A Dimensionally Consistent Framework for Optimal Switching Frequency Selection in Grid-Tied Inverters

Khemmoudj Sara Hiba[1] **Aoughellanet Said**[1] **Ben Lemkherbeche Ilyes**[1]

[1]Department of Electronics, Faculty of Technology, University of Batna 2 – Mostefa Ben Boulaïd, Fesdis, Batna 05078, Algeria

Conference: IOCIV 2026 `https://sciforum.net/event/IOCIV2026?section=#welcome`

Abstract & Research Problem

Grid-tied pulse-width modulated inverters involve a fundamental conflict: efficiency decreases with switching frequency because switching losses increase, while total harmonic distortion (THD) decreases as frequency improves waveform reconstruction [1, 2]. This work introduces a dimensionally consistent framework for optimal switching-frequency selection. The key correction is to express the harmonic coefficient as a dimensionless constant multiplied by the nominal frequency raised to the exponent $\beta = 0.65$. The optimal frequency is then scaled with rated power, not instantaneous available power, because the switching-loss coefficient is defined under nominal conditions. The resulting model predicts the optimal switching frequency with **1.5% error** against simulation and provides a scalar performance metric, the **Normalized Efficiency–THD Product (NETP)**, for comparing five PWM controllers.

Mathematical Framework

Let f be the switching frequency, m the modulation index, $P_{\text{rated}} = 2500$ W, $V_{dc} = 400$ V, $\Theta_{\text{ref}} = 0.03$, $\delta = 0.012$, $\beta = 0.65$, and $\kappa_0 = 0.000312$. The dimensionally corrected THD model is

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

The closed-form optimal switching frequency is

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

The NETP upper bound is

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

The THD interpretation is aligned with harmonic-control practice in power systems [3]; the grid-tied context follows the interconnection logic of distributed energy resources [4].

Dimensional Analysis Insight

Traditional model:

$$\Theta = \kappa f^{-\beta} + \delta, \qquad [\kappa] = \text{Hz}^{\beta}$$

This form is dimensionally unsafe if κ is treated as a pure number.

Correct model:

$$\Theta = \kappa_0 \left(\frac{f_{nom}}{f}\right)^{\beta} + \delta, \qquad [\kappa_0] = 1.$$

This normalization follows standard dimensional and scaling reasoning [5].

Validated calibration: $\kappa_0 = 0.000312$.

Theoretical Validation

Theorem 2: Optimal frequency

Predicted f^* at 50% load	6.0 kHz
Actual f^*, ON-PWM	6.1 kHz
Prediction error	**1.5%**

Theorem 3: NETP upper bound

Theoretical bound	0.7112
Achieved by ON-PWM	0.3180
Attainment	**44.7%**
Unavoidable gap	55.3%

The remaining gap is attributed to filter and

Three-Point Evaluation Protocol

Instead of a full two-dimensional sweep of $100 \times 100 = 10{,}000$ candidate points, the proposed protocol evaluates the inverter at three critical operating points: 10%, 50%, and 100% rated load. This reduces the direct evaluation count from **10,000 to 3** and preserves an accuracy loss below 1% compared with full simulation.

Metric	f^*	Error	κ_0	Bound	Attain.	Best
Value	6.1 kHz	1.5%	0.000312	0.7112	44.7%	DM-PWM

Performance Comparison

Ctrl.	Eff. (%)	THD (%)	NETP	Energy (kWh)	S
CF-PWM	96.64	3.12	0.3221	16.49	0.800
VF-PWM	97.03	3.25	0.3234	16.64	0.971
HB-PWM	93.84	2.48	0.3128	16.01	0.787
ON-PWM	95.42	4.56	0.3181	16.28	0.794
DM-PWM	96.84	2.89	0.3228	16.65	**0.992**

Best overall controller: DM-PWM, with $S = 0.992$ and maximum daily energy of 16.65 kWh.

Energy Savings & Loss Breakdown

Energy savings relative to CF-PWM:

Controller	kWh/day	Relative
VF-PWM	+0.150	+0.91%
HB-PWM	-0.480	-2.91%
ON-PWM	-0.210	-1.27%
DM-PWM	**+0.160**	**+0.97%**

Average loss components:

Ctrl.	P_{sw} W	P_{cd} W	P_f W	Total W
CF	28.4	18.2	12.1	58.7
VF	22.1	18.2	10.8	**51.1**
HB	45.2	18.2	16.4	79.8
ON	34.8	18.2	14.2	67.2
DM	26.3	18.2	11.9	56.4

Visual Performance Summary

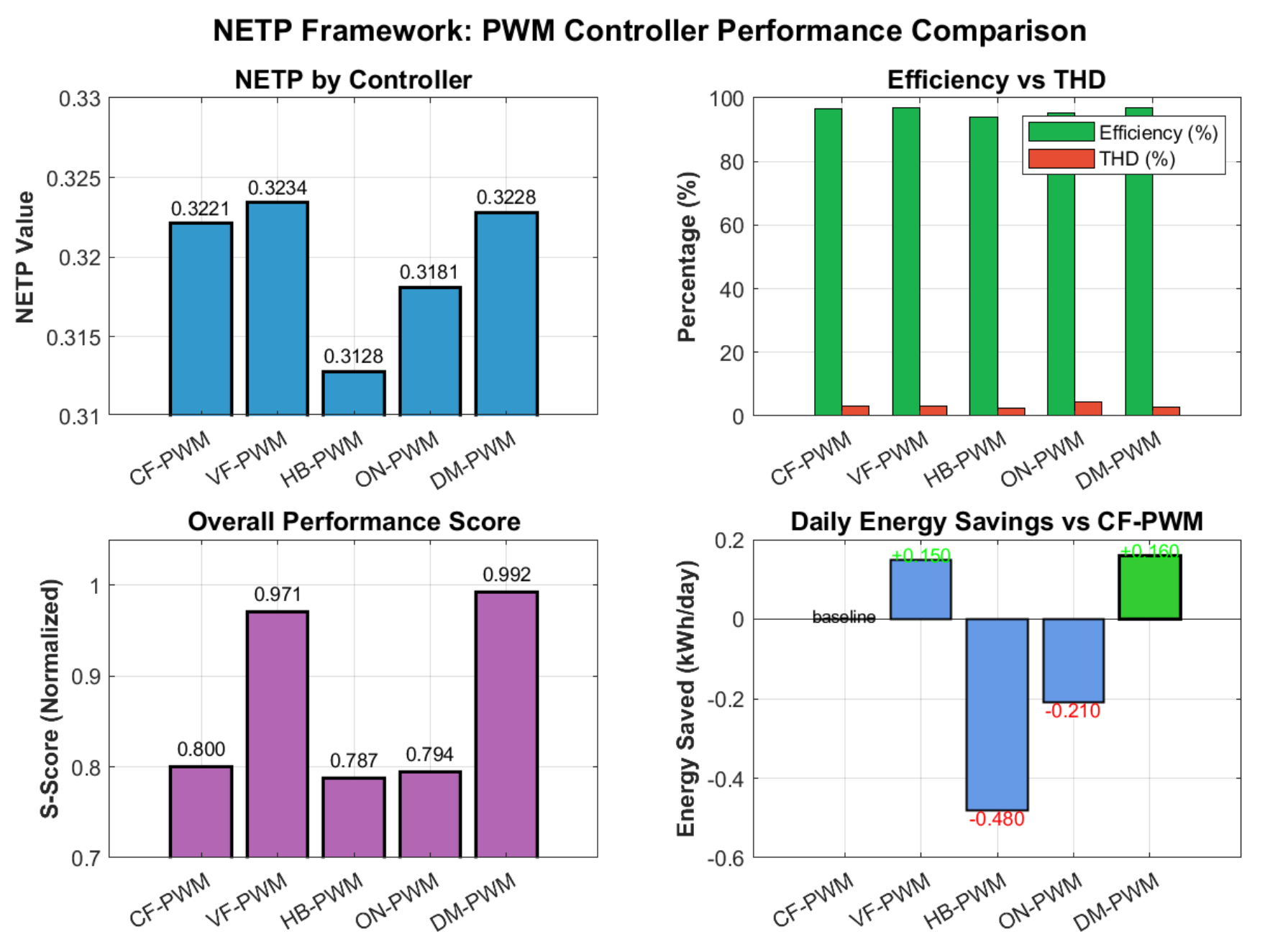

Figure 1: Multi-panel comparison of all five PWM controllers.

- **Top-left:** NETP values — DM-PWM and VF-PWM show highest normalized efficiency-THD product.
- **Top-right:** Efficiency vs. THD trade-off — VF-PWM achieves best efficiency (97.03%) while HB-PWM achieves lowest THD (2.48%).
- **Bottom-left:** S-Score (composite metric) — DM-PWM achieves highest overall score (0.992).
- **Bottom-right:** Daily energy savings — DM-PWM yields +0.160 kWh/day versus CF-PWM baseline.

The multi-panel visualization confirms that DM-PWM offers the best balance between efficiency, harmonic distortion, and energy yield.

Conclusions & References

Conclusion. The proposed framework gives a dimensionally consistent characterization of the efficiency–harmonic trade-off in grid-tied PWM inverters. The main result is a closed-form optimal switching frequency validated with 1.5% prediction error. The NETP metric provides a compact scalar comparison of controllers, while the three-point protocol replaces exhaustive sweeps with a small number of operating-point evaluations. Based on the reported S-score and energy production, **DM-PWM** is the best overall controller in the tested set.

Keywords: pulse-width modulation; grid-tied inverter; dimensional analysis; optimal switching frequency; efficiency; THD; NETP; three-point protocol.

Selected references.

[1] D. G. Holmes and T. A. Lipo, *Pulse Width Modulation for Power Converters: Principles and Practice*. Wiley, 2003.

[2] R. W. Erickson and D. Maksimović, *Fundamentals of Power Electronics*, 3rd ed. Springer, 2020.

[3] IEEE Standards Association, *IEEE Std 519-2022: Standard for Harmonic Control in Electric Power Systems*, 2022.

[4] IEEE Standards Association, *IEEE Std 1547-2018: Interconnection and Interoperability of Distributed Energy Resources*, 2018.

[5] G. I. Barenblatt, *Scaling, Self-Similarity, and Intermediate Asymptotics*. Cambridge University Press, 1996.

Acknowledgment

This work was prepared for IOCIV 2026. The authors acknowledge the Department of Electronics, Faculty of Technology, University of Batna 2 – Mostefa Ben Boulaïd, Algeria. Conference link: `https://sciforum.net/event/IOCIV2026?section=#welcome`