Design, Simulation, and Analysis of a PV Power and Reverse Osmosis System for a house in Iran

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Introduction

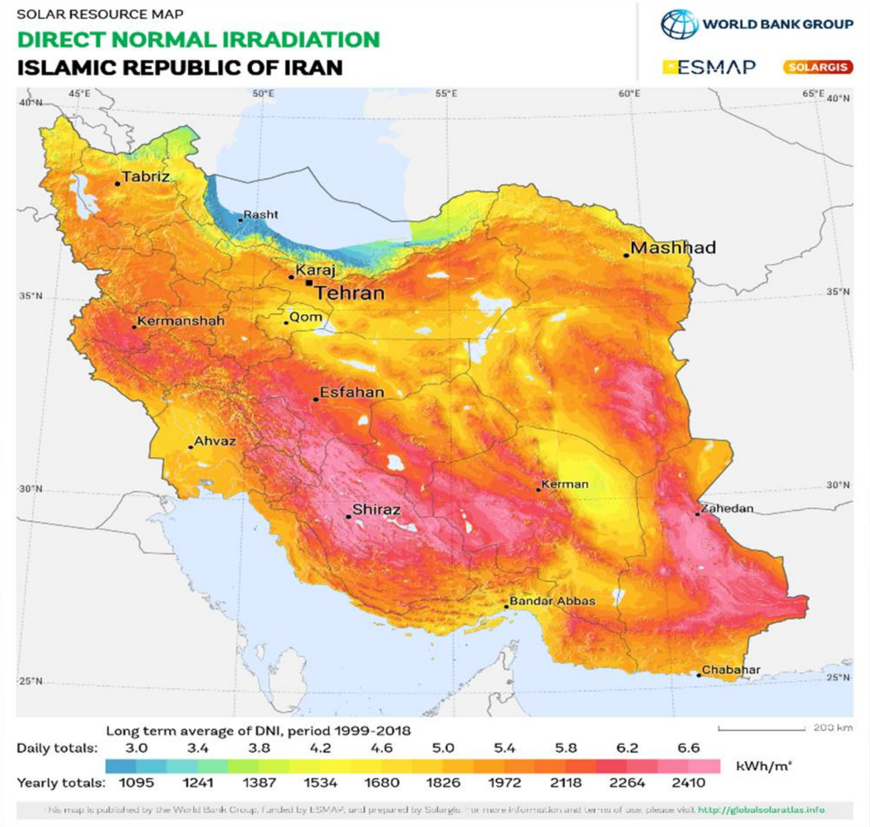
Motivation

- Greenhouse gas emissions increasing and needs for climate change mitigation
- Finding replacement for fossil fuel resources
- Potable water scarcity and needs for water desalination in rural areas
- Designing small-scale cost effective multi-purposes PV system
- Improving the efficiency of PV systems

Introduction

Electricity and renewable resources in Iran

- Iran: 4th in oil reservoirs - 2th in natural gas reservoirs
- Electricity: 14% by hydropower between 1950 to 2000
- 30000 MW wind power capacity
- Geothermal energy productions potential: 14 locations
- 300 sunny days - annual average of 2200 kWh/m2 solar radiation
- PV panels with 10% efficiency - 1% of Iran's total areas → 9 million MWh of energy



Introduction

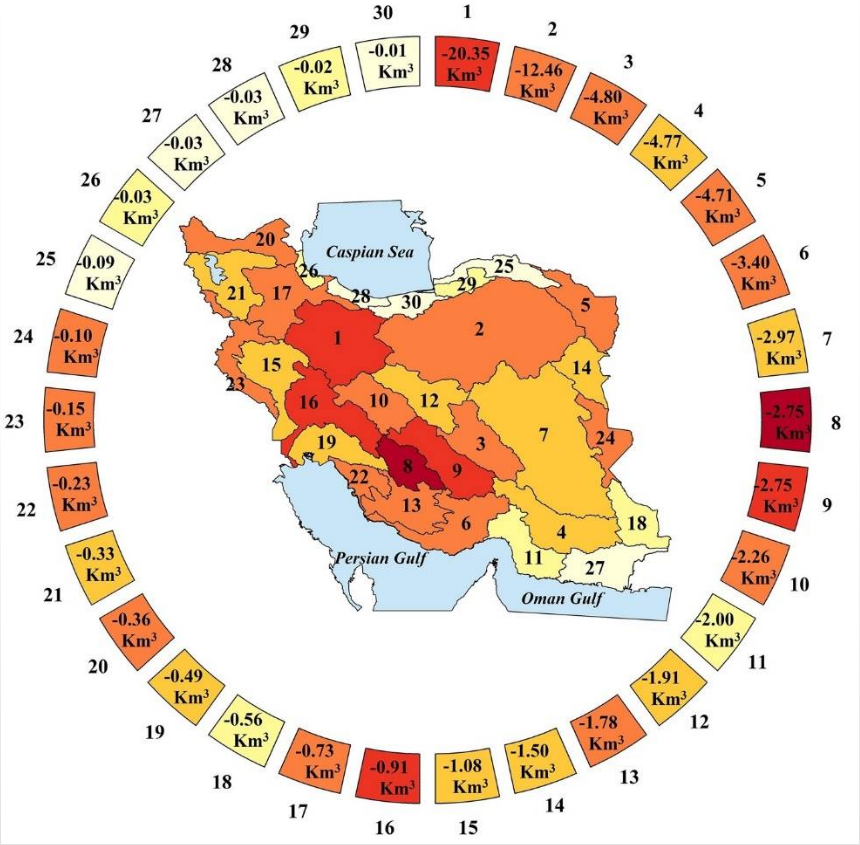
Renewable Systems in Iran

- Wind Farms: Manjil and Rudbar (100.8 MW) - Tarom (Qazvin Province) (200 MW)
- PV Power Stations: Hamedan (14 MW) – Isfahan (10 MW)
- Meshkinshahr geothermal power plant (Ardabil) (250 MW)

Introduction

Potable water resources and water scarcity in Iran

- Fresh water sources in Iran dropped from 3,935 m^3 per person in 1979 to 1732 m^3 → water stress
- Total average available potable water in Iran: 137 km^3
- Environmental factors: closed rivers – lake volumes – increasing droughts
- Human water withdrawal: uptake fresh water > 3 * Recharge water
- Human water withdrawal + Environmental factors → Ground water depletion



Introduction

Water Desalination in Iran

- First desalination plant: installed in 1960 in Khark Island
- Operational desalination capacity in Iran: 400,000 m^3/d
- 15 community-based plants: Chabahar, Bandar Abbas, Bushehr, Zahedan, and Qeshm Island

Chabahar–Kenarak RO desalination plant

RO desalination plant installed in Bandar Lengeh

Literature Review

PVRO System Design and System Optimization

Ref. No	Reference	Field of research	Comment
1	M. A. Alghoul	PVRO Design	Designed and implemented a small-scale PVRO system for Malaysian conditions
2	F. Banat	PVRO Design	A small-scale PV-driven RO system was designed for a village in Jordan
3	S. Gorjian	PVRO Design	Designed and implemented a small-scale stand-alone photovoltaic-thermal (PVT) system for a RO desalination unit in Tehran, Iran
4	M. Akorede	Optimization	Categorized renewable energy system’s optimization methods
5	M. W. Saleem	Optimization	Developed and optimized PVRO systems for three different cities of Pakistan
6	A. Maleki	Optimization	Investigated three stand-alone hybrid renewable energy systems for a water desalination system in Iran
7	A. Mostafaeipour	Optimization	Did the techno-economic analysis for PVRO systems in nine different districts of Bushehr province in Iran

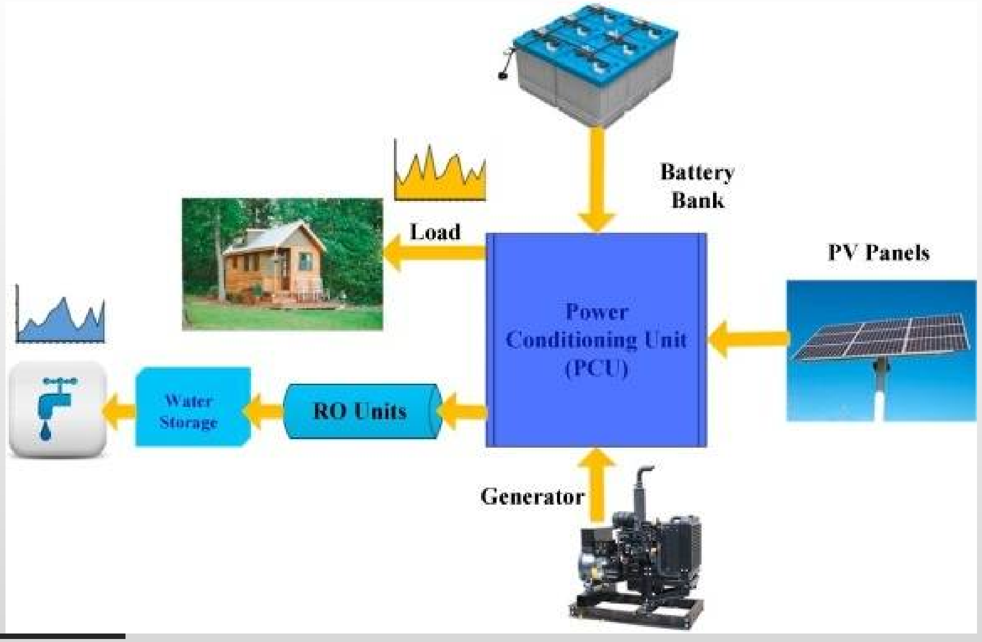
Literature Review

Dynamic Modelling and MPPT Control Techniques

Ref. No	Reference	Field of research	Comment
8	C. Riverol	Dynamic Modeling	They proposed a model based on the parameters estimation, real data from the system, and a zero-poles discrete model
9	A. Gambier	Dynamic Modeling	Three different groups of RO dynamic models were described
10	B. Jiang	Dynamic Modeling	Designed, simulated, and analyzed a hybrid PV system for a rural house in China
11	N. S. Jayalakshmi	Dynamic Modeling	A stand-alone PV-battery system dynamic model was simulated and analyzed with MATLAB/Simulink
12	L. O. Aghenta	Dynamic Modeling	Designed and simulated a stand-alone hybrid PV system for a rural house in Nigeria
13	S. M. Sadek	MPPT Techniques	Designed a PV battery system with a conventional P&O and P&O-based FLC MPPT controller
14	N. H. Selman	MPPT Techniques	Three different MPPT controllers, including P&O, incremental conductance, and FLC, were presented
15	B. Bendib	MPPT Techniques	Compared the P&O and FLC MPPT controller results in a PV system with a DC-DC buck converter to evaluate the system's efficiency

Research Objectives

1. To investigate current water system and design a water system configuration with RO components.
2. To design and simulate two isolated hybrid renewable energy systems with HOMER software.
3. To present a Transfer function-based dynamic model for the reverse osmosis system.
4. To model the PV system in MATLAB/Simulink and check the system's dynamic behavior.
5. To propose and simulate different MPPT control techniques for the PV system



Site Selection and Water System Configuration

Selected Site Characteristics

- A Rural house with 4 people living in it
- Sinak village, Lavasana District, Tehran Province, Iran
- Electricity: Stand-alone diesel generator for lighting, running appliances
- Water source: Well water with TDS of 600 ppm

Front view of the house

Side view of the house

Site Selection and Water System Configuration

Water System components in the house

- Submersible pump: located in the well - depth of 25 meters - can pump water up to 38 meters
- Atmospheric tank: 3 meters above ground - capacity of 1000 litres
- Jet pump: pressurizes the water and supplies the house
- Daily water usage: 1500 littres for washing and cleaning – 100 littres for drinking and cooking

Site Selection and Water System Configuration

Water Desalination Systems

- Water desalination: process of removing salt / inappropriate ingredients - ocean or well water
- IDA: 5 million m^3/day in 1980 increased to 100 million m^3/day in 2020 - 18,500 desalination plants - 183 countries

1. **Membrane desalination**: semi-permeable membrane is used to trap contaminants
   - Reverse Osmosis (RO): pressurized water
   - Forward Osmosis (FO): concentration difference
   - Electrodialysis (ED) and Electrodialysis Reversal (EDR): electrical potential differences
2. **Thermal desalination**: based on water evaporation and distillation - high salty water
   - Multi-Stage Flash (MSF) method
   - Multi-Effect Desalination (MED) method
   - Mechanical Vapor Compression (MVC) - Thermal Vapor Compression (TVC)

Site Selection and Water System Configuration

RO Method

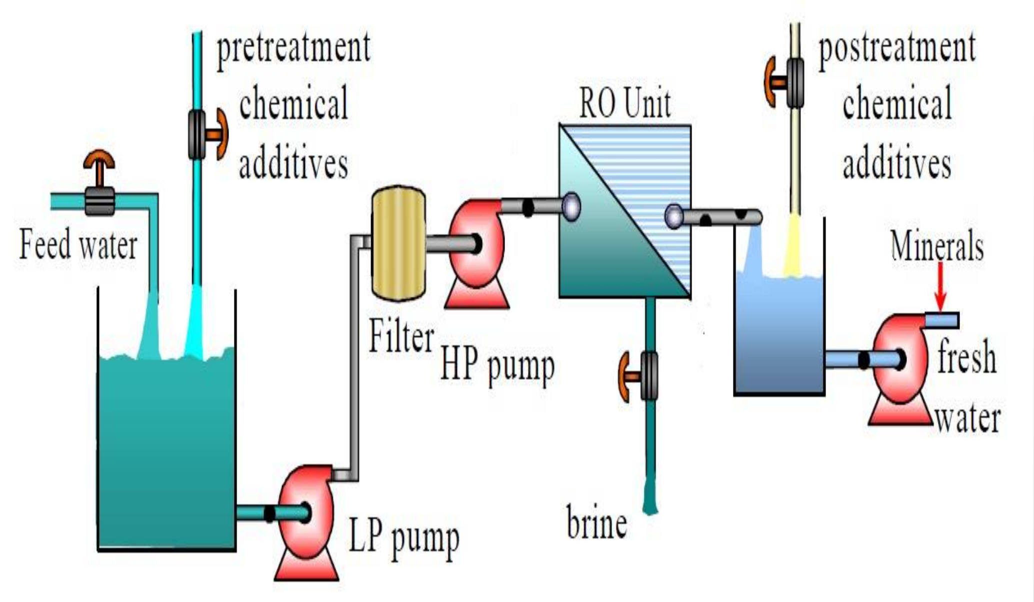
- ➢ The reverse osmosis (RO) method: tremendously popular →

less investment and operation cost + less environmental effects + available in small-scale

- ➢ IDA report: in 2014, 65% of the global desalination → RO method

- Osmosis: is the movement of solvent molecules from a region of <u>high water</u> potential to a region of <u>low water</u> potential

1. Filter
2. Low pressure pump
3. High pressure pump
4. RO unit (membrane)
5. Storage



Site Selection and Water System Configuration

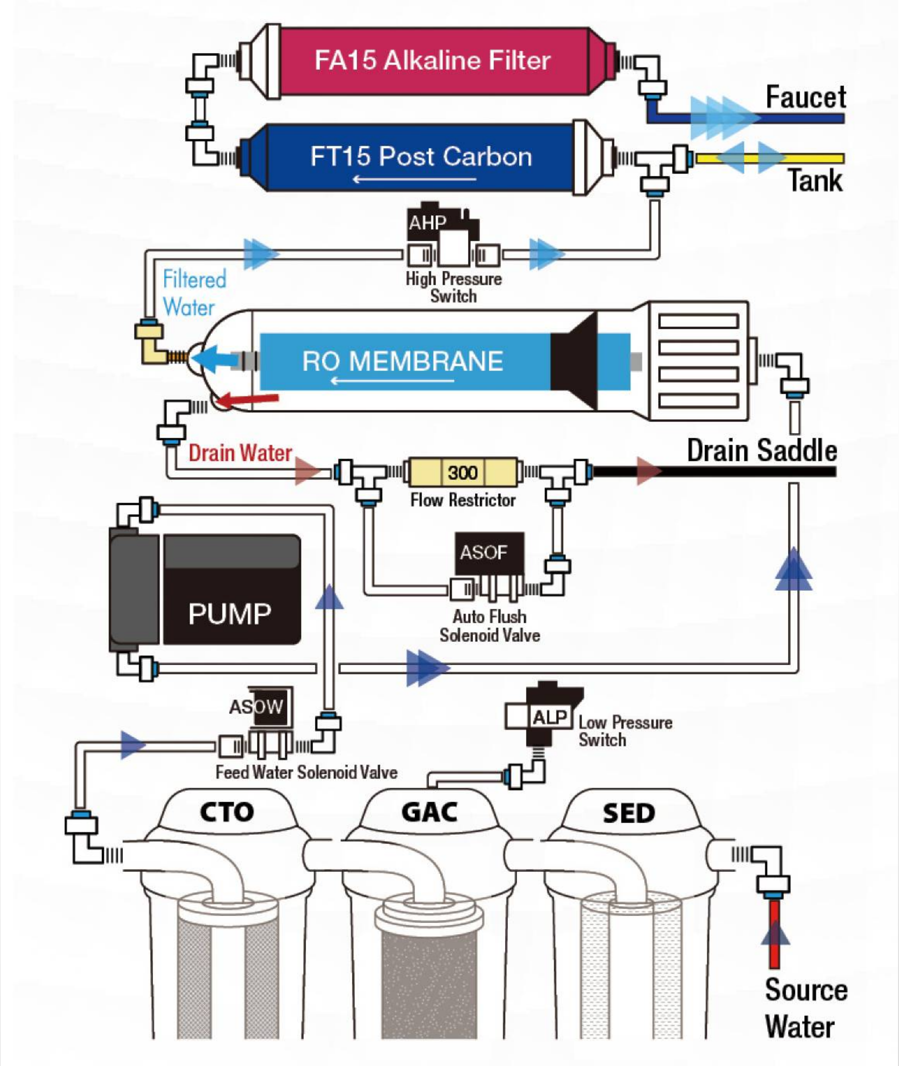
RO system

ISpring RCC7P-AK

- Capacity: 75 gallons per day (GPD) / 284 litters
- Incoming Water Pressure: 30 PSI - 70 PSI

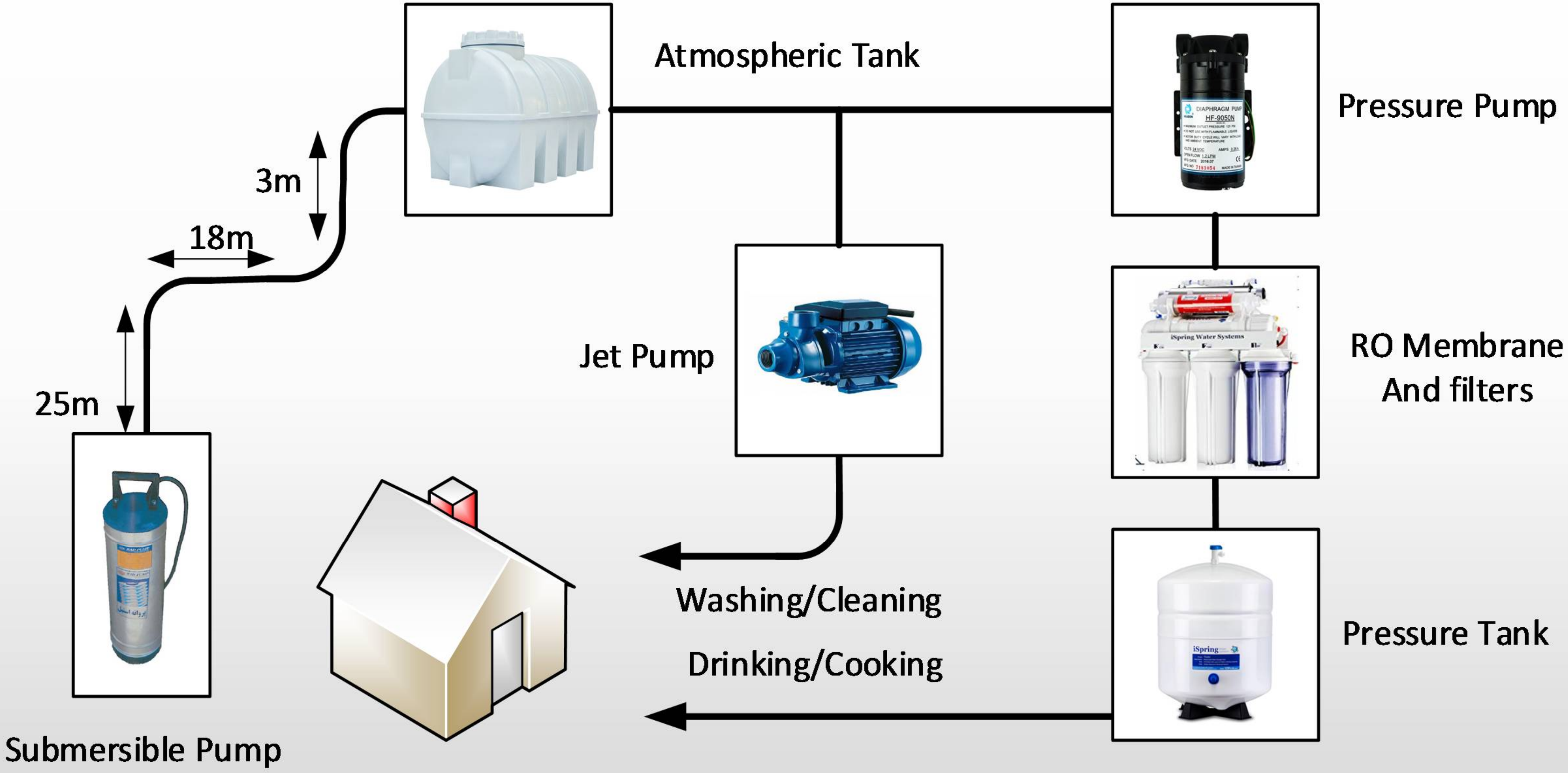
  Operating water temperature range: 40 – 100 °F

  Maximum TDS: 750 ppm
- 3 Pre-filters: PP sediment filter, Carbon KDF (GAC) filter, Carbon block (CTO) filter
- Booster pump
- Reverse Osmosis (RO) Membrane: removes contaminants down to 0.0001 microns
- 2 Post-filtration: Carbon and Alkaline filter



Site Selection and Water System Configuration

water system configuration



Methodology and HOMER Software

- HOMER Software: designing, simulating and optimizing micro-grids → Renewable systems
- Considerations for PV system design in HOMER: (1) Designed system is cost-effective. (2) The system has a high renewable fraction. (3) Environmental factors are considered.
- Method: Comparison of two possible scenarios for powering the house and RO system with PV
  - Photovoltaic system with Battery storage
  - Photovoltaic system with Battery storage and gas generator
- Possible sources: PV power generation – natural gas generator
- Loads: Regular Load → house energy consumption

  Deferrable load → Water system energy consumption
- Deferrable load: requires a certain amount of energy when excess energy exists in the system

Water System Load Sizing

- Submesible Pump: pumping 1500 litres → work for 30 minutes

  Power rating = 1100 watts → daily energy (E_{sp}) is 0.55 kWh

- Jet Pump: provide water for washing and cleaning → work 1 hour

  Power rating = 470 watts → daily energy (E_{jp}) is 0.47 kWh

- Pressure Pump: Pressurize 100+10 littres for desalination

  Power rating = 60 watts - RO capacity is 75 GPD →

  daily energy (E_{pp}) = daily GPD × time for 1 GPD × pump wattage

$$= \left(\frac{110}{3.785}\right)\left(\frac{24}{75}\right)60 \cong 0.55\,kWh$$

- Water system daily energy consumption (E_{ro}): $E_{ro} = E_{sp} + E_{jp} + E_{pp} = 1.57\ kWh/day$

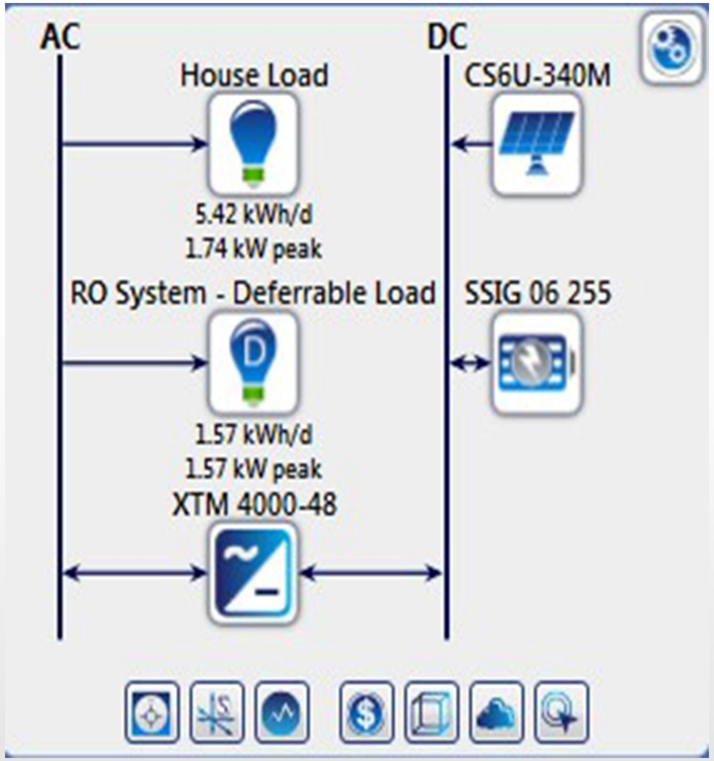
House Load

- There is no metering system in the house → Survey
- List of house appliances by their wattage and energy consumption
- Total daily house load is approximately 5.42 kWh/day.

Household appliances	Rated watts (watt)	Timed used (hour)	Daily energy consumption (kWh)
Refrigerator	150	8	1.2
Microwave	900	0.3	0.27
Electric meat grinder	350	0.1	0.035
Blender	400	0.1	0.04
Cooker hood	140	0.4	0.056
Washing machine	200	0.3	0.06
Vacuum cleaner	900	0.2	0.18
Electric shaver	15	0.2	0.003
TV 42" LCD	120	3	0.36
Laptop	50	8	0.4
Home phone	6	24	0.144
Home internet router	10	24	0.24
Wall-mounted gas boiler	140	6	0.84
Light bulb - LED*6	72	2	0.144
Light bulb - Common*2	200	3	0.6
Light Bulb - LED*38	266	2	0.532
Extractor Fan*2	40	8	0.32

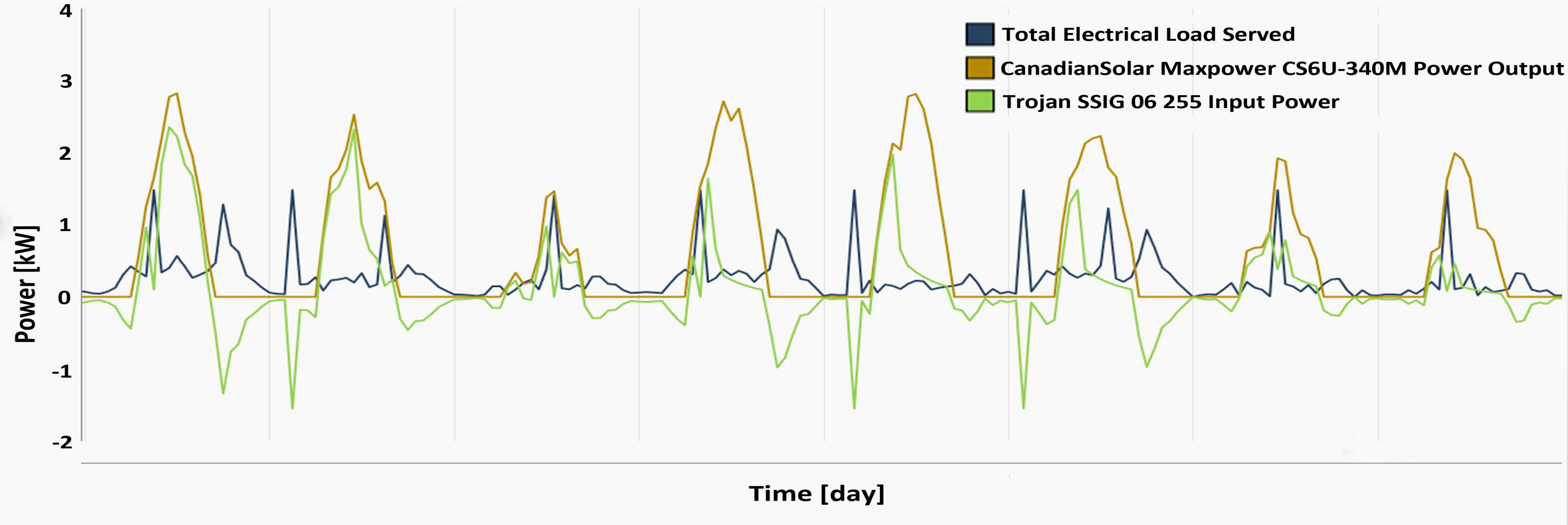
PV-Battery System Optimization

- Regular and deferrable loads
- PV panels: CanadianSolar - CS6U-340M - 340 watts power rating - 17.49% efficiency
- Battery: Trojan battery - SSIG-06-255 - maximum capacity 255 Ah - nominal voltage 6 volts - 85% efficiency
- Inverter: power rating 20% more than the total peak load
- Optimization results:
  - 2.68 kW PV array → 8 panels
  - 24, 6 volts batteries & 48 DC bus → 3 strings and 8 in each string → total capacity is 765 Ah



Power Balance in PV-Battery System

- Dispatch control strategy: decision-making about how the resources serve the loads, is critical because timing for switching on/off the components will affect system sizing.
- **Cycle Charging (CC):** PV panels feed regular and deferrable loads with higher priority, and excess energy will charge the battery



PV-Battery System Cost Summary

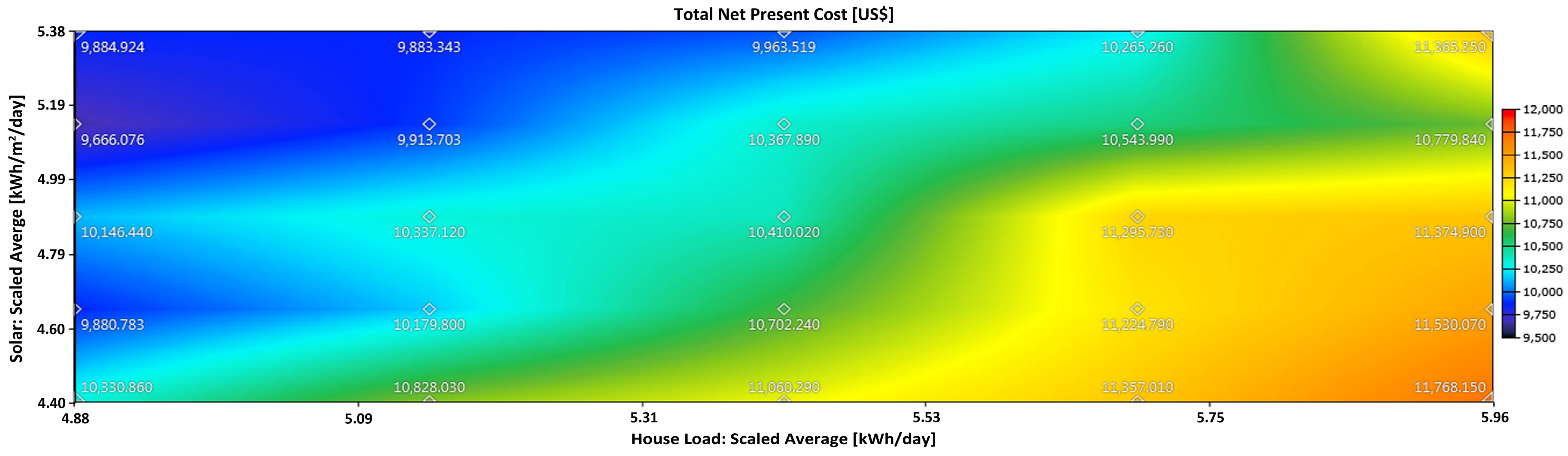
Cost Summary	Capital	Replacement	O&M	Total
CanadianSolar MaxPower CS6U-340M	$2,363.05	$0.00	$224.02	$2,587.07
Trojan SSIG 06 255	$4,800.00	$1,898.29	$542.96	$7,039.41
Studer Xtender XTM 4000-48	$370.40	$245.42	$35.91	$618.46
System	$7,533.45	$2,143.71	$802.89	$10,244.93

- Net present cost (NPC) during the project's lifetime (25 years): $10,245
- Cost of Energy (COE): 0.31 $/kW

Sensitivity Analysis for PV-Battery System

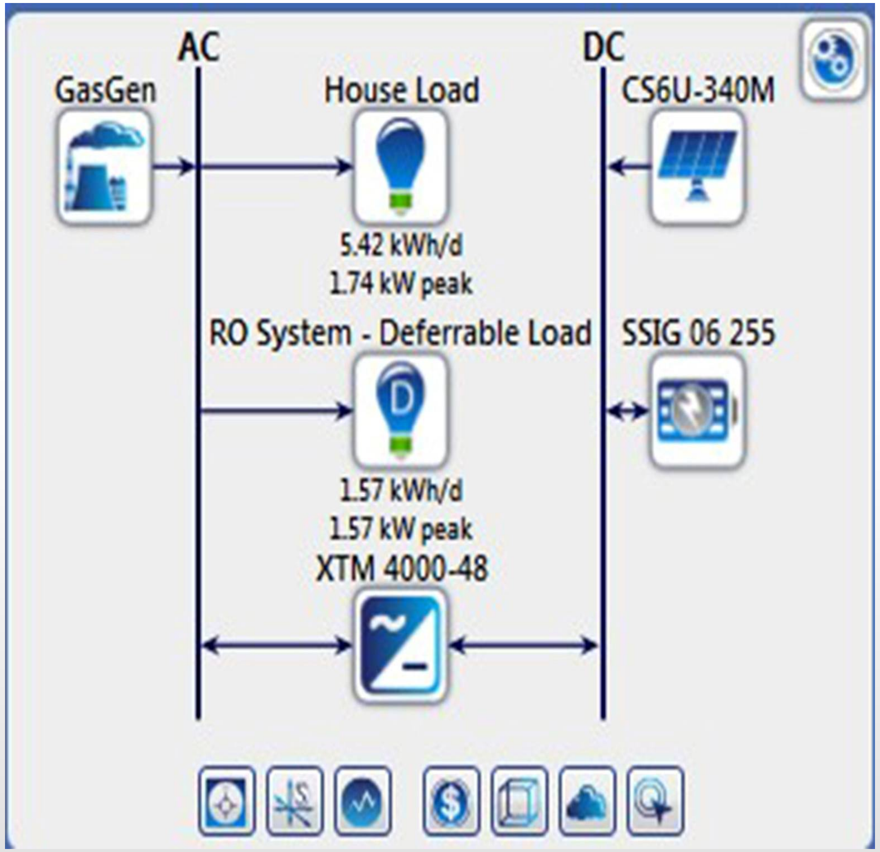
- Sensitivity Analysis: check the system's robustness
  - system's output: cost of the system (NPC)
  - Variable inputs: regular house load - solar radiation
- Each sensitivity variable: ± 10% and ± 5% of the normal amount of the variables →

  NPC : $9,885 to $11,768



PV-Battery-Gas Generator System Optimization

- Adding components to the system: more controllability and complexity
- Natural gas : available for cooking/heating - gas price 0.1 $/m^3$
- Gas generator: capacity: 1 kW
- Optimization results
  - 1.28 kW PV array → 4 panels
  - 8, 6 volts batteries & 48 DC bus → 1 strings → total capacity is 255 Ah

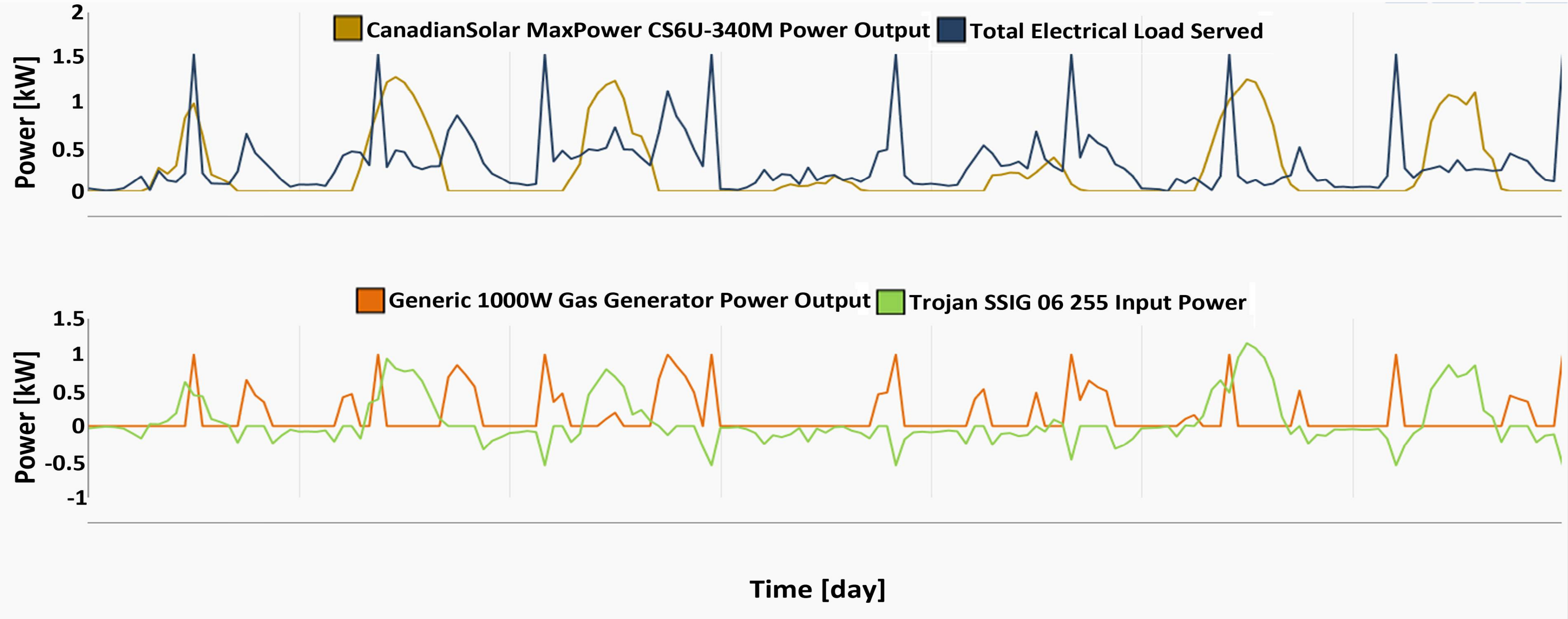


Power Balance in PV-Battery-Gas Generator System

- **Load following (LF)** dispatch strategy: generator produces power to serve regular load - renewable sources feed deferrable load and battery storage →

  deferrable load and batteries have a lower priority for the gas generator

- This control strategy is more complex



PV-Battery-Gas Generator System Cost Summary

Cost Summary	Capital	Replacement	O&M	Fuel	Total
CanadianSolar MaxPower CS6U-340M	$1,127.16	$0.00	$106.86	$0.00	$1,234.02
Generic 1000W Gas Generator	$400.00	$82.98	$1,149.90	$515.38	$2,084.44
Trojan SSIG 06 255	$1,600.00	$1,274.13	$180.99	$0.00	$2,920.67
Studer Xtender XTM 4000-48	$132.54	$87.82	$12.85	$0.00	$221.30
System	$3,259.70	$1,444.92	$1,450.60	$515.38	$6,460.43

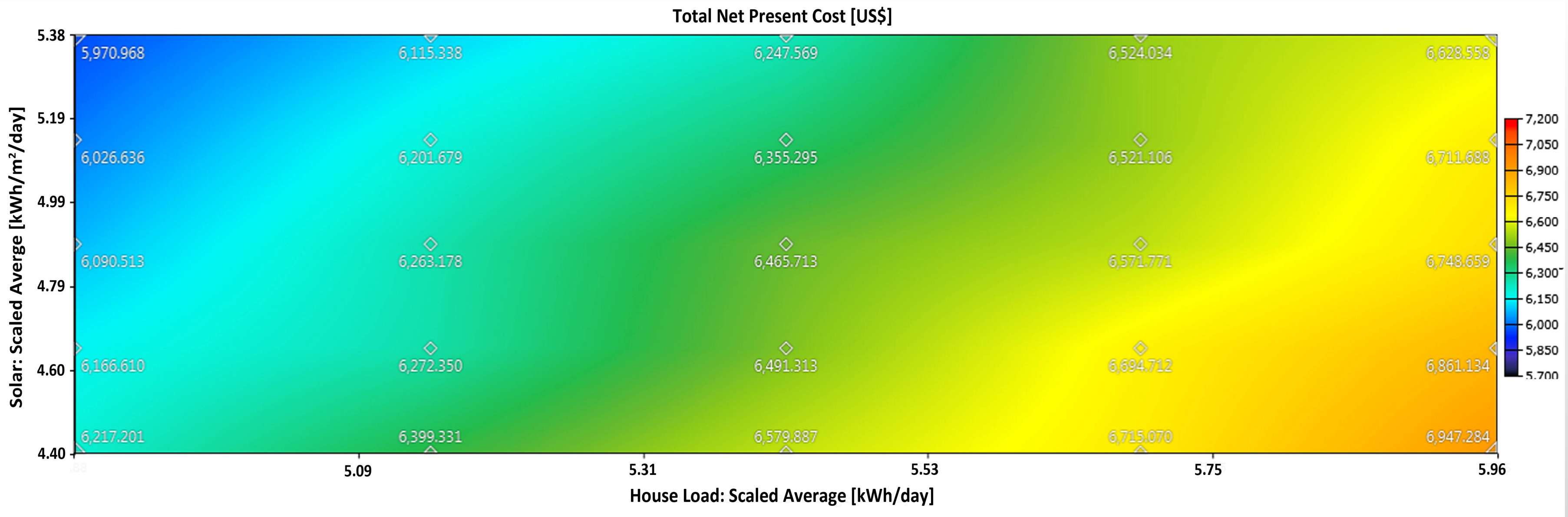
- Fuel Price: $515
- Net present cost (NPC) during the project's lifetime (25 years): $6,460
- Cost of Energy (COE): 0.2 $/kW

PV Systems Design, Optimization, and Analysis in HOMER

Sensitivity Analysis for PV-Battery-Gas Generator System

- Sensitivity Analysis:
  - system's output: cost of the system (NPC)
  - Variable inputs: regular house load - solar radiation – gas price
- Each sensitivity variable: ± 10% and ± 5% of the normal amount of the variables →

  NPC : $5,970 to $6,947

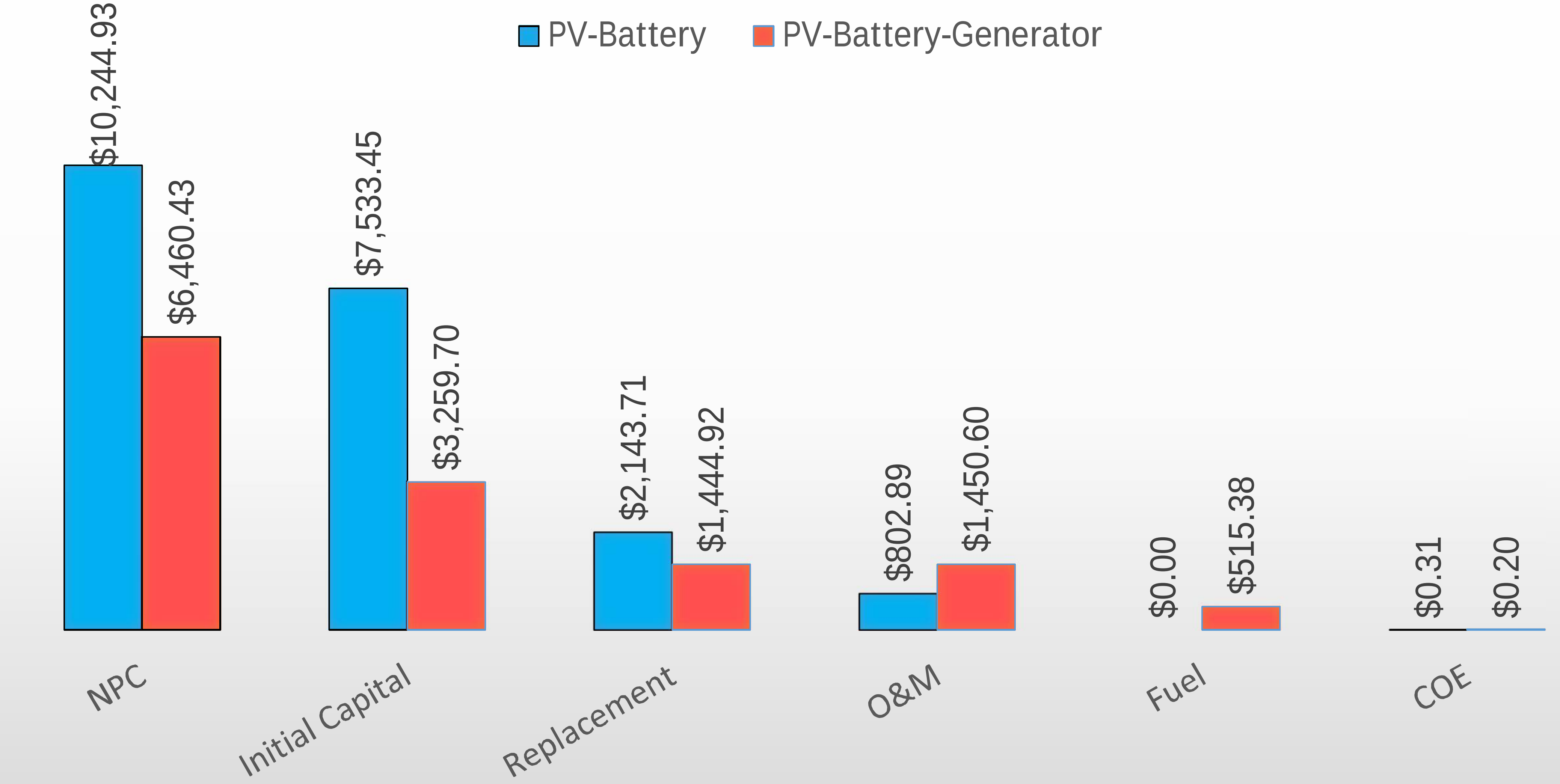


Technical Comparison

	PV-Battery	PV-Battery-Generator
PV	2.68 kW	1.28 kW
Generator	0	1.068 kW
Battery Numbers	24	8
Converter	4 kW	4 kW
Renewable fraction	100%	58.1%
Fuel	0	399 m^3/year
Autonomy	100 h	33.5 h
Excess electricity	1,665 kWh/year	511 kWh/year
Unmet Load	1.08 kWh/year	1.57 kWh/year
CO2 Emission	0	770 kg/year
Dispatch	CC	LF

PV Systems Design, Optimization, and Analysis in HOMER

Economical Comparison



Sensitivity Comparison

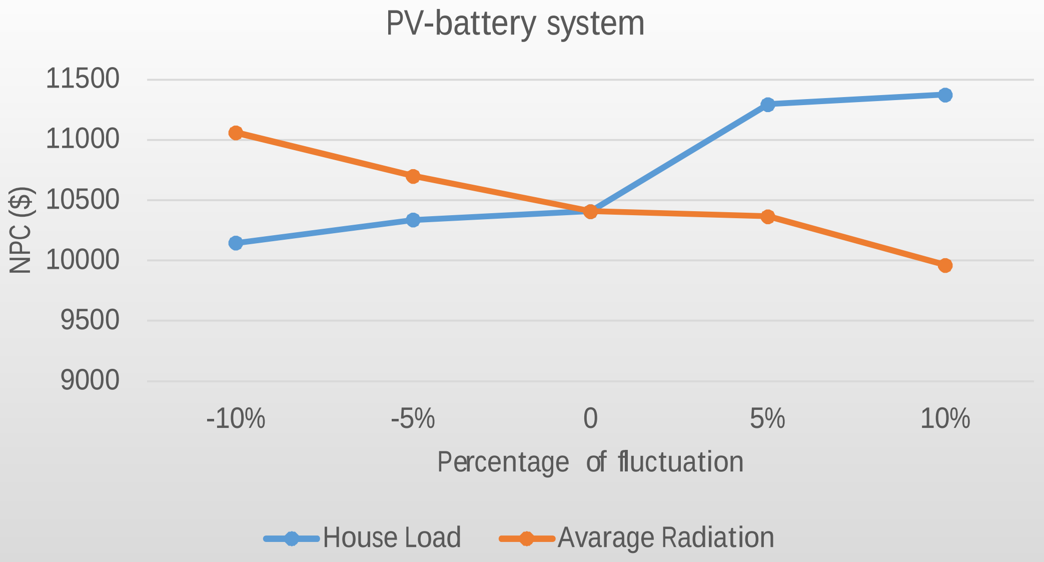
Percentages of variations in each variable from -10% to 10% when others are fixed to zero variation

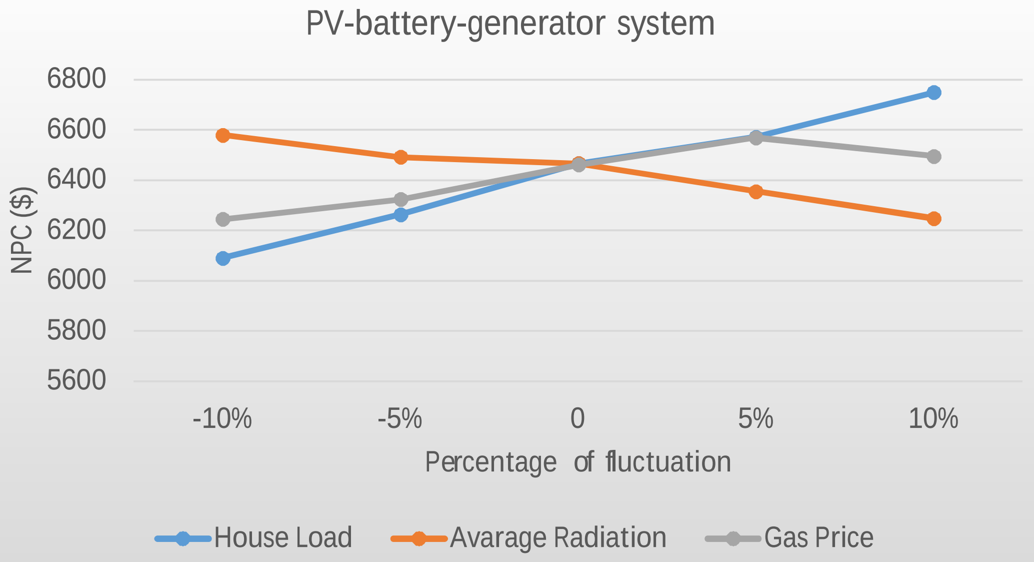
NPC variations:

- Load variation: -2.5% to 9.2%
- Radiation variation: 6.2% to -4.2%

NPC variations:

- Load variation: -5.8% to 4.3%
- Radiation variation: 1.7% to -3.3%
- Gas price variation: -3.3% to 1.6%





Dynamic Modeling and Control Systems in MATLAB

Methodology and MATLAB/Simulink

- Dynamic modelling: designing a dynamic model can simulate the system's behavior to any changes in input parameters and system internal changes.
- Modelling consists of two separate parts in MATLAB/Simulink software:
  1. Transfer function-based dynamic modelling for the small-scale reverse osmosis unit
  2. Electrical dynamic simulation model for PV power system in various conditions
- Electrical dynamic simulation is conducted for PV-battery system and system sizing achieved in system optimization analysis

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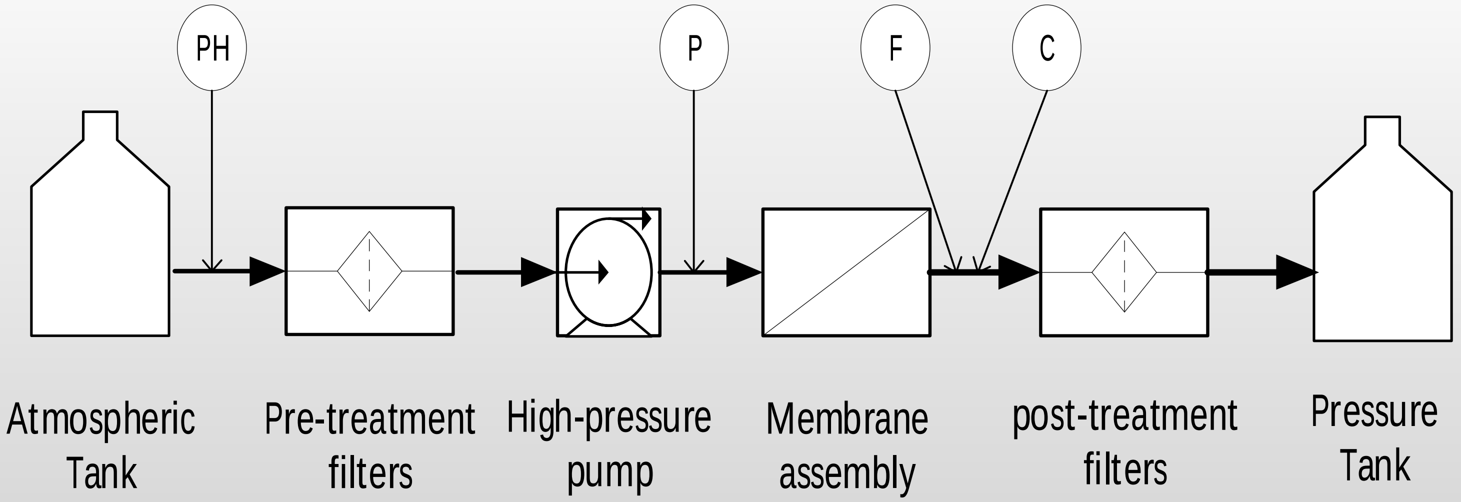
RO System Model

- Designing linear dynamic model for RO unit is essential → applying control techniques to the system model → decrease water production cost and increase system efficiency
- Main parts: pre-treatment filters, high-pressure pump, membrane assembly, post-treatment filter
- Parameters in the system:
  - Inputs: feed water PH (PH) and feed water pressure (P)
  - Outputs: output water flow rate (F) and output water conductivity (C)



Transfer Function-Based Model for RO Unit

- Transfer function matrix: time-discrete model in z-domain and transformation to s-domain

$$\begin{bmatrix} F \\ C \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \times \begin{bmatrix} P \\ PH \end{bmatrix}$$

- The system is generally open-loop stable because each subsystem of the model is stable

$$G_{ij}(s) = \frac{K_{ij}(\tau_{ij}s+1)}{\tau^2_{ij}s^2 + 2\varsigma_{ij}\tau_{ij}s+1}$$

- Standard TF matrix selected in for this research:

$$\begin{bmatrix} F \\ C \end{bmatrix} = \begin{bmatrix} \frac{0.007(0.056s+1)}{0.213s^2+0.7s+1} & 0 \\ \frac{-7.3(0.35s+1)}{0.213s^2+0.7s+1} & \frac{-57(0.32s+1)}{0.6s^2+1.8s+1} \end{bmatrix} \times \begin{bmatrix} P \\ PH \end{bmatrix}$$

- Desired output → Output water flow rate

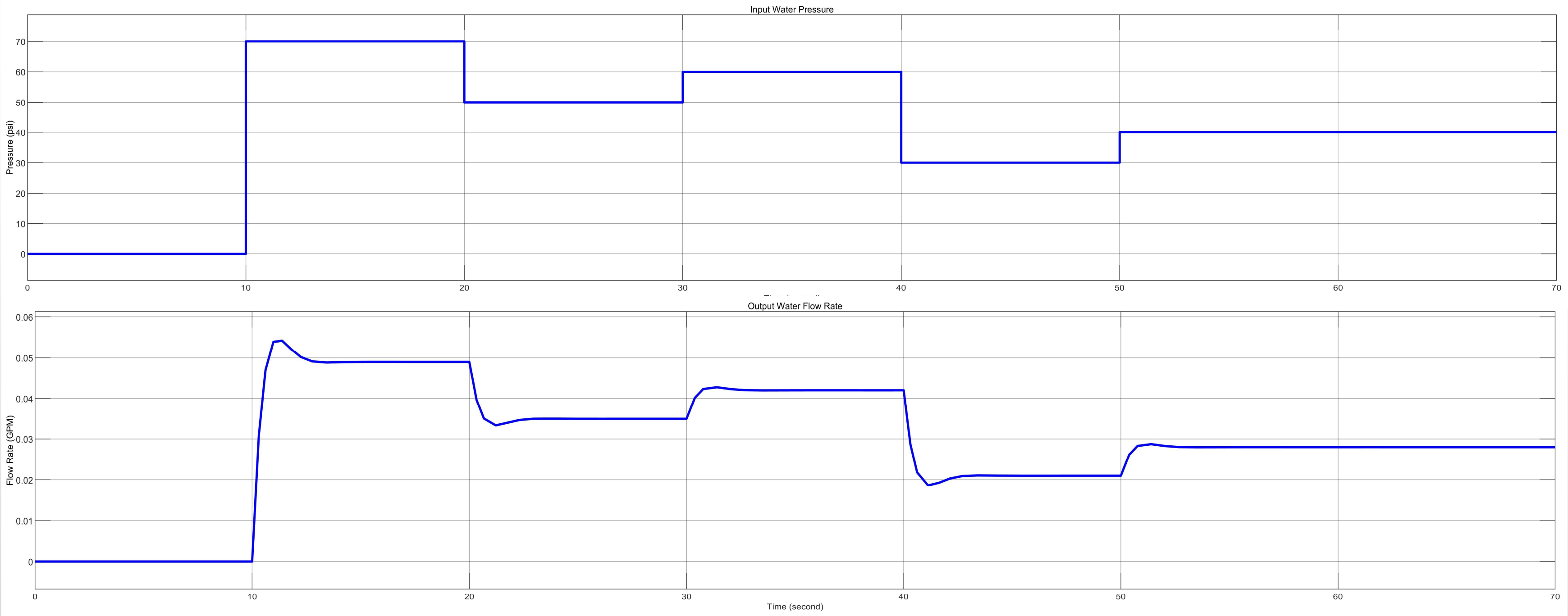
  PH is close to 7 and stable → it is not considered in modelling

- G_{11} : relationship between feed water pressure (psi) and output flow rate (GPM)

$$G_{11} = \frac{F}{P} = \frac{0.000392s + 0.0007}{0.213s^2 + 0.7s + 1}$$

RO Unit Dynamic Simulation Results

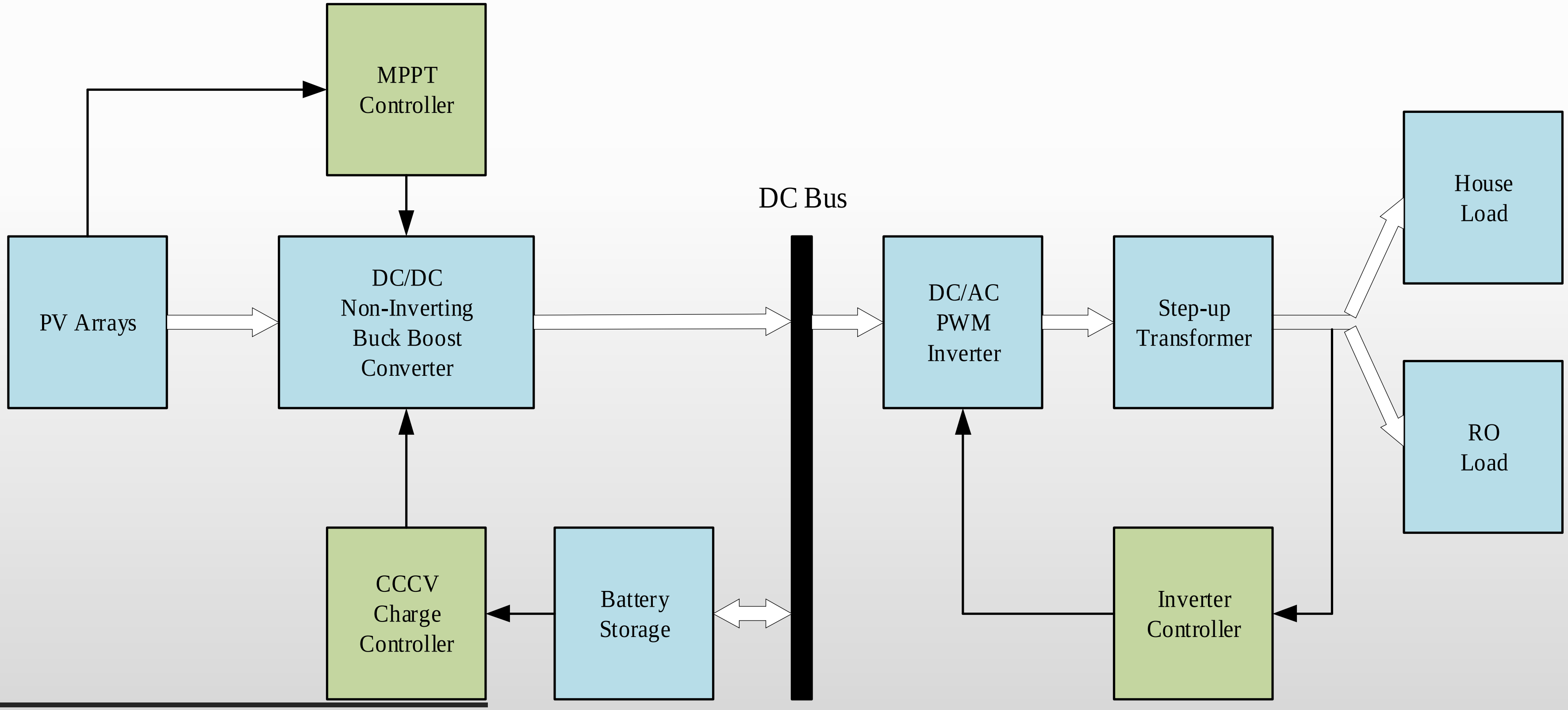
- Maximum pressure of 70 psi, produce maximum desalinated water with a 0.052 GPM
- Decreasing the input pressure → can decrease the output flow rate→ less water production → more working hours for a certain amount of output water → pressure booster
- The transfer function precisely models the dynamic of the RO unit



Dynamic Modeling and Control Systems in MATLAB

PV System Schematic

- Main electrical components
- Control units



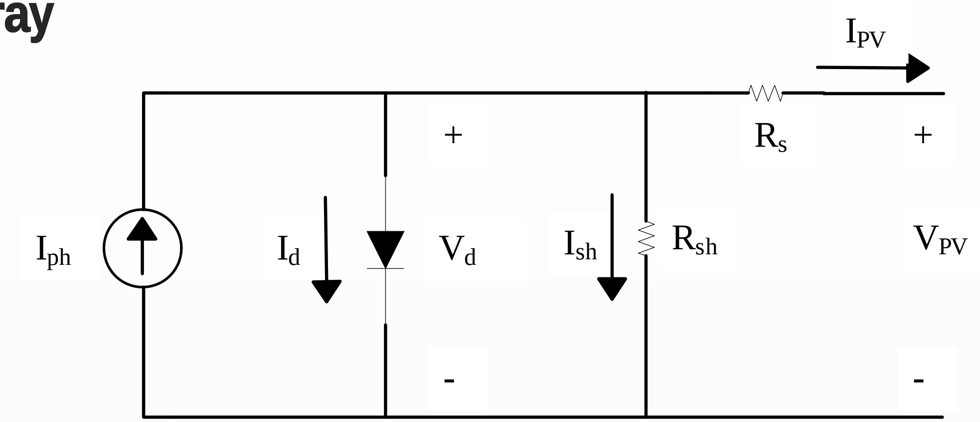
Dynamic Modeling and Control Systems in MATLAB

PV Arrays and Battery System

- PV cell (PN junction diode) → PV module → **PV array**
- Mathematical expressions (single diode mode)

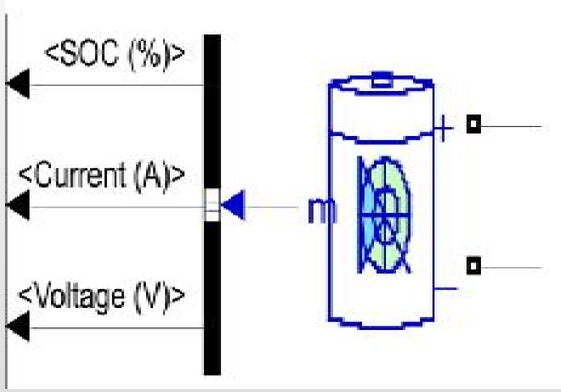
$$I_d = I_0\left[\exp\left(\frac{V_d}{V_T}\right) - 1\right] \qquad I_{PV} = I_{ph} - I_d - \frac{V_d}{R_{sh}}$$

$$V_T = \frac{KT}{q} \times A \times N_{cell} \qquad V_d = V_{PV} + R_s I_{PV}$$



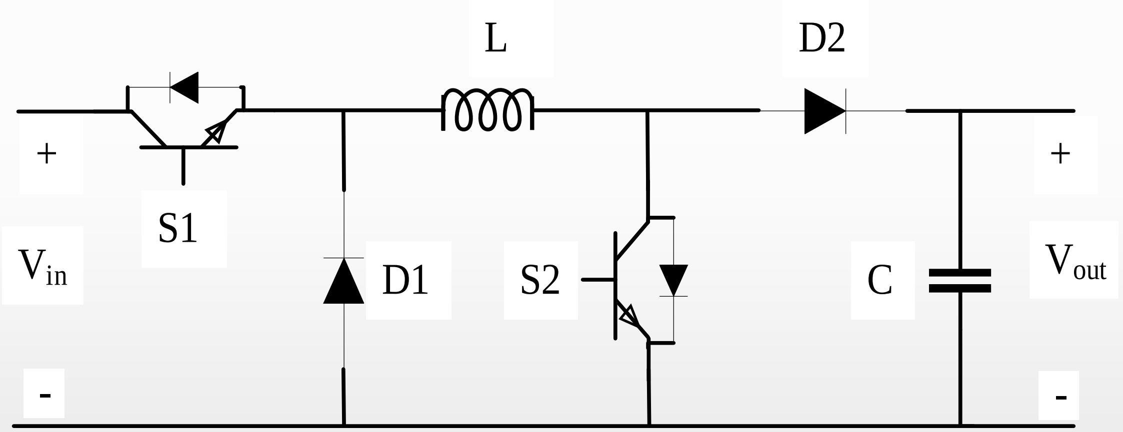
- 4 strings in parallel, 2 series in string. Output power = 2.72 kW, output voltage at MPP = 75.8 V.

- **Battery system**: bi-directional element → charge and discharge
- Lead acid batteries connected to 48 volts DC bus
- 3 strings of batteries, 8 series batteries in string
- total capacity of the battery bank =765 Ah



Non-Inverting Buck-Boost Converter

- Non-inverting buck boost converter (NIBB): Stabilizing PV output - feeds the inverter - charges the battery system in fix and stable 48 volts
- Benefits: non-inverted output, low complexity, low voltage stress, high reliability, switch low losses, low cost of the topology
- Working in both buck and boost → appropriate for renewable applications



- Double-purposes converter

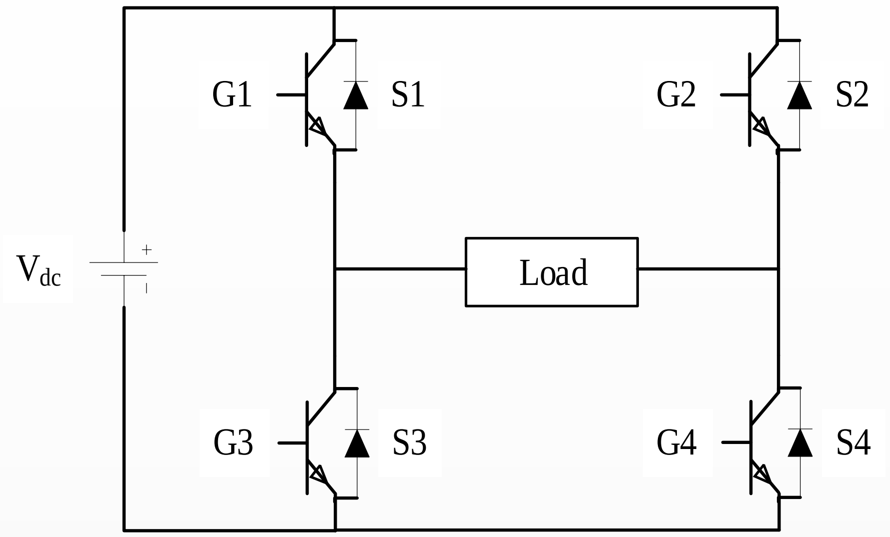
1. Generated signal from MPPT technique → S1
2. Generated signal from battery charger → S2

$$V_{out} = \frac{D_1}{1 - D_2} V_{in}$$

PWM Inverter and Transformer

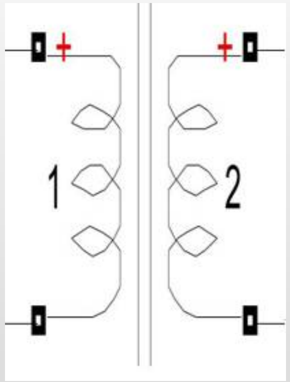
- **Inverter**: H-bridge single-phase PWM inverter
- Convert: NIBB 48 V DC → 48 V AC with freq. 50 Hz

Switches Mode	Voltage Level
S1, S4 ON / S2, S3 OFF	$+V_{dc}$
S2, S3 ON / S1, S4 OFF	$-V_{dc}$



- **Transformer**: 48 V of the inverter to 220 volts RMS voltage with 60 Hz freq.

$$\frac{N_p}{N_S} = \frac{V_p}{V_S} = \frac{I_S}{I_P}$$



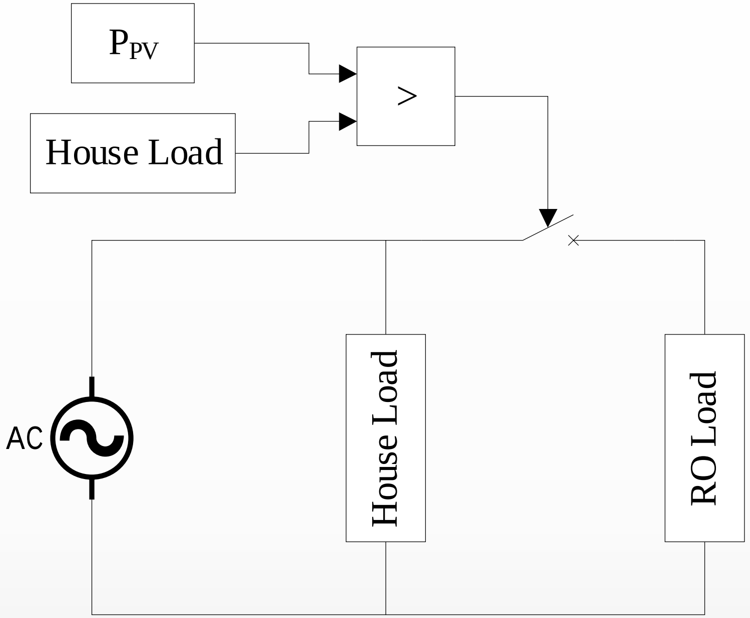
Load Model and MPPT controller

- **Load model**: Two loads defined

1. House load: average of 1000 watts
2. Ro load: 1100 watts

- Breaker: model the loads priority
- Algorithm: PV power < house load → breaker open

  PV power > house load → breaker close → RO load



- **MPPT controller**: forces panel to work on optimum operating point to extract maximum power
- Perturb and Observe (P&O) method

CCCV battery Charge Controller

- CCCV method works in two stages:

1. Constant current (CC) zone or bulk stage
2. Constant voltage (CV) or abortion stage

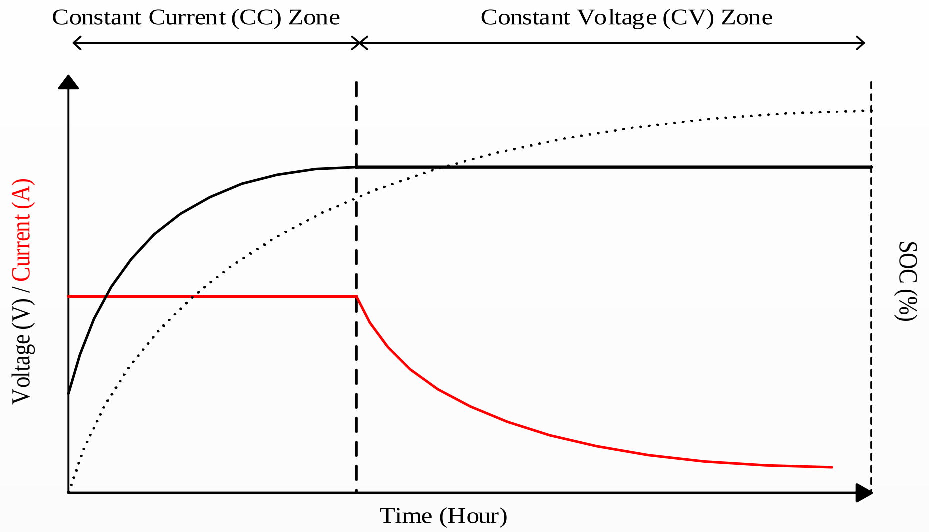
- CCCV charge controller: 3 main sections

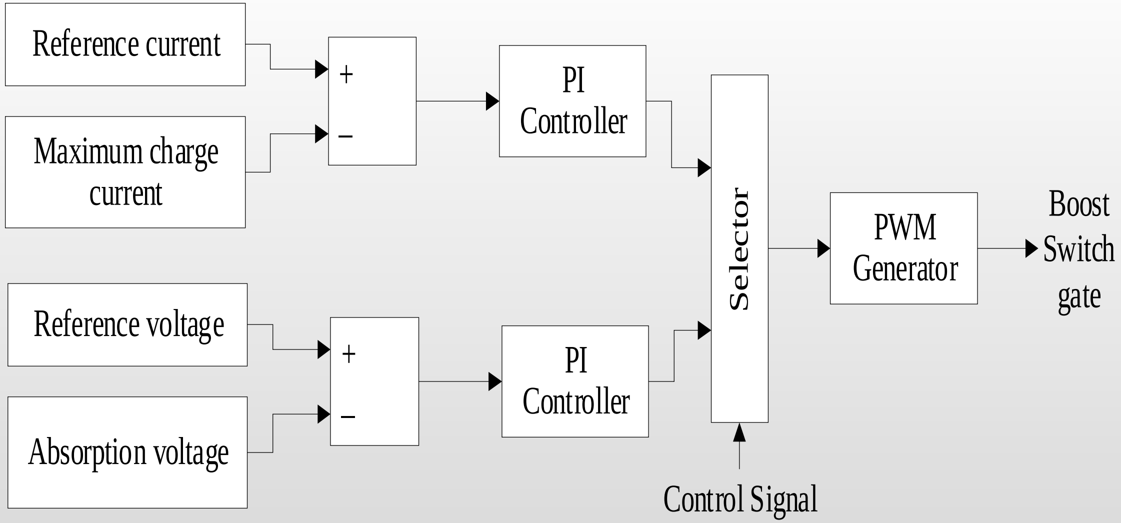
1. CCCV code-based function
2. Current controller

   Reference current: 13% * Max capacity

3. Voltage controller

   Reference Voltage: Absorption voltage





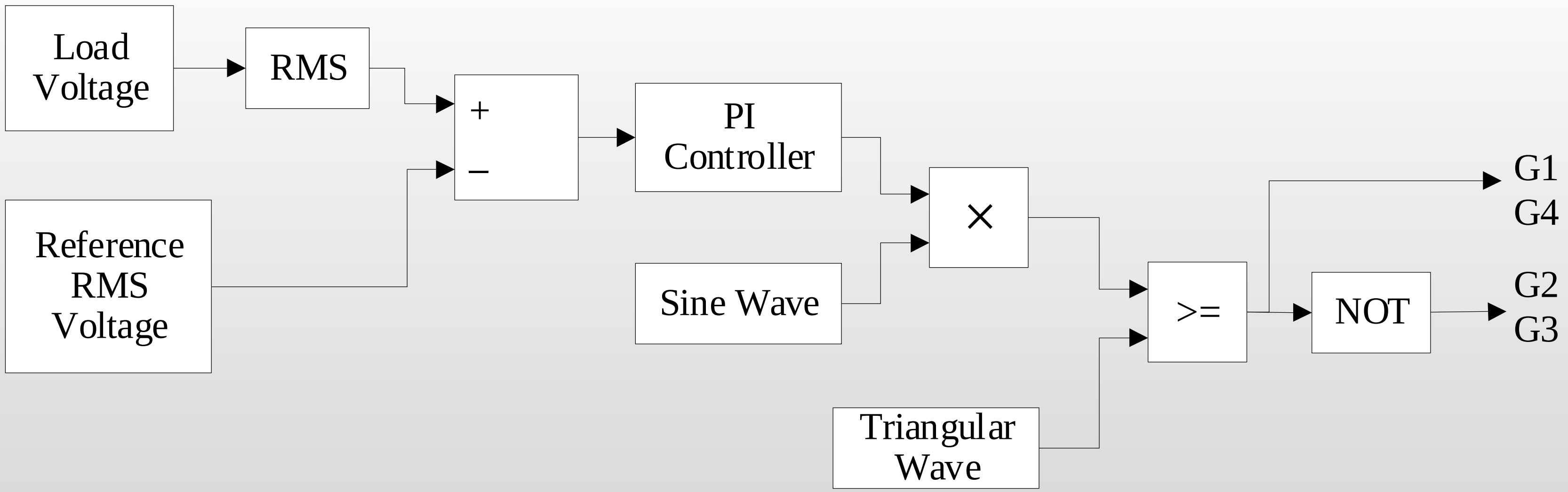
Inverter Voltage Controller

- Inverter controller: Control output voltage and frequency and has 2 connected parts:

1. Voltage regulator: fix the output voltage RMS to 220 V
2. SPWM generator: bipolar method → sine wave (reference signal) and triangular wave (carrier signal) fix the freq. @ 50 Hz

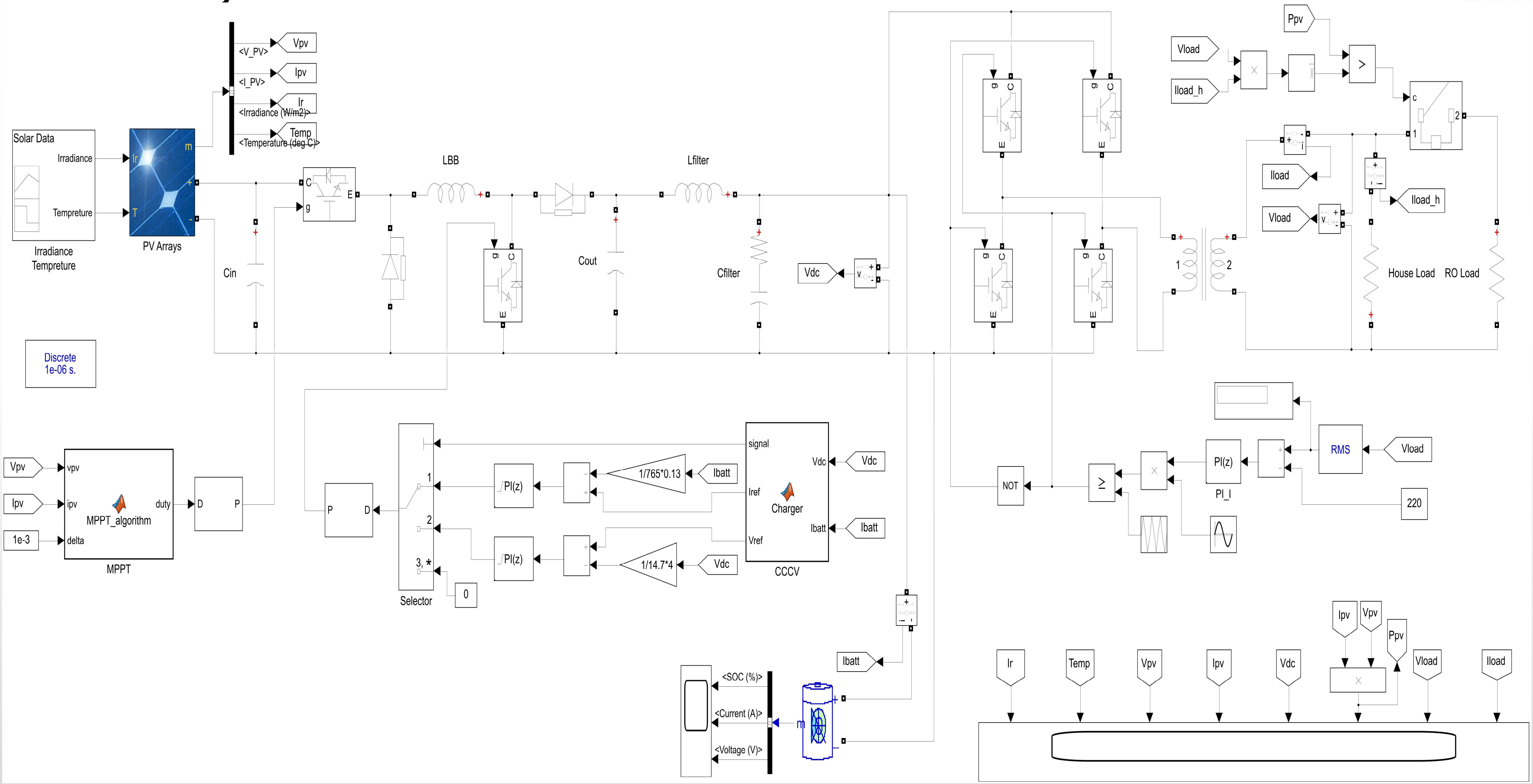
- two important factors:

$$m_a = \frac{V_{m,reference}}{V_{m,carrier}} \qquad m_f = \frac{f_{carrier}}{f_{reference}}$$



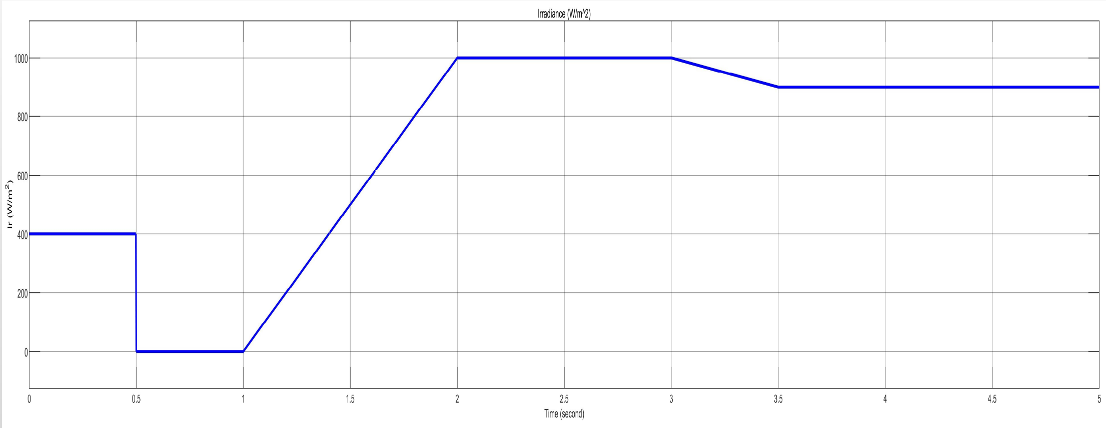
Dynamic Modeling and Control Systems in MATLAB

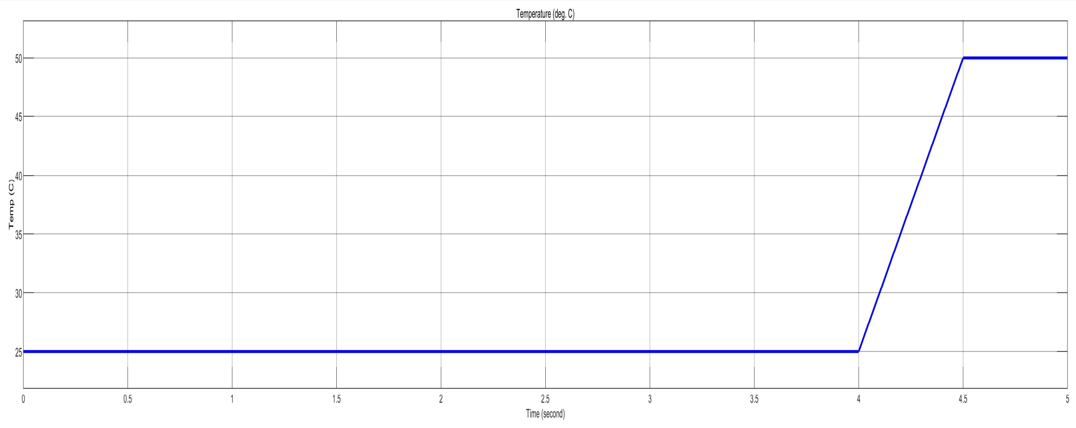
PV Battery MATLAB Simulation



Simulation Results

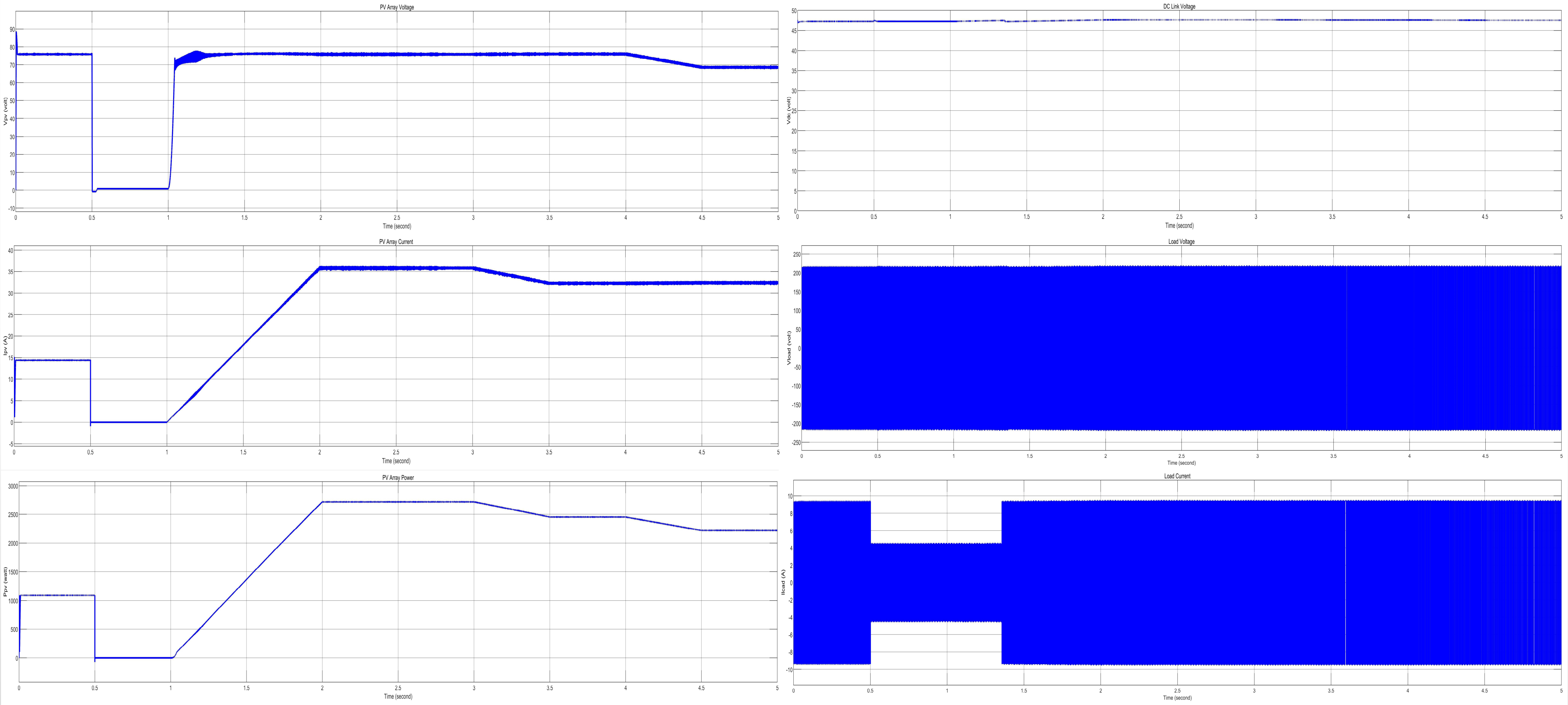
1. Condition 1: **normal condition** between 0 to 0.5 sec.→ 400 W.m^2 and 25 °C / PV: 75.8 V, 14.5 A, 1100 W / DC link 24 V / RO load connected / Battery discharging mode: SOC decrease, positive current
2. Condition 2: **no irradiance** between 0.5 to 1 sec.→ DC link 48 V/ AC: 220 V, 50 Hz. / RO load disconnected / battery discharge mode: SOC decrease, positive current
3. Condition 3: **zero to max Irradiance** between 1 to 3 sec.→ PV: 36 A, 2720 W / 1.3 sec. : RO load connected / battery still discharging – 1.85 sec : charging mode
4. Condition 4: **net zero energy** between 3 to 5 sec.→ Temperature increase: power decrease & voltage drop 68.5 V / Battery current = 0 / PV production = house and RO loads





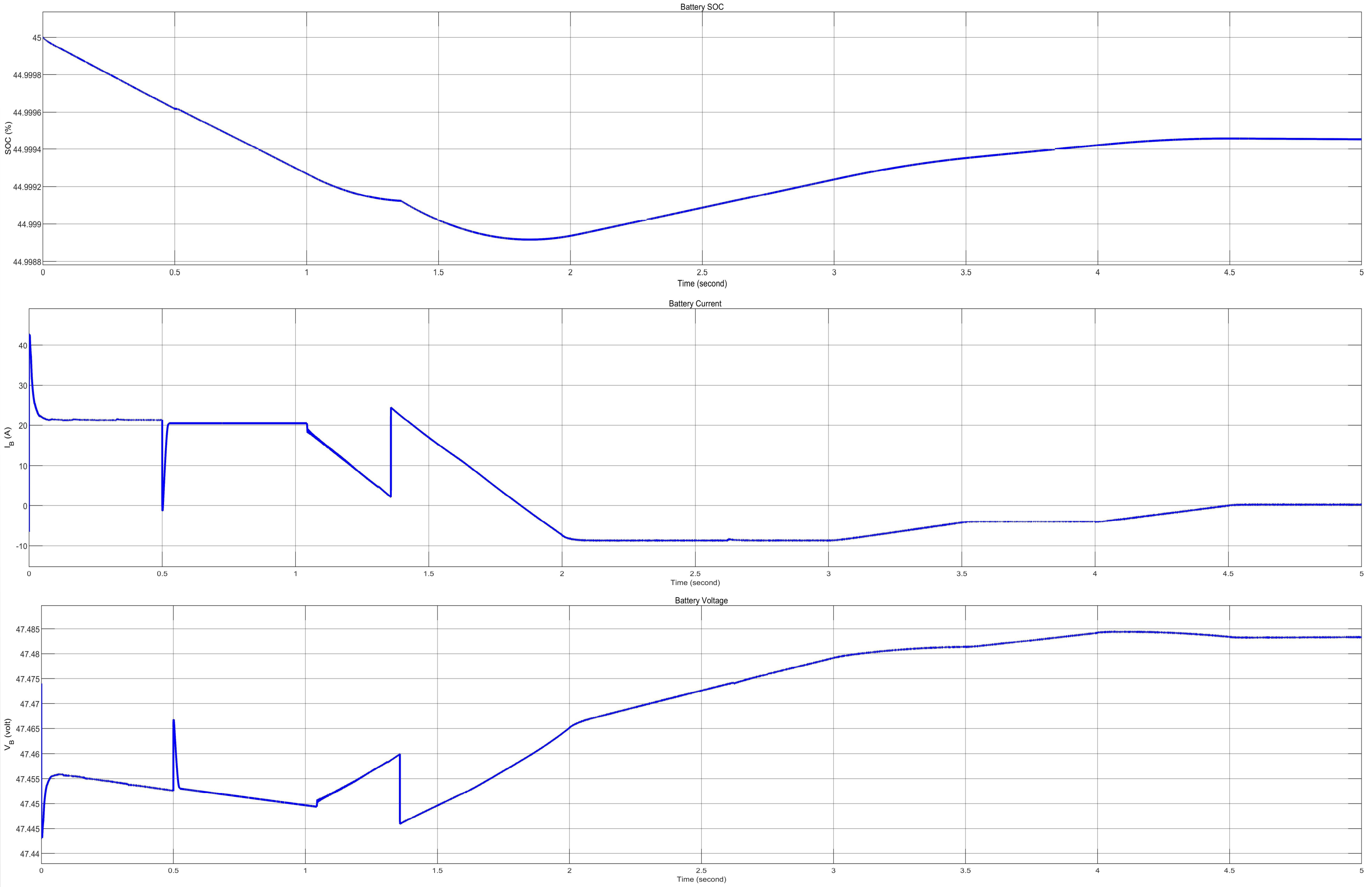
Dynamic Modeling and Control Systems in MATLAB

Simulation Results



Dynamic Modeling and Control Systems in MATLAB

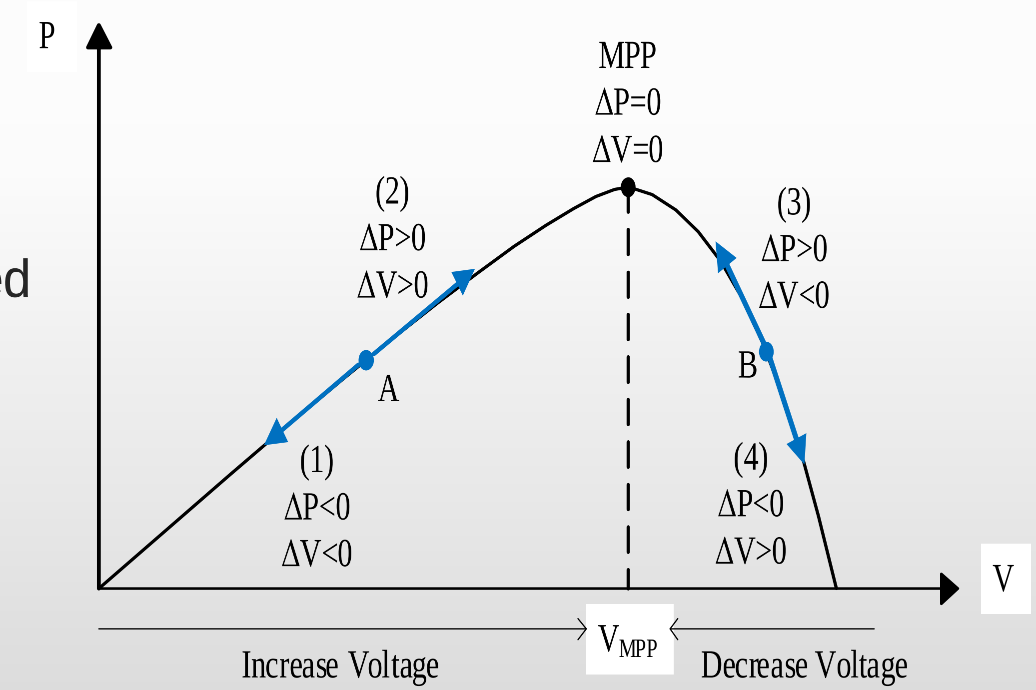
Simulation Results



MPPT Techniques in PV System

MPPT Techniques

- Change in irradiance and temperature→ Change the operation point (V, I, P)
- Change in the PV output voltage by the converter→
  force the panel to work in maximum power point → Maximum Power Point Tracking (MPPT)
- Two categories for MPPT techniques:
  - Traditional algorithms
  - Artificial intelligence algorithms
- 3 MPPT techniques introduced, designed, simulated
  in MATLAB/Simulink and compared
  1. Perturb and Observe method (P&O)
  2. Incremental Conductance method (InC)
  3. Fuzzy Logic controller Method (FL)

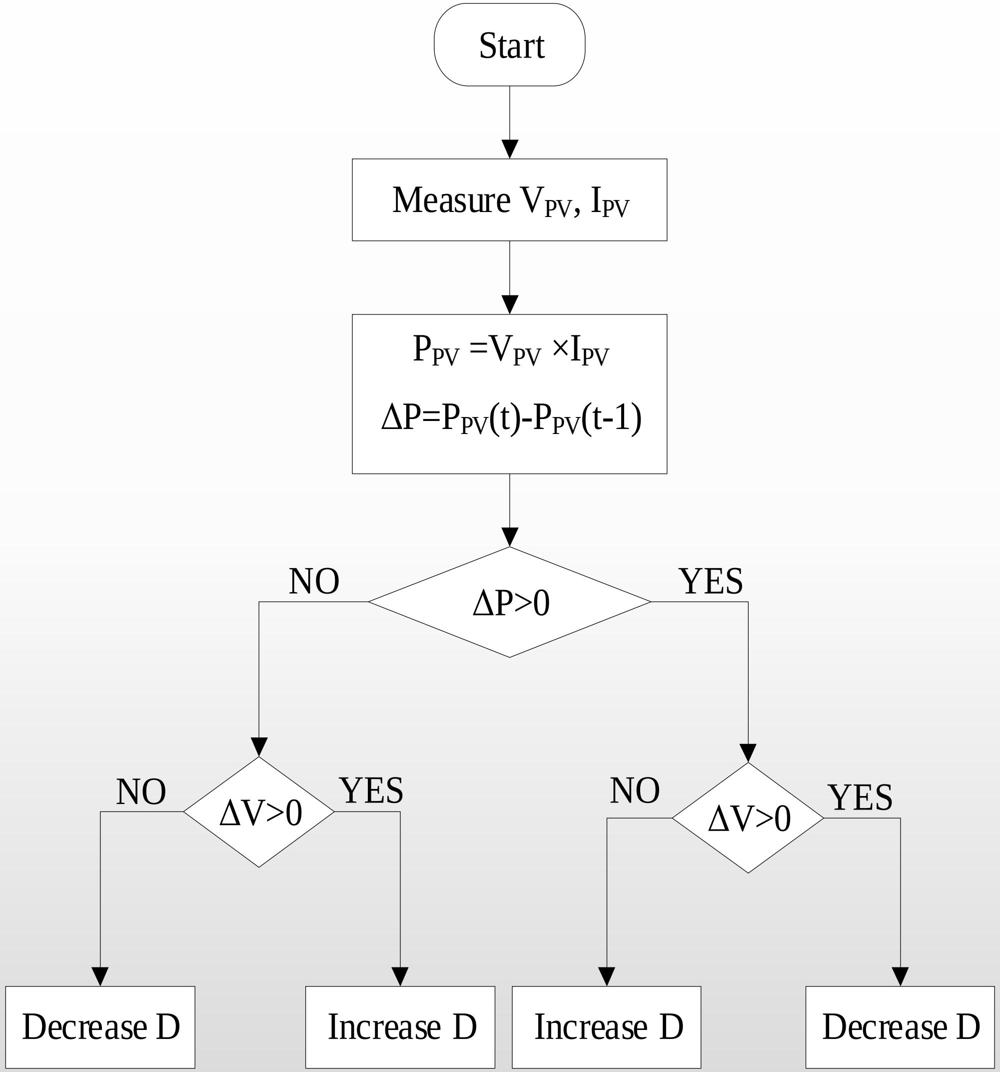


MPPT Techniques in PV System

Perturb and Observe (P&O) Method Flow chart

- P&O Method: oldest, simple, most commonly used
- Small perturbation will be applied to voltage and Observe Power

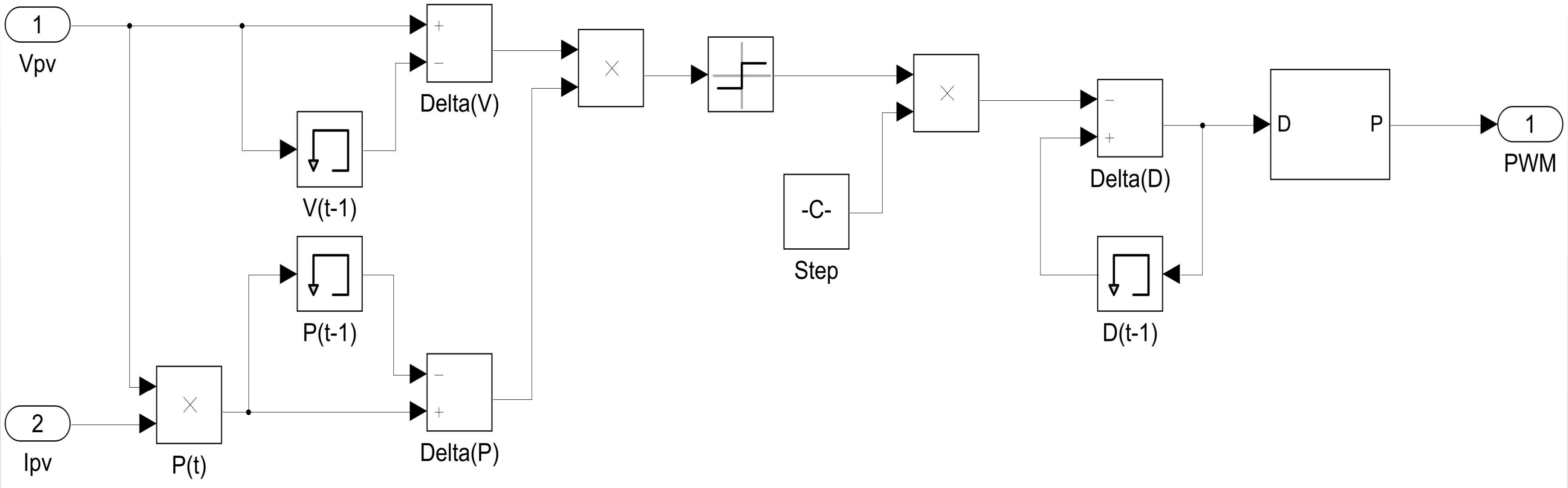
1. ΔP is positive→ OP in region 2 or 3→ moving to MPP→ next perturbation in same direction
2. If ΔP is negative→ OP in region 1 or 4 → moving away from MPP→ next perturbation in the opposite direction



MPPT Techniques in PV System
Perturb and Observe (P&O) Method MATLAB Simulation

- signs of the ΔV and ΔP are determining the voltage changes:

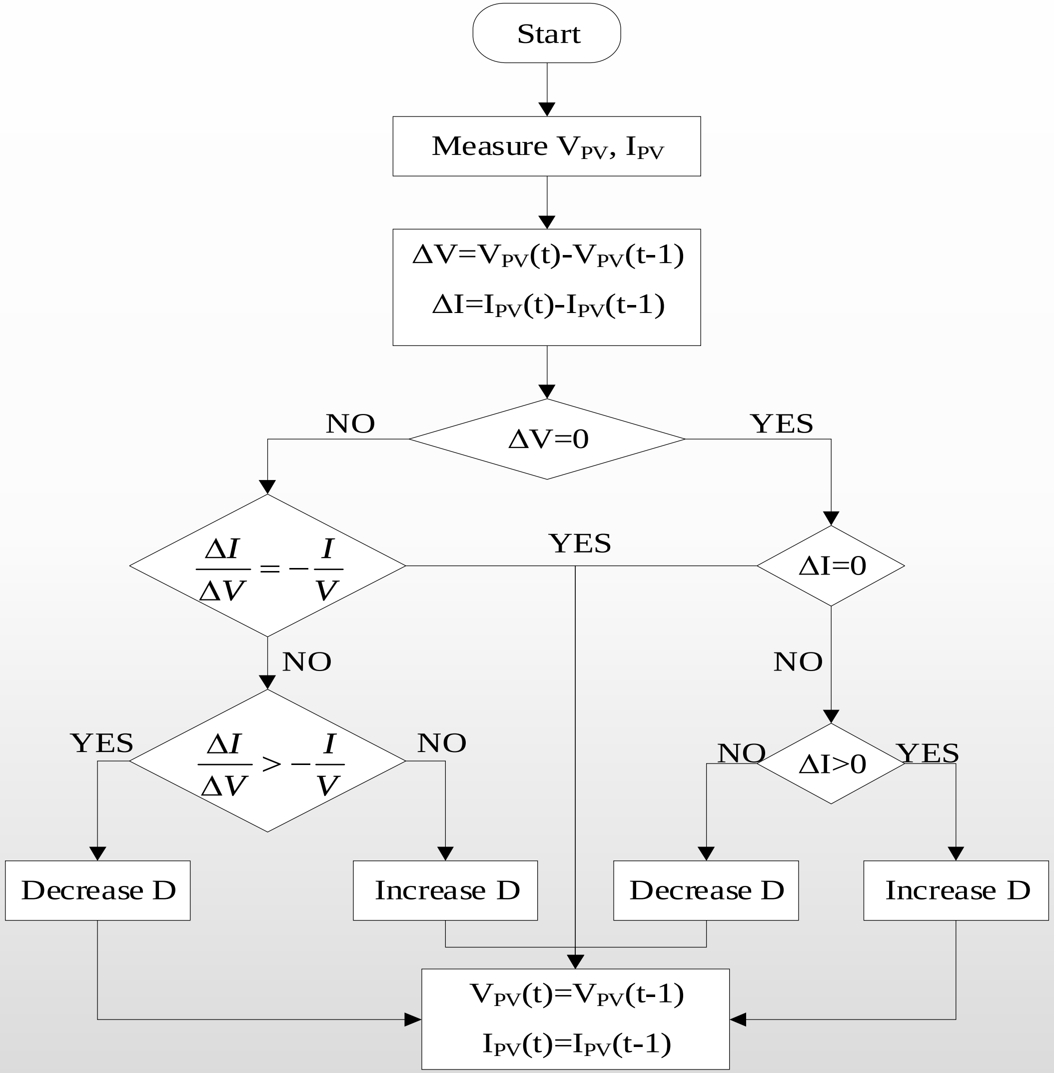
1. If ΔV and ΔP have the same signs→ regions 1 or 2→ sign detector pass (+1)→ duty cycle will be decreased.
2. If ΔV and ΔP have the opposite signs→ regions 3 or 4→ sign detector pass (-1)→ duty cycle will be increased.



MPPT Techniques in PV System

Incremental Conductance (InC) Method Flow chart

- In P&O method, controller perturbs voltage continuously→ OP oscillate around the MPP even if the controller detects it
- InC method : based on conductance definition→ I/V
- dP/dV= power cure slope, if zero→ MPP / if positive→ point A / If negative→ point B
- Denominator is hub in InC method
  1. If dV is zero→ check dI
  2. If dV is not zero → check the conductance



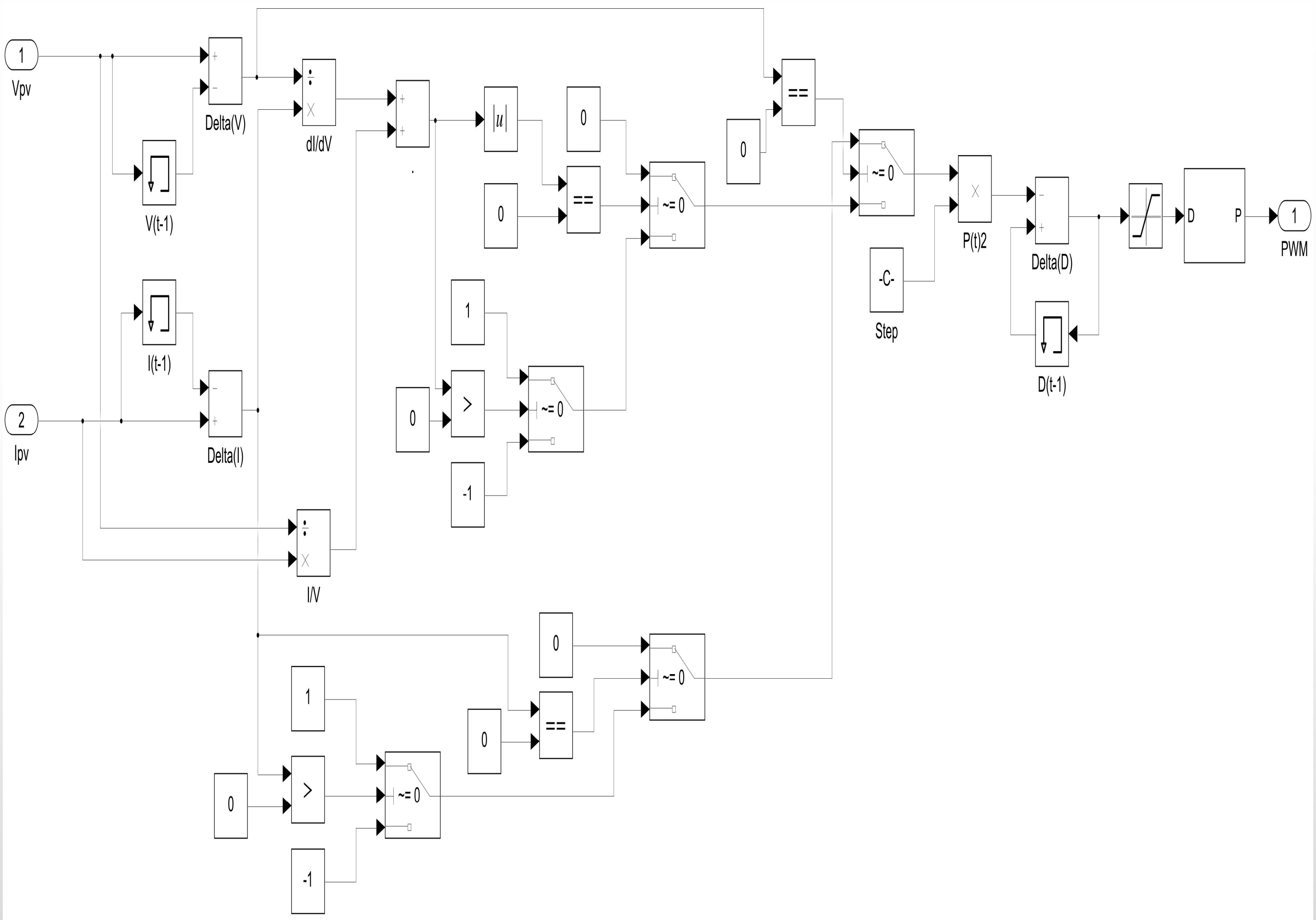
Incremental Conductance (InC) Method MATLAB Simulation

$$\frac{dP}{dV}=\frac{d(IV)}{dV}=I+V\frac{dI}{dV}\cong I+V\frac{\Delta I}{\Delta V}$$

$$I+V\frac{\Delta I}{\Delta V}=0\Rightarrow\frac{\Delta I}{\Delta V}=-\frac{I}{V}\Rightarrow MPP$$

$$I+V\frac{\Delta I}{\Delta V}>0\Rightarrow\frac{\Delta I}{\Delta V}>-\frac{I}{V}\Rightarrow V\uparrow\Rightarrow D\downarrow$$

$$I+V\frac{\Delta I}{\Delta V}<0\Rightarrow\frac{\Delta I}{\Delta V}<-\frac{I}{V}\Rightarrow V\downarrow\Rightarrow D\uparrow$$

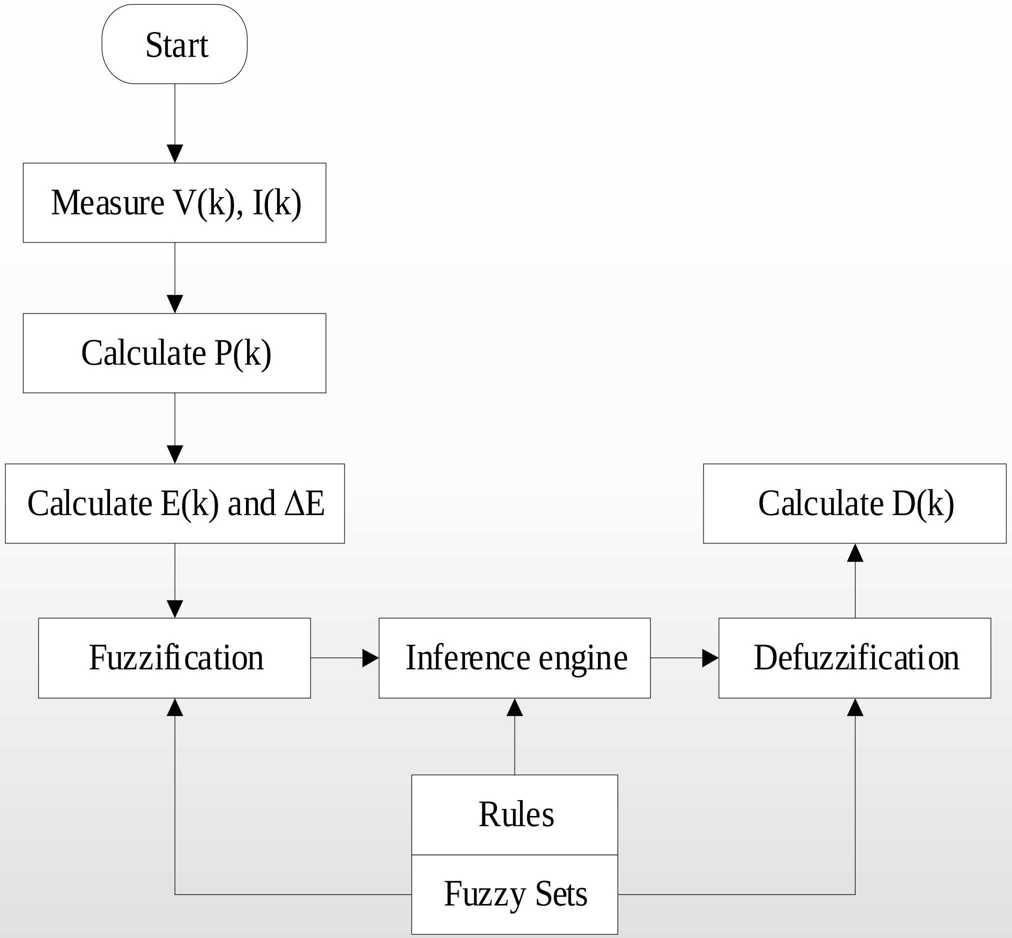


MPPT Techniques in PV System

Fuzzy Logic (FL) Method Flow chart

- Advantages: work in nonlinear conditions with imprecise inputs, accurate mathematical model not required
- Disadvantages: complexity specially in adaptive FL
- flowchart comprises two main parts:
  1. Preparing the inputs for FL controller, appropriate PWM output from the controller
  2. Designing the FL controller
- Power curve:

$$E(k) = \frac{\Delta P}{\Delta V} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)}$$



MPPT Techniques in PV System

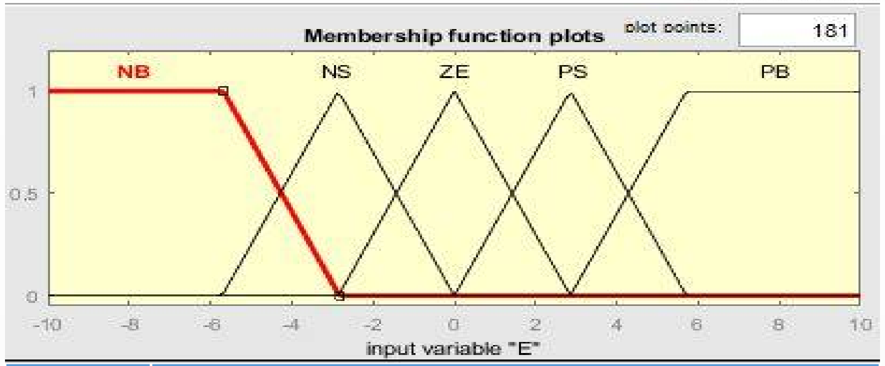
Rule-Based Inference Engine for Fuzzy Logic Controller

1. **Fuzzification**: defines a fuzzy space for inputs and output (not quantities)→ converts inputs (d, dE) and output (dD) with the help of fuzzy membership functions→ (NB),(NS),(ZO),(PS),(PB)
2. **Rule-Based Inference engine**: defining certain rules to specify fuzzy output sets to a combination of fuzzy input sets

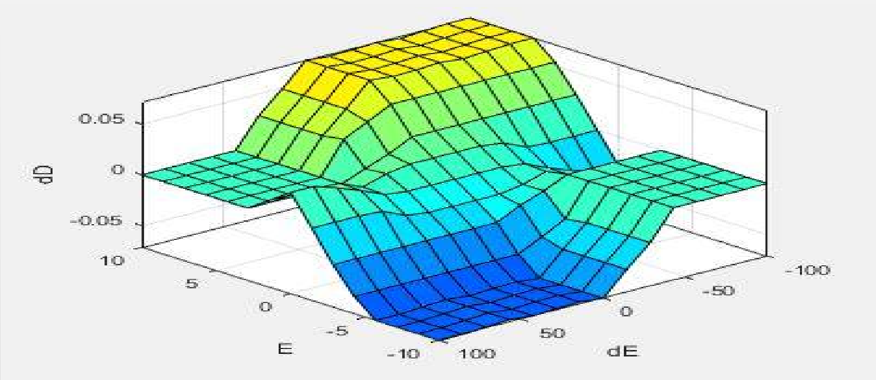
- If-then statements based on Mamdani fuzzy inference method
- 25 rules designed to move the OP in the P-V curve to MPP
- Ex. if E is NB and ΔE is ZE, then ΔD is NB→

  if the slope is negative big and the displacement of E is zero, the OP is far away from MPP on the right side without changes→ D should be greatly decreased

3. **Defuzzification**: process of transferring fuzzy sets to actual mathematical numbers. Center of area (COA) algorithm is used



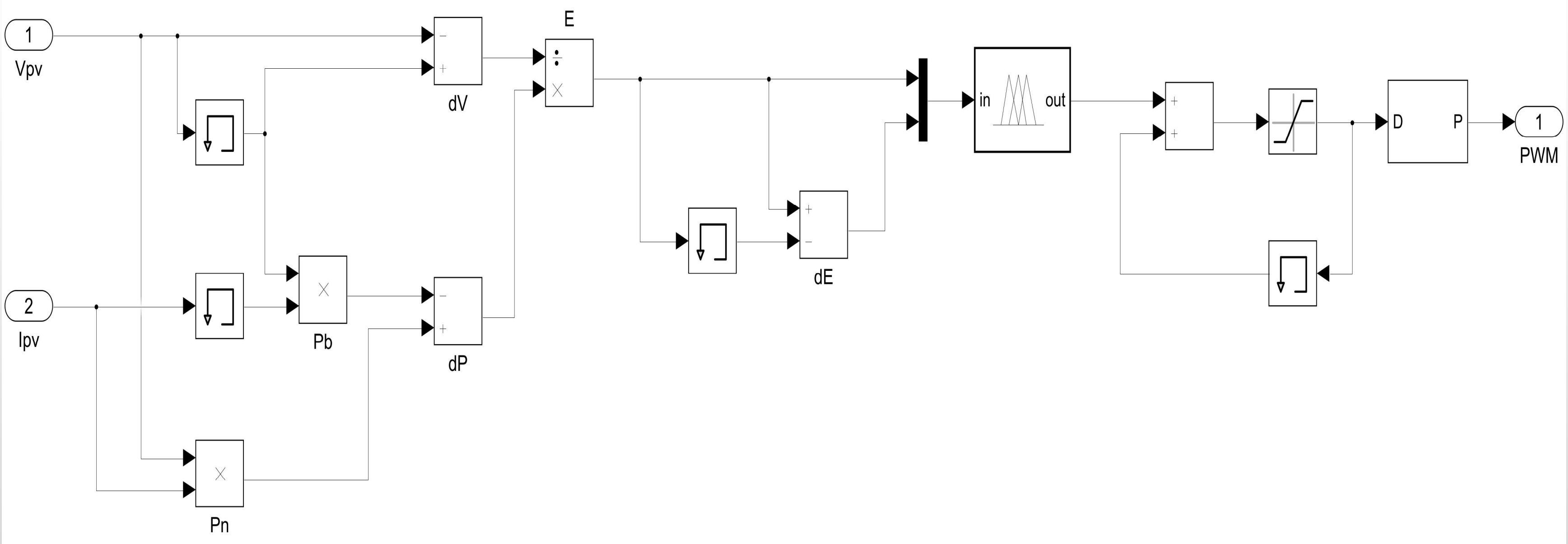
E	ΔE				
	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE



MPPT Techniques in PV System

Fuzzy Logic (FL) Method MATLAB Simulation

- In FL MPPT method: V, I, dV, dP, E, dE are defined.
- For generating PWM signal in FL, same as other methods, the duty cycle goes to a PWM generator and then it will be applied to the buck switch in NIBB.



MPPT Techniques in PV System

Comparison Results

- 400, 1000, 100 W/m^2→ 1088, 2720, 272 watts
- Power @max Irradiance: 2.72 W / 25 °C

1. **Sudden changes:** cloud shadows / running system with high irradiance→

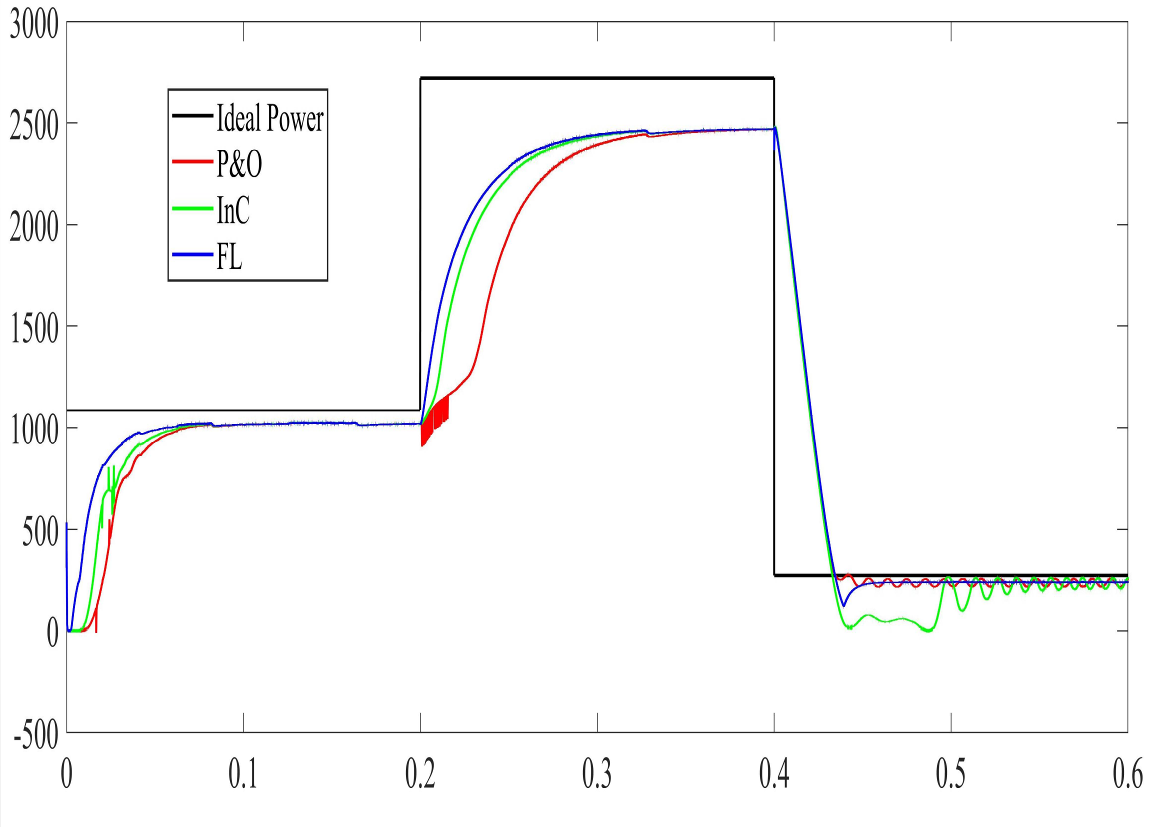
   Conventional methods cannot follow: 0.4 to 0.4 sec. and running with Ir > 600 W/m^2

   FLC operates precisely

2. **Oscillations:**

   Conventional methods: too much oscillations

   FLC: fewer oscillations with minimum undershoot



MPPT Techniques in PV System

Comparison Results

3. **Delivered power:** average delivered power and efficiency (power/ideal power) at DC bus with 400, 1000 W/m^2→

FLC: 942, 2294 W. 86.5%, 84.3% efficiency

Technique	Average Power @ 400 W/m2	Average Efficiency (%)	Average Power @ 1000 W/m2	Average Efficiency (%)
Ideal Power	1088 W	100%	2720 W	100%
P&O	870 W	79.90%	2121 W	77.90%
InC	899 W	82.60%	2252 W	82.70%
FL	942 W	86.50%	2294 W	84.30%

4. **Rise time:** 10% to 90% of target power. Transient from 400 to 1000 W/m^2→

FLC: Fastest response, rise time: 0.054 seconds.

Technique	Time reached to 10% (s)	Time reached to 90% (s)	Rise time (s)
P&O	0.218	0.285	0.067
InC	0.208	0.264	0.056
FL	0.203	0.257	0.054

Conclusion

- water system and the house surveyed and dafter designing a RO system, a pressure pump, RO membrane, and pressure tank were added. Two different loads were defined in the system: deferrable RO load and regular house load
- Two scenarios with PV were designed in HOMER. system with gas generator has less capital cost and NPC, use LF dispatch, consumes yearly 399m^3 gas. PV battery system is environmentally friendly, has fewer O&M costs, more autonomy, less control complexity, CC dispatch. sensitivity analysis proved PV battery system is less sensitive because of fewer sensitivity variables.
- Output flow rate of the suggested transfer function-based model for RO follow changes in the input pressure. For instance, RO desalinate water with 0.052 GPM when input pressure is 70 psi.
- Electrical dynamic modeling results showed that the PV battery system with NIBB, CCCV charger, inverter can deliver stable power to the loads in four various conditions: 1. Normal condition 2. No irradiance condition 3. Zero to Max irradiance condition 4. Net zero energy condition.
- For MPPT Techniques, FLC controller has better results compare with P&O and InC method in four categories: Sudden changes, Oscillations, Delivered power, rise time

Future Works

1. Whole house reverse osmosis system can be designed to supply the house for all purposes.
2. A small-scale wind turbine can be added to the proposed systems for fewer PV panels and more renewable penetration.
3. Designing a dynamic model for a PV-battery-natural gas generator in MATLAB/Simulink.
4. Designing a grid-connected version of the proposed PVRO system.
5. A low-cost IOT– based power metering system can be designed for the house by Arduino or ESP32 boards
6. Designing a SCADA system for the proposed RO system to measure and monitor the reverse osmosis system's parameters like water PH, pressure, or flow rate.
7. To increase the efficiency more sophisticated MPPT techniques can be designed for the PV system, such as neuro-fuzzy logic or artificial neural network.

Publications

- M. Mousavi and M. T. Iqbal, “Optimum Sizing Comparison of Stand-alone Hybrid PV Systems for a Rural House in Iran Equipped with a RO Water Desalination System,” accepted for publication in the Jordan Journal of Electrical Engineering, April 2021.
- M. Mousavi and M. T. Iqbal, “Design and Dynamic Modelling of a Hybrid PV-Battery System for a House with an RO Water Desalination Unit in Iran,” submitted with the Journal of Energy Systems, July 2021.
- M. Mousavi and M. T. Iqbal, “MPPT Techniques Comparison for a Small-Scale PVRO System in Iran,” accepted at the 12th Annual IEEE IEMCON conference, Vancouver, August 2021.
- R. Sundararajan, M. Mousavi, H. Hassanien and M. T. Iqbal, “Dynamic simulation of an isolated solar-powered charging facility for 20 electric vehicles in St. John’s, Newfoundland,” presented at the 29th Annual IEEE NECEC conference St. John's, November 19th, 2020.

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Any Questions?

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