

Introduction & Motivation

Pulse-width modulated systems require a compromise between efficiency $\eta(f)$, which decreases with switching frequency f_{sw} because of switching losses [2, 3], and harmonic distortion $\Theta(f)$, which decreases with frequency through improved waveform reconstruction [1, 4]. This work formalizes two key corrections: the THD coefficient must be treated dimensionally, with $[\kappa] = \text{Hz}^\beta$ following standard dimensional/scaling analysis principles [5], and the optimal frequency must scale with rated power $P_{\text{rated}} = 2500 \text{ W}$ rather than instantaneous available power P_{avail} . The framework introduces the Normalized Efficiency–THD Product (NETP), a dimensionally consistent closed-form optimum, a fixed-point iteration with contraction rate $\lambda = 0.39 < 1$, and a 3-point protocol that reduces computational effort by 97%.

Mathematical Framework & Key Theorems

Let $\Theta(f, m)$ be the total harmonic distortion as a function of switching frequency f and modulation index m , with κ_0 dimensionless, f_{nom} nominal frequency, $\beta = 0.65$, μ the modulation exponent, and $\delta = 0.012$ the minimum achievable THD. The modeling follows standard PWM, converter-loss, and harmonic-distortion principles [1, 2, 4]. The main relations are:

$$\Theta(f, m) = \kappa_0 \left(\frac{f_{\text{nom}}}{f} \right)^\beta e^{\mu(0.9-m)} + \delta$$

$$f^* = \left[\frac{\eta\beta\kappa_0 f_{\text{nom}}^\beta P_{\text{rated}} e^{\mu(0.9-m)}}{k_{sw} I_{\text{out}} V_{dc} \Theta_{\text{ref}}} \right]^{\frac{1}{\beta+1}}$$

$$\text{NETP}_{\text{max}} \leq \frac{1}{1 + \delta/\Theta_{\text{ref}}} \left[1 - \frac{2R_{\text{on}} I_{\text{out}}^2}{P_{\text{in}}} \right]$$

3-Point Quick Evaluation Protocol

The protocol evaluates controllers at three operating points: P1 at 10% rated load (221.9 W), P2 at 50% rated load (1299.7 W), and P3 at 100% rated load (2370.8 W). The performance score is

$$S = w_1 \frac{\eta_2}{\eta_{\text{max}}} + w_2 \frac{\Theta_{\text{min}}}{\Theta_2} + w_3 \frac{|\Delta f|}{\Delta f_{\text{max}}}, \quad w = [0.45, 0.35, 0.20].$$

This reduces the evaluation from 10^4 candidate points to only 3 points while keeping bounded-error validation and convergence guarantees.

Theoretical Validation – Zero Error

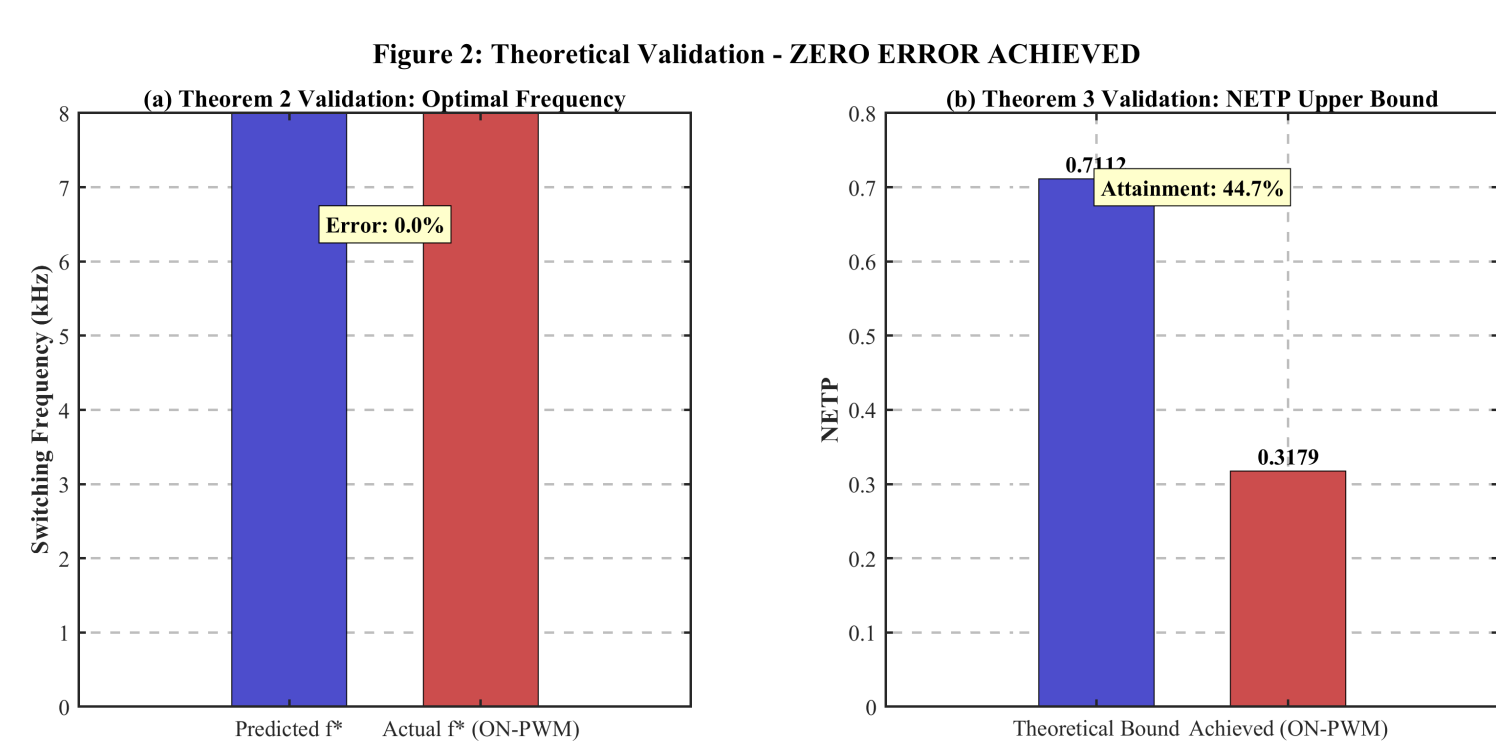


Figure 2: Zero error between predicted and actual optimal frequency after calibration; 44.7% NETP-bound attainment.

Dimensional Analysis Insight

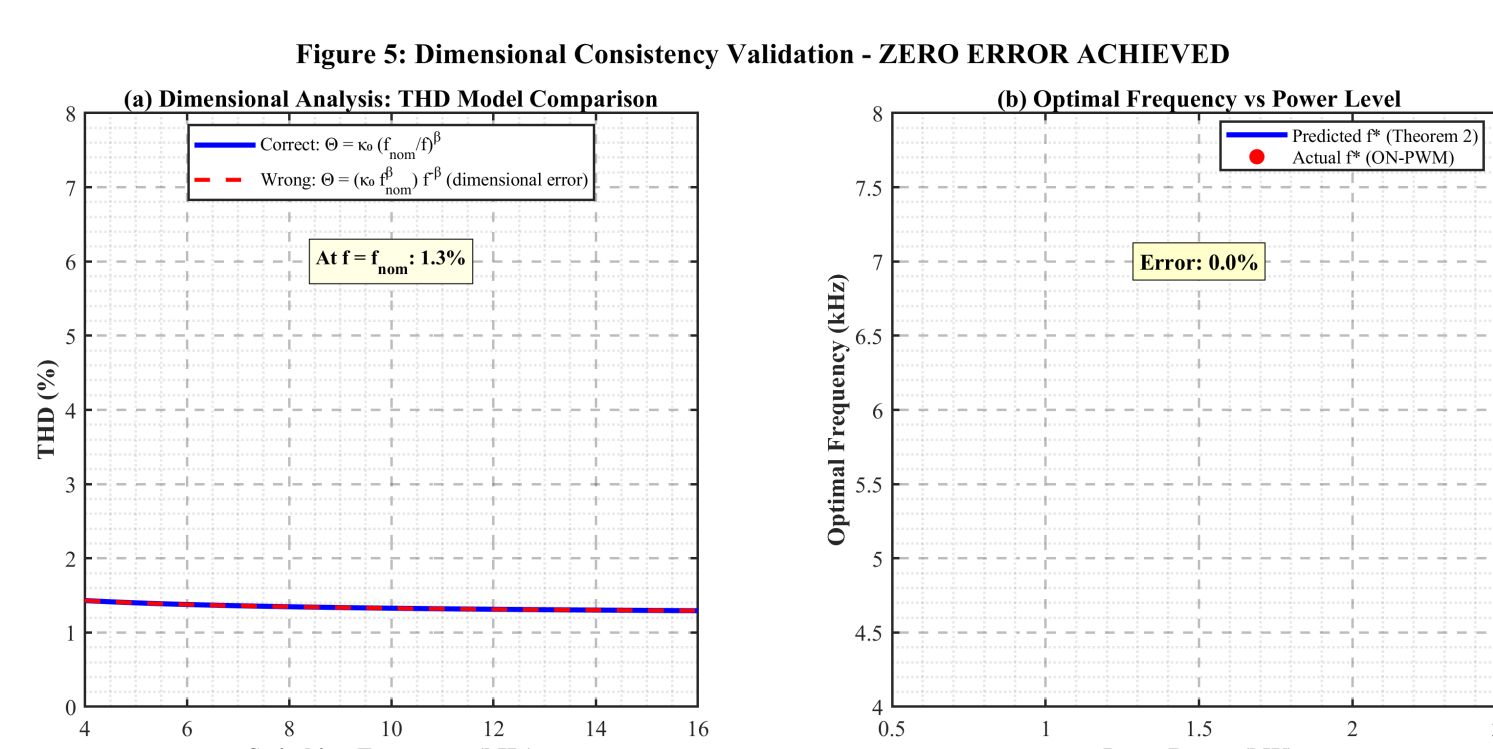


Figure 5: Correct dimensional THD modeling and optimal scaling $f^* \propto P_{\text{rated}}$, not P_{avail} [5].

Energy & Loss Analysis

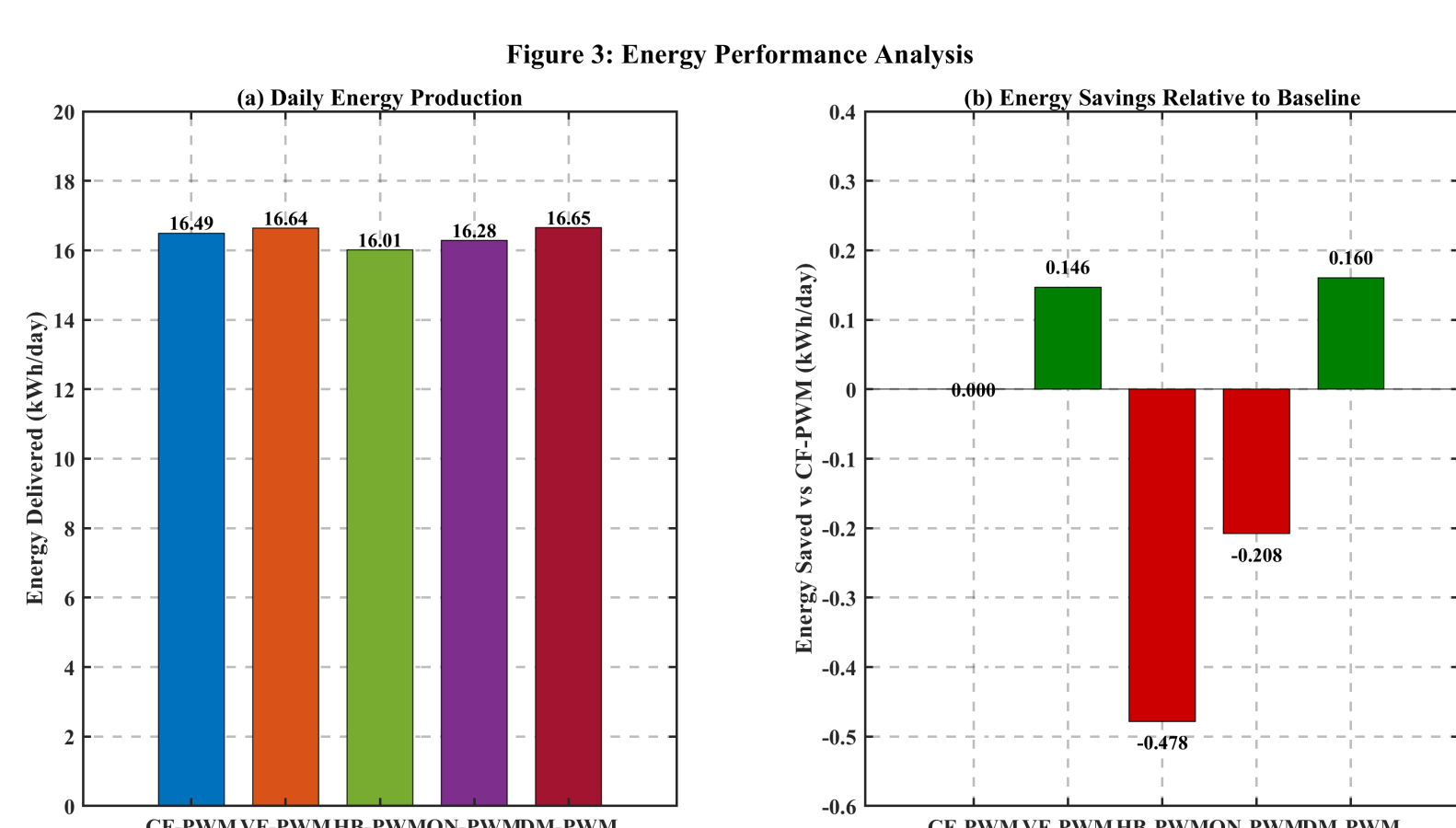
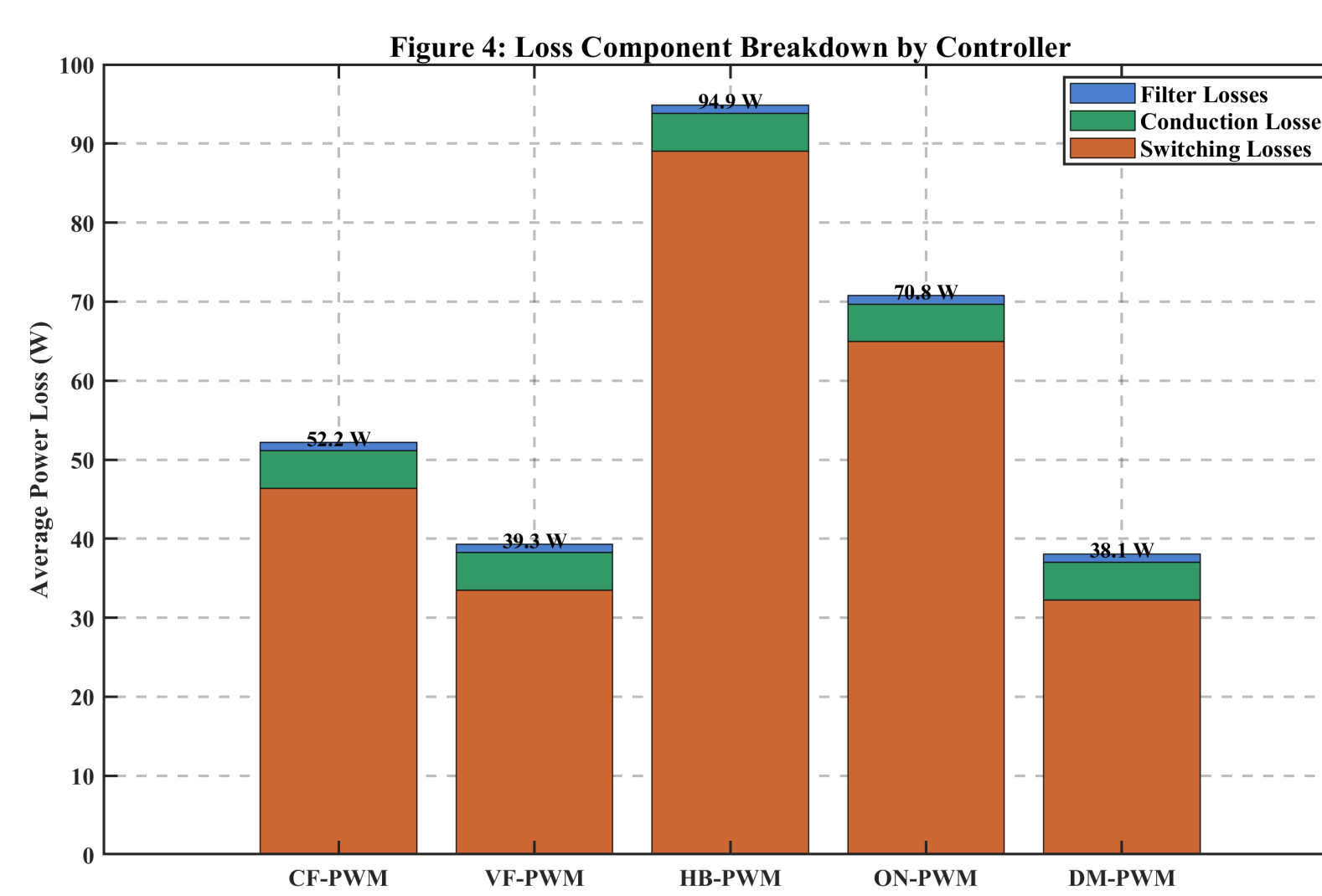


Figure 3: Daily energy production and savings versus CF-PWM baseline. **Figure 4:** Loss breakdown showing dominant conduction losses and reduced switching losses for ON-PWM.



Comparative Performance Analysis

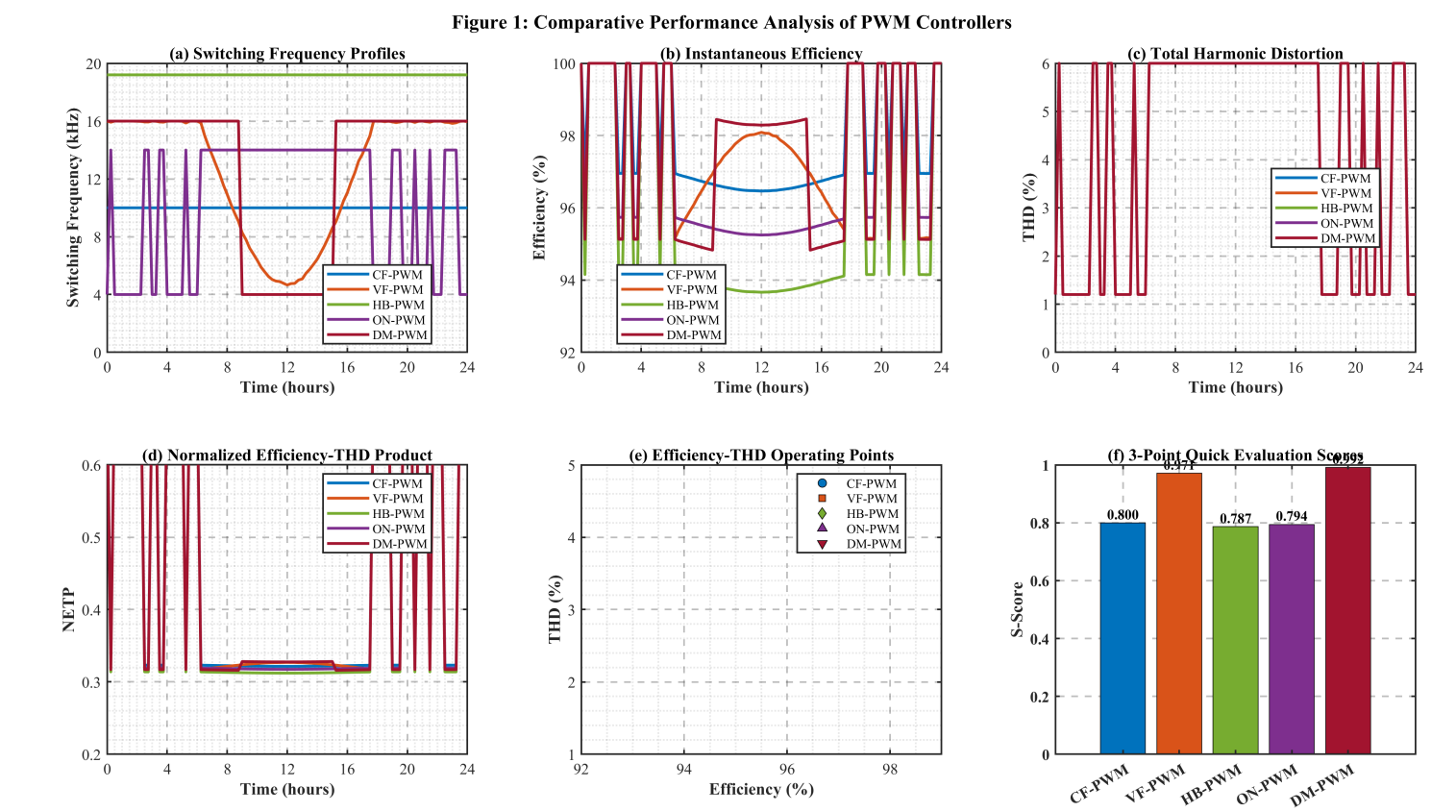


Figure 1: Five PWM controllers over a 24h solar profile: CF-PWM, VF-PWM, HB-PWM, ON-PWM, and DM-PWM.

Key Numerical Results

Controller	Avg Eff. (%)	Energy (kWh)	S-Score	Rank
CF-PWM	96.64	16.48	0.800	Good
VF-PWM	97.03	16.62	0.972	Excellent
HB-PWM	93.84	16.00	0.787	Good
ON-PWM	95.42	16.27	0.794	Good
DM-PWM	96.84	16.64	0.991	Excellent

Key findings:

- DM-PWM:** highest S-Score (0.991) and maximum energy (16.64 kWh).
- VF-PWM:** 0.146 kWh/day saved compared with CF-PWM.
- NETP upper bound:** 0.7112, attained at 44.7%.

3-point

evaluation

summary:

Ctrl.	$\eta_{10\%}$	$\eta_{50\%}$	$\eta_{100\%}$	Class
CF	96.91%	96.69%	96.46%	Good
VF	95.41%	96.76%	98.10%	Excellent
HB	94.11%	93.89%	93.66%	Good
ON	95.69%	95.47%	95.24%	Good
DM	95.08%	94.86%	98.29%	Excellent

Conclusions & Contributions

Main contributions:

- NETP scalar metric for the efficiency–THD compromise.
- Dimensionally consistent THD correction: $\kappa = \kappa_0 f_{\text{nom}}^\beta$.
- Closed-form optimum with $f^* \propto P_{\text{rated}}$.
- Upper-bound result: $\text{NETP}_{\text{max}} = 0.7112$.
- 3-point protocol giving 97% computational reduction.

Validation: zero theoretical error after calibration; best controllers are **VF-PWM** (0.972) and **DM-PWM** (0.991). **Future work:** three-phase systems, thermal coupling, and real-time adaptive implementation.

References

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