From Thermoelectric Generators to Utility Scale Wind Power: University of Colorado Denver's Efforts in Renewable Energy Research

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Table of contents

• Introduction
• Energy & Power Systems Program at CU Denver
• Micro energy management system research
• Research on solar power
• Research on wind power
Introduction

• Located a few blocks from here
• A vibrant urban campus
• CU Denver offers B.S.E.E., M.S.E.E., M. Engr. and Ph.D. in Engineering & Applied Science
• 12 faculty member, two specializing in Energy & Power Systems
Energy & Power Systems Program at CU Denver

Fernando Mancilla-David
Associate Professor

• Ph.D. University of Wisconsin-Madison, 2007
• Power systems, power electronics, renewable energy systems
Energy & Power Systems Program at CU Denver

Jae-Do Park
Assistant Professor
• Ph.D. Pennsylvania State University, 2007
• Electric machines & drives, power electronics, renewable energy systems
Energy & Power Systems Program at CU Denver

Specialty Foundations
- ELEC 3164-3: Energy Conversion
- ELEC 3724-1: Energy Conversion Lab

Specialty (Core Courses in Power Engineering)
- ELEC 4164/5164-3: Electric Drive Systems
- ELEC 4170/5170-1: Electric Drive Lab
- ELEC 4174/5174-3: Power Electronic Systems
- ELEC 4174/5174-1: Power Electronic Lab
- ELEC 4184/5184-3: Power Systems Analysis
- ELEC 4444/5444-1: Power Systems Lab

Graduate
- ELEC 5710-3: Advanced Electric Drive Systems
- ELEC 5725-3: Advanced Electric Machinery
- ELEC 5755-3: Renewable Energy Systems
- ELEC 5774-3: Power Systems Dynamics and Protection
- ELEC 5194-3: Power System Operation and Control
- ELEC 5800-3: Special Topics in Energy and Power Systems
Micro Energy Management System

- Small-scale renewable energy system
  - Harvesting of ambient energy (micro power)
    - Waste heat, vibration, waste water, etc
  - Available energy harvesting devices
    - Thermoelectric generators (TEG), piezoelectric materials, microbial fuel cell (MFC), etc
  - New applications
    - Wireless sensor networks, wearable devices, remote sensors, autonomous actuators
Micro Energy Management System

• UCD Research in this area
  – System modeling for various energy resources
  – Resource-specific energy harvesting techniques
  – Low power and low voltage operations
  – Power converter topologies and control schemes
  – Practical energy management system (EMS)
  – Currently focusing on TEGs and MFCs
Thermoelectric Generators (TEGs)

• Electricity using temperature differential
  – Semiconductor-based heat-electricity energy conversion
  – Non-moving part, compact, reliable, long life
  – Low efficiency, low power output
  – Space craft power supply, automotive waste heat recovery, appropriate technology applications (e.g., cook stoves, vaccine carriers)
Thermoelectric Generators (TEGs)

• Operational characteristics

TEG module schematic

Typical output characteristics
Thermoelectric Generators (TEGs)

• Application examples

- Radioisotope Thermoelectric Generator, Voyager, NASA
- Exhaust waste heat recovery prototypes, DOE/Industry sponsorship

Thermoelectric Generators (TEGs)

- Current-sensorless power estimation and MPPT implementation (2015)
  - Conventionally voltage and current are measured to track optimal operating point
  - Current measurement is costly when it comes to low power energy harvesting system
  - Using an inexpensive microcontroller, MPPT is achieved without current measurements

Park and Bond, 2015
Thermoelectric Generators (TEGs)

- Current-sensorless power estimation and MPPT implementation (2015)

**Control scheme**

**Maximum power tracking transient**

Park and Bond, 2015
Thermoelectric Generators (TEGs)

- H/W model-based uninterrupted MPPT using temperature measurements (2014)
  - Compensates drawback of conventional impedance matching model
  - Improves dynamic performance with much simpler configuration
  - Achieves continuous energy harvesting without interruption

Park, Lee, and Bond, 2014
Thermoelectric Generators (TEGs)

- H/W model-based uninterrupted MPPT using temperature measurements (2014)

Drawback of conventional Impedance matching model

Proposed control scheme

Experimental MPPT performance

Park, Lee, and Bond, 2014
Research on solar power

Example of research

• Detailed modeling of a PV array of an arbitrary size
• Estimation of solar irradiance
• Fault ride through control of PV inverters
Detailed modeling of a PV array of an arbitrary size
Detailed modeling of a PV array of an arbitrary size

\[ I_{\text{pv}} = I'_r - I'_0 \left[ \exp \left( \frac{q(v_{\text{pv}} + i_{\text{pv}} R'_S)}{N_S n k T} \right) - 1 \right] - \frac{v_{\text{pv}} + i_{\text{pv}} R'_S}{R'_P} \]

\[ I'_r := N_P I_{\text{irr}}; \quad I'_0 := N_P I_0; \quad R'_S := \frac{N_S}{N_P} R_S; \quad R'_P := \frac{N_S}{N_P} R_P \]

\[ I_{\text{irr}} = \frac{G}{G_{\text{ref}}} (I_{\text{irr,ref}} + \alpha_T (T - T_{\text{ref}})) \]

\[ I_0 = I_{0,\text{ref}} \left( \frac{T}{T_{\text{ref}}} \right)^3 \exp \left( \frac{E_{\text{g,ref}}}{k T_{\text{ref}}} - \frac{E_g}{k T} \right) \]

\[ R_P = R_{P,\text{ref}} \left( \frac{G}{G_{\text{ref}}} \right) \]

\[ R_S = R_{S,\text{ref}} \]

\[ n = n_{\text{ref}} \]
Estimation of solar irradiance

\[
I = I'_{irr}(G,T) + F(I,V,T) - \frac{C_3}{G}(V + C_2I)
\]

\[
I'_{irr}(G,T) = G(C_4 + C_5T)
\]

\[
F(I,V,T) = -I'_0(T) \left[ \exp \left( \frac{C_1}{T} (V + C_2I) \right) - 1 \right]
\]

\[
I'_0(T) = C_6T^3 \exp \left( C_7 - \frac{C_8}{T} + \frac{C_9T}{T+C_{10}} \right)
\]

\[
y(t) = I(t) - F(I(t),V(t),T(t))
\]

\[
\Phi(G,t) := G(C_4 + C_5T(t)) - \frac{C_3}{G}(V(t) + C_2I(t))
\]

\[
\dot{G} = \gamma[y - \Phi(\dot{G})]
\]

\[
\lim_{t \to \infty} \dot{G}(t) = G
\]
Estimation of solar irradiance

![Graph showing solar irradiance estimation and comparison with a pyranometer.](image-url)
Fault ride through control of PV inverters
Fault ride through control of PV inverters
Fault ride through control of PV inverters
Research on wind power

Example of research

- Construction of small-scale axial flux windmills
- Estimation of wind speed
- Modeling & control of small-scale windmills for maximum power point tracking
- Modeling & control of Type-2 wind turbines for sub synchronous resonance damping
Construction of small-scale axial flux windmills

Renewables on the roof:

- Windmill:
  - PMSG Axial flux machine
  - 1 kW nominal
  - 1.2 kW maximum
  - 8 ft blades diameter
  - “small tower”
- Solar Panels:
  - 340 W
- Battery Bank:
  - 320 Ah
- Other:
  - Charge controller
  - Divert load
  - Webcam
Construction of small-scale axial flux windmills

Alpine windmill:

- Windmill:
  - PMSG Axial flux machine
  - 1.2 kW nominal
  - 1.5 kW maximum
  - 12 ft blades diameter
  - 63 ft tower
- Battery Bank:
  - 320 Ah
- Other:
  - Charge controller
  - dc/dc buck converter
  - Divert load
  - Anemometer
  - Webcam
Estimation of wind speed

Immersion & Invariance:

\[ \hat{v}_w = \dot{\hat{v}}^I_w = \gamma \left[ \frac{1}{J} T_e - \Phi (\omega_m, \hat{v}_w^I + \gamma \omega_m) \right] \]

\[ \hat{v}_w = \hat{v}_w^I + \gamma \omega_m, \]

where \( \gamma \) is an adaptation gain.

The estimator is asymptotically consistent under conditions usually satisfied in practice:

\[ \lim_{t \to \infty} \hat{v}_w(t) = v_w \]
Estimation of wind speed

![Graph showing wind speed estimation](image)
Modeling & control of small-scale windmills for maximum power point tracking
Modeling & control of small-scale windmills for maximum power point tracking
Modeling & control of small-scale windmills for maximum power point tracking
Modeling & control of Type-2 wind turbines for sub synchronous resonance damping
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Modeling & control of Type-2 wind turbines for sub synchronous resonance damping
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