Baylor University

AI-Based Control of Hybrid PV and Advanced Pumped-Storage Hydropower Plant for Power System Resiliency

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Outline

Renewable energy sources (RESs) and energy storage systems (ESSs)

Pumped storage hydropower (PSH)

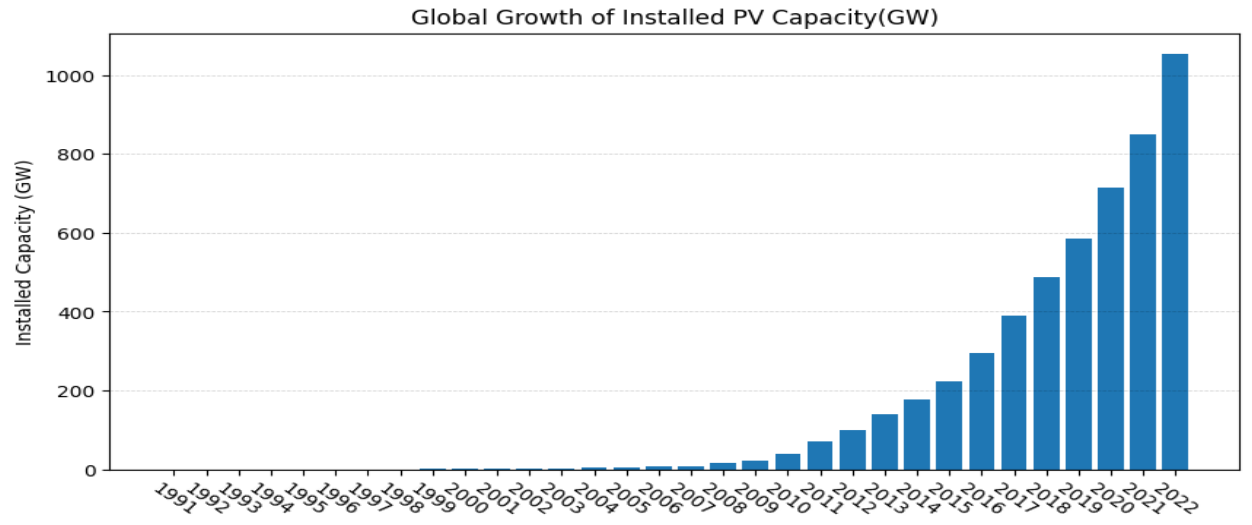
- Types
- Comparison of types

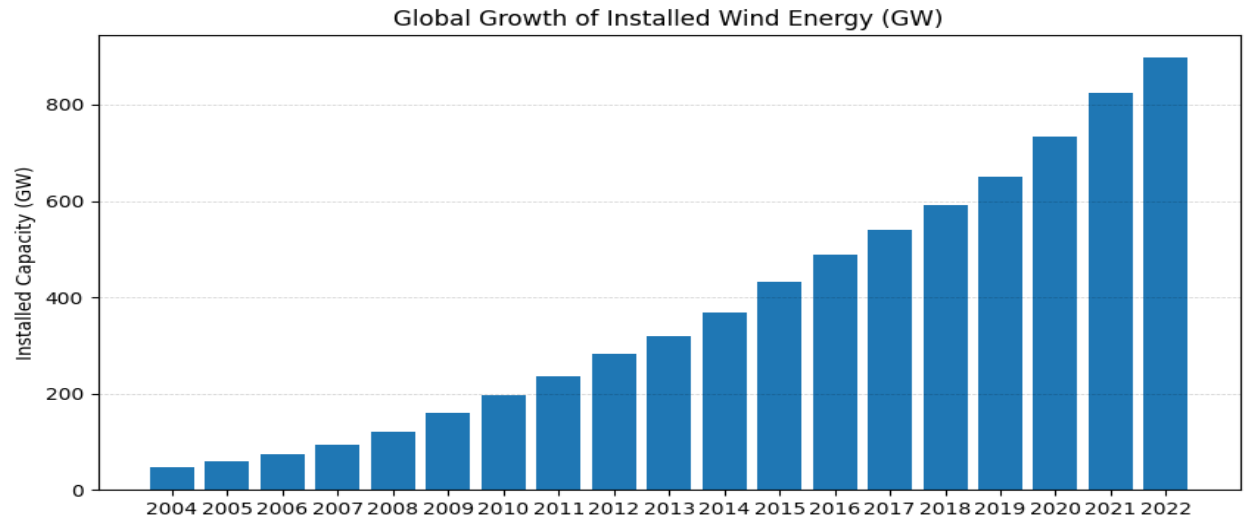
Neural Network-Based Control for Hybrid ASPSH and PV

- Modeling and control
- Results

Conclusion and future work

Global Growth of Installed Wind and PV Generation





The race to a green economy, research and development, and improved market policies over the years has been key drivers that exponentially increased the amount of grid installed renewables.

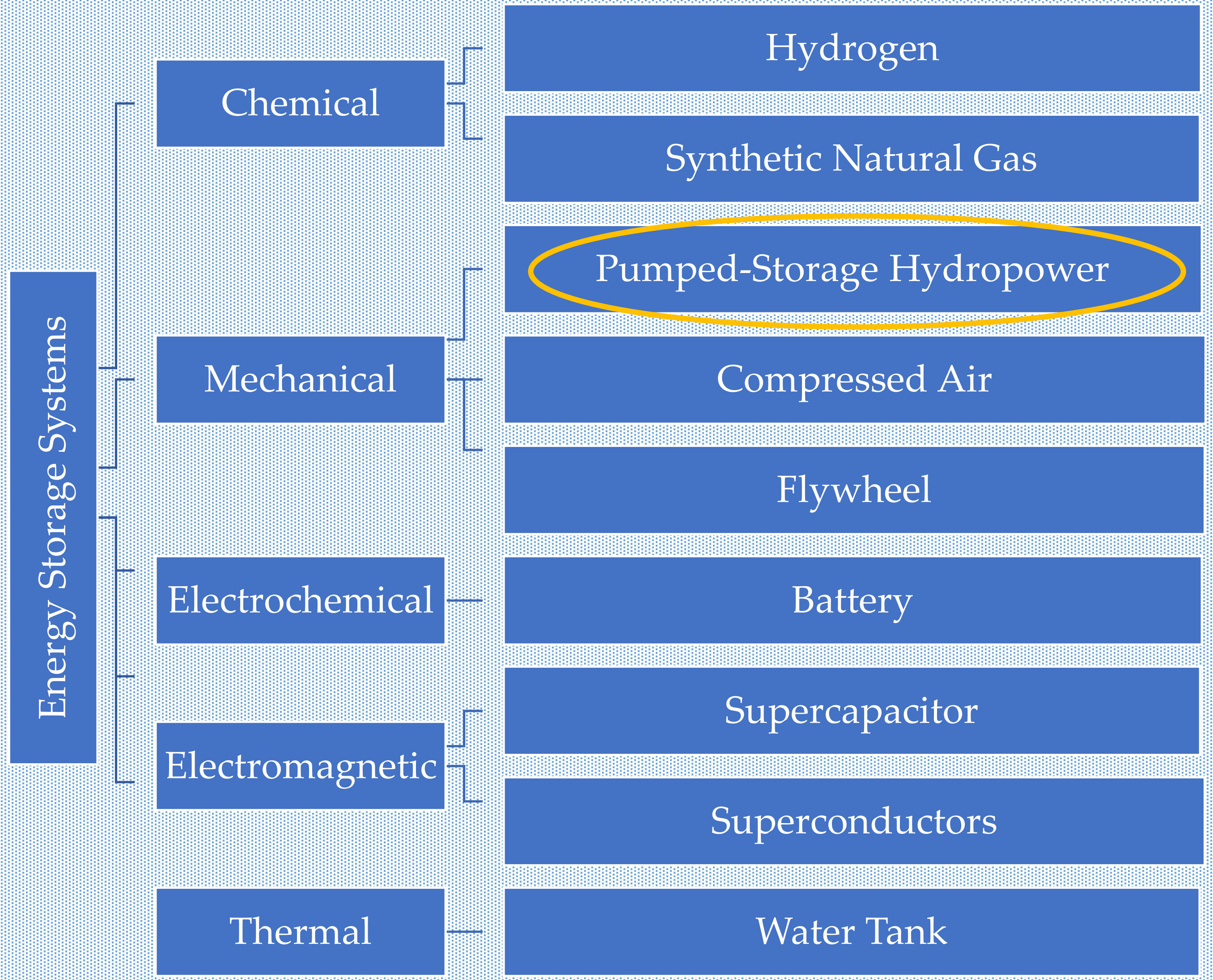
Challenges imposed on the grid by the increasing capacity of installed renewables:

- Decreased grid’s total inertia
- Increased intermittency and unpredictability of power imbalance between demand and generation
- Increased grid power quality concerns
- Irregular energy price pattern

[3] “Growth of photovoltaics,” Wikipedia, May 15, 2023. https://en.wikipedia.org/wiki/Growth_of_photovoltaics
[4] “Wind power by country,” Wikipedia, Apr. 23, 2023. https://en.wikipedia.org/wiki/Wind_power_by_country

Energy Storage Systems (ESSs)

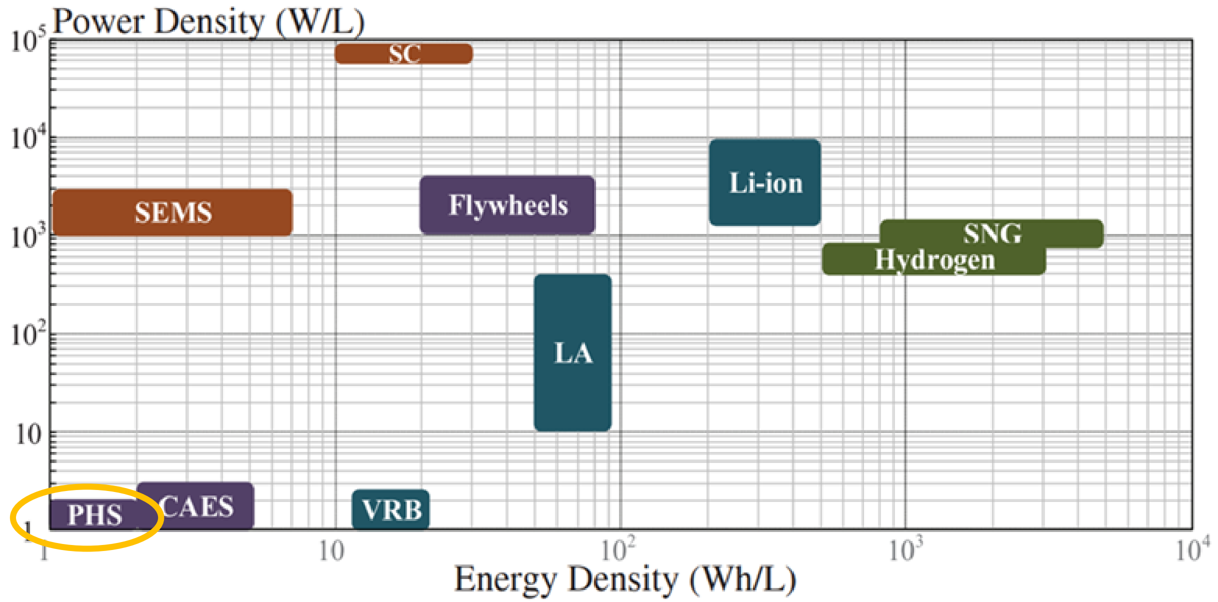
Categorizing ESSs based on its technology:

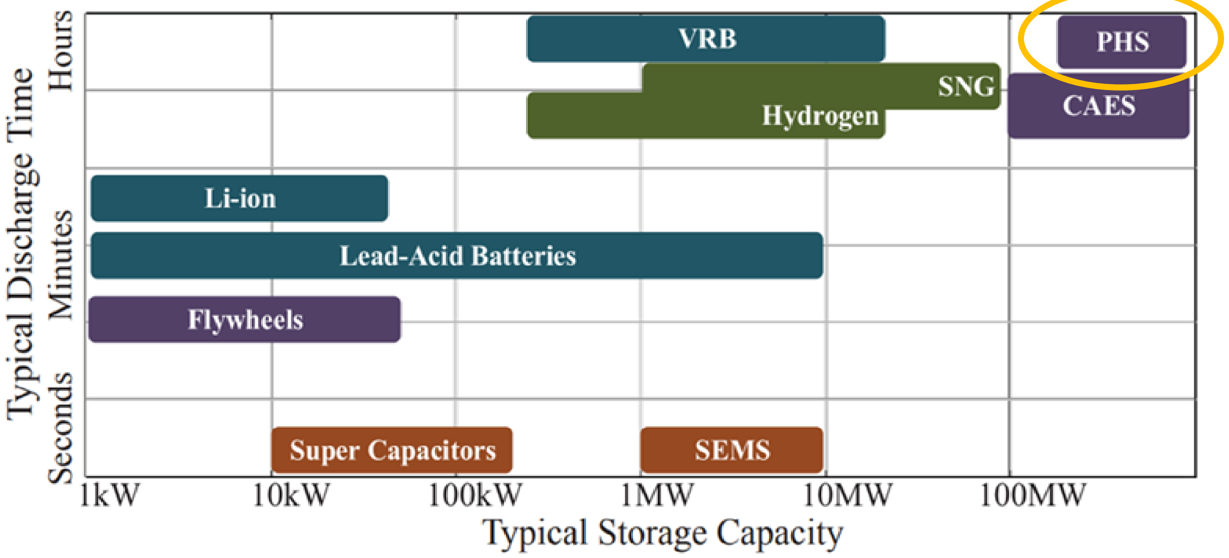


ESSs together with appropriate controllers can be used to achieve the following functions:

- Peak Shaving and Load leveling
- Renewable Integration
- Voltage and Frequency Regulation
- Reserve
- Black Start and Load following

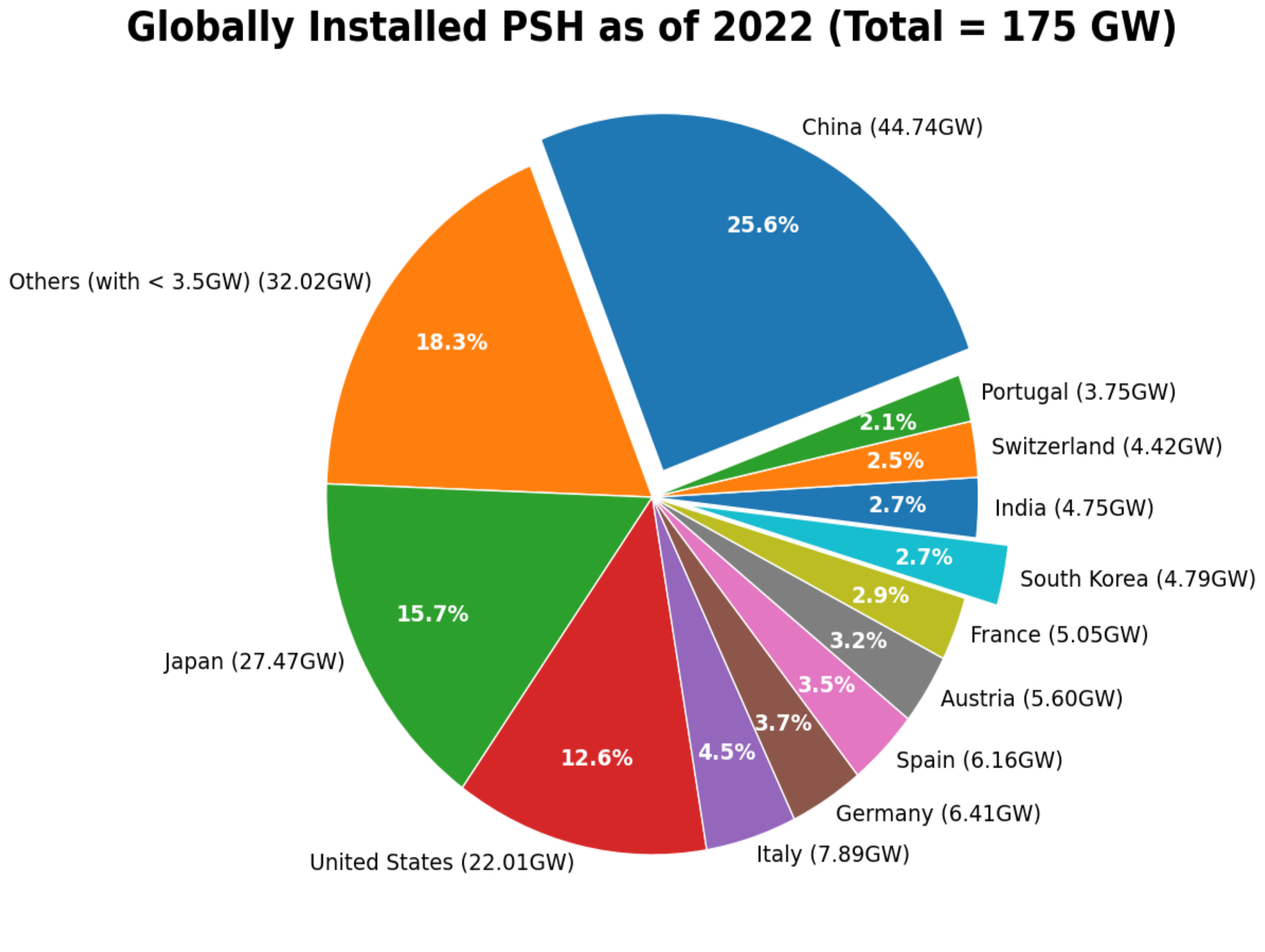
Comparison of ESSs Characteristics

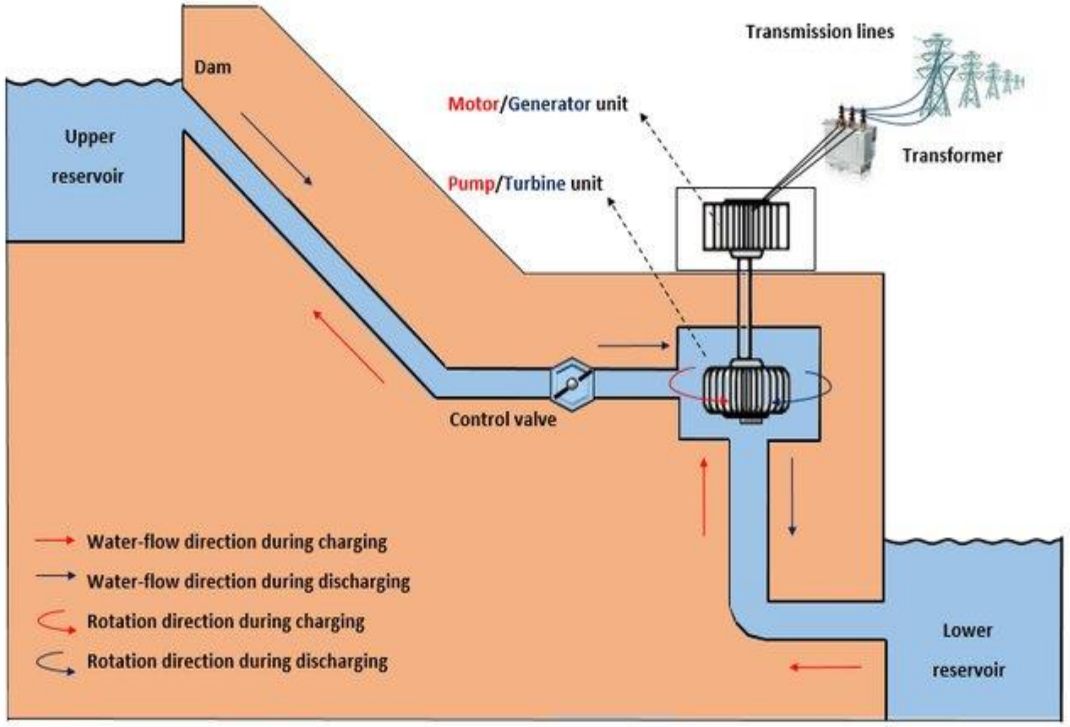




ESS	Daily Self-Discharge (%)	Lifetime (years)	Cycling Times (cycles)	Discharge Efficiency (%)	Response Time
Lead Acid Battery (LA)	0.1–0.3	3	~1k	~85	milliseconds
Lithium-Ion Battery (Li-ion)	0.1–0.3	5–10	~5k	~85	milliseconds
Vanadium Redox Battery (VRB)	Small	5–15	~10k	~85	milliseconds
Pumped-Storage Hydropower (PSH)	~0	40–60	~30k	~87	minutes
Compressed Air Energy Storage (CAES)	~0	20–40	~10k	~75	minutes
Flywheel Energy Storage (FES)	100	~15	~20k	~90	seconds
Supercapacitor (SC)	20–40	10–30	~50k	~95	milliseconds
Superconducting Magnetic Energy Storage (SMES)	10–15	20+	~100k	~95	milliseconds
Hydrogen (H_2)	~0	15	~10k	~59	seconds
Synthetic Natural Gas (SNG)	~0	15	~20k	~50	seconds

Pumped-Storage Hydropower (PSH)



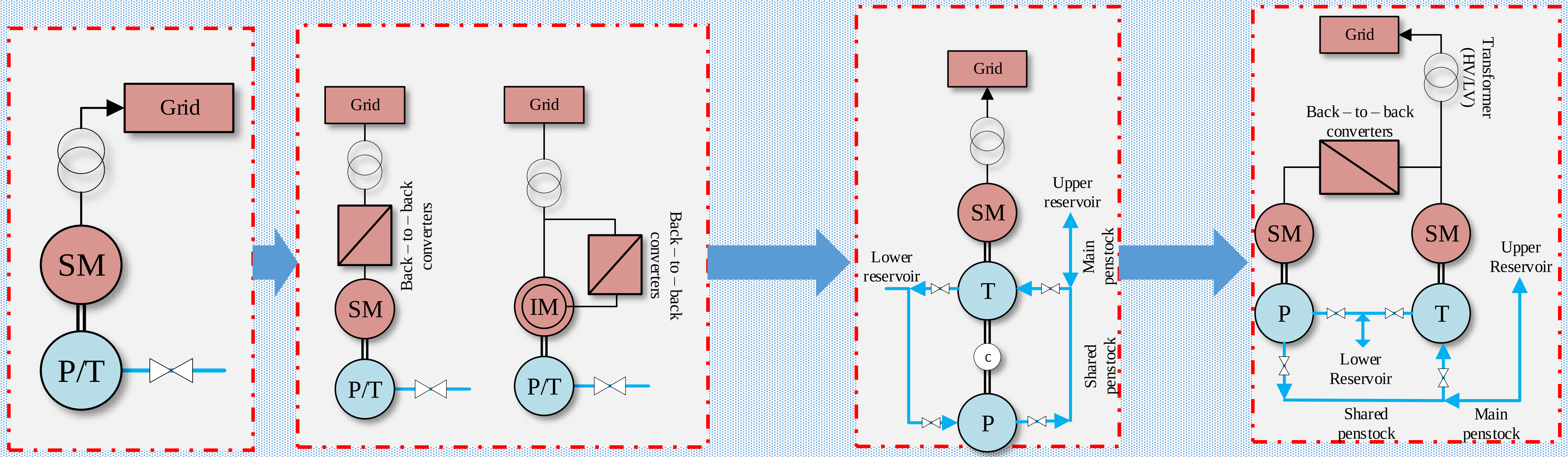


Drawbacks of PSH

- Low power and energy density
- Low response time (in minutes)
- Very high capital cost
- Geographical safety concerns

"2023 World Hydropower Outlook," International Hydropower Association. [Online]. Available: https://www.hydropower.org/publications/2023-world-hydropower-outlook

The Evolution of Pumped-Storage Hydropower (PSH)



Conventional PSH

- Generation mode flexibility

Adjustable speed PSH

- Generation mode flexibility
- Pump mode flexibility

Ternary PSH

- Generation mode flexibility
- Pump mode flexibility
- Rapid mode change

Quaternary PSH

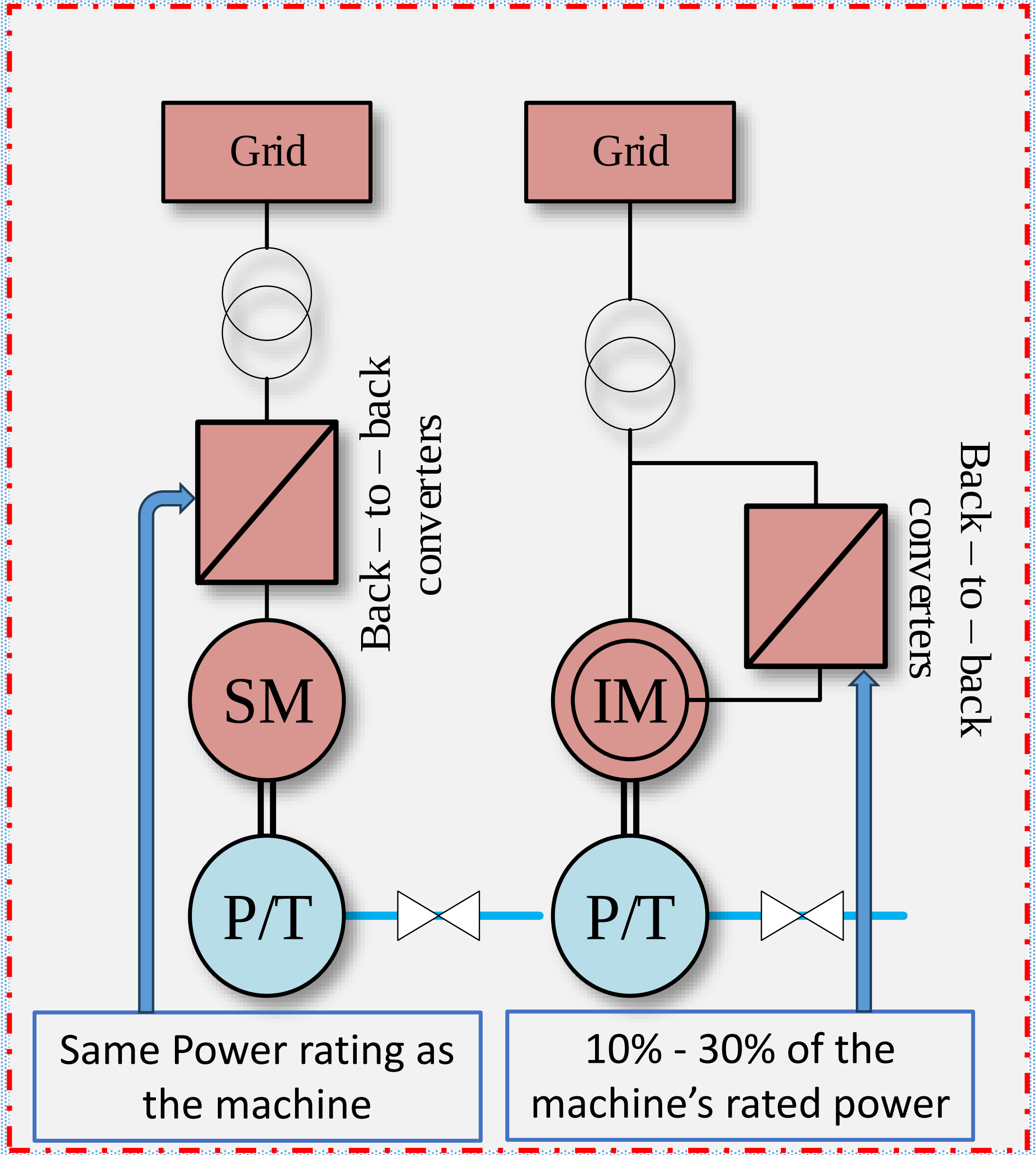
- Generation mode flexibility
- Pump mode flexibility
- Rapid mode change

SM = synchronous machine, IM = induction machine, T = turbine, P = pump, C = clutch, P/T = pump-turbine

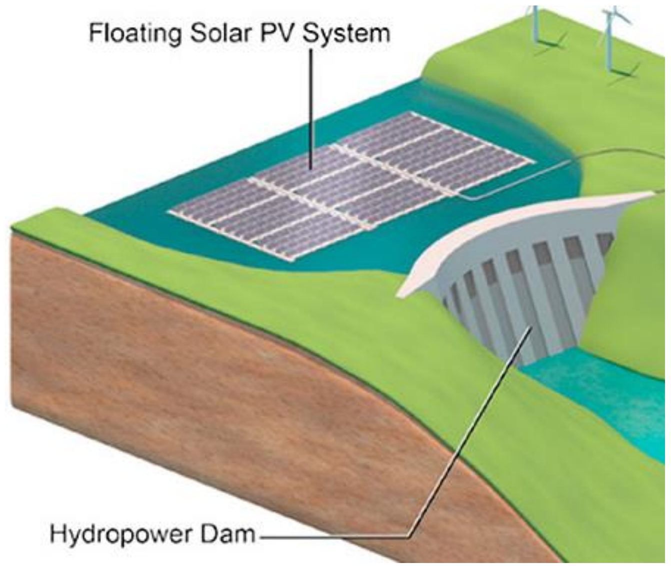
Adjustable Speed Pumped-Storage Hydropower (ASPSH)

Benefits of ASPSH:

- It can assist in regulation services while in the pumping mode;
- The rotating speed of ASPSH can be optimized to achieve greater operating efficiency for partial load in the generating mode for a given head and flow rate;
- Operating at optimal speed eliminates rough zone operations, therefore reduces wear and tear;
- It provides flexible real power support because of the decoupled control of active and reactive power through the converter;
- It has a good dynamic response in the case of a grid disturbance;



AI-Based Control of Hybrid PV and Advanced Pumped-Storage Hydropower Plant for Power System Resiliency



Benefits of PVs installed on hydropower's reservoir surface

("Where Sun Meets Water: Floating Solar Market Report," 2018):

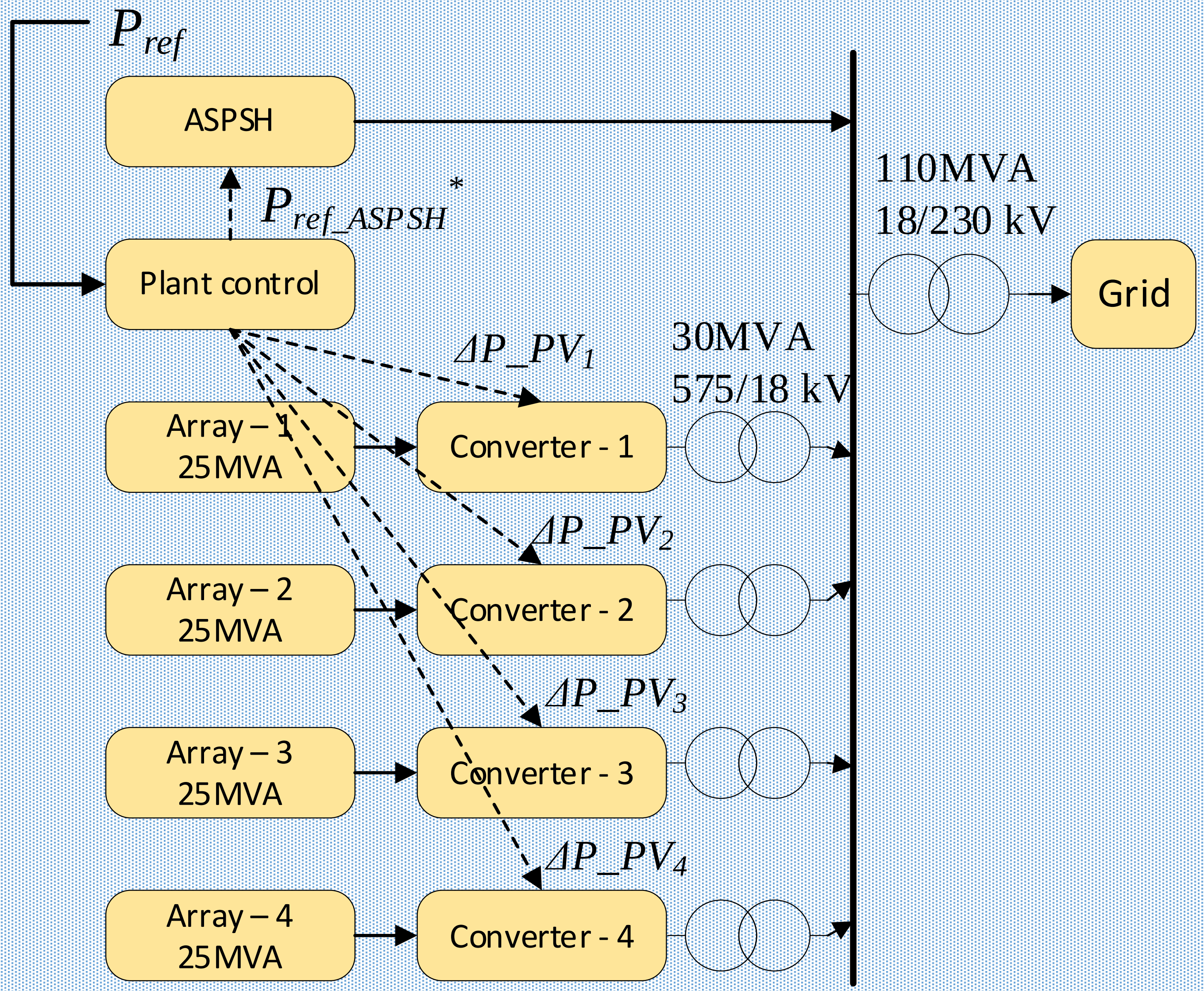
- Reduction in capital cost because of utilizing existing hydropower site infrastructure
- Reduced shading, decreased dust presence, and water-cooling effects improve energy yield
- Eliminates the need for large-scale site preparation
- Adds additional capacity and flexibility to the plant

Gevorgian and O’Neill (2016): with an accurate estimation of available maximum power and DC operating voltage required for the power output, PV converters can deliver fast frequency response (FFR) and power oscillation damping to the grid.

- Estimation of PV’s maximum power with Second-order polynomial models perform well only for constant irradiance and temperature but becomes highly inaccurate in transient states.

To improve the flexibility of the ASPSH: by taking advantage of the additional PV generation and the FFR potential of the PV converters, we opted to use a neural network (NN) model to predict the available maximum power and required DC operating voltage. Also, the NN model for the maximum power estimation is employed to coordinate the operation of the hybrid unit.

The Hybrid Plant

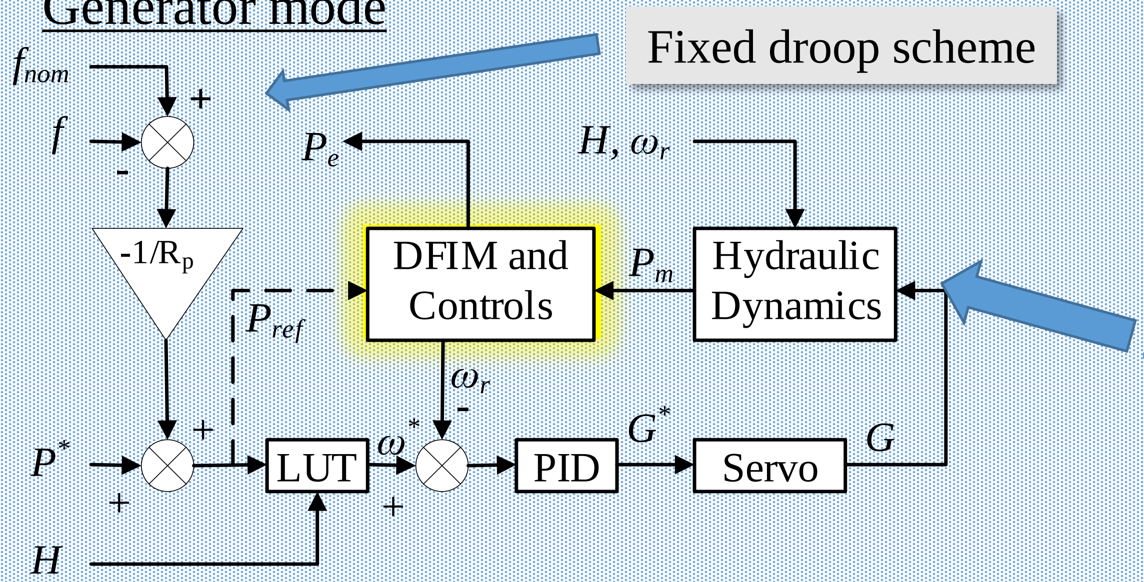


The schematic for the hybrid PV-ASPSH plant.

- The hybrid plant used for this study is designed as shown.
- It comprises a 100MVA DFIM-based ASPSH and a PV plant rated 100MVA consisting of four individual PV arrays of 25MVA with a lumped DC/DC converter and a lumped DC/AC inverter.
- The two units are coupled together to the grid using a 110MVA step-up transformer.

The ASPSH Unit Model and Control

Generator mode



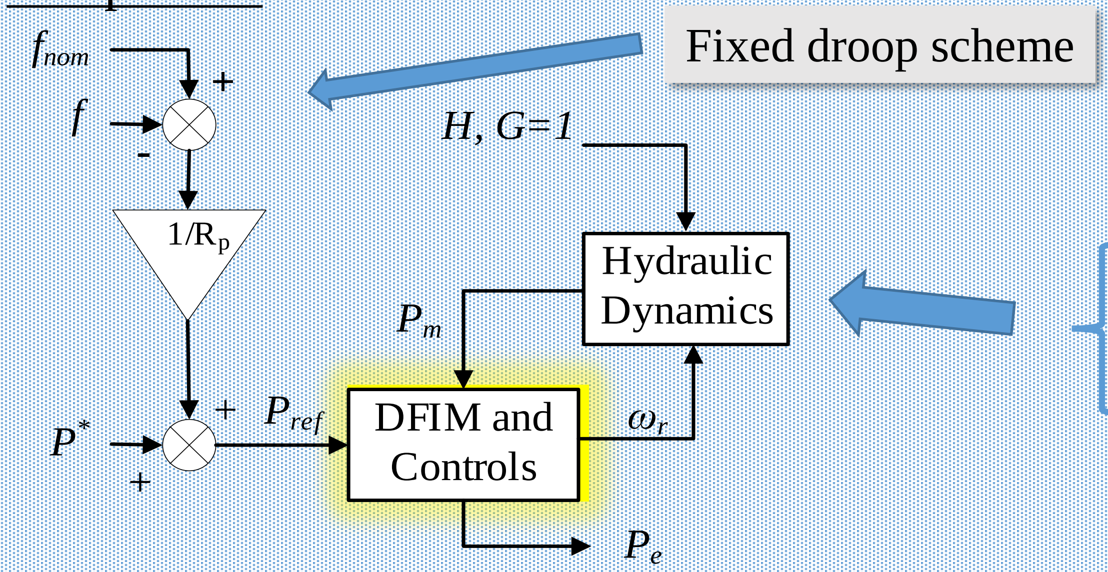
$$\frac{dq_t}{dt} = \frac{[1 - h - h_l]}{T_w}$$

Water time constant → $T_w = \frac{LQ_{base}}{Ah_{base}g} s$

Gate, Head and Discharge relationships → $q = G\sqrt{h}$

Mechanical output of turbine → $P_m = A_t h(q - q_{nl}) - DG\Delta\omega$

Pump mode



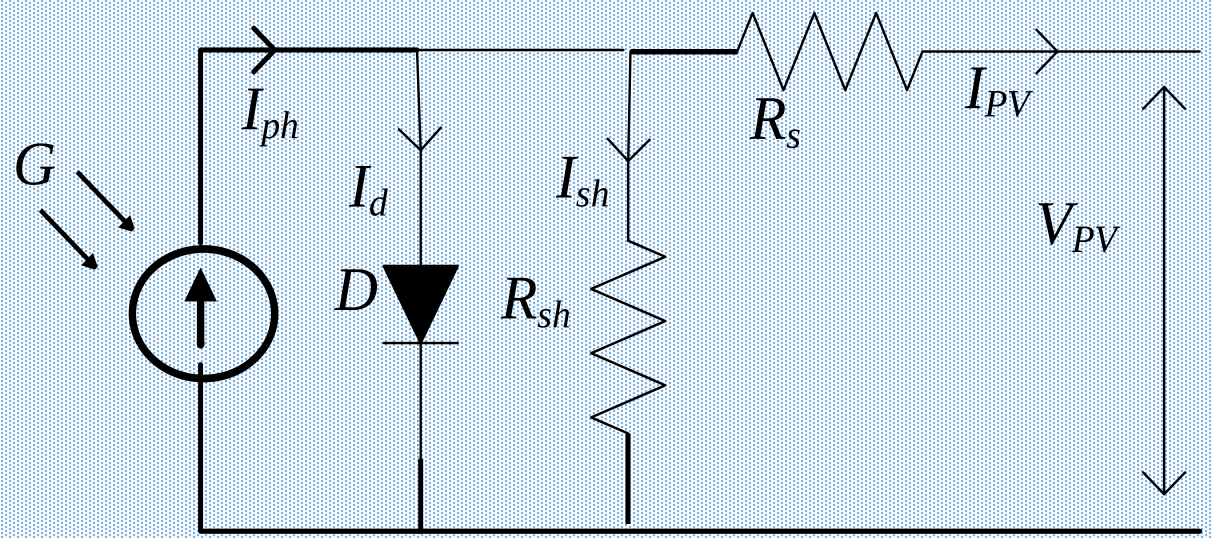
$$\frac{dq_p}{dt} = \frac{-[1 - H - h_l]}{T_w}$$

Head and Discharge relationship → $H = \alpha - \beta q^{1.75}$

Mechanical output of pump → $P_m = A_t h(q - q_{nl}) - DG\Delta\omega$

The PV Unit Model and Control

The solar module dynamics is modeled as a current source as shown below



Solar module model.

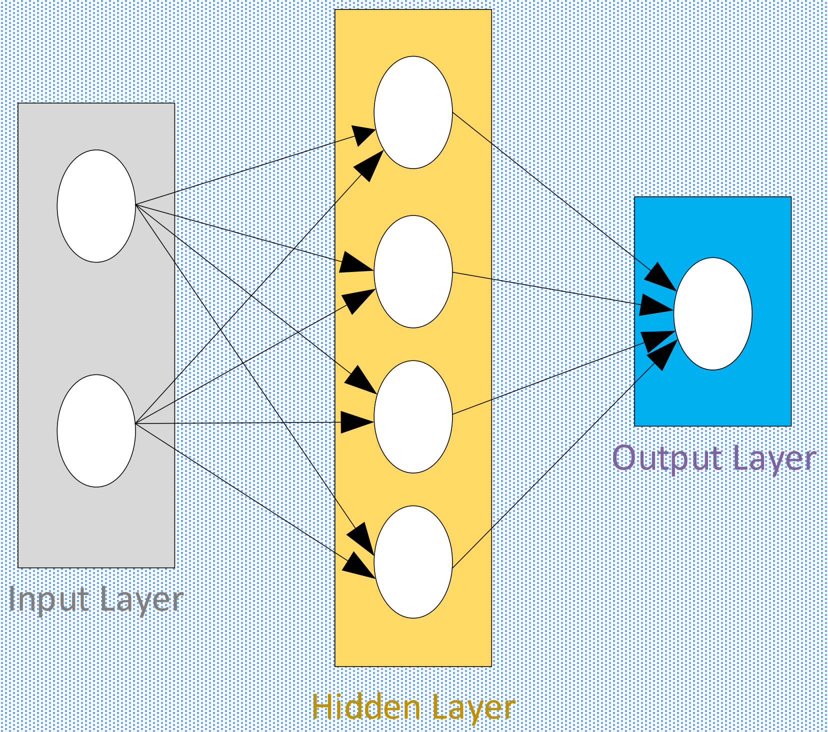
An array is formed by multiplying the generated current and voltage by the number of modules in series and the number of parallel strings, respectively.

Each array has its temperature and irradiance sensor.

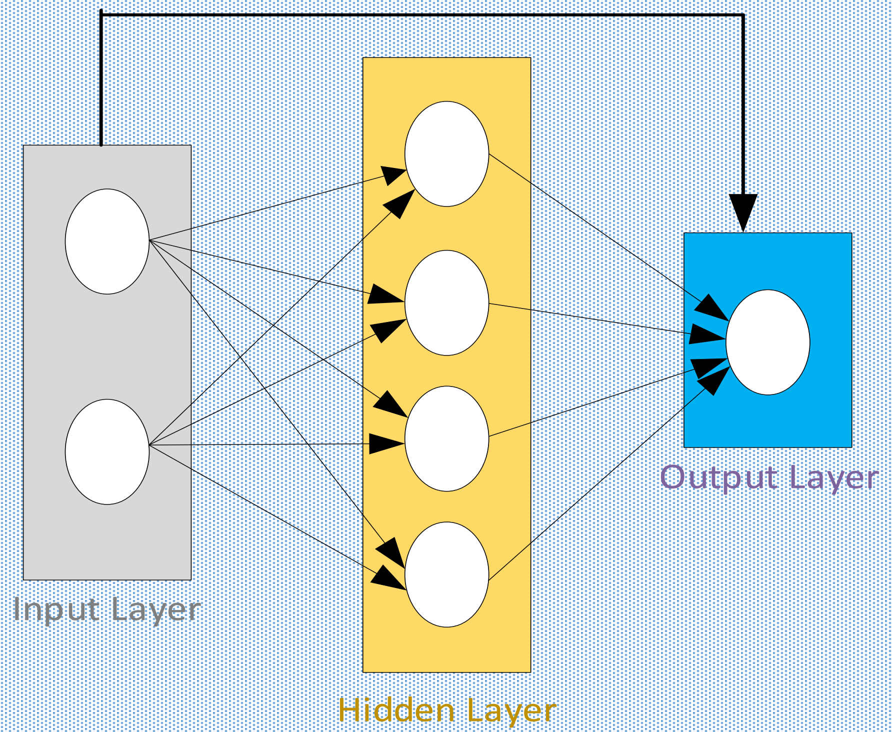
Neural Network (NN) Training

The following methods were utilized and compared for best results:

- Feed-forward NN (FFNN) with one hidden layer, and
- Cascade-forward NN (CFNN) with one hidden layer – Each layer has a connection from the input and previous layer.



FFNN

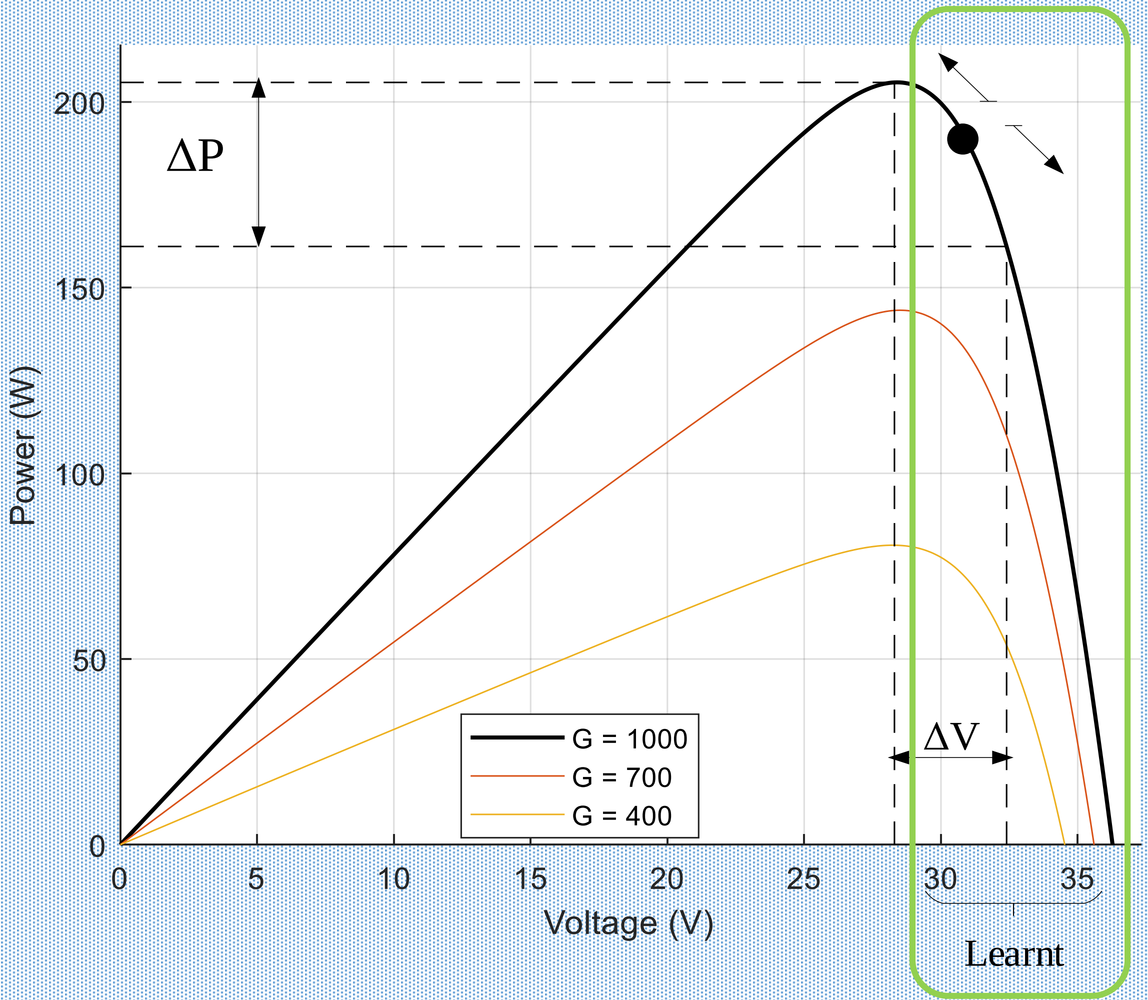


CFNN

NN Training for Maximum Power Point (MPP) and Voltage Estimation

- To generate the NN for MPP estimation (NN_P), the MPPs were regressed as a function of irradiance (G) and temperature (T).

- For the voltage estimation NN (NN_V), the terminal voltage of the module was regressed for given power output, irradiance, and temperature. Only the right-hand side (RHS) of the P–V characteristics was learnt for the following reasons:
  - (a) To prevent the NN from learning two voltage values for the same power level,
  - (b) It requires less control effort, and
  - (c) It is a boost converter



P–V characteristics of the PV at T = 298K.

NN Training Results and Comparison

The Levenberg-Marquardt algorithm was employed for training and performance was analyzed using the Mean square error (MSE). Tables 1 and 2 show the comparison of the FFNN and CFNN performance for different number of hidden neurons.

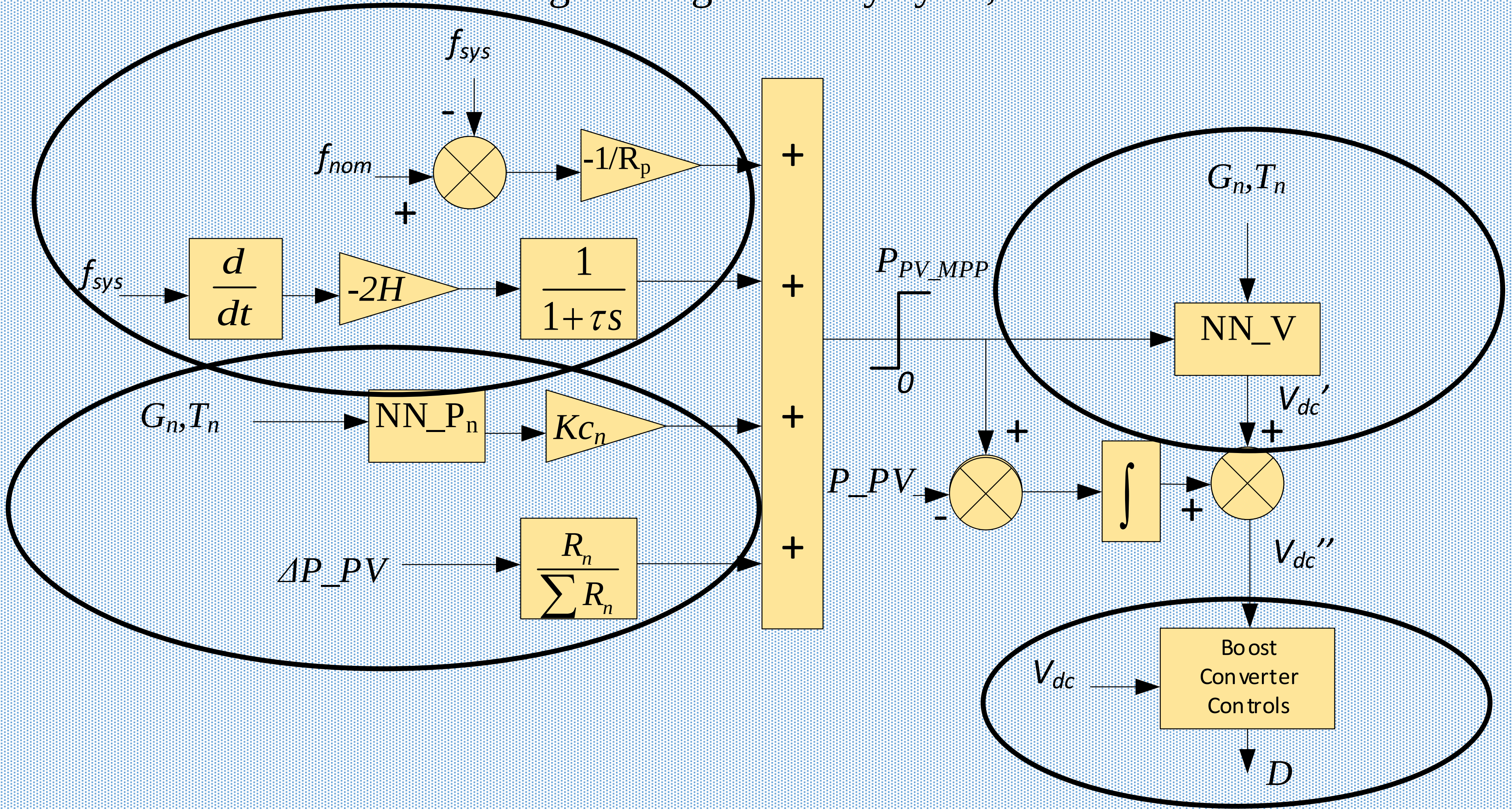
Table 1. MSE for FFNN and CFNN for NN_P

NN_P	FFNN	CFNN
3 neurons	9.1×10^{-4}	2.1×10^{-4}
9 neurons	7.32×10^{-5}	7.76×10^{-5}
15 neurons	1.01×10^{-4}	6.5×10^{-5}

Table 2. MSE for FFNN and CFNN for NN_V

NN_P	FFNN	CFNN
3 neurons	2.56×10^{-2}	1.3×10^{-2}
9 neurons	2.8×10^{-3}	3.2×10^{-3}
15 neurons	8.1×10^{-4}	9.7×10^{-4}

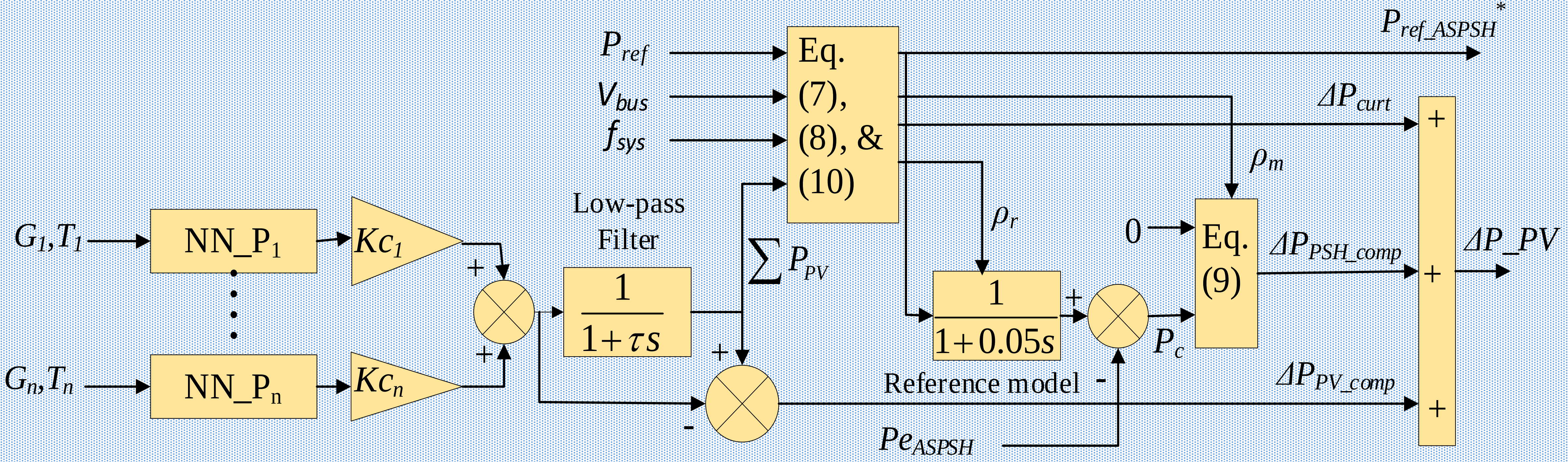
- The array controller as shown below is equipped with a fixed droop and virtual inertia control capability.
- It uses the trained NN_P to track the required set-point for the array and also, implements the hybrid plant command on the PV plant reserve through ΔP_PV.
- Then, the trained NN_V is used to generate the DC voltage for the required power setpoint.
- Finally, with an integrator, the predicted DC voltage is corrected to eliminate possible errors. The boost converter tracks the corrected DC voltage through the duty cycle, *D*.



The Hybrid Plant Control

The hybrid plant control is designed to utilize the NN power estimator to perform the following functions:

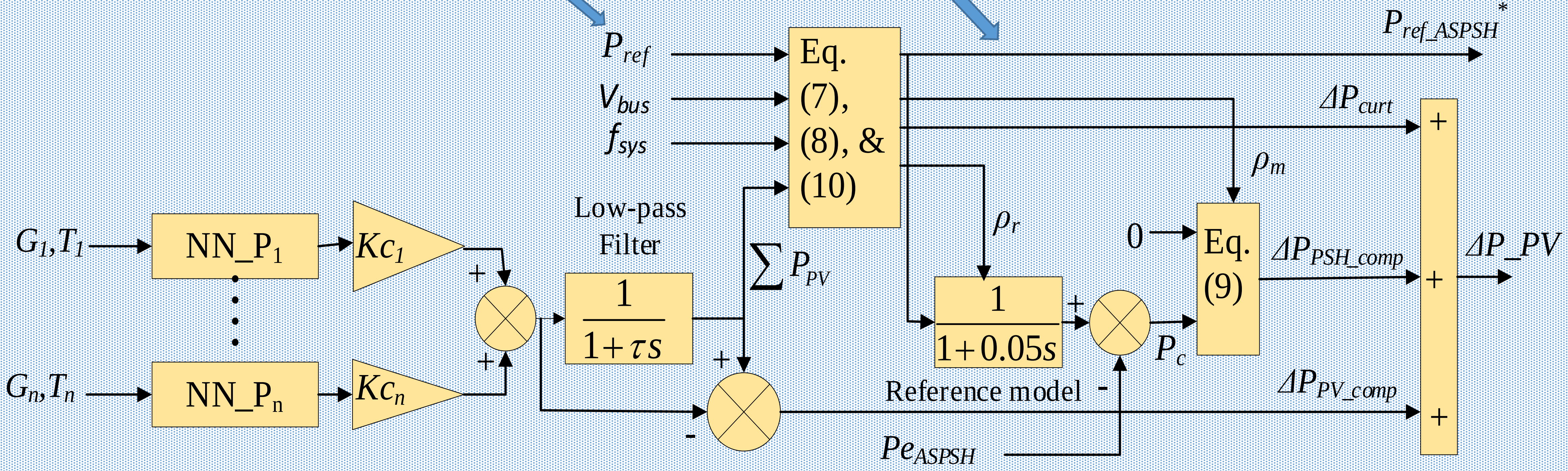
- Assign power reference to the ASPSH
- Curtail the PV plant power output when needed
- Compensate for the nonlinearities of the ASPSH unit through the PV plant reserve, while also preventing it from compensating for the primary frequency control (PFC) of the ASPSH
- Account for fast transient in insolation through the PV plant reserve only



The power reference sent to the ASPSH unit is computed and constrained (taking into account the minimum and maximum possible generation and pumping of the ASPSH unit) as shown below, using the sum of the estimated PV power output.

$$P_{ref\_ASPSH} = P_{ref} - \sum_{i=1}^{N} P_{PV_i},$$

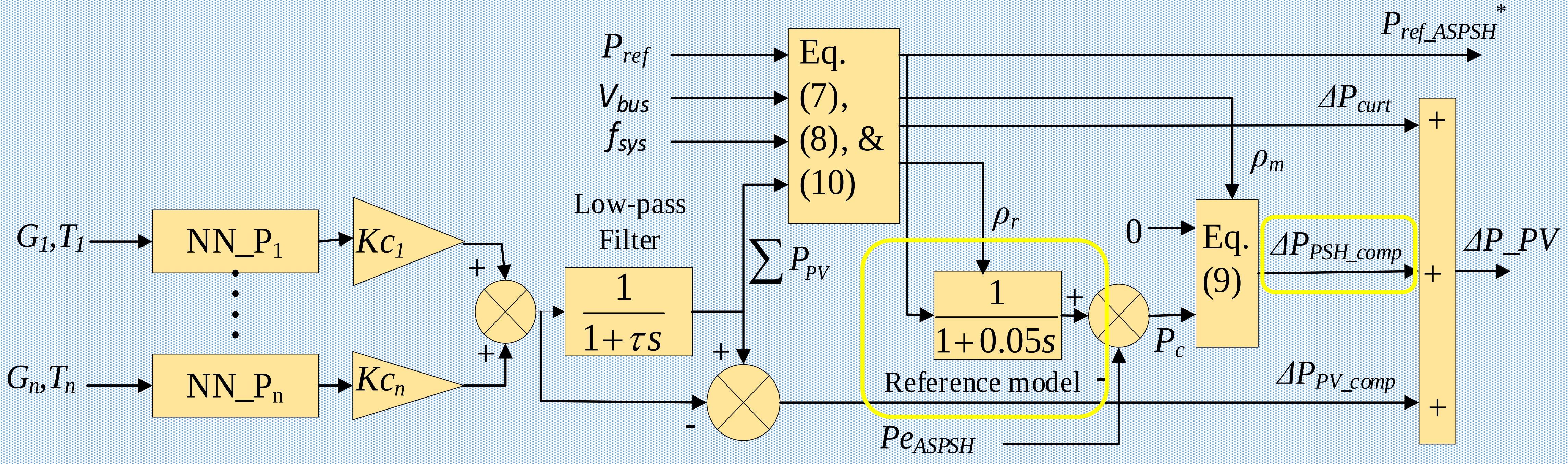
$$P_{ref\_ASPSH}{}^{*} = \begin{cases} \underline{PG}_{ASPSH}, P_{sch} > 0, P_{ref\_ASPSH} < \underline{PG}_{ASPSH} \\ \overline{PG}_{ASPSH}, P_{sch} > 0, P_{ref\_ASPSH} > \overline{PG}_{ASPSH} \\ \underline{PP}_{ASPSH}, P_{sch} < 0, P_{ref\_ASPSH} < \underline{PP}_{ASPSH} \\ \overline{PP}_{ASPSH}, P_{sch} < 0, P_{ref\_ASPSH} > \overline{PP}_{ASPSH} \end{cases},$$



- The dynamic response of the ASPSH unit was depicted with a first-order reference model and the PV plant reserve compensates for the differences between the actual and desired plant behavior through ΔP_{PSH_comp}
- (8) and (9) below are used to prevent the PV plant reserve from compensating for PFC of the ASPSH unit in the case of a network disturbance

$$\rho_m = \begin{cases} 1, V_{\min} < V < V_{\max} \text{ and } & f_{\min} < f < f_{\max} \\ 0, & otherwise \end{cases}, \quad (8)$$

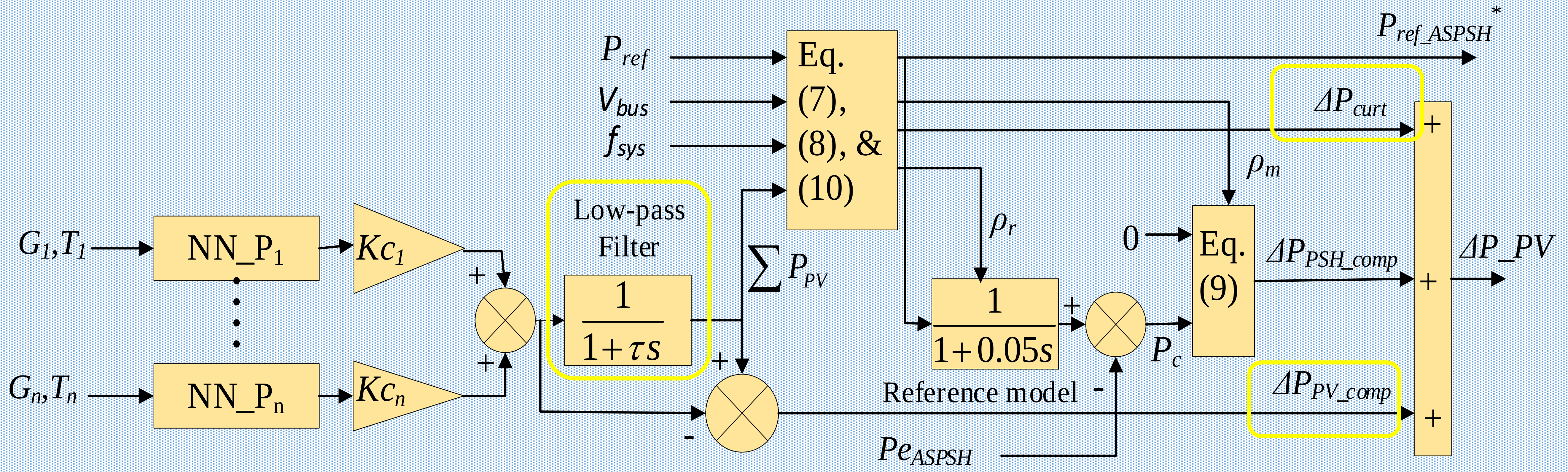
$$\Delta P_{PSH\_comp} = \begin{cases} 0, \rho_m = 0 \\ P_c, \rho_m = 1 \end{cases}, \quad (9)$$



- The hybrid plant control employs a low-pass filter to prevent fast transients in insolation from reflecting in the power reference to the ASPSH unit but compensated for by the PV plant reserve through ΔP_{PV_comp}

- It also takes the difference between the hybrid plant's reference and its total generation, *curt_PV*, and curtail the PV power output as shown in (10)

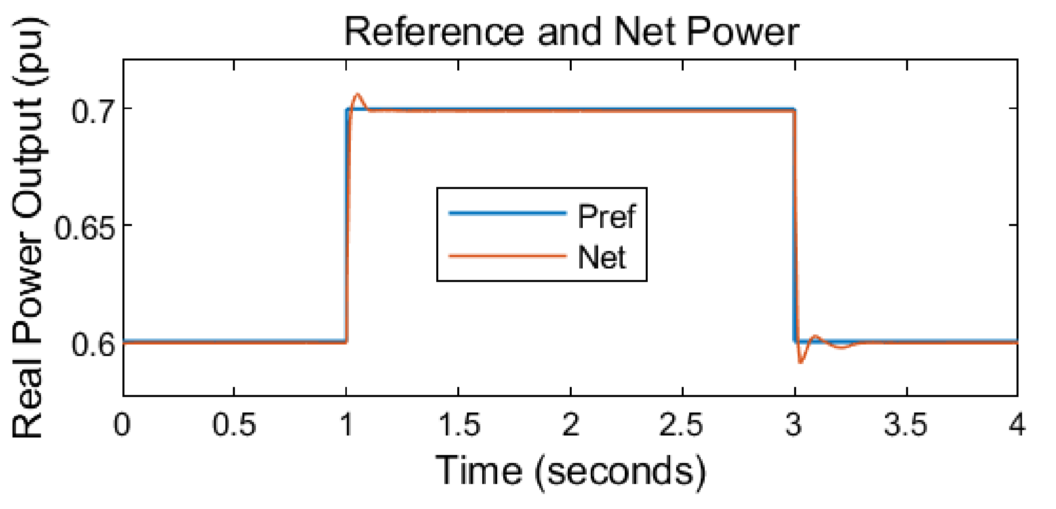
$$\Delta P_{curt} = \begin{cases} curt\_PV, & curt\_PV < 0 \\ 0, & curt\_PV > 0 \end{cases}, \qquad (10)$$



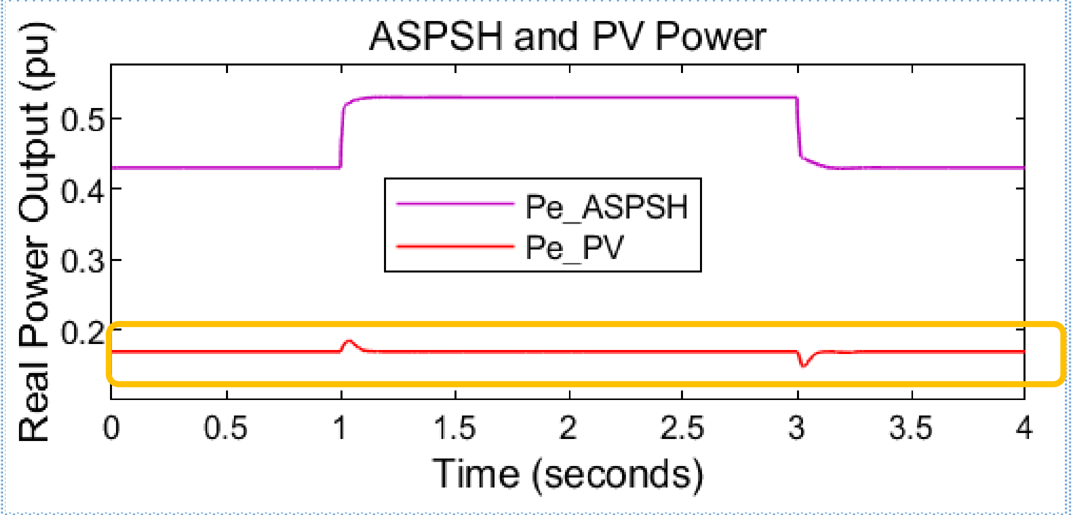
Results

To demonstrate the performance of the hybrid system and validate its control scheme, it was integrated into an infinite bus and tested for its set-point tracking capabilities, the firming capabilities of the ASPSH for the plant, and the ability of the controller to observe the operational constraints of the ASPSH unit and curtail the PV system accordingly.

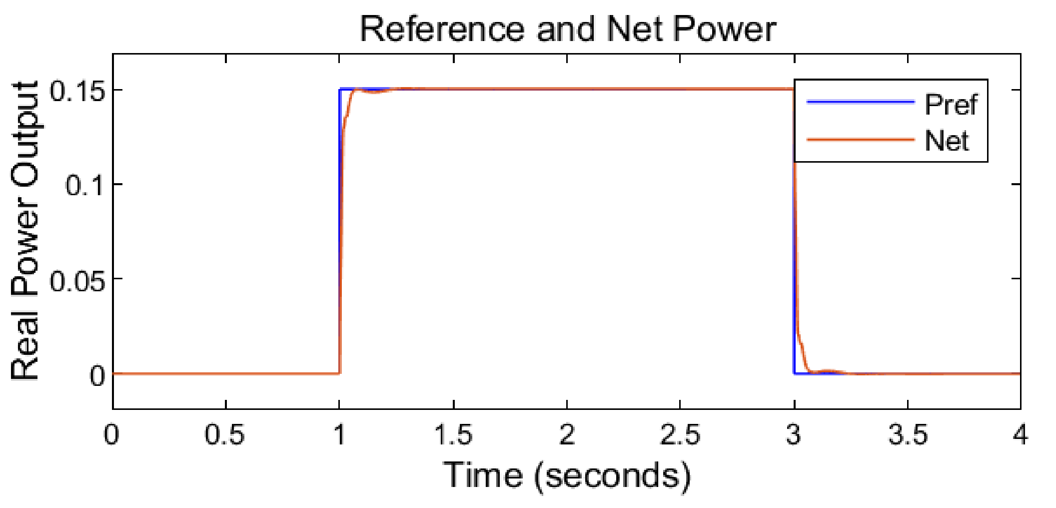
Testing the Hybrid System Control Scheme and Performance



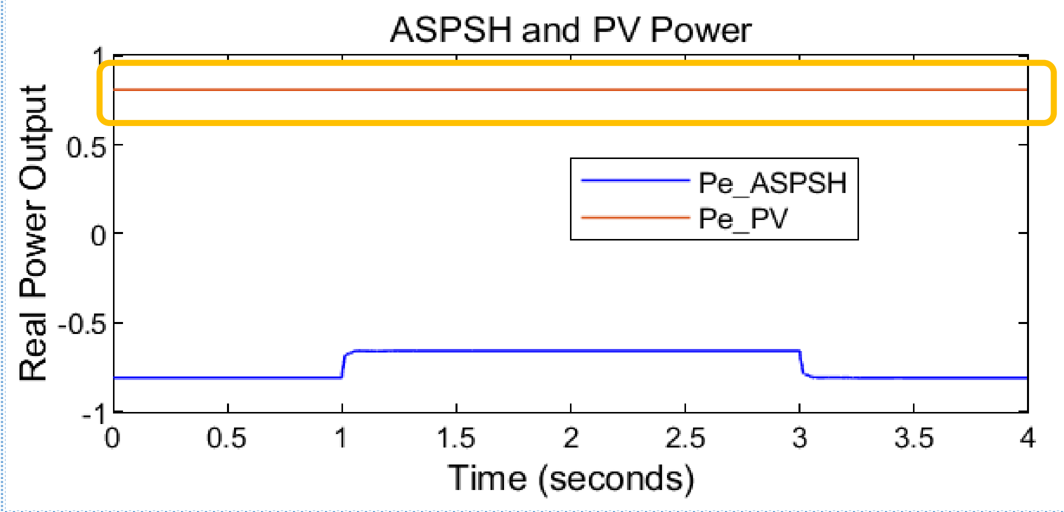
Reference and net power in generation mode.



ASPSH and PV individual power in generation mode.

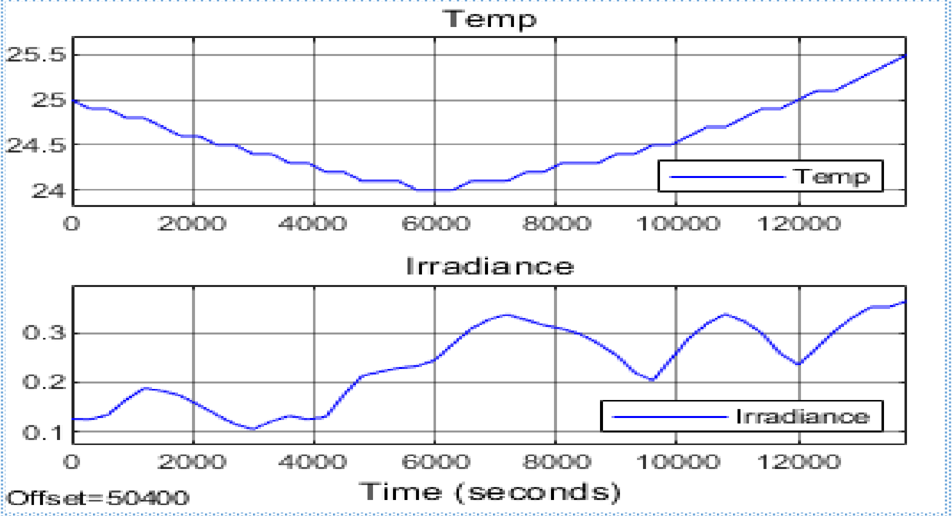


Reference and net power in pump mode.

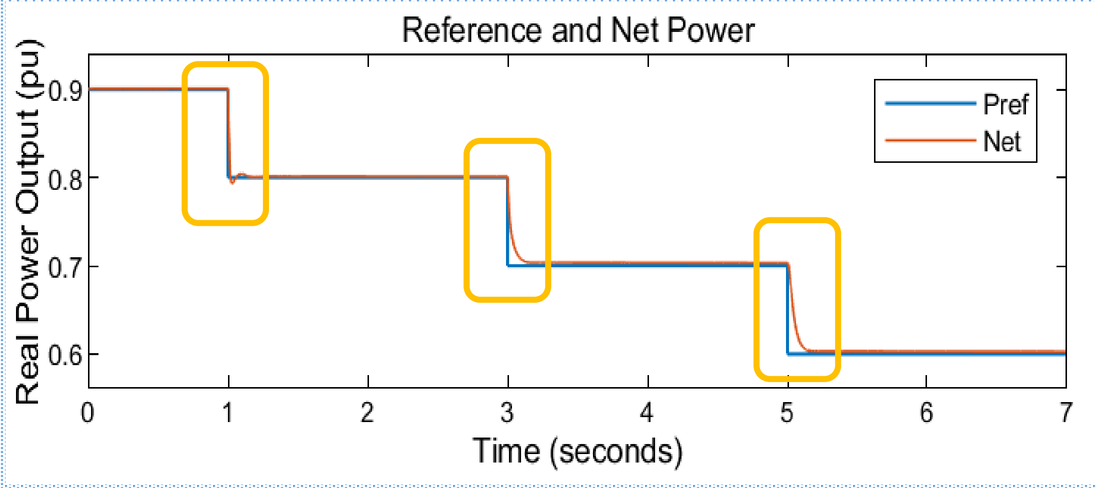


ASPSH and PV individual power in pump mode.

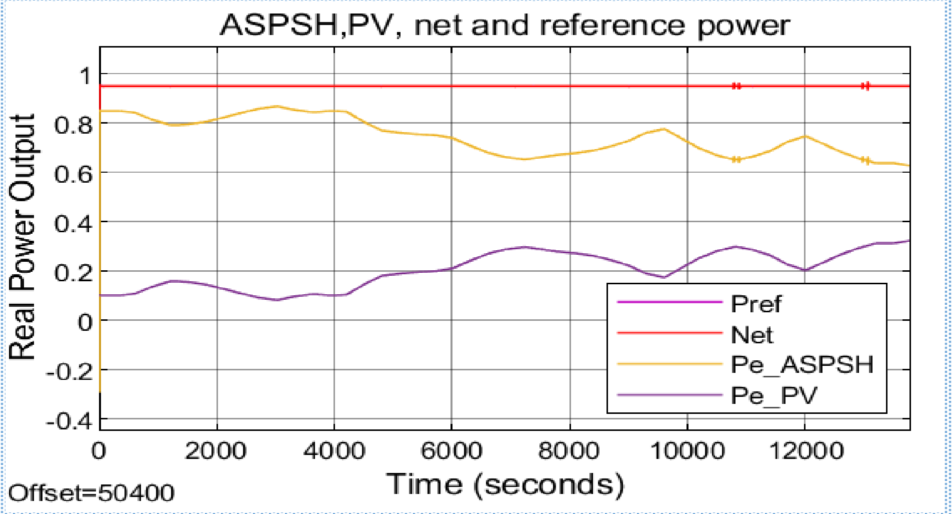
Testing the Hybrid System Control Scheme and Performance



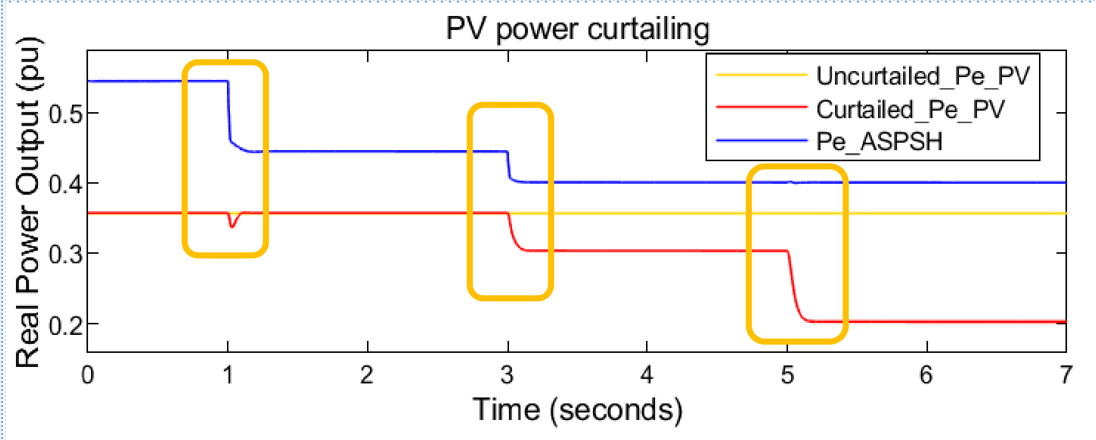
Irradiance and temperature profile.



Hybrid plant reference and net power output with curtailed PV.

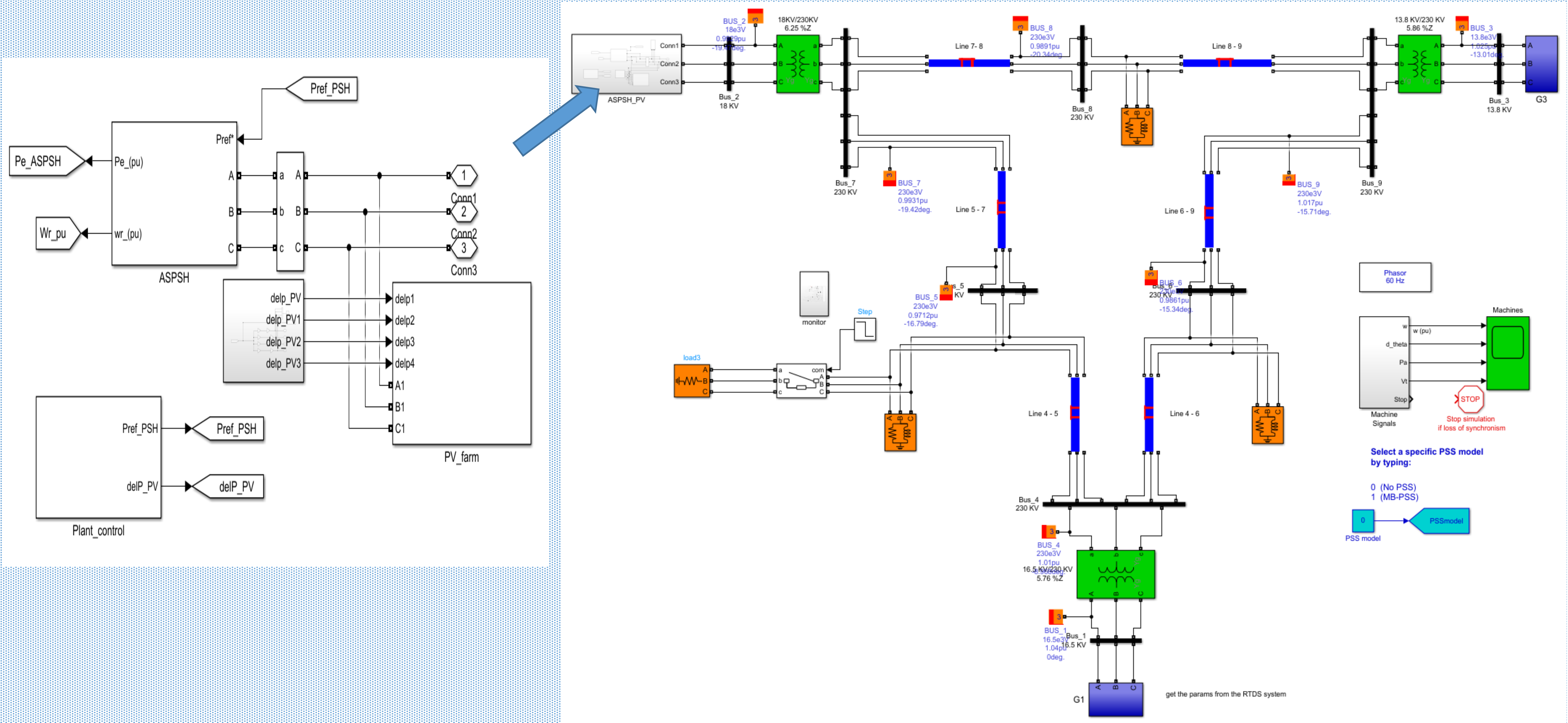


ASPSH, PV, net, and reference power.

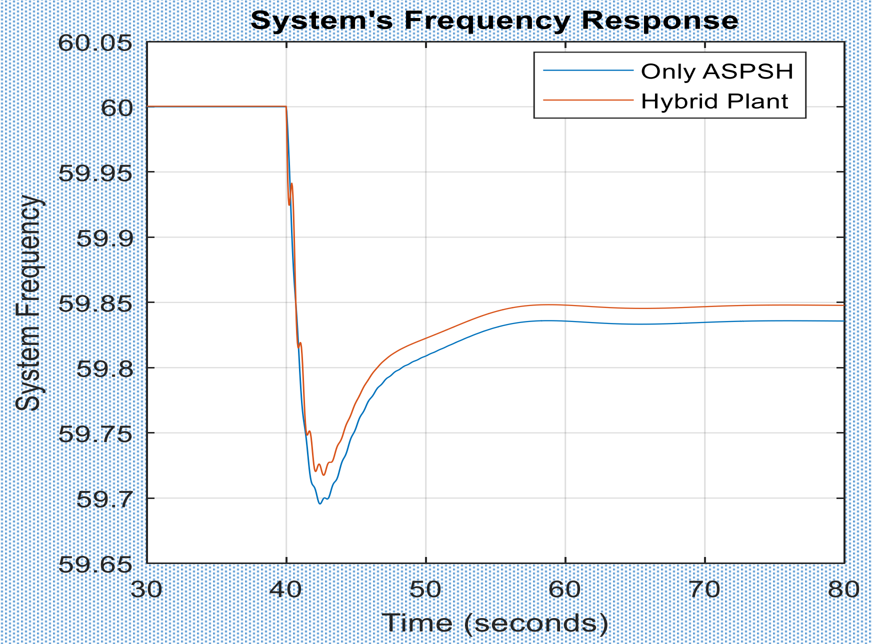


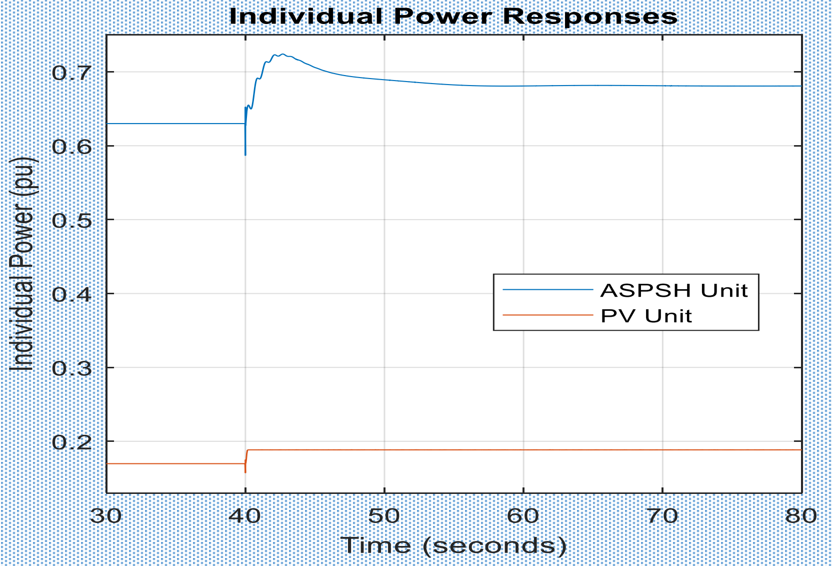
PV and ASPSH power output to demonstrate the PV curtailing function of the controller.

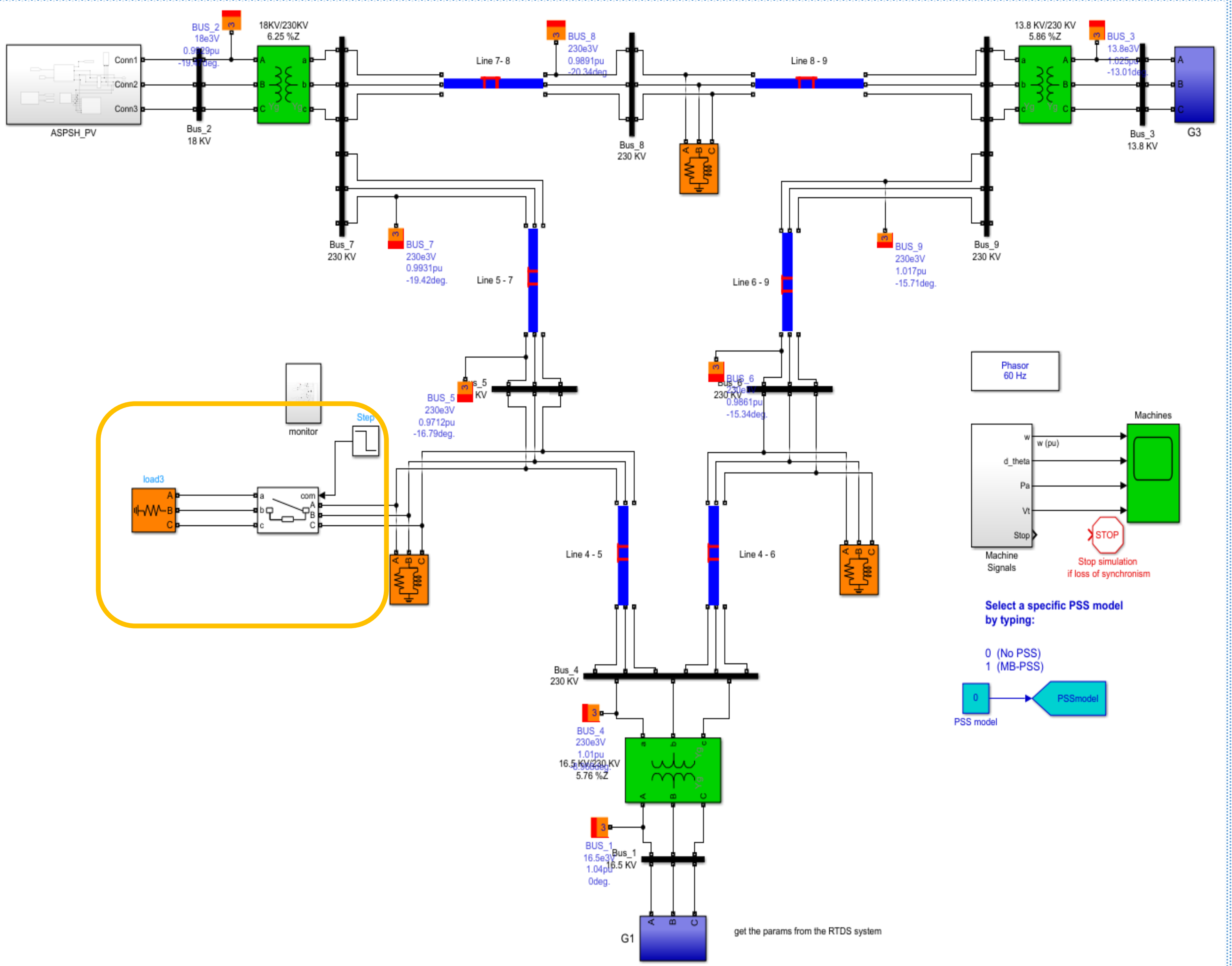
Integration in 9-bus Test System



Frequency Response (FR) Contribution of the PV Unit







Conclusion

- The proposed system has the advantage of additional generation capacity, more flexibility when PV is available, and better responses compared to the PV plant and ASPSH individual responses.
- The designed AI-based hybrid plant control successfully controlled the two sources simultaneously while observing the ASPSH operational constraints.
- The added generation of the PV plant and its capability to participate in FR improved the hybrid plant Frequency Response (FR) .

Questions?

Thank You