemes and management systems; (iv) Enabling energy harvesting and conversion solutions.

Advances in nanotechnology, microelectronics and micro-electromechanical systems (MEMS) [1, 2] result in commercialization and deployment of various minirobots, surface and air vehicles, etc. The energy module, which includes the energy source and other subsystems, is a key component. High-altitude, outer and deep space vehicles, robots as well as underwater platforms require specific modules and electronic devices which operate under extreme temperature, mechanical loads, interference and radiation. The controlled high-energy density power systems must be designed, tested and characterized.

We examine enabling inorganic and organic photovoltaic cells, nanotechnology-enabled electronic devices, front-end microelectronic components, efficient energy harvesting solutions, low-loss energy conversion and novel energy storage schemes. The controlled energy conversion, storage and distribution are accomplished by an energy management system. A coherent energy management implies consistent sensing, processing, optimization and control of energy conversion. Advanced sensing, data acquisition and processing are achieved by nanoscale electronics, optoelectronics and MEMS. The studied modular energy systems may operate in the range from milli-watts to hundreds of watts within continuous and pulse energy conversion and release capabilities. The proof-of-concept portable light-duty energy systems are tested and substantiated achieving a sufficient technology level.

2. SCALABLE AND MODULAR ENERGY SYSTEMS

With an overall objective to develop a scalable high-performance power system technology for high-energy density portable energy sources, the modular design is performed using nanoscale electronics and MEMS [1-4]. The power integrity, effective energy management and functionality must be guaranteed by matching compliant components and modules with the electric loads, energy harvesting and storage capabilities.

Figure 1 illustrates a modular power system which includes photovoltaic cells, power electronics (dc/dc converter, chargers, controllers, filters, sensors, etc.), MEMS, rechargeable battery and other modules.

![Figure 1: Modular self-sustained power system](image-url)
One needs to accommodate the application- and system-specific peak, continuous and pulse loading conditions, as well as time-varying \( RLC \) loads, such as electromechanical devices, antennas, communication components, electronics, etc. Therefore, specific energy sources, converters and power electronic modules are used taking into account the rated and peak continuous and pulse loading conditions. Figure 2 documents the images of photovoltaic cells, supercapacitors, lithium-ion rechargeable battery, high-frequency high-efficiency \( dc/dc \) converters, etc. The varying \( RLC \) loads are the transmitters, receivers, permanent-magnet actuators and propulsion motors, servos, sensors and other devices [5–7].

3. Analysis and Control of Energy Systems

The nonlinear steady-state and dynamic analyses of energy systems component, such as photovoltaic cells and others, is reported in [3–5]. Depending on irradiation, incident angle, temperature and other factors, the output solar cell voltage \( u_{cell}(t) \) varies. The output voltage, applied to the \( i \)th \( RLC \) load \( u_{RLC}(t) \), must be controlled and stabilized. The \( dc/dc \) buck-boost and boost converters are used [5,8]. The nanoscale electronics and nanotechnology-enabled components (MOSFETs, inductors and capacitors) are used. To stabilize the output voltage at the RL load, consider a one-quadrant boost converter with a filter. The converter schematics is shown in Figure 3 [5].

Figure 3: Controlled boost converter with the varying RL load

When the MOSFET is closed, using the currents and voltages as the state variables \( x=[u_C, i_l, i_{RL}]^T \), one has

\[
\begin{align*}
\frac{du_C}{dt} &= -\frac{1}{C} i_{RL}, \quad \frac{di_l}{dt} = \frac{1}{L} \left[-(r_l + r_c) i_l + u_{cell}\right], \\
\frac{di_{RL}}{dt} &= \frac{1}{L_c} \left[u_C - (R_L + r_c) i_{RL}\right].
\end{align*}
\]

When the MOSFET is open, the capacitor \( C \) is charged by the voltage source. The differential equations are

\[
\begin{align*}
\frac{du_c}{dt} &= \frac{1}{C} (i_l - i_{RL}), \quad \frac{di_l}{dt} = \frac{1}{L} \left[-u_c - (r_l + r_c) i_l + r_c i_{RL} + u_{cell}\right], \\
\frac{di_{RL}}{dt} &= \frac{1}{L_c} \left[u_c + r_c i_l - (R_L + r_c) i_{RL}\right].
\end{align*}
\]

The comparator drives the MOSFET with the switching frequency \( f \). Using the time when the MOSFET is on and off, one has \( f = 1/(t_{on} + t_{off}) \). The voltage applied to the load \( u_{RL} \) is regulated by controlling the switching on and off durations \( t_{on} \) and \( t_{off} \), respectively. The average voltage applied to the load depends on \( t_{on} \) and \( t_{off} \). The duty cycle \( d_d = \frac{t_{on}}{t_{on} + t_{off}} \in [0, 1] \) varies between 0 and 1. Neglecting small resistances \( r_l \) and \( r_c \), one obtains \( u_{RL} = \frac{1}{1 - d_d} \).

Using the averaging concept [5,8], we have

\[
\begin{align*}
\frac{du_c}{dt} &= \frac{1}{C} (i_l - i_{RL} - i_d), \\
\frac{di_l}{dt} &= \frac{1}{L} \left[-u_c - (r_l + r_c) i_l + r_c i_{RL} + u_{cell}\right], \\
\frac{di_{RL}}{dt} &= \frac{1}{L_c} \left[u_c + r_c i_l - (R_L + r_c) i_{RL} - r_c i_d\right].
\end{align*}
\]

Figure 2: Devices, components and modules of autonomous energy systems:
(a) Photovoltaic cells;
(b) Rechargeable supercapacitors and lithium ion battery;
(c) High-frequency buck-boost and boost converters;
(d) Loads: Electric motors, servos, transmitters and receivers.
The electronic components are fabricated using nanotechnologies. High-permeability and low eddy current losses ferrites are used in high-performance ferrite-core toroidal inductors. The soft, low coercivity and high-Q ferrites are the iron, zinc and manganese or nickel oxides. The high permeability soft ferrites Mn$_2$Zn$_{1-x}$Fe$_2$O$_4$, high resistivity high-frequency Ni$_x$Zn$_{1-x}$Fe$_2$O$_4$, and other ferrites are used. The structure and magnetic properties of MnFe$_2$O$_4$ ferrites depend on the preparation methods, such as the ceramic technique, combustion, co-precipitation, sol-gel and citrate. The citrate method gives the smallest lattice and ~15 nm particles, while the flash combustion results in ~40 nm. The ceramic technique results in the larger particle size, relative permeability ~2000, uniformity, etc.

In ferrite inductors, the relative permeability $\mu_r$ varies as a function of the load. For the toroidal inductors,

$$ L = \mu \frac{N^2 h}{2\pi} \ln \frac{R_o}{R_i} \quad (2) $$

where $\mu$ is the permeability, $\mu = \mu_0 \frac{dB}{dH}$; $B$ and $H$ are the magnetic field density and intensity, $H$=N/m; $l$ is the length; $h$ is the thickness; $R_{out}$ and $R_{in}$ are the outer and inner radii.

The field intensity $H$ and density $B$ vary with current. The permeability $\mu$ also varies as a function of $i$. Using the nonlinear BH curve, one has $\mu(i, \frac{dB}{dH}) = \mu_0 \frac{dB}{dH}$. Hence $[9]$

$$ B(H, \frac{dB}{dH}) = B_{max} \tanh(aH - \text{sgn}(\frac{dB}{dH})bH), $$

$$ L(i, \frac{dB}{dH}) = B_{max} \left[ 1 - \text{tanh}^2 \left( ci - d \text{sgn}(\frac{dB}{dH}) \right) \right], \quad (3) $$

where $B_{max}$, $a$, $c$, $d$ and $H$ are the constants which depend on the BH curves of the nanostructured ferrites.

For a 2 mH ferrite toroidal inductor, $N=60$, $B_{max}=0.4$ T, $R_{out}=14$ mm, $R_{in}=7$ mm, $a=0.001$, $b=0.001$, $c=0.005$ and $d=0.05$. The nonlinear magnetization curve and varying inductance $L(i) = f(id/dt)$ are reported in Figure 4. The nonlinear model (3) is used in design. The converter with the RL load is described by nonlinear differential equations

$$ \frac{di}{dt} = \frac{1}{C} \left[ (i_L - i_{RL} - i_d) \right], $$

$$ \frac{di}{dt} = \frac{1}{L_c} \left[ -u_c - (r_c + r_L)r_c + r_L i_{RL} + u_c d_d + (r_r - r_L)r_d - r_J d_d + u_{cell} \right], $$

$$ \frac{di}{dt} = \frac{1}{L_L} \left[ u_c + r_L i_L - (r_L + r_J) i_{RL} - r_L i_d \right], \quad (4) $$

### 4. Experimental Results

We examine a high-energy density power system with high-efficiency solar cells and energy storage devices. The specific energy of super- and hybrid capacitors varies from ~1 to 30 W-h/kg, while for lithium-ion batteries, one may ensure ~300 W-h/kg. For different loads and loading conditions, depending on the specified converter’s output voltage $u_{output}(t)$, we synthesize and verify nonlinear proportional-integral-derivative and sliding mode control laws [4, 10]. Using the tracking error $e = u_{reference}(t) - u_{converted}(t)$, we design and test the following control algorithms

$$ u(t) = k_p e + k_d \frac{d}{dt} e, \quad u(t) = k_p e + k_d \frac{d}{dt} e + k_i e, \quad u(t) = k_p e + k_d \frac{d}{dt} e + k_i e + k_i \frac{d}{dt} e, \quad \text{and} \quad u(t) = u_{max} \tanh(k_p e + k_d \frac{d}{dt} e + k_i e) \text{for } k_p > 0, k_d > 0, k_i > 0. \quad (5) $$

Nonlinear control algorithms (5) are tested in the closed-loop energy systems with the RLC loads. The experimental results are documented in Figure 5 for the time-varying $R$ and $L$. The evolution of $i_{RL}(t)$ and $u_{converted}(t)$ are given by the first and second oscilloscope’s channels, respectively. The steady-state values and transient dynamics are reported for different reference voltages $u_{reference}(t)$ and time-varying loads. The tracking error $e(t)$ is less than 1% under the peak loads, and, the settling time is ~1 msec. At the rated load, the converter’s efficiency is ~91%. The comparison of the experimental and analytic studies is summarized in Table 1.

<table>
<thead>
<tr>
<th>Assigned $\mu_{reference}$ which corresponds $d_D$</th>
<th>Analytic, modeling and simulation results $u_{output}$ [V]</th>
<th>Experimental results (closed-loop system) $u_{output}$ [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.6</td>
<td>10.54</td>
<td>10.6</td>
</tr>
<tr>
<td>13.4</td>
<td>13.35</td>
<td>13.4</td>
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<tr>
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<td>17.35</td>
<td>17.4</td>
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<tr>
<td>21</td>
<td>20.95</td>
<td>21</td>
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We depart from solutions reported in [11, 12]. A dynamic maximum power tracking algorithm and efficiency optimization scheme are implemented ensuring optimal energy conversion with minimal losses. The voltage stabilization, voltage tracking and high-efficiency energy management ensure optimal energy harvesting, conversion, distribution and storage. To achieve optimal performance, we minimize the performance functional $J$ using the power losses $P_{losses}$, tracking error $e_j$, energy, energy transfer $\Delta E_j$ and other integrands for $j$th components and modules. In particular, using the weighting coefficients $q_j$, we have

$$ J = \min_{P_{losses}, e_j, \Delta E_j} \max_{\theta_j} \left[ \sum_j q_j P_{losses,j} + \sum_j q_j e_j + \sum_j q_j \Delta E_j \right]. \quad (6) $$

Using (6), performance and capabilities are measured by quantitative estimates, measures and metrics. Efficiency $\eta$, energy density, robustness, stability and other measures are examined in the full operating envelope. The consistent analytic measures and estimates are consistently used. Adequate cost, durability, integrity, modularity, storage capacity and other metrics are achieved.
5. CONCLUSIONS

For nanotechnology-enabled self-sustained power systems, we designed and substantiated a scalable modular technology. Advanced MEMS, electronic, photovoltaic and energy storage hardware solutions were used. Optimal energy conversion and management was ensured by designing practical minimal-complexity control laws. The proposed design ensures safety, affordability, accessibility, scalability, efficiency, effectiveness, simplicity, compliance, etc. The proposed concept meets specifications imposed in aerospace, automotive, biotechnology, consumer electronics, medical, naval, robotic, security and other applications. The effectiveness and applicability of modular portable energy systems were substantiated through experiments and technology transfer developments.

REFERENCES