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Hybrid Neuro-Fuzzy Controllers for Robust Maximum Power Point Tracking under Variable Environmental Conditions

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INTRODUCTION & AIM

Solar energy, while essential for sustainability, contends with the technical instability of I-V curves, which fluctuate according to environmental conditions. To mitigate this issue, this study proposes the use of the Adaptive Neuro-Fuzzy Inference System (ANFIS) as a superior evolution over traditional MPPT methods, such as P&O. The advantage of this hybrid approach lies in its capacity for dynamic adaptation and its elimination of the need for complex mathematical modeling. Its efficacy is validated through real experimental data, ensuring greater precision even under rapid climatic changes.

METHOD

The study utilized a database of 17,193 real-world irradiance samples from a university plant. Simulations were conducted in MATLAB/Simulink using Yingli polycrystalline modules (245 W, 15.1% efficiency). The key modeling aspects were:

- **Data Partitioning:** 80% for training and 20% for validation.
- **Parameters Tested:** A combination of membership functions (5 and 8) and training epochs (100 and 150).
- **Selection Criteria:** Lowest prediction error and highest R^2.
- **Analysis:** Fig. 1 illustrates the behavior of the V_{ref} variable in relation to environmental and operational conditions.

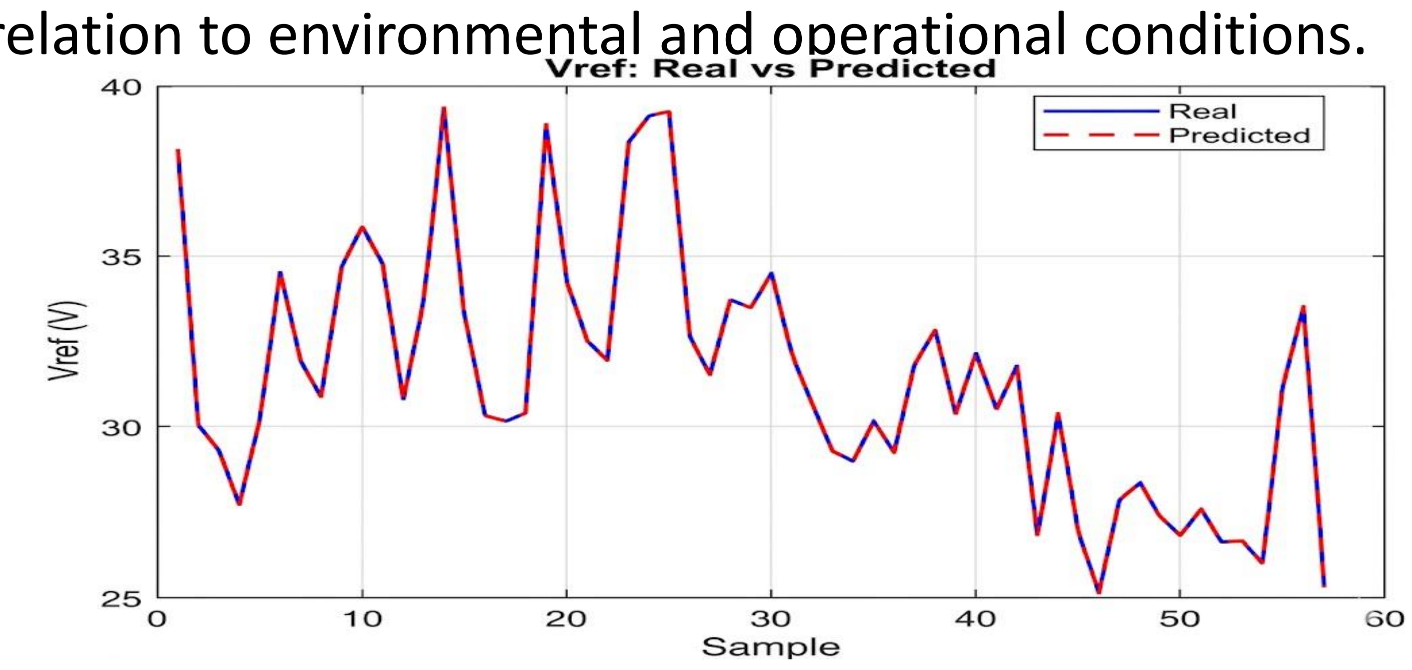

Fig. 1. Error analysis between the estimated and actual values of the Variable V_{ref}.

Figure 2 illustrates the process of collecting and processing cloud-based field data to feed the ANFIS controller within the MATLAB/Simulink environment. This configuration generates a PWM signal that drives a DC-DC converter, ensuring the photovoltaic system operates at its MPP, even under fluctuating weather conditions.

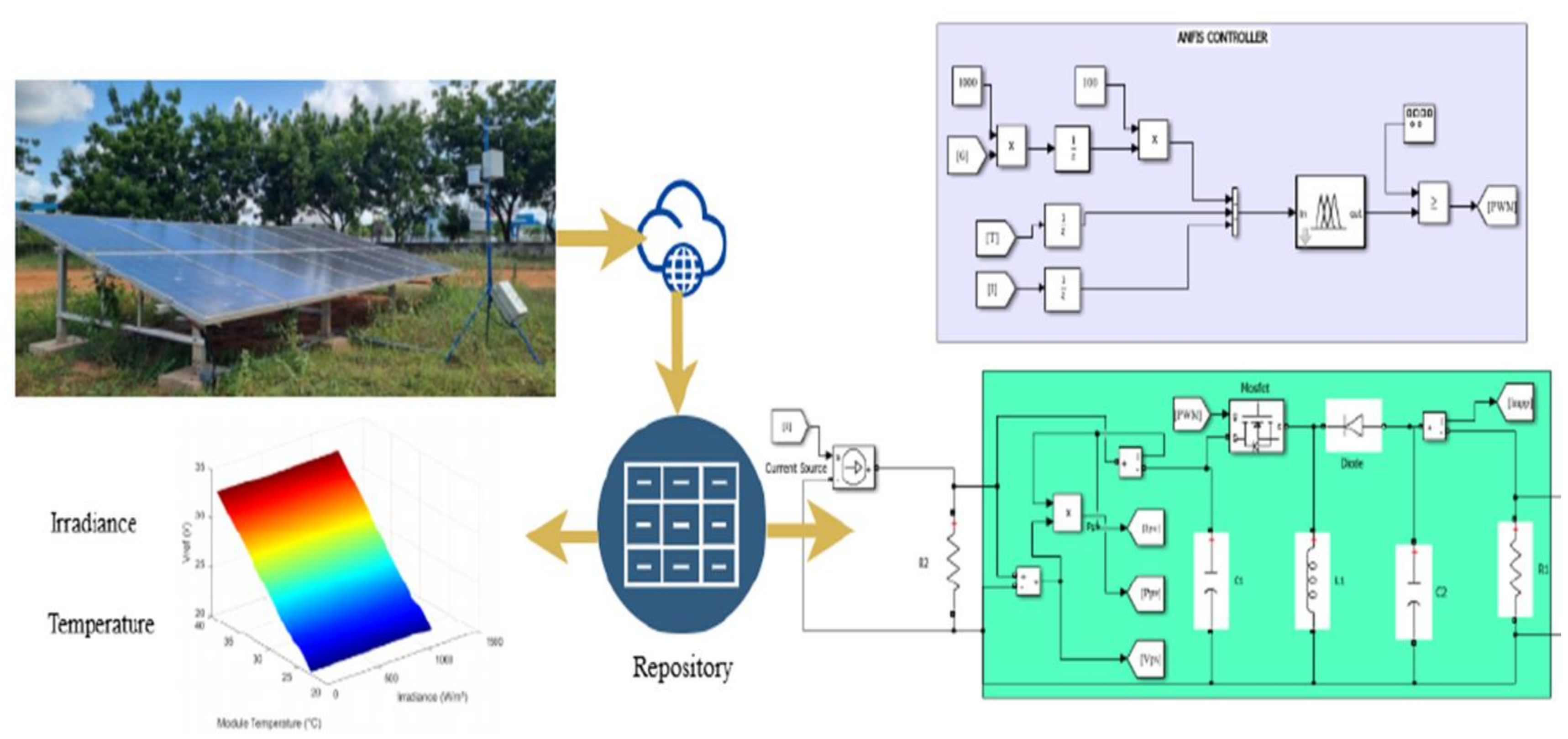

Fig. 2: Photovoltaic Conversion System Architecture with MPPT Control, Simulink Modeling, and Data Repository Integration.

RESULTS & DISCUSSION

The simulation results obtained using the ANFIS controller are presented in the following figures. As illustrated in Fig. 3 a) and b), a pronounced oscillation in voltage V_{PV} and current I_{PV} levels is observed during the initial moments, a phenomenon characteristic of the system's transient state. Following this interval, both the real and estimated values converge to nearly identical levels. This behavior demonstrates the efficacy of the ANFIS controller in performing maximum power point tracking with high precision and stability.

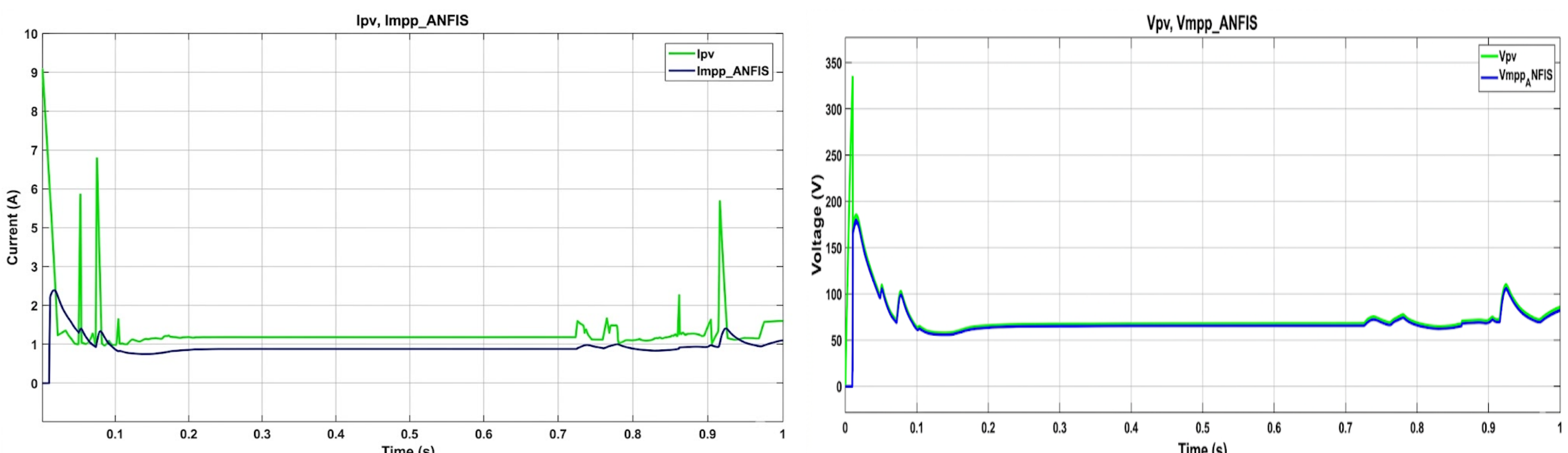

Fig. 3. Results obtained for the photovoltaic generator: (a) voltage and (b) current, comparing theoretical and actual values.

Table 1 provides a detailed comparative analysis of various ANFIS controller configurations applied to MPPT in a photovoltaic system. The study evaluated six distinct scenarios based on variations in the number of MF, the quantity of rules, and the total number of training epochs. To validate performance, operational parameters such as the P_{PV}, the P_{mpp}, and the tracking time were considered. Additionally, the accuracy of the models was quantified using rigorous statistical metrics, including MAE, MSE, RMSE, and the R^2.

Table 1: Summary of results for the proposed simulation scenarios using the ANFIS controller.

Cenários	FP	Regras	Épocas	P_{pv}(kW)	P_{mpp}(kW)	Time (s)	MAE	MSE	RMSE	R^2
A_1	3	9	100	1,710	1,708	0,011	1,1649	2,5313	1,5912	0,6568
A_2	3	9	150	1,703	1,571	0,016	3,1520	10,3506	10,1738	0,1697
B_1	5	125	100	1,709	1,708	0,097	0,5017	0,799	0,8660	0,8973
B_2	5	125	150	1,708	1,601	0,919	1,0443	2,3268	1,5254	0,5149
C_1	8	512	100	1,712	1,710	0,013	0,6734	0,9687	0,9842	0,8412
C_2	8	512	150	1,714	1,711	0,028	0,5624	0,6895	0,8303	0,9067

CONCLUSION

The ANFIS methodology demonstrated high efficacy and speed in MPPT under real-world climatic variations. Scenario C2 (8 membership functions, 512 rules, and 150 epochs) exhibited the best performance, achieving an R^2= 0.9067 and an RMSE = 0.8303. It is concluded that the rigorous tuning of hyperparameters is essential to balancing precision and computational complexity.

FUTURE WORK / REFERENCES

Benchmark the ANFIS performance against CNN or LSTM architectures using irradiance time series.

Abdellatif, Walid SE, et al. "A Fuzzy Logic Controller Based MPPT Technique for Photovoltaic Generation System." International Journal on Electrical Engineering & Informatics 13.2 (2021).