A Survey on Maximum Power Point Tracking Algorithms Across Diverse Power Sources

Gabriel Marcano

Agenda

- Introduction
- Historical Overview
- Brief Theory
- Energy Sources
- Ontology
- Survey
- Future Trends
- Conclusion

Introduction

Powering sensors is not always easy

1. City of San Diego, Public Meeting, Smart Streetlights. 2019-09-10.

Powering sensors is not always easy

1. City of San Diego, Public Meeting, Smart Streetlights. 2019-09-10.
2. Ian Bailey, public domain

Renewable power sources can help...

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2. Micro-hydro Turbine. https://janesvillehomesolar.com/micro-hydro-energy-services/ Accessed 2022-04-14.

Renewable power sources can help… but they need help!

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2. Micro-hydro Turbine. https://janesvillehomesolar.com/micro-hydro-energy-services/ Accessed 2022-04-14.

From space...

1. NASA, Public domain, via Wikimedia Commons

From space... to our Earth

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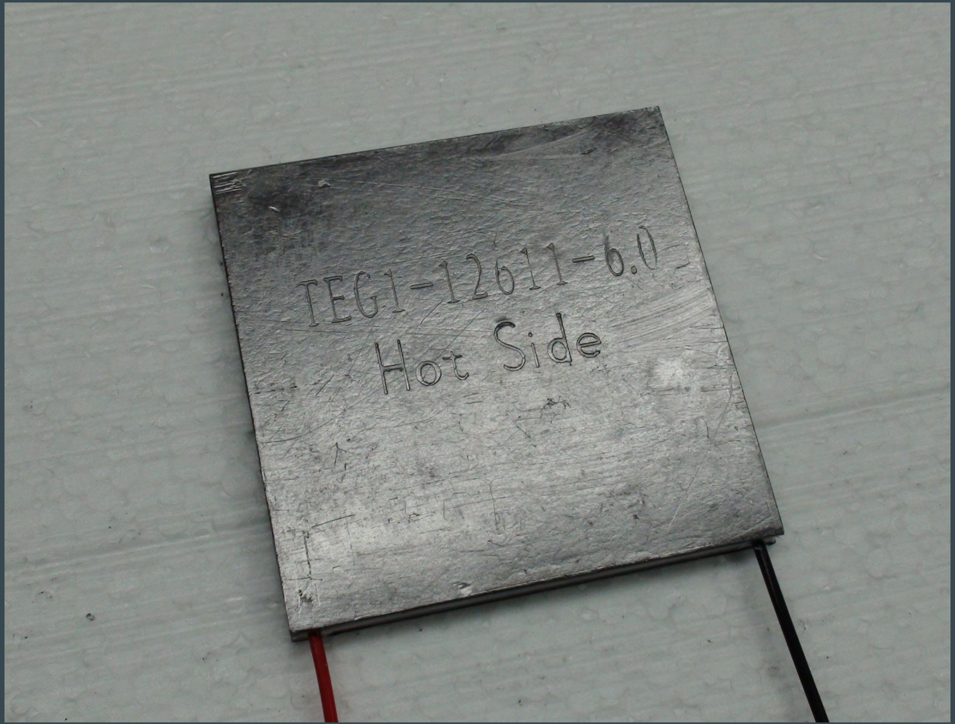

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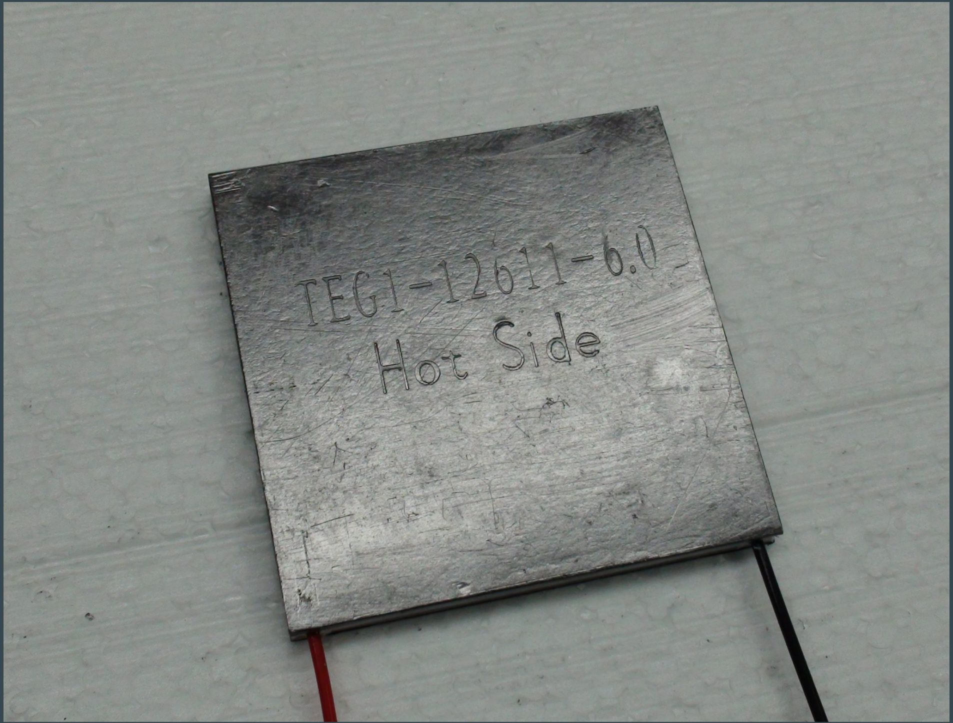

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2. Mudwatt. https://www.magicalmicrobes.com. Accessed 2021-11-10.

MPPT for Energy Sources Surveyed

High Power	Low Power

MPPT for Energy Sources Surveyed

High Power	**Low Power**
Solar	

MPPT for Energy Sources Surveyed

High Power	Low Power
Solar	
Wind	

MPPT for Energy Sources Surveyed

High Power	Low Power
Solar	
Wind	
Tidal	

MPPT for Energy Sources Surveyed

High Power	**Low Power**
Solar	
Wind	
Tidal	
Hydroelectric	

MPPT for Energy Sources Surveyed

High Power	Low Power
Solar	
Wind	
Tidal	
Hydroelectric	
Proton-Exchange Membrane Fuel Cells	

MPPT for Energy Sources Surveyed

High Power	**Low Power**
Solar	Piezoelectric
Wind	
Tidal	
Hydroelectric	
Proton-Exchange Membrane Fuel Cells	

MPPT for Energy Sources Surveyed

High Power	**Low Power**
Solar	Piezoelectric
Wind	Radio Frequency Harvesting
Tidal	
Hydroelectric	
Proton-Exchange Membrane Fuel Cells	

MPPT for Energy Sources Surveyed

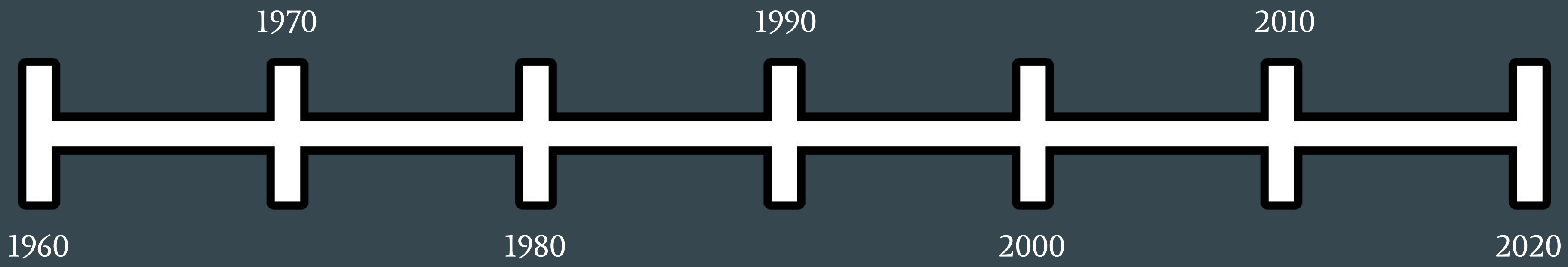
High Power	**Low Power**
Solar	Piezoelectric
Wind	Radio Frequency Harvesting
Tidal	Thermoelectric
Hydroelectric	
Proton-Exchange Membrane Fuel Cells	

MPPT for Energy Sources Surveyed

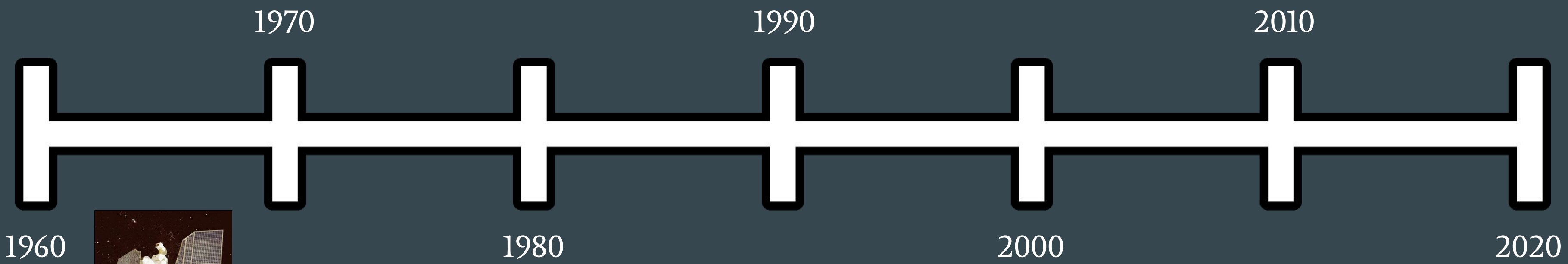
High Power	**Low Power**
Solar	Piezoelectric
Wind	Radio Frequency Harvesting
Tidal	Thermoelectric
Hydroelectric	Microbial Fuel Cells
Proton-Exchange Membrane Fuel Cells	

Historical Overview

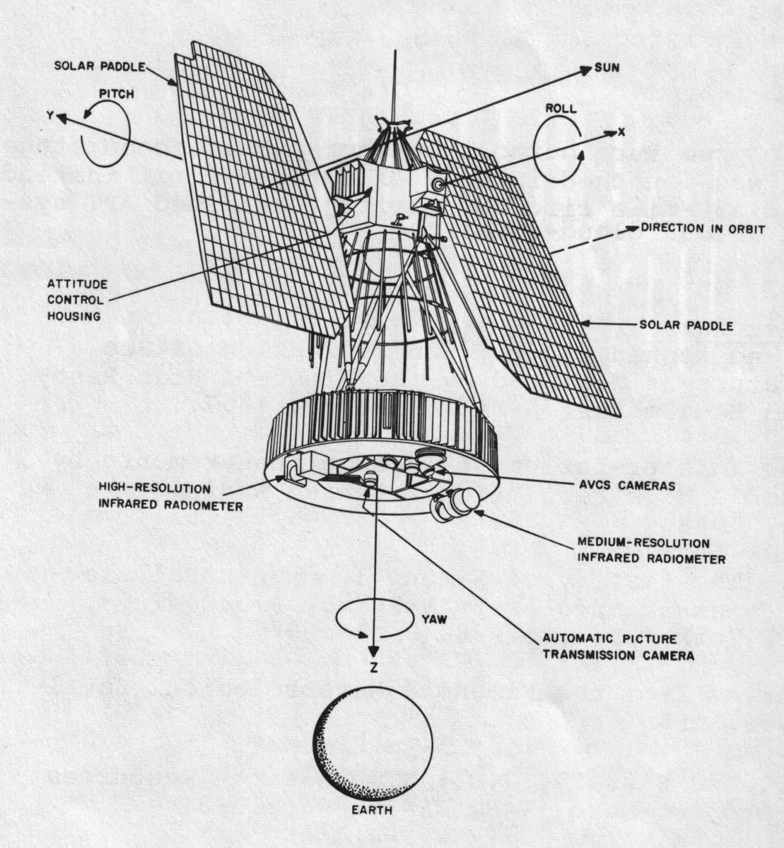
MPPT Timeline (1960s - 2022)



1960s - The Beginning



1960s - Nimbus Program



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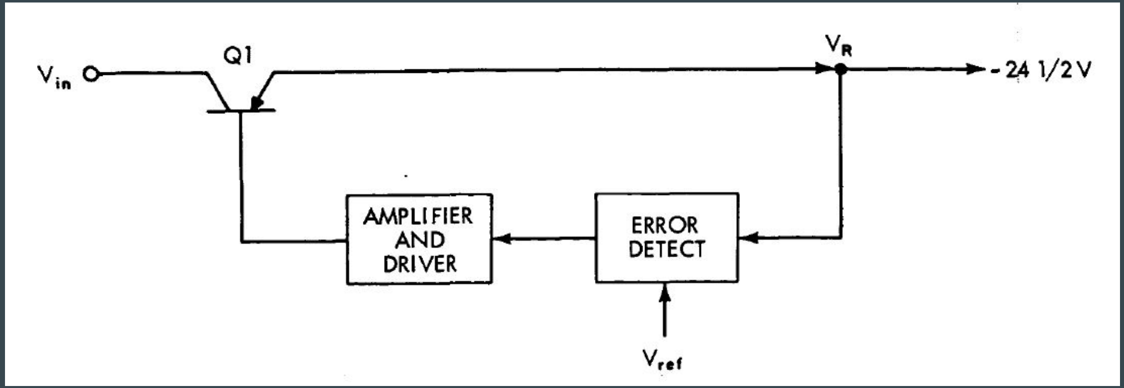
1960s - Nimbus 1 & 2



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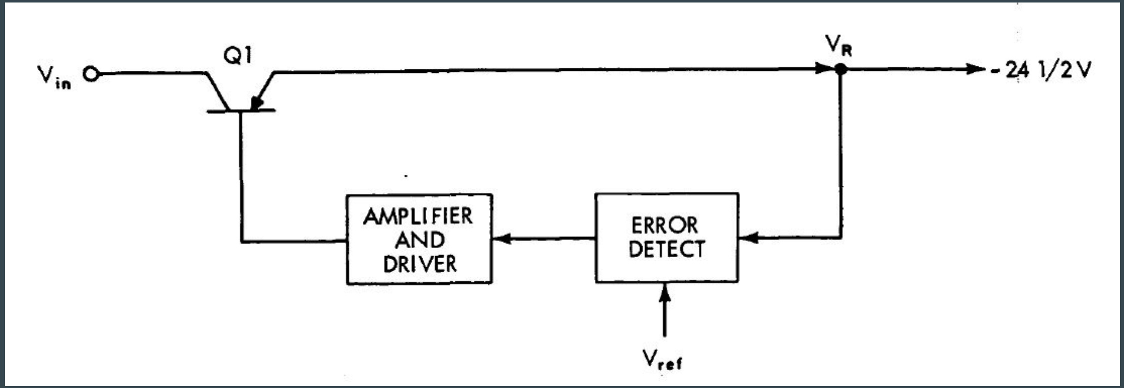
1960s - Nimbus 1 & 2



- Dissipative power regulation

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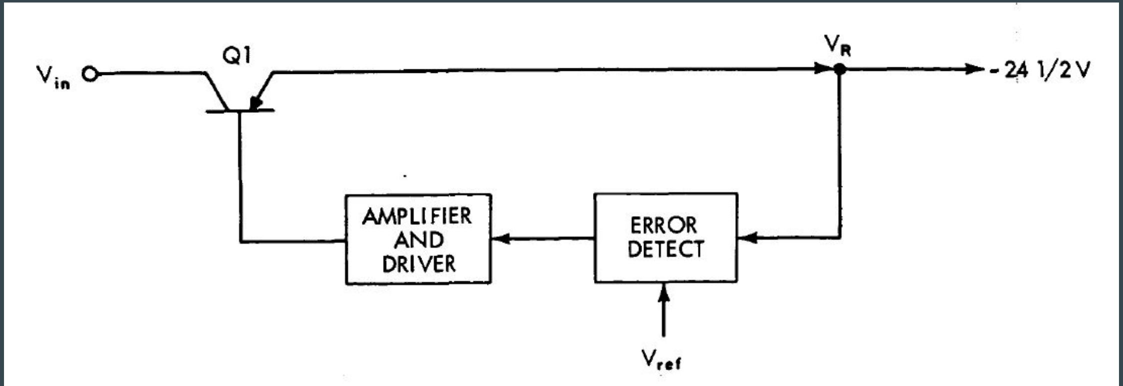
1960s - Nimbus 1 & 2



- Dissipative power regulation
  - Problem: 75% efficiency

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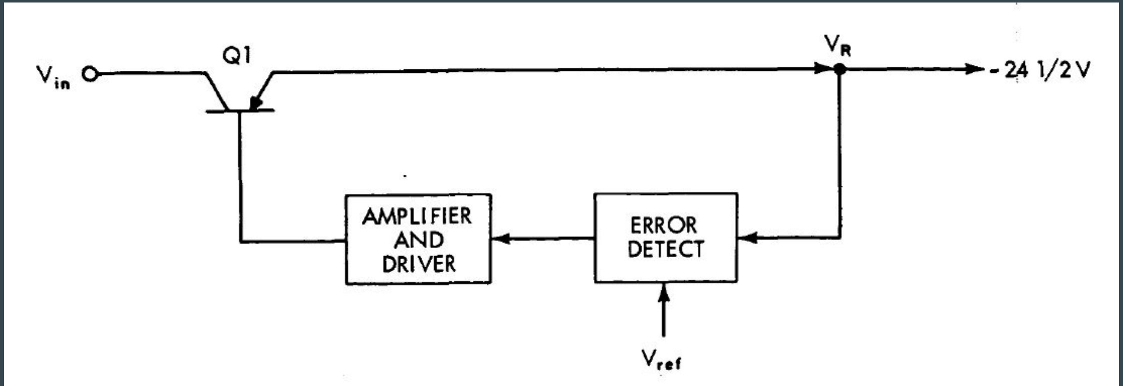
1960s - Nimbus 1 & 2



- Dissipative power regulation
  - Problem: 75% efficiency
- Next Gen used switching regulator

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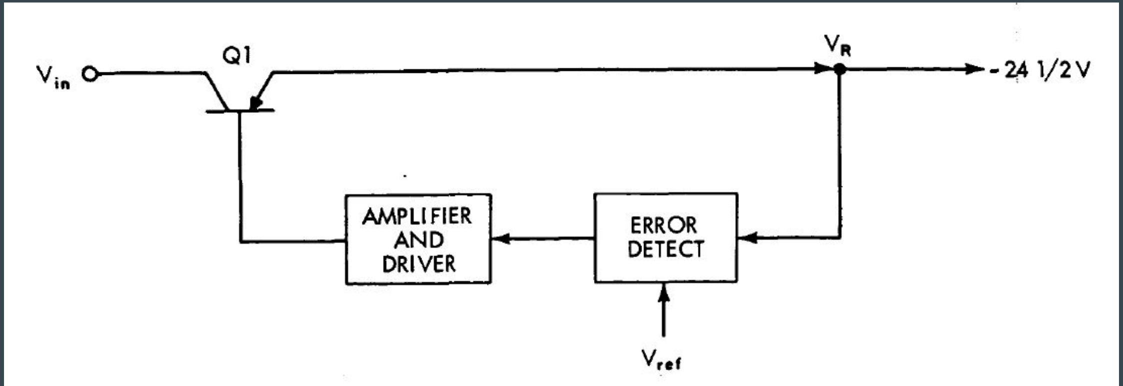
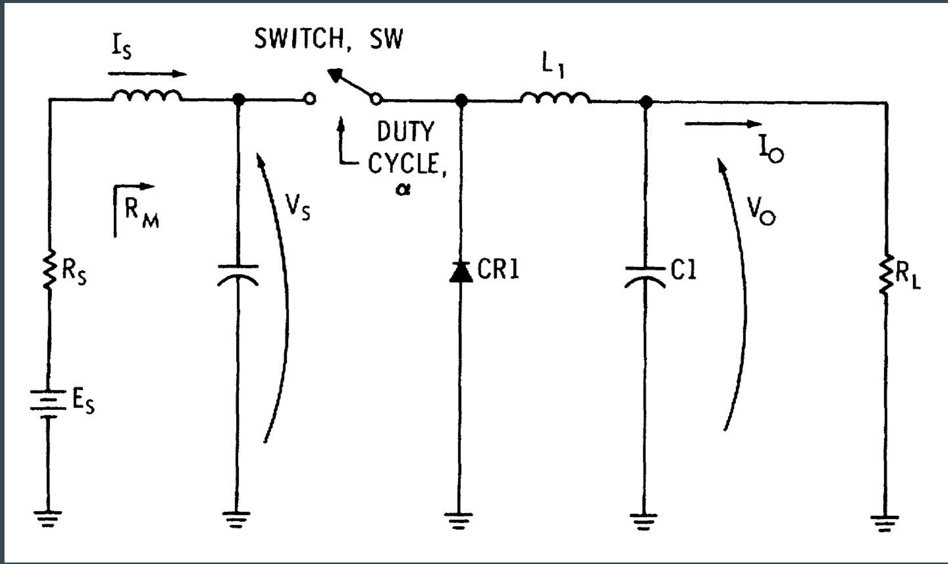
1960s - Nimbus 1 & 2



- Dissipative power regulation
  - Problem: 75% efficiency
- Next Gen used switching regulator
  - 90% efficiency!

1. NASA, Public domain, via Wikimedia Commons
2. NASA. Public domain, via https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1964-052A (Accessed 2022-04-14)

1960s - But we can make it better (MPPT)!



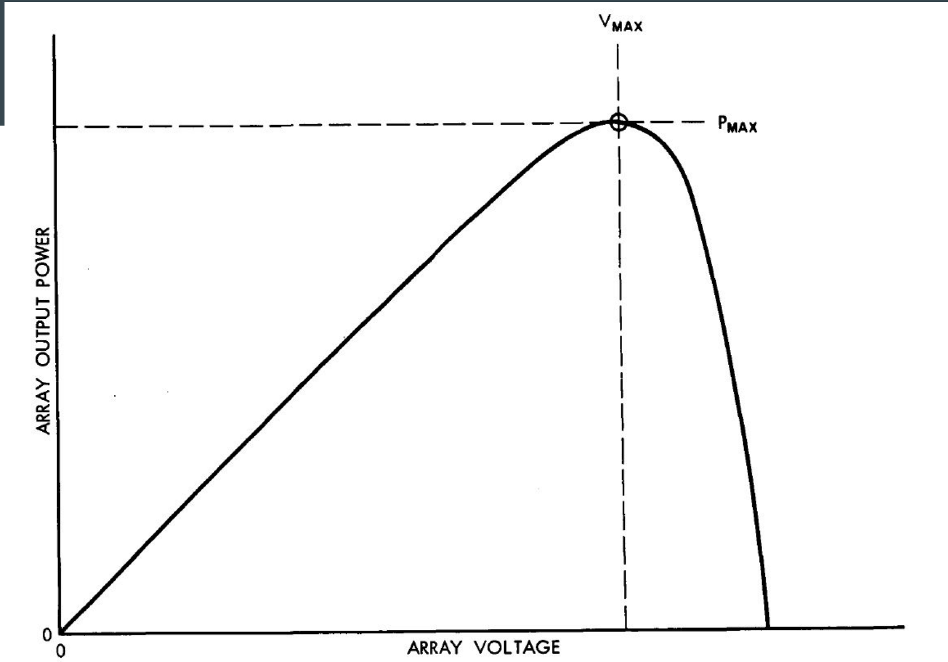


Figure 7. Solar-Cell Array Power vs Voltage Characteristic

1. C. M. MacKenzie, R. C. Greenblatt and A. S. Cherdak, "Nimbus Power Systems (1960-1969)," in IEEE Transactions on Aerospace and Electronic Systems, vol. AES-2, no. 6, pp. 26-37, Nov. 1966, doi: 10.1109/TAES.1966.4501985.
2. Charles N. Bolton and Paul S. Nekrasov, Analysis of the Advanced Nimbus Power Systems. Technical Report NASA-TM-X-55852. 1967.

1970s - Down to Earth

1970

1990

2010

1960

1980

2000

2020

1970s - Terrestrial Solar

- First surveys comparing MPPT
- Terrestrial applications

1. NASA, Public domain via https://www.nasa.gov/glenn/2020/history/nasa-lewis-designed-the-first-solar-electric-village (Accessed 2022-04-18)

1970s - Terrestrial Solar

- First surveys comparing MPPT
- Terrestrial applications
- Solar Energy Research, Development, and Demonstration Act of 1974
- Energy Tax Act of 1978

1. NASA, Public domain via https://www.nasa.gov/glenn/2020/history/nasa-lewis-designed-the-first-solar-electric-village (Accessed 2022-04-18)

1970s - Digital MPPT!

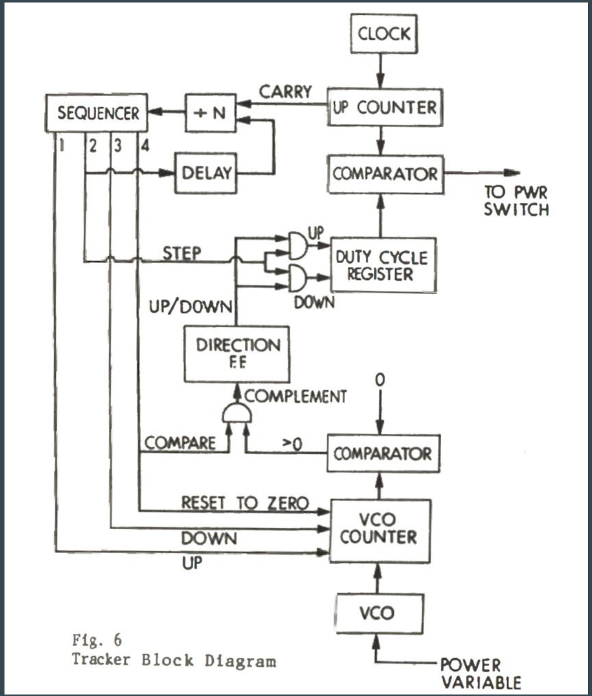


Fig. 6
Tracker Block Diagram

- First surveys
- Terrestrial applications
- Solar Energy Research, Development, and Demonstration Act of 1974
- Energy Tax Act of 1978
- First digital implementations

1. Landsman, E. E., “Maximum power trackers for photovoltaic arrays”, in <i>13th Photovoltaic Specialists Conference</i>, 1978, pp. 996–1000.

1980s - New Algorithms, and Applications for Wind Sources

1970

1990

2010

1960

1980

2000

2020

1980s - New Algorithms, and Applications for Wind Sources

- Wind!

1. DOE, Public domain, via https://www.energy.gov/eere/wind/history-us-wind-energy (Accessed 2022-04-17)

1980s - New Algorithms, and Applications for Wind Sources

- Wind!
- Incremental Conductance
- Open Circuit Voltage

1. DOE, Public domain, via https://www.energy.gov/eere/wind/history-us-wind-energy (Accessed 2022-04-17)

1980s - New Algorithms, and Applications for Wind Sources

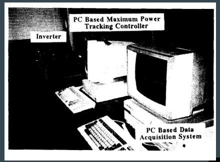
- Wind!
- Incremental Conductance
- Open Circuit Voltage
  - 75% of OCV ~ MPP

1. DOE, Public domain, via https://www.energy.gov/eere/wind/history-us-wind-energy (Accessed 2022-04-17)

1990s - More Power Sources, Artificial Neural Networks

1970

1990



2010

1960

1980

2000

2020

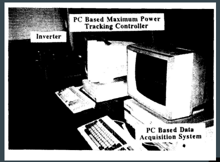
2000s - 2022

1960

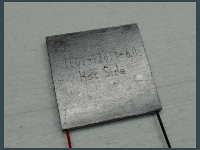
1970

1980

1990



2000



2010

2020

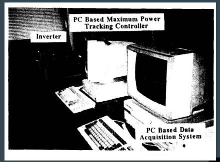
2000s - 2022

1960

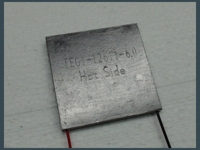
1970

1980

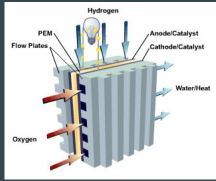
1990



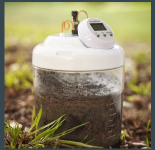
2000



2010



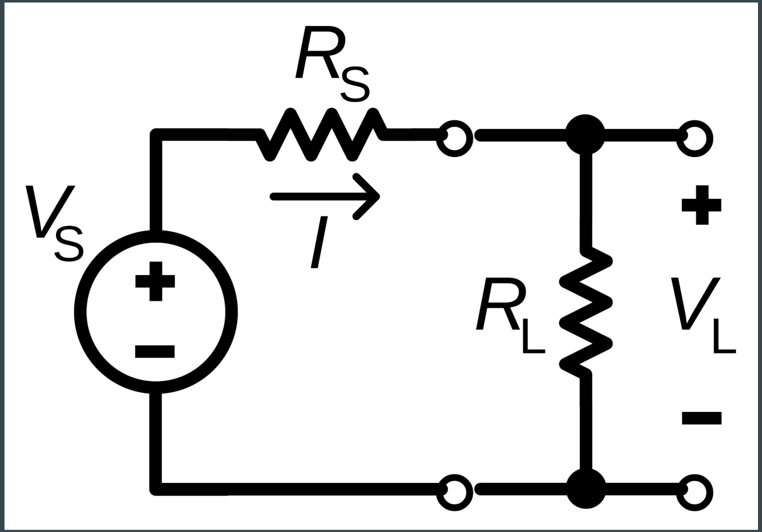
2020



Brief Theory

Maximum Power Transfer Theorem

Given a source and load that can be described by:



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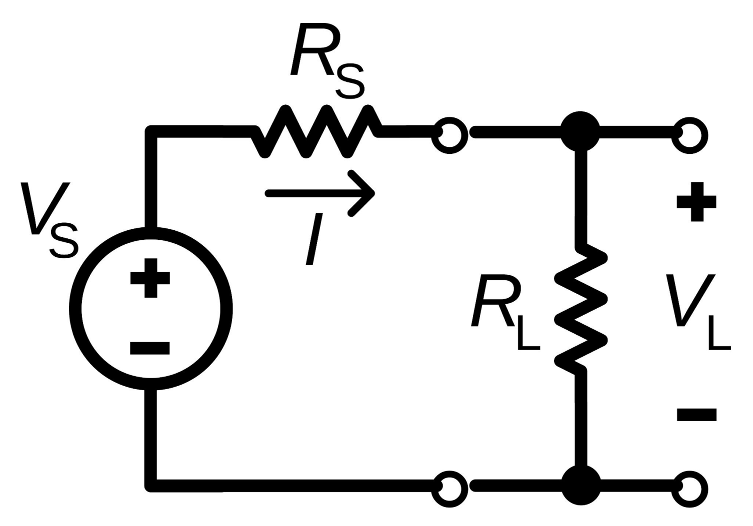
Maximum Power Transfer Theorem

Given a source and load that can be described by:



Maximum power transfer occurs when
$R_L = R_S$

Power at the Source and Load Must be Equal

$$P_L = V_L * I = \frac{I^2}{R}$$

$$P_S = V_S * I = \frac{I^2}{R}$$

$$P_S = P_L$$

Efficiency at the MPP

$$E = \frac{P_L}{P_S + P_L}$$

- At MPP, $P_S = P_L$

Efficiency at the MPP

$$E = \frac{P_L}{P_S + P_L}$$

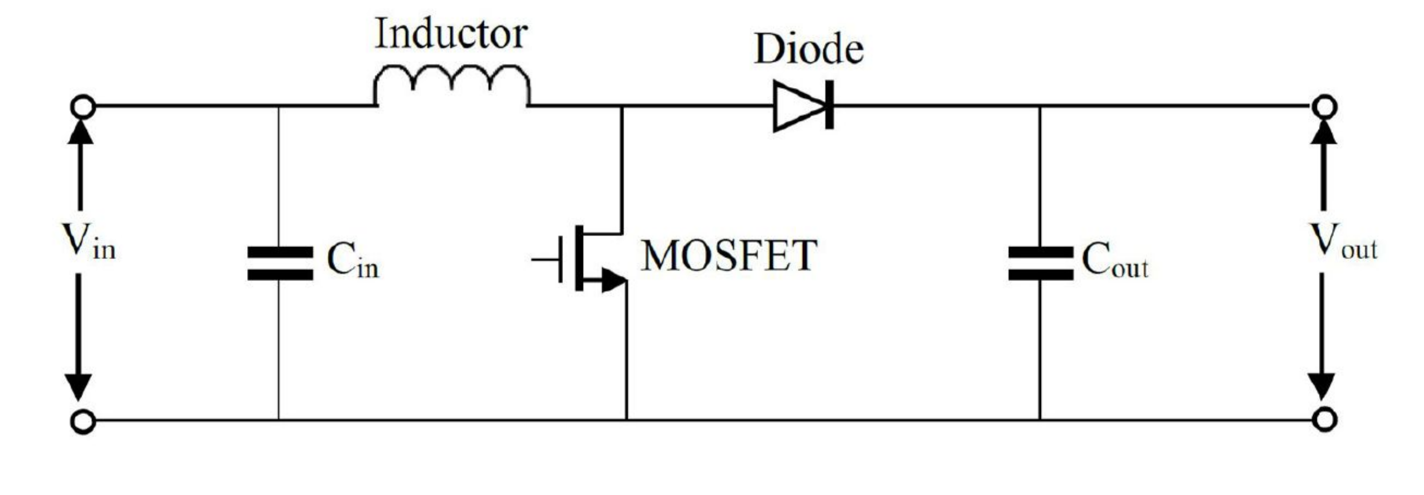
$$E = \frac{1}{2}$$

- At MPP, $P_S = P_L$
- EFFICIENCY: 50%!

Efficiency as Used in the MPPT Literature

$$E = \frac{P_{L_{actual}}}{P_{L_{max}}}$$

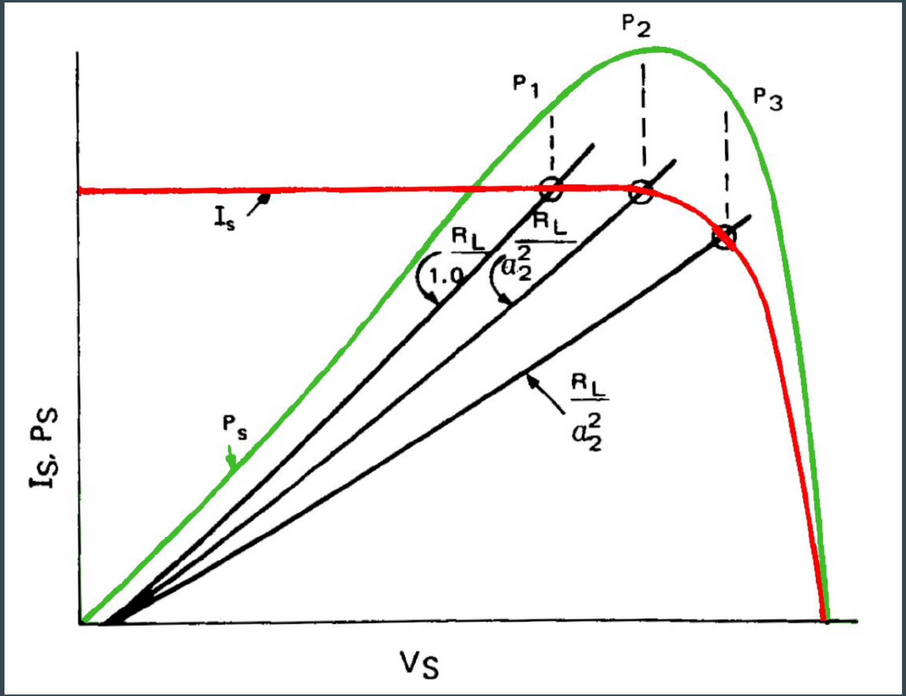
Switching Voltage Regulators



- Resistance to load controlled by PWM signal to switch
- LLC resonant converter!
- Split-phase flipping-capacitor!

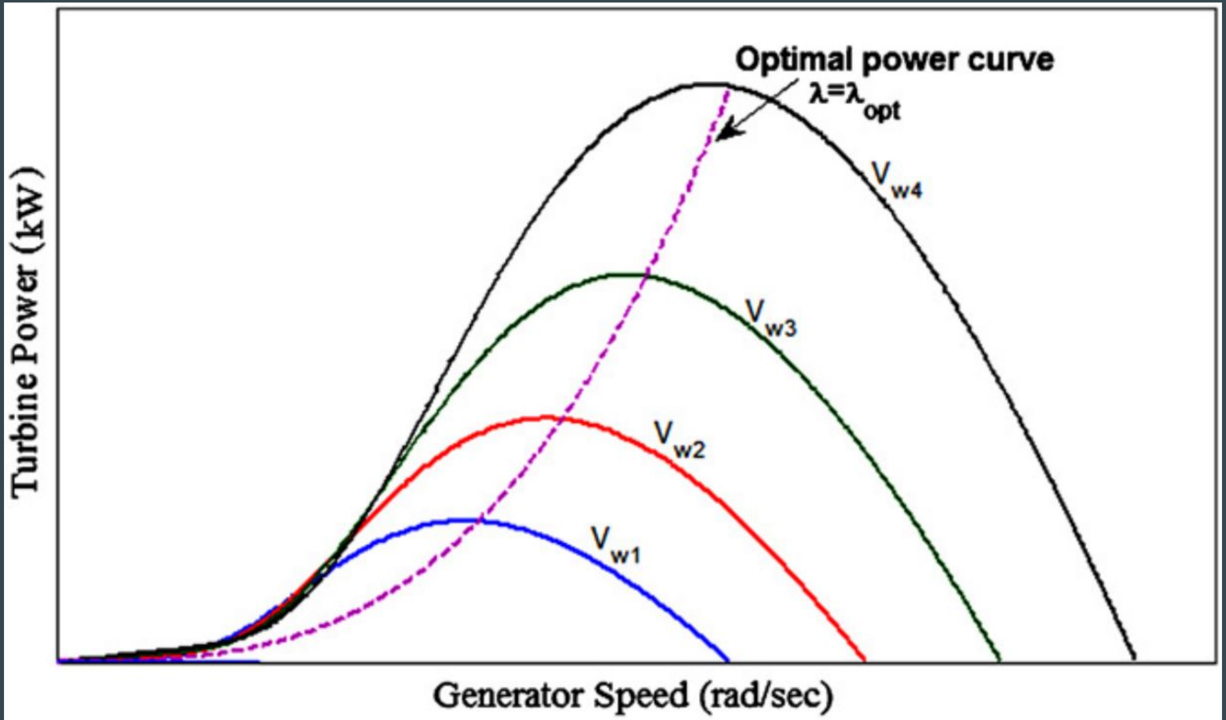
Energy Sources

Solar



1. Astro-Electronics Division, Radio Corporation of America. 1967. Advanced Voltage Regulator Techniques as Applied to Maximum Power Point Tracking Systems for the Nimbus Meteorological Satellite. Technical Report. Radio Corporation of America. Prepared for National Aeronautics and Space Administration.

Wind



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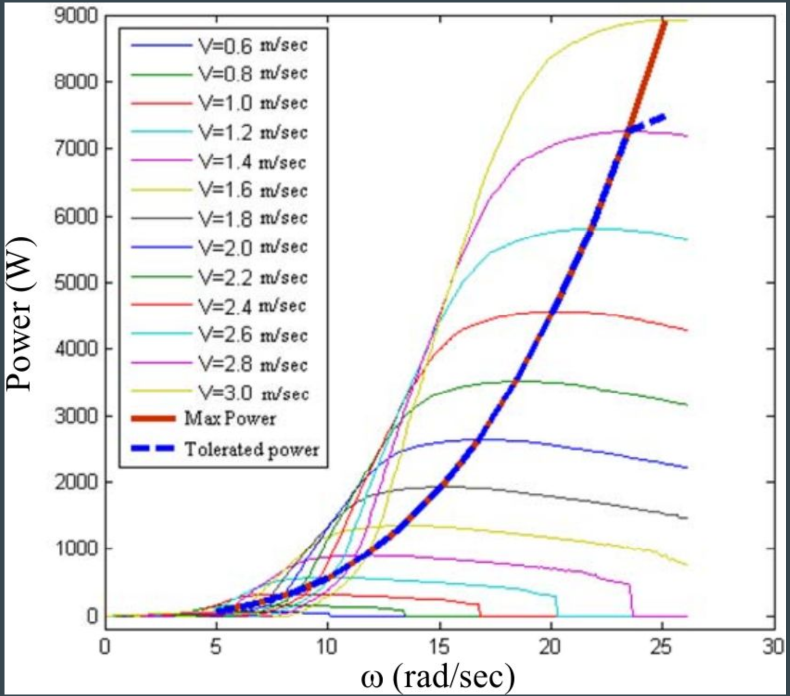
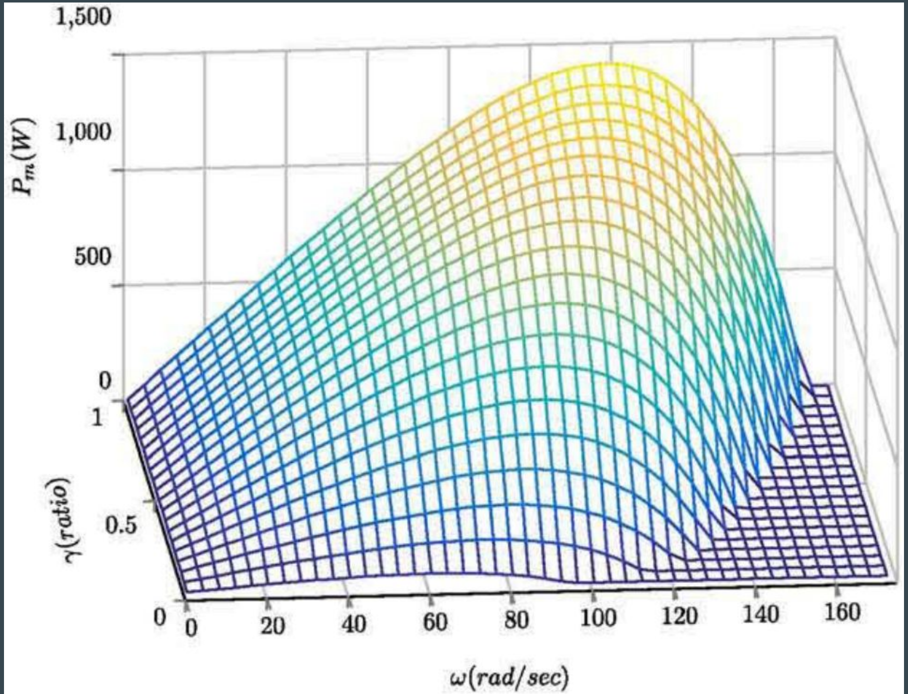
Tidal



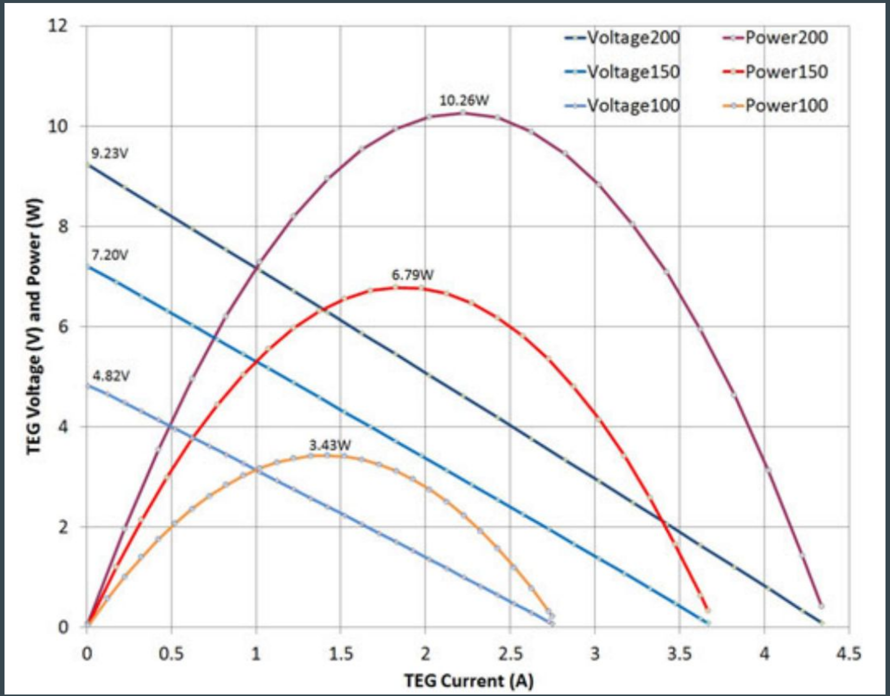
1. Astro-Electronics Division, Radio Corporation of America. 1967. Advanced Voltage Regulator Techniques as Applied to Maximum Power Point Tracking Systems for the Nimbus Meteorological Satellite. Technical Report. Radio Corporation of America. Prepared for National Aeronautics and Space Administration.

Micro/Pico Hydroelectric



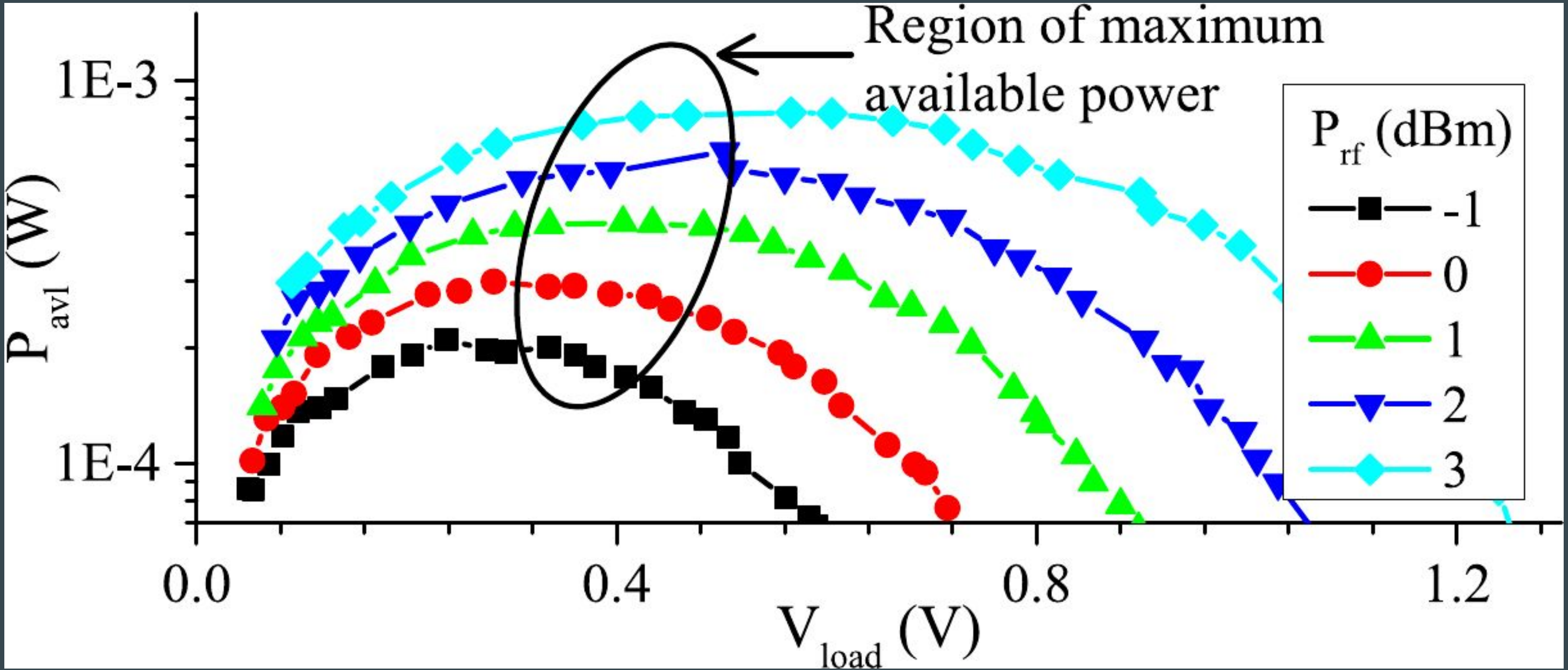
1. Astro-Electronics Division, Radio Corporation of America. 1967. Advanced Voltage Regulator Techniques as Applied to Maximum Power Point Tracking Systems for the Nimbus Meteorological Satellite. Technical Report. Radio Corporation of America. Prepared for National Aeronautics and Space Administration.

Thermoelectric



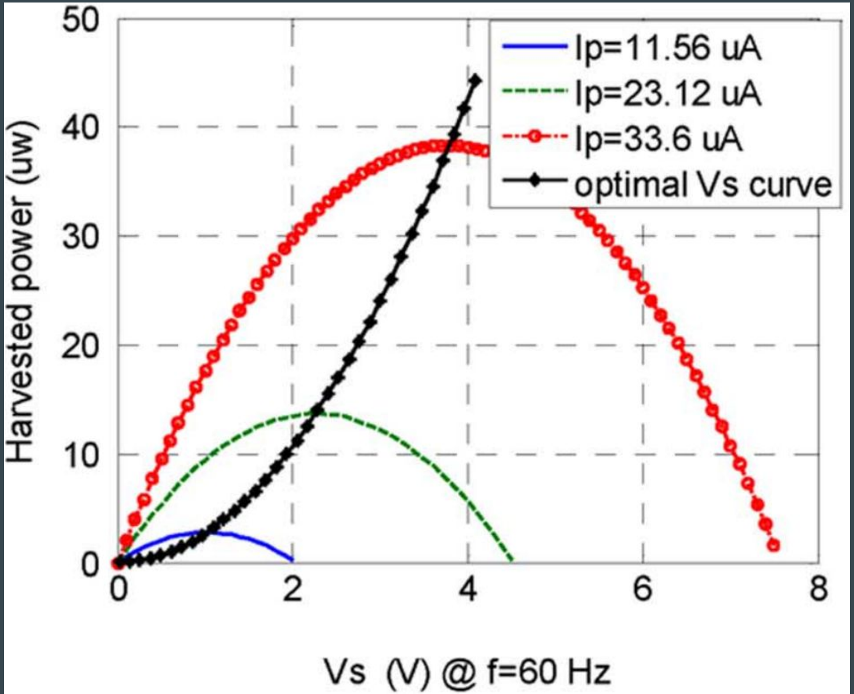
1. Astro-Electronics Division, Radio Corporation of America. 1967. Advanced Voltage Regulator Techniques as Applied to Maximum Power Point Tracking Systems for the Nimbus Meteorological Satellite. Technical Report. Radio Corporation of America. Prepared for National Aeronautics and Space Administration.

Radio Frequency



1. Astro-Electronics Division, Radio Corporation of America. 1967. Advanced Voltage Regulator Techniques as Applied to Maximum Power Point Tracking Systems for the Nimbus Meteorological Satellite. Technical Report. Radio Corporation of America. Prepared for National Aeronautics and Space Administration.

Piezoelectric



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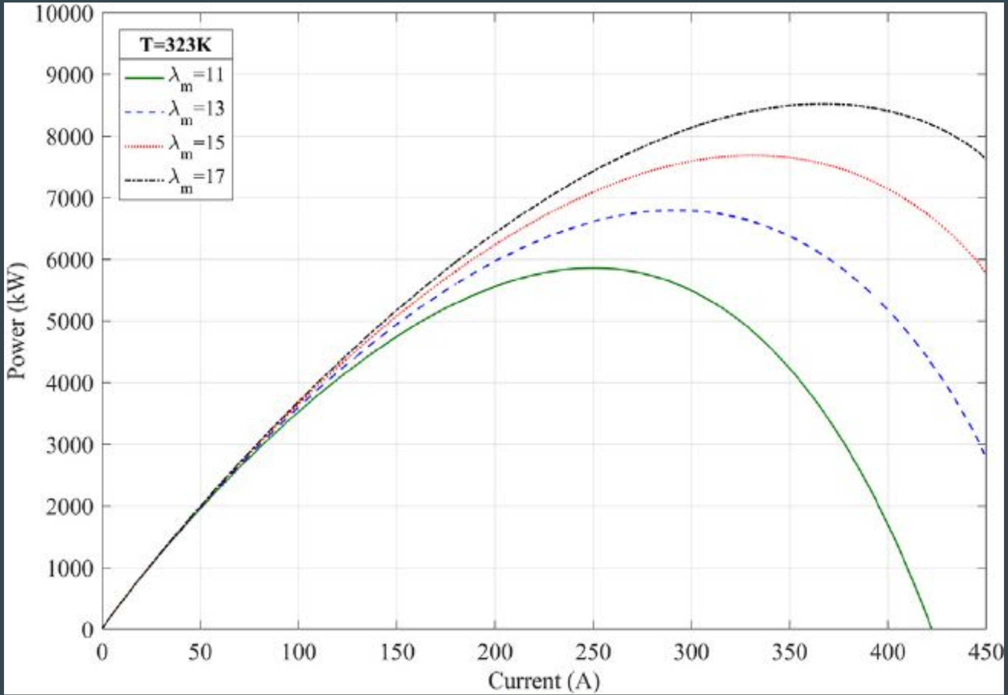
Proton-Exchange Membrane Fuel Cell



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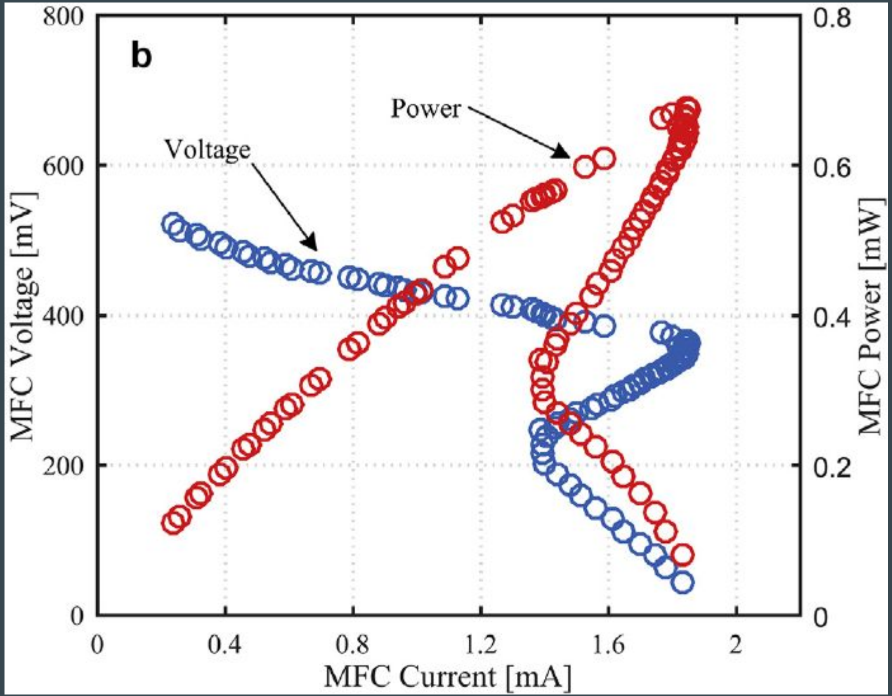
Microbial Fuel Cell



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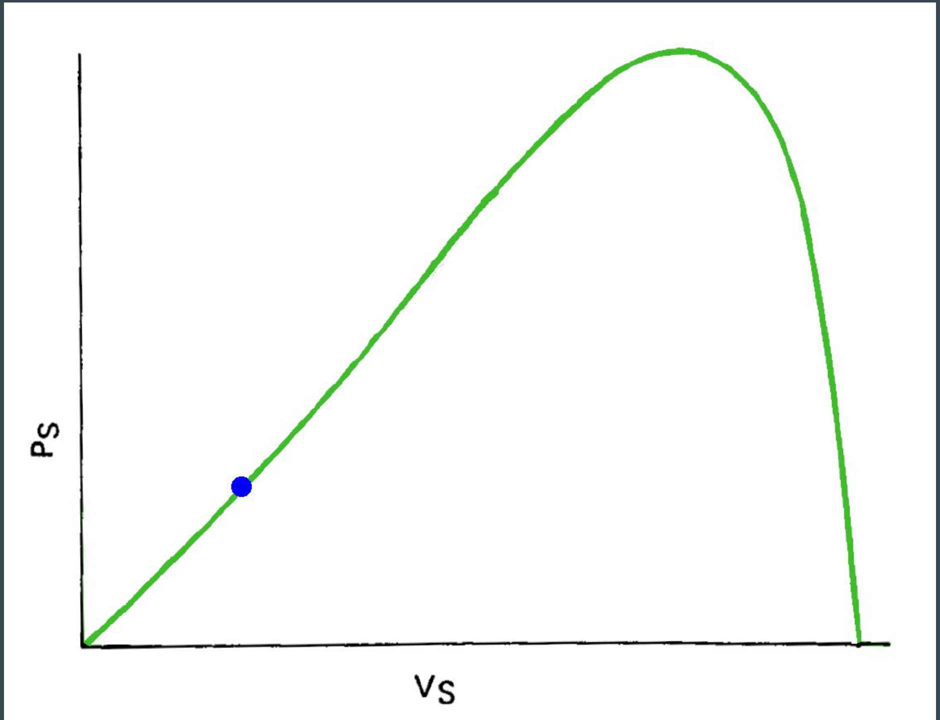
Ontology

Functional Methods

- Perturb and Observe
- Incremental Conductance
- Open Circuit Voltage
- Closed Circuit Current
- Model-based

Functional Methods: Perturb and Observe (P&O)

-



Functional Methods: Perturb and Observe (P&O)

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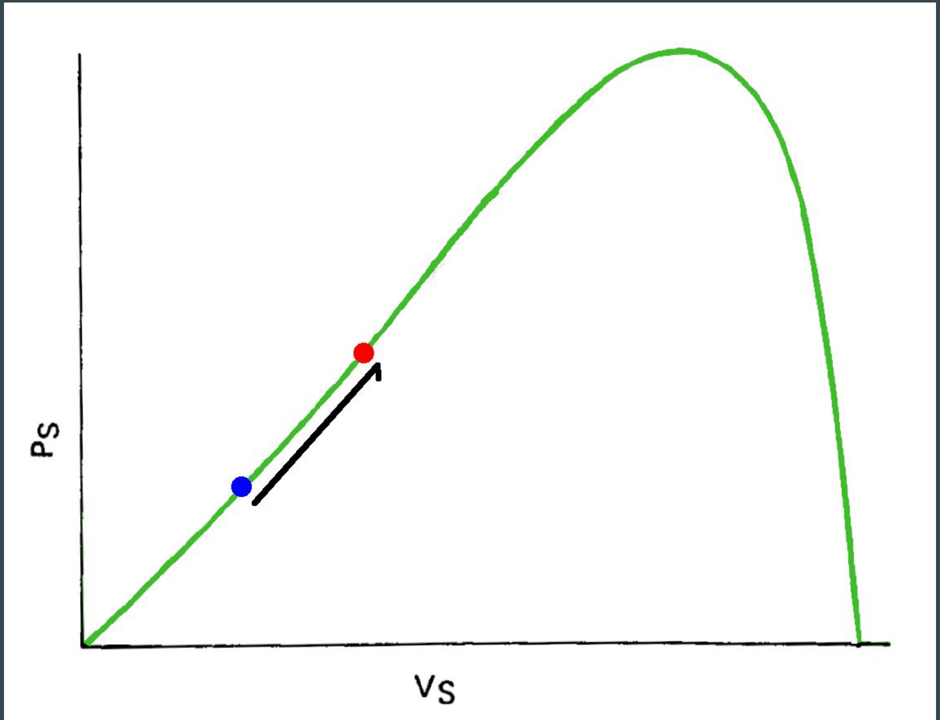

Functional Methods: Perturb and Observe (P&O)

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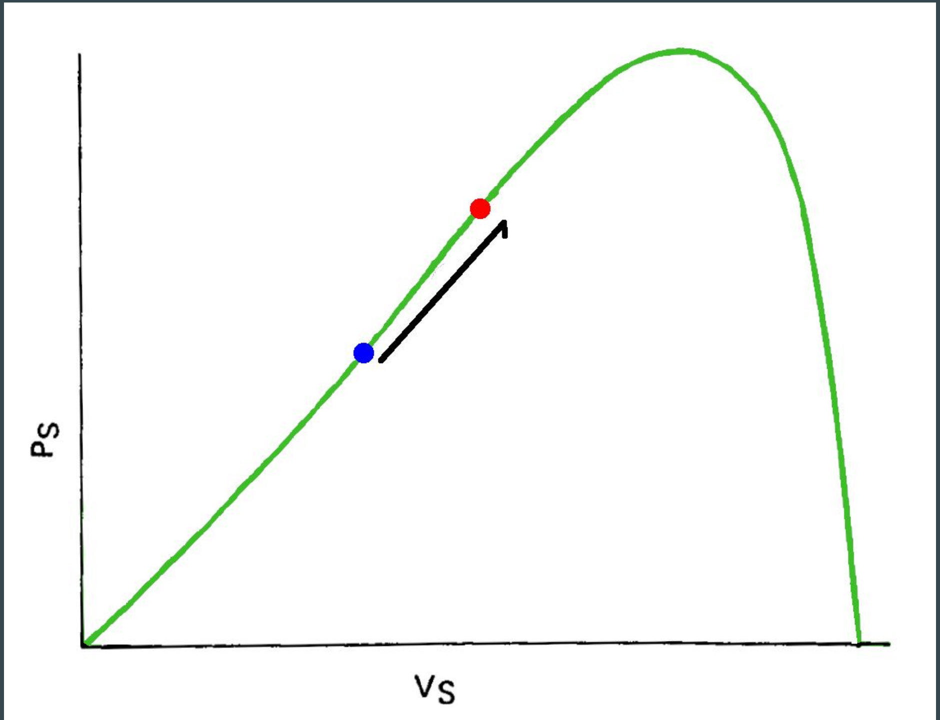

Functional Methods: Perturb and Observe (P&O)

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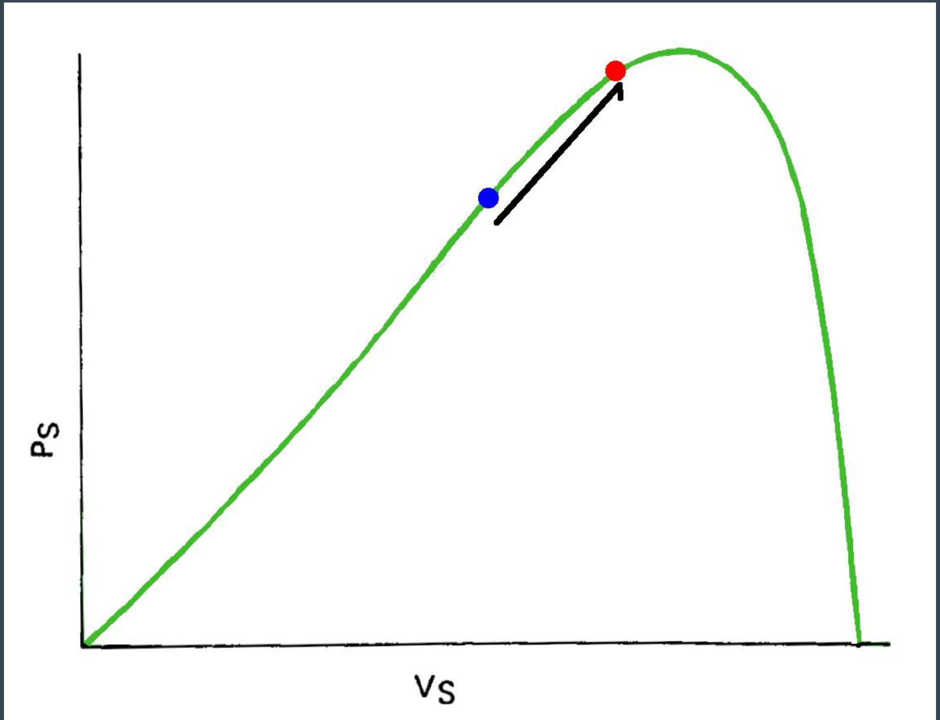

Functional Methods: Perturb and Observe (P&O)

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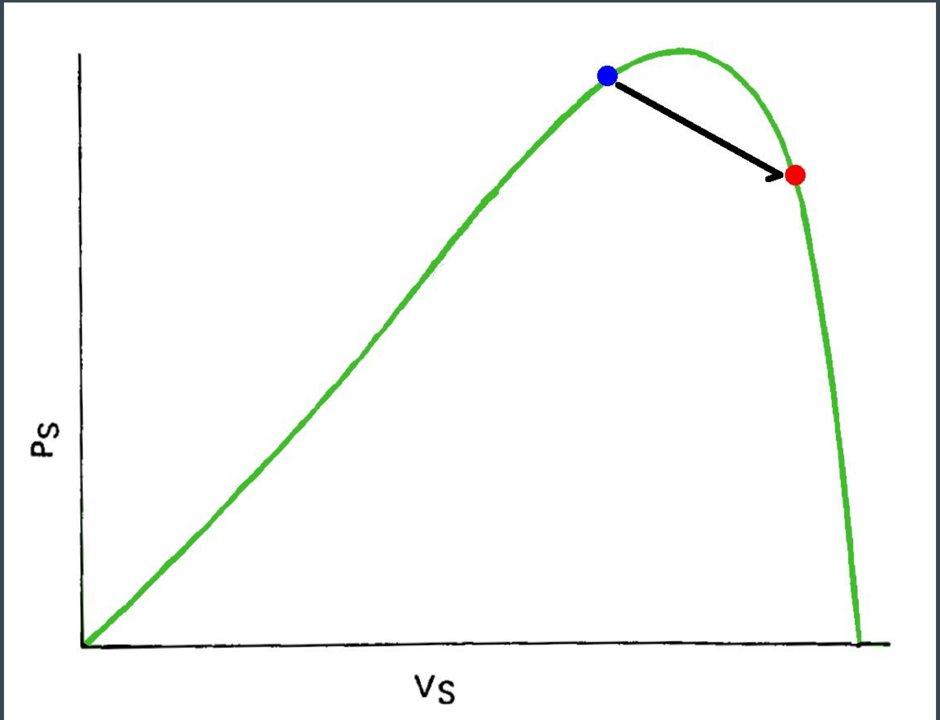

Functional Methods: Incremental Conductance (INC)

- At maximum power point, $$\frac{dP}{dV} = 0$$
- Compares dI and dV with I and V $$\frac{-I}{V} = \frac{dI}{dV}$$
- Unlike P&O, can settle on MPP without oscillation*

Functional Methods: Open Circuit Voltage and Closed Circuit Current

- Attempt to keep Voltage/Current at some % of the Open/Closed circuit reading
- ~75% Open Circuit Voltage
- ~85% Closed Circuit Current
- Problems:
  - Estimate
  - Both require interrupting harvesting

Functional Methods: Model-based

- Anything relying on model information to estimate MPP
- Simplest to implement, usually require little control hardware
- Problem: Usually only estimates

(Spoiler, these are the most common in the survey)

Computational Methods

- Fuzzy Logic
- Artificial Neural Network
- Artificial Intelligence Algorithms
- Other Algorithms

Computational Methods: Fuzzy Logic

- Mapping precise values to “fuzzy” or inexact values
  - E.g. Positive Big, Positive Small, Zero, Negative Small, etc.
- Converges faster than P&O and no oscillation!
- Problem: Require domain expertise to develop logic table and membership mapping from precise values to fuzzy values

Computational Methods: Artificial Neural Network

- Leveraging layers of neurons to model systems
  - Using back-propagation algorithm for training
- Much faster than P&O, converge quickly
- Problem: Requires a lot of training data
- Example: Adaptive Neuro Fuzzy Inference System
  - Can be trained to figure out fuzzy logic membership classes and mapping

Artificial Intelligence Algorithms

- Particle Swarm Optimization
  - Using particles to find target condition
- Greedy Search
- Grey Wolf Optimization
  - Mimics hierarchy and hunting behavior
- Problem: Complex to implement, somewhat slow
- Converge accurately

Computational Methods: Other Algorithms

- Catch-all for other algorithms (very rare in my search)
- One paper: linear search + binary search
  - Important: this particular approach done in hardware!

Hybrid Methods

- Combine methods, compensate for weaknesses
- Examples:
  - Combine estimates with hill-climbing
  - ANFIS (ANN), PSO (AI)

Survey Results

Summary Table

Method	Type	Complexity	Efficiency	Convergence Speed	Convergence Accuracy	Sources Applicable	Tracks True MPP	Vulnerable to Oscillation
P&O [28, 30, 42, 45, 47] [7, 8, 33, 56, 73]	Functional	Low	Good	Moderate-Fast	Moderate-Good	Many	Yes*	Yes
OCV [18, 58, 77, 80] [19, 50, 63, 84, 84]	Functional	Low	Moderate	Fast	Approx.	Many	No	No
Model [11, 46, 53, 60, 65] [23, 26, 78, 86, 87] [10, 20, 69]	Functional	Low	Variable	Fast	Moderate-Good	Many	No	No
FMIM, P&O [76]	Hybrid	Moderate	High	Fast	Good	Solar	Yes*	Yes
ANN [41]	Computational	High	High	Fast	Good	Many	Yes*	No
Fuzzy Logic [4, 62]	Computational	High	High	Fast	Good	Many	Yes*	No
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ANN, AI [64, 85]	Hybrid	High	High%	Fast	Good	Many	Yes	No
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OCV [18, 58, 77, 80] [19, 50, 63, 84, 84]	Functional	Low	Moderate	Fast	Approx.	Many	No	No
Model [11, 46, 53, 60, 65] [23, 26, 78, 86, 87] [10, 20, 69]	Functional	Low	Variable	Fast	Moderate-Good	Many	No	No
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Solar

Publication	Type
An Optimal Frequency-Modulated Hybrid MPPT Algorithm for the LLC Resonant Converter in PV Power Applications.	Hybrid
An Experimental Estimation of Hybrid ANFIS–PSO-Based MPPT for PV Grid Integration Under Fluctuating Sun Irradiance.	Hybrid
Development of a microcontroller-based, photovoltaic maximum power point tracking control system.	P&O
Optimization of perturb and observe maximum power point tracking method.	P&O
A Fixed Zone Perturb and Observe MPPT Technique for a Standalone Distributed PV System.	P&O

Wind

Publication	Type
An Improved Mechanical Sensorless Maximum Power Point Tracking Method for Permanent-Magnet Synchronous Generator-Based Small Wind Turbines Systems	Model
Nonlinear Optimal Control for PMSG-Based Wind Energy Conversion Systems.	Model
Design of a maximum power tracking system for wind-energy-conversion applications.	Model
A Novel Algorithm for Fast and Efficient Speed-Sensorless Maximum Power Point Tracking in Wind Energy Conversion Systems.	P&O
Two-Stage Variable Proportion Coefficient Based Frequency Support of Grid-Connected DFIG-WTs.	Fuzzy Logic

Tidal

Publication	Type
Power Smoothing Control in a Grid-Connected Marine Current Turbine System for Compensating Swell Effect.	Model
Power Control of a Nonpitchable PMSG-Based Marine Current Turbine at Overrated Current Speed With Flux-Weakening Strategy.	Model
Design of Maximum Power Point Tracking for Dynamic Power Response of Tidal Undersea Kite Systems.	P&O
Optimized Energy Extraction in Tidal Current Technology using Evolutionary Algorithm.	AI

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Thermoelectric

Publication	Type
A Battery-Less Thermoelectric Energy Harvesting Interface Circuit With 35 mV Startup Voltage.	Model
Platform architecture for solar, thermal and vibration energy combining with MPPT and single inductor.	Model
Dynamic Surrogate Model Based Optimization for MPPT of Centralized Thermoelectric Generation Systems Under Heterogeneous Temperature Difference.	Hybrid
Hybrid Global Maximum Power Point Tracking Algorithm for a Thermoelectric Generation System.	Hybrid
A Fully Integrated Power Converter for Thermoelectric Energy Harvesting With 81% Peak Efficiency and 6.4-mV Minimum Input Voltage	OCV

Radio Frequency

Publication	Type
An Event-Driven Multi-Input Multi-Output BuckBoost Converter with Adaptive MPPT for Wide Power Range RF Energy Harvesting.	Hybrid
Resistor Emulation Approach to Low-Power RF Energy Harvesting.	Model
Ambient RF Energy Harvesting in Urban and Semi-Urban Environments.	OCV
A Reconfigurable Rectifier With Optimal Loading Point Determination for RF Energy Harvesting From -22 dBm to -2 dBm.	OCV
A 500-nW-to-1-mW Input Power Inductive Boost Converter With MPPT for RF Energy Harvesting System.	Model

Piezoelectric

Publication	Type
Low-Power Design of a Self-powered Piezoelectric Energy Harvesting System With Maximum Power Point Tracking.	P&O
Vibration Energy Scavenging System With Maximum Power Tracking for Micropower Applications.	Model
An Efficient Maximum Power Point Tracking Architecture for Weakly Coupled Piezoelectric Harvesters based on the source I–V curve.	Model
Piezoelectric Energy-Harvesting Interface Using Split-Phase Flipping-Capacitor Rectifier With Capacitor Reuse for Input Power Adaptation.	OCV
A 32nA Fully Autonomous Multi-Input Single-Inductor Multi-Output Energy-Harvesting and Power-Management Platform with 1.2×105 Dynamic Range, Integrated MPPT,and Multi-Modal Cold Start-Up.	OCV

Proton-Exchange Membrane Fuel Cell

Publication	Type
Low-Frequency Current Oscillations and Maximum Power Point Tracking in Grid-Connected Fuel-Cell-Based Systems.	P&O
High Voltage Gain Interleaved Boost Converter With Neural Network Based MPPT Controller for Fuel Cell Based Electric Vehicle Applications.	ANN
A Differential Evolution-Based Optimized Fuzzy Logic MPPT Method for Enhancing the Maximum Power Extraction of Proton Exchange Membrane Fuel Cells.	Fuzzy Logic
Recent Approach of Forensic-Based Investigation Algorithm for Optimizing Fractional Order PID-Based MPPT With Proton Exchange Membrane Fuel Cell.	Model
Predictive Maximum Power Point Tracking for Proton Exchange Membrane Fuel Cell System.	Model

Microbial Fuel Cell

Publication	**Type**
Design of Transformer-Based Boost Converter for High Internal Resistance Energy Harvesting Sources With 21 mV Self-Startup Voltage and 74% Power Efficiency.	Model
Power Management System With Integrated Maximum Power Extraction Algorithm for Microbial Fuel Cells.	OCV
A Power Management System for Microbial Fuel Cells With 53.02% Peak End-to-End Efficiency.	OCV
Soil Power? Can Microbial Fuel Cells Power Non-Trivial Sensors?	OCV

Research Trends & Conclusion

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- Tidal, hydroelectric, and MFC MPPT research nascent
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- Advances in semiconductor technology leading to more complex low-power MPPT systems

Questions?