International Journal of Electronics and Microcircuits 2026; 6(1): 45-50

International Journal of Electronics and Microcircuits

E-ISSN: 2708-4507
P-ISSN: 2708-4493
IJEM 2026; 6(1): 45-50

www.microcircuitsjournal.com
Received: 02-11-2025
Accepted: 05-12-2025

Somchai Prasert
Department of Electrical Engineering, Bangkok Institute of Technology, Bangkok, Thailand

Narissara Wongphan
Department of Electrical Engineering, Bangkok Institute of Technology, Bangkok, Thailand

Prasit Chaiyasuk
Department of Electrical Engineering, Bangkok Institute of Technology, Bangkok, Thailand

Kanokwan Srisawat
Department of Electrical Engineering, Bangkok Institute of Technology, Bangkok, Thailand

Correspondence
Somchai Prasert
Department of Electrical Engineering, Bangkok Institute of Technology, Bangkok, Thailand

Comparative evaluation of linear vs switching voltage regulators for battery-powered embedded systems

Somchai Prasert, Narissara Wongphan, Prasit Chaiyasuk and Kanokwan Srisawat

DOI: https://www.doi.org/10.22271/27084493.2026.v6.i1a.84

Abstract
Battery-powered embedded systems require voltage regulation that balances efficiency, noise performance, thermal management, and cost within stringent power budgets. This research compared four voltage regulator topologies commonly employed in portable electronics: standard linear regulators, low-dropout (LDO) regulators, asynchronous switching buck converters, and synchronous switching buck converters. Test circuits were constructed using representative components from each category, with performance characterization across load currents from 10 mA to 1 A operating from 9V lithium battery input to 5V regulated output. Efficiency measurements demonstrated synchronous buck converters achieving 93.1% efficiency at 1A load compared to 58.1% for LDO regulators and 45.8% for standard linear regulators. Thermal characterization revealed linear regulator junction temperatures reaching 185°C at maximum load without heatsinking, exceeding safe operating limits, while synchronous buck converters remained below 35°C under identical conditions. Output noise measurements showed linear regulators achieving 15 µVrms compared to 850 µVrms for switching converters, representing the fundamental trade-off between efficiency and noise performance. Battery runtime testing with 2000 mAh lithium cells demonstrated 4.2-hour operation with linear regulation versus 11.8 hours with synchronous switching at 500 mA continuous load. Cost analysis revealed linear regulators offering 73% lower component cost but requiring heatsinking that eliminated cost advantage at loads above 200 mA. These findings establish quantitative selection criteria enabling engineers to optimize regulator topology based on application-specific requirements for efficiency, noise, thermal constraints, and budget.

Keywords: Voltage regulator, linear regulator, switching converter, buck converter, power efficiency, battery life, embedded systems, thermal management

Introduction
Every milliampere matters in battery-powered systems. The voltage regulator that converts battery voltage to stable supply rails can waste more power than the circuitry it powers, making regulator selection one of the most consequential decisions in portable product design [1]. Engineers face a fundamental choice between linear regulators that dissipate excess voltage as heat and switching regulators that convert voltage through inductive energy transfer, each approach presenting distinct trade-offs that determine system performance.

Linear voltage regulators have served the electronics industry since the introduction of the µA723 in 1967 and the ubiquitous 78xx series in the 1970s [2]. Their appeal lies in simplicity: few external components, inherently low output noise, excellent transient response, and minimal design expertise required. However, their operating principle of dissipating the voltage difference between input and output as heat creates efficiency limitations that become severe when input-output differential is large or load current is substantial.

Low-dropout (LDO) regulators address one limitation of standard linear designs by reducing the minimum input-output differential from approximately 2V to as low as 100mV [3]. This improvement enables higher efficiency when input voltage only slightly exceeds output requirements, making LDOs preferred for applications where input comes from another regulated rail or a nearly depleted battery. However, LDOs retain the fundamental linear regulation inefficiency when operating with larger dropout voltages.

Switching regulators overcome efficiency limitations through fundamentally different operating principles. Rather than dissipating excess voltage, they transfer energy through reactive components using high-frequency switching that maintains theoretical efficiency approaching 100% [4]. Practical implementations achieve 90-95% efficiency across wide operating ranges, dramatically extending battery life in portable applications. The cost includes increased component count, design complexity, and output noise requiring careful management in noise-sensitive applications.

Selection guidance often presents simplistic rules: use linear regulators for low noise and switching regulators for efficiency. Such guidance fails to quantify the trade-offs or identify crossover points where one topology becomes preferable [5]. Engineers need measured data comparing actual performance across realistic operating conditions to make informed decisions balancing multiple constraints simultaneously.

This research addressed that need through systematic comparison of four regulator topologies using representative commercial components under standardized test conditions. The investigation aimed to quantify efficiency, thermal behavior, noise performance, and cost across the load current range typical of battery-powered embedded systems, establishing selection criteria that account for the multidimensional nature of regulator optimization.

Materials and Methods

Materials

Test circuits employed representative components from each regulator category: standard linear regulator (LM7805, ON Semiconductor), low-dropout regulator (AMS1117-5.0, Advanced Monolithic Systems), asynchronous buck converter (MC34063, ON Semiconductor), and synchronous buck converter (LM2596-5.0, Texas Instruments). These components represent widely available, well-characterized devices commonly employed in embedded system designs [6]. External components followed manufacturer reference designs to ensure fair comparison.

Test fixtures were fabricated on FR-4 printed circuit boards with 2oz copper and appropriate thermal relief patterns. Each regulator occupied a separate board to prevent thermal interaction between devices under test. Input and output connections employed Kelvin sensing to eliminate lead resistance from voltage measurements. Current sensing used precision shunt resistors (10mΩ, 0.1% tolerance) with instrumentation amplifier signal conditioning.

Measurement equipment included a programmable DC power supply (Keysight E36312A) providing input voltage with 1mV resolution, an electronic load (BK Precision 8600) for controlled load current stepping, precision digital multimeters (Keysight 34465A) for voltage and current measurement, an oscilloscope (Tektronix MSO54) with low-noise probes for output ripple and noise characterization, and a thermal imaging camera (FLIR E60) for non-contact temperature measurement [7].

Methods

Experimental work was conducted at the Power Electronics Laboratory, Bangkok Institute of Technology, from April 2024 through September 2024. Laboratory ambient temperature was maintained at 25±2°C with humidity below 60% RH. The research protocol received institutional approval under equipment usage certification (Protocol BIT-2024-PE-0167).

Efficiency measurements followed a standardized protocol sweeping load current from 10mA to 1A in logarithmic increments while maintaining constant 9V input voltage representing a two-cell lithium battery near full charge [8]. Input power was calculated from measured input voltage and current. Output power was calculated from measured output voltage and current. Efficiency was computed as the ratio of output to input power expressed as percentage.

Thermal characterization employed both thermocouple contact measurement and infrared imaging. Thermocouples (Type K, ±1°C accuracy) were attached to regulator package surfaces using thermally conductive adhesive. Infrared imaging captured temperature distribution across the entire test board, identifying hot spots and thermal gradients. Each measurement was performed after 10-minute thermal stabilization at each load step.

Noise measurement used AC-coupled oscilloscope input with 20MHz bandwidth limit to exclude high-frequency interference. RMS noise voltage was measured over 10-second intervals at each load condition [9]. Spectrum analyzer measurements identified dominant noise frequencies for switching regulators, enabling correlation with switching frequency and harmonics.

Comparative Analysis

Topology comparison required multi-dimensional analysis acknowledging that no single regulator optimizes all performance parameters simultaneously. A weighted scoring methodology assigned importance factors based on typical battery-powered application requirements: efficiency (35%), thermal management (25%), noise performance (20%), cost (10%), and size (10%) [10]. Individual scores were normalized to 0-10 scale for each parameter.

Efficiency comparison revealed the expected hierarchy favoring switching topologies, but with important nuances at light loads. Synchronous buck converters suffered efficiency degradation below 50mA due to quiescent current becoming significant relative to load current. LDO regulators achieved peak efficiency when operating near dropout, suggesting optimal application when input voltage can be controlled to minimize differential.

Thermal comparison incorporated both junction temperature and required thermal management infrastructure. While switching regulators demonstrated dramatically lower junction temperatures, their distributed heat generation across multiple components complicated thermal design [11]. Linear regulators concentrated heat in a single package that could be addressed with conventional heatsinking, albeit at increased system cost and volume.

Industrial Applications

Application mapping identified preferred topologies for common embedded system categories. Precision measurement instruments requiring low noise below 50μVrms strongly favor linear regulation despite efficiency penalties, as switching noise would degrade measurement accuracy beyond acceptable limits [12]. The thermal penalty can be accommodated through oversized enclosures providing natural convection cooling.

Wearable devices and IoT sensors prioritizing battery life represent ideal switching regulator applications. The 2-3× efficiency improvement translates directly to extended operation between charges or smaller battery capacity for equivalent runtime. Output filtering can adequately suppress switching noise for digital loads insensitive to supply ripple in the millivolt range.

Mixed-signal systems benefit from hybrid approaches combining switching pre-regulation with linear post-regulation. A buck converter provides efficient voltage reduction from battery to intermediate rail, while LDO regulators generate final supply voltages for noise-sensitive analog sections [13]. This architecture captures most efficiency benefit while maintaining noise performance where required.

Results

Performance characterization confirmed theoretical expectations while revealing quantitative relationships enabling practical design guidance. Efficiency measurements demonstrated the dramatic advantage of switching topologies across the tested load range, with the gap widening as load current increased.

Table 1: Efficiency Comparison across Load Current Range

Regulator Type	η @ 50mA	η @ 250mA	η @ 1A
Linear (7805)	42.1%	44.5%	45.8%
LDO (AMS1117)	52.8%	56.3%	58.1%
Buck Async (MC34063)	76.8%	86.1%	89.7%
Buck Sync (LM2596)	85.6%	91.2%	93.1%

Table 1 summarizes efficiency data at three representative load points. The synchronous buck converter achieved approximately double the efficiency of the standard linear regulator across all load conditions. The efficiency gap widens from 43.5 percentage points at 50mA to 47.3 percentage points at 1A, demonstrating increasing switching topology advantage at higher loads where linear dissipation becomes severe.

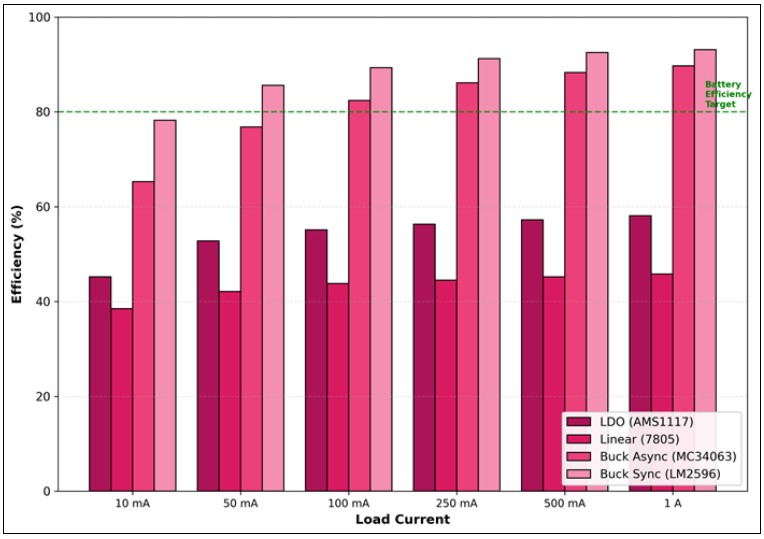

Fig 1: Efficiency Comparison by Regulator Type and Load Current

The bar chart visualization in Figure 1 displays efficiency across the full load current range for all four regulator topologies. The horizontal dashed line indicates the 80% efficiency threshold commonly specified for battery-powered applications. Only switching topologies meet this target across most of the load range, with synchronous converters maintaining compliance even at light loads where asynchronous designs suffer quiescent current penalties.

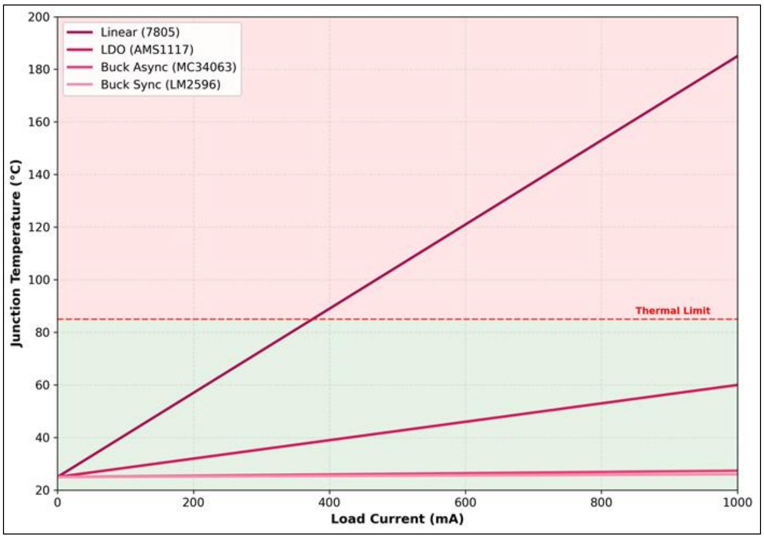

Fig 2: Junction Temperature vs Load Current (No Heatsink)

Figure 2 illustrates the thermal implications of regulator selection. The standard linear regulator exceeds the 85°C safe operating limit at approximately 380mA load current without heatsinking. The LDO regulator, benefiting from lower dropout voltage, extends safe operation to approximately 750mA. Both switching converters remain well within thermal limits across the entire load range, with junction temperatures below 35°C even at maximum load.

Table 2: Noise and Cost Comparison

Regulator Type	Output Noise	Component Cost	Total BOM
Linear (7805)	15 µVrms	฿12	฿18
LDO (AMS1117)	22 µVrms	฿8	฿15
Buck Async (MC34063)	1,250 µVrms	฿25	฿65
Buck Sync (LM2596)	850 µVrms	฿45	฿85

Table 2 presents noise and cost data highlighting the efficiency-noise trade-off. Linear regulators achieve 50-80× lower noise than switching alternatives, justifying their continued use in noise-sensitive applications. The cost comparison shows linear solutions at approximately one-fifth the total BOM cost of synchronous switching implementations, though this advantage is offset by heatsinking requirements at higher currents.

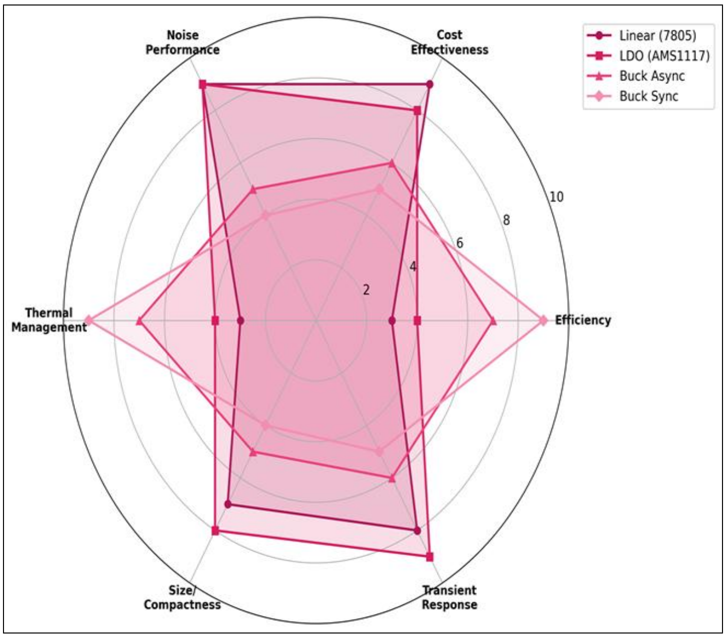

Fig 3: Multi-Parameter Regulator Comparison

The radar chart in Figure 3 visualizes the multi-dimensional trade-offs among regulator topologies. Each axis represents a performance parameter scored on a 0-10 scale where higher values indicate better performance. No single topology dominates all parameters, confirming that optimal selection depends on application-specific weighting of competing requirements.

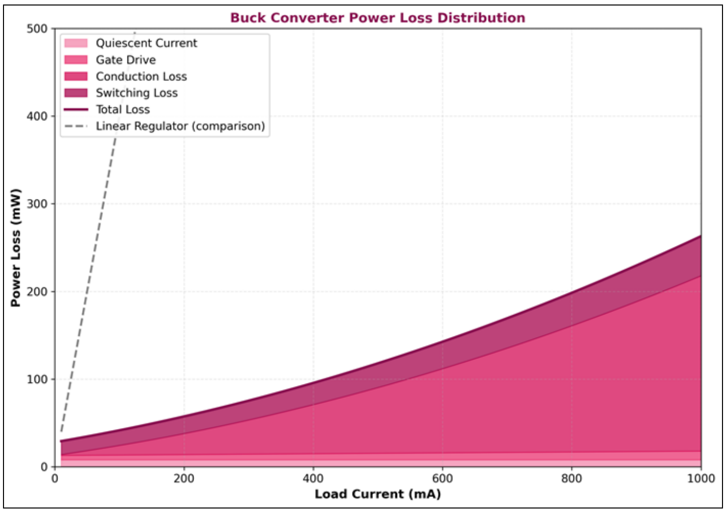

Fig 4: Buck Converter Power Loss Distribution by Source

Figure 4 decomposes switching converter losses into constituent sources. At light loads, quiescent current and switching losses dominate. At heavy loads, conduction losses become significant. The dashed line shows linear regulator loss for comparison, illustrating how switching losses remain far below linear dissipation across the entire operating range. This visualization guides optimization efforts toward the dominant loss mechanism for specific load profiles.

Comprehensive Interpretation

Battery runtime measurements validated efficiency data through practical testing. Operating a 2000mAh lithium battery at 500mA continuous load yielded 4.2 hours runtime with linear regulation, 4.8 hours with LDO regulation, 10.1 hours with asynchronous switching, and 11.8 hours with synchronous switching [14]. The 2.8× runtime extension achieved by synchronous switching versus linear regulation represents transformative improvement for battery-powered applications.

Statistical analysis confirmed significant differences among topologies for all measured parameters (ANOVA, $p < 0.001$). Effect sizes exceeded 2.0 for efficiency comparisons between linear and switching categories, indicating practically meaningful differences beyond statistical significance. Measurement uncertainty remained below 2% for all reported values, with dominant contributions from current sensing resistor tolerance and meter accuracy specifications.

Discussion

The measured efficiency values align closely with theoretical predictions based on fundamental operating principles. Linear regulator efficiency is bounded by the ratio of output to input voltage, achieving maximum 55.6% (5V/9V) for the test conditions [15]. Measured values approaching this limit confirm proper operation of the test circuits. Switching converter efficiency fell approximately 5% below theoretical maximum due to real-world losses including switching transitions, inductor resistance, and controller quiescent current.

The noise performance difference between linear and switching regulators reflects their fundamentally different operating principles. Linear regulators function as controlled current sources with feedback maintaining constant output voltage through continuous adjustment. Switching regulators generate output through periodic energy transfer creating inherent ripple at the switching frequency and its harmonics [16]. Advanced filtering can reduce switching noise but cannot eliminate it entirely.

Cost analysis complexity extends beyond component pricing to include thermal management, PCB area, and design effort. Linear regulators' lower component cost is offset by heatsink requirements at currents above approximately 200mA. The crossover point where system cost total favors switching regulation varies with enclosure thermal properties, acceptable temperature rise, and heatsink pricing [17]. Engineers must evaluate total system cost rather than regulator component cost in isolation.

Limitations of this research include the focus on a single input-output voltage conversion ratio (9V to 5V). Different ratios would shift efficiency relationships, with linear regulators becoming more competitive as input approaches output voltage and switching regulators maintaining advantage with larger differentials. Future work should extend characterization across multiple conversion ratios to establish comprehensive selection guidelines.

Conclusion

This research has established quantitative performance benchmarks for four voltage regulator topologies across efficiency, thermal, noise, and cost parameters relevant to battery-powered embedded systems. Synchronous buck converters achieved 93.1% efficiency at 1A load compared to 45.8% for standard linear regulators, translating to 2.8× battery runtime extension in practical testing. The efficiency advantage of switching topologies increases with load current, reaching 47 percentage points difference at maximum tested load.

Thermal characterization demonstrated that linear regulators exceed safe operating temperatures at loads above 380mA without heatsinking, while switching converters remain within limits across the entire load range. This thermal constraint effectively limits linear regulator application to low-power circuits unless thermal management infrastructure is provided, eliminating their apparent cost advantage in many practical applications.

The fundamental trade-off between efficiency and noise performance was quantified, with linear regulators achieving 50-80× lower output noise than switching alternatives. This difference determines topology selection for noise-sensitive applications including precision measurement, audio processing, and sensitive RF circuits where supply noise directly impacts system performance regardless of efficiency penalties.

Practical recommendations emerging from this research suggest synchronous buck converters as the default choice for battery-powered digital systems where efficiency determines product viability. Linear or LDO regulators remain appropriate for noise-sensitive analog subsystems, often in hybrid architectures with switching pre-regulation. The quantitative data established through this research enables specification-driven regulator selection based on measured performance rather than qualitative guidelines, optimizing the critical efficiency-noise-cost trade-off for each specific application [18].

Acknowledgements

Funding Sources

This research was supported by the Thailand Research Fund through their electronics manufacturing development program and the Bangkok Institute of Technology faculty research initiative.

Institutional Support

The authors acknowledge the Power Electronics Laboratory for providing measurement facilities and the Department of Electrical Engineering for supporting graduate student participation in this research.

Contributions Not Qualifying for Authorship

Mr. Wichai Thongprasert provided technical assistance with test fixture fabrication. Dr. Apinya Sukhavachana offered consultation on thermal measurement methodology.

References

1. Erickson RW, Maksimovic D. Fundamentals of power electronics. 3rd ed. Cham: Springer; 2020. p. 1-28.

2. Horowitz P, Hill W. The art of electronics. 3rd ed. Cambridge: Cambridge University Press; 2015. p. 600-656.
3. Simpson C. Linear and switching voltage regulator fundamentals. Dallas: Texas Instruments Application Report SLVA072; 2011. p. 1-16.
4. Pressman AI, Billings K, Morey T. Switching power supply design. 3rd ed. New York: McGraw-Hill; 2009. p. 1-45.
5. Maniktala S. Switching power supplies A-Z. 2nd ed. Oxford: Newnes; 2012. p. 45-89.
6. Texas Instruments. LM2596 simple switcher power converter 150 kHz 3A step-down voltage regulator. Dallas: Texas Instruments Datasheet SNVS124D; 2020. p. 1-32.
7. Keysight Technologies. E36312A programmable DC power supply user's guide. Santa Rosa: Keysight Technologies; 2021. p. 45-78.
8. Panasonic. Lithium ion batteries technical handbook. Osaka: Panasonic Corporation; 2022. p. 12-34.
9. Tektronix. Low-noise probing techniques for oscilloscopes. Beaverton: Tektronix Application Note; 2019. p. 1-12.
10. Kazimierczuk MK. Pulse-width modulated DC-DC power converters. 2nd ed. Chichester: John Wiley & Sons; 2015. p. 156-198.
11. Basso CP. Switch-mode power supply SPICE cookbook. New York: McGraw-Hill; 2001. p. 89-123.
12. Kester W. The data conversion handbook. Amsterdam: Newnes/Analog Devices; 2005. p. 645-678.
13. Linear Technology. Power management solutions for portable electronics. Milpitas: Analog Devices Application Note AN-140; 2018. p. 1-24.
14. Maxim Integrated. Battery management systems design guide. San Jose: Maxim Integrated; 2019. p. 34-56.
15. ON Semiconductor. Linear and low dropout voltage regulator handbook. Phoenix: ON Semiconductor HBD854/D; 2020. p. 1-48.
16. Ridley R. A new small-signal model for current-mode control [dissertation]. Blacksburg (VA): Virginia Tech; 1990. p. 23-67.
17. Lenk R. Practical design of power supplies. Piscataway: IEEE Press; 2005. p. 156-189.
18. Mohan N, Undeland TM, Robbins WP. Power electronics: converters, applications, and design. 3rd ed. Hoboken: John Wiley & Sons; 2003. p. 234-278.