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A Review on Various Converters Used in DC and AC Locomotives

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Abstract — The growing dependence of electric and diesel-electric locomotives on onboard electronic control, monitoring, communication and protection subsystems has created a sustained demand for compact, reliable and multi-voltage auxiliary DC power supplies. This paper presents a structured review of the DC-DC converter topologies used to realize such auxiliary supplies in DC and AC locomotives, with particular emphasis on isolated converter families and, within them, the multi-output flyback converter. The classification of isolated converters is first summarized, followed by a critical review of multi-output flyback architectures, closed-loop control techniques (proportional-integral, peak-current-mode, and advanced disturbance-rejection methods), and efficiency-enhancement techniques such as active-clamp circuits, regenerative snubbers, soft switching and wide-bandgap (GaN/SiC) devices. A comparative analysis of the reviewed techniques is presented, and the research gaps that motivate further work — particularly the limited literature that couples a complete 110 V-to-24 V/5 V design methodology with PI closed-loop control and hardware validation in a single framework — are identified. The review is intended to guide the selection of converter topology and control strategy for compact auxiliary power modules used in railway traction electronics.

Keywords — DC-DC Converters; Locomotive Auxiliary Power; Isolated Converters; Flyback Converter; Multi-Output Converters; PI Control; Wide-Bandgap Devices.

I. Introduction

Electric and diesel-electric locomotives host a large and growing population of electronic subsystems, including traction control cards, protection relays, sensing and monitoring modules, driver interface panels and communication equipment. Each of these subsystems requires a regulated, and usually isolated, DC voltage that is different from the primary auxiliary battery bus, which is commonly maintained at 72 V, 110 V or 24 V DC depending on the rolling stock design. Deriving several regulated voltage rails from a single high-voltage DC bus, while keeping the power module compact, light and reliable, is therefore a recurring design problem in locomotive electronics.

DC-DC converters are the standard building block used to solve this problem. They are broadly classified into non-isolated converters, which are simple and efficient but do not provide electrical separation between input and output, and isolated converters, which use a high-frequency transformer to provide galvanic isolation, improved safety and noise immunity. Because railway auxiliary electronics require both isolation (for personnel and equipment safety) and multiple output voltages (for logic, sensing and interface circuits), isolated multi-output converter topologies are of particular interest.

This paper reviews the converter topologies, control techniques and efficiency-enhancement methods reported in the literature for isolated DC-DC conversion, with the specific objective of identifying a suitable topology and control approach for a compact 110 V-to-24 V/5 V auxiliary power module intended for electric locomotive control electronics. The review is organized as follows: Section II summarizes locomotive auxiliary power requirements; Section III classifies isolated DC-DC converters; Section IV reviews multi-output flyback converter architectures; Section V reviews control techniques; Section VI reviews efficiency-improvement techniques including wide-bandgap devices; Section VII presents a comparative analysis; Section VIII identifies research gaps; and Section IX concludes the paper.

II. Auxiliary Power Requirements in DC and AC Locomotives

Both DC and AC electric locomotives carry a battery-backed auxiliary DC bus — typically in the range of 24 V to 110 V — that remains available even when the main traction supply is interrupted. This bus feeds the control electronics cards of the auxiliary converters, the driver's cab equipment, the train communication network, protection relays and emergency lighting. Individual electronic cards on this bus typically require 24 V DC for relay coils, contactor drivers and field interface circuits, and 5 V DC (or 3.3 V in modern designs) for microcontroller, FPGA and sensor-interface circuits. Because the auxiliary bus voltage is comparatively high (110 V in many DC locomotive designs) and carries switching noise from traction converters, the auxiliary power supply must additionally provide galvanic isolation and adequate input-voltage tolerance.

Using a dedicated DC-DC converter for every required voltage rail is functionally straightforward but increases the number of magnetic components, printed-circuit-board area, cost and thermal load inside an already space-constrained locomotive control cubicle. This motivates the use of a single isolated converter capable of generating several regulated outputs from one high-frequency transformer, which is the central theme of this review.

III. Classification of Isolated DC-DC Converters

Isolated DC-DC converters can be grouped into single-switch converters (flyback, forward), two-switch converters (push-pull, half-bridge, full-bridge), resonant converters (series resonant, parallel resonant, LLC resonant) and transformer-based special topologies (Cuk, SEPIC, Zeta). Figure 1 summarizes this classification. Among these, the flyback converter is repeatedly favoured in the reviewed literature for low- to medium-power auxiliary supplies because it combines the transformer's energy-storage and isolation functions in a single magnetic component and readily accommodates multiple secondary windings for multi-output operation, at the cost of comparatively higher output ripple and voltage stress on the primary switch relative to two-switch or resonant topologies.

Push-pull, half-bridge and full-bridge converters are generally preferred at higher power levels because the transformer core is used more effectively (bidirectional flux excursion) and the semiconductor voltage stress is lower, but they require two or more switches and associated gate-drive isolation, increasing complexity and cost for the comparatively low power levels (of the order of a few hundred watts) typical of locomotive control-card auxiliary supplies. Resonant converters (series, parallel, LLC) offer soft-switching and hence high efficiency at high switching frequency but involve a more elaborate design procedure and are more commonly reported for higher-power or communication-equipment power supplies. Cuk, SEPIC and Zeta derived isolated topologies are used less frequently in this application space and are included here for completeness of classification.

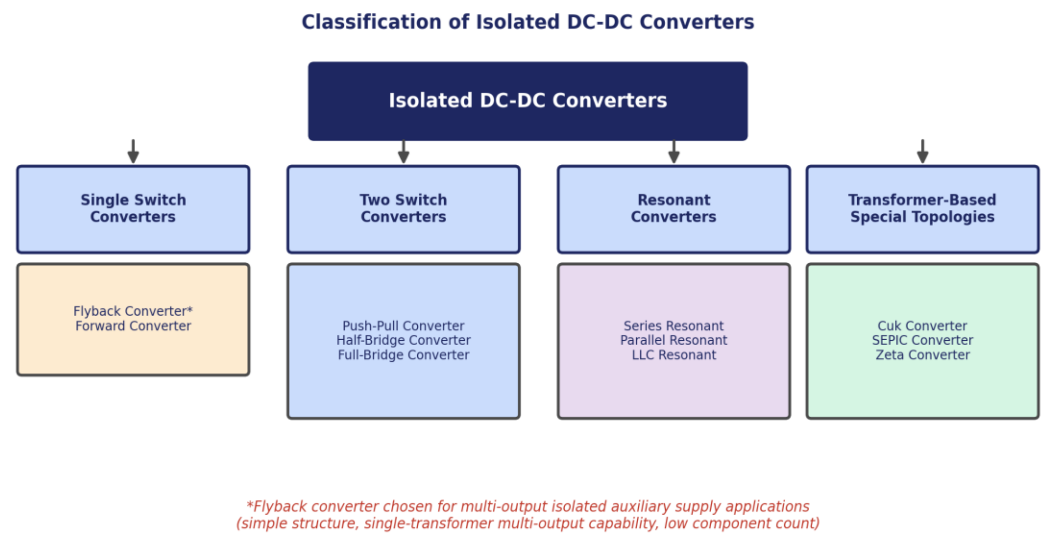

Fig. 1. Classification of isolated DC-DC converters relevant to locomotive auxiliary power design.

IV. Multi-Output Flyback Converter Topologies

A number of studies have specifically addressed the design of multi-output flyback converters and the cross-regulation problem that arises when several secondary windings share one transformer core and one feedback loop. Tahan et al. proposed a single-input multiple-output flyback-based power supply with an additional compensation network that allows more independent regulation of the individual outputs. Leng and Chiu designed a three-output flyback converter using synchronous rectification on the secondary side, reporting improved efficiency and reduced cross-regulation error because diode conduction losses were reduced. Granello et al. modeled and experimentally validated dual-output flyback converters that use capacitive coupling between the outputs, showing a reduction in cross-regulation error under unbalanced loading.

These studies consistently show that the achievable regulation and cross-regulation performance of a multi-output flyback converter depend strongly on the transformer winding configuration (leakage inductance distribution among windings), the output rectifier and filter design on each channel, and the choice of which output is used as the primary feedback variable. In the converter design reviewed in Section VI of this paper, the higher-power 24 V output is used as the sensed feedback channel, while the 5 V auxiliary output is regulated indirectly through the transformer turns ratio and output-filter design, which is consistent with the approach generally adopted in the reviewed literature for asymmetric-load multi-output flyback supplies.

V. Control Techniques for Flyback Converters

Closed-loop voltage-mode control using a proportional-integral (PI) compensator remains the most widely reported control method for flyback converters intended for industrial and auxiliary power applications, primarily because of its simple structure, ease of tuning, and satisfactory steady-state accuracy. In this scheme, the sensed output voltage is compared with a reference, and the resulting error drives a PI compensator whose output sets the PWM duty ratio applied to the primary-side MOSFET.

More advanced control techniques reported in the literature include peak-current-mode control, which improves transient response and provides inherent cycle-by-cycle current limiting at the expense of additional current-sensing circuitry; variable-frequency control, which can improve light-load efficiency; and linear active disturbance-rejection control (LADRC), which Yu et al. demonstrated for continuous-conduction-mode flyback converters with improved regulation under load disturbance and parameter variation. Despite the availability of these advanced methods, PI control continues to be the preferred choice in practical industrial and auxiliary power-supply designs because of its simplicity, low implementation cost, and adequate performance for the moderate dynamic requirements of auxiliary control-electronics loads.

VI. Efficiency Improvement Techniques

Switching losses, transformer leakage-inductance losses, rectifier-diode conduction losses and the voltage spike appearing across the primary MOSFET at turn-off are the principal loss mechanisms and stress factors that limit the efficiency and reliability of conventional hard-switched flyback converters. To mitigate these effects, the literature reports three broad families of techniques: (i) dissipative and regenerative snubber circuits, (ii) active-clamp flyback topologies, and (iii) wide-bandgap semiconductor devices.

A conventional resistor-capacitor-diode (RCD) snubber is simple and inexpensive but dissipates the leakage energy as heat, reducing efficiency. Regenerative snubber topologies instead store the leakage energy in a clamping capacitor and return it to the input source or the load, improving efficiency relative to a dissipative RCD snubber. Active-clamp flyback converters go further by recycling the leakage energy through an auxiliary clamp switch and enabling zero-voltage switching (ZVS) of the main switch, which reduces both switching loss and electromagnetic interference, at the cost of a more complex control scheme.

The use of gallium-nitride (GaN) and silicon-carbide (SiC) power devices has been shown to further improve flyback converter performance because of their lower on-resistance, lower gate charge and higher permissible switching frequency compared with silicon MOSFETs. Cacciotto et al. reported the optimization of a regenerative snubber for a GaN-based USB-PD quasi-resonant flyback converter, demonstrating an efficiency improvement over a conventional RCD snubber, and other studies of GaN-based quasi-resonant and active-clamp flyback converters report substantial gains in power density and efficiency, albeit with increased device cost and more demanding gate-driver and layout design.

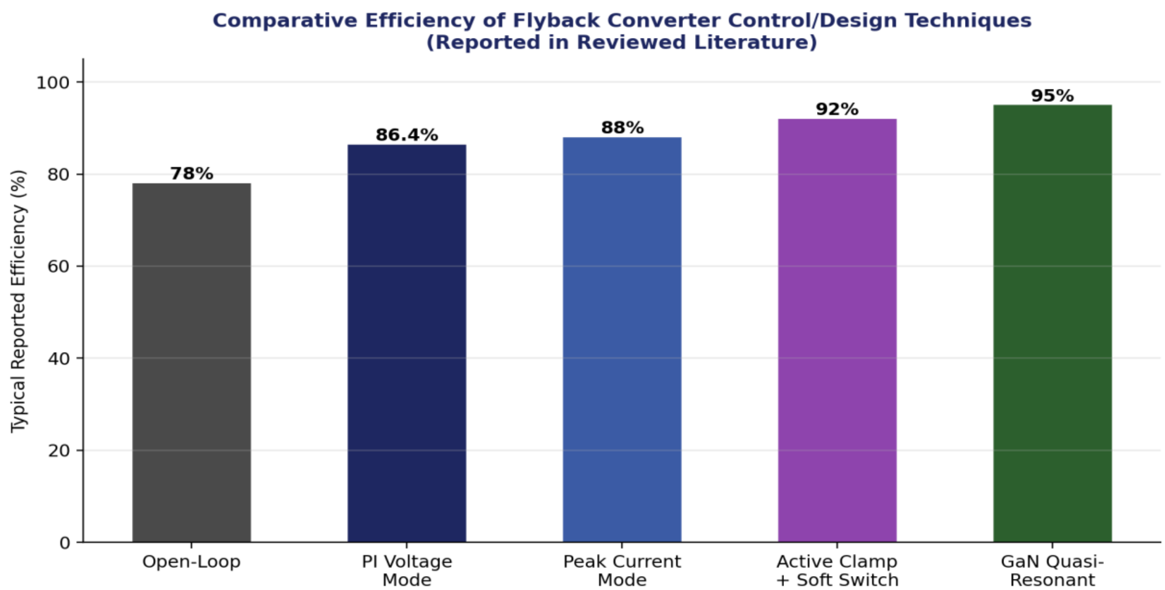

Fig. 2. Comparative efficiency ranges typically reported in the literature for different flyback converter control and design techniques.

VII. Comparative Analysis

Table I compares the principal converter/control combinations discussed in this review against the design adopted for the locomotive auxiliary power module referenced in this study, in terms of number of outputs, control method, primary contribution and remaining limitation.

Reference / Approach	Topology	Control Method	Key Contribution	Limitation
Tahan et al.	Multi-output flyback	Compensation-based	Improved independent regulation of outputs	Increased control complexity
Leng & Chiu	3-output flyback, synchronous rectification	Voltage-mode	Improved efficiency and cross-regulation	More switching components
Granello et al.	Dual-output flyback, capacitive coupling	Voltage-mode	Reduced cross-regulation error	Specific coupling arrangement needed
Cacciotto et al.	GaN quasi-resonant flyback	Quasi-resonant	Higher efficiency via regenerative snubber	Higher device cost/complexity
Yu et al.	CCM flyback	LADRC	Improved disturbance rejection	More complex than PI
Present review — reference design	Multi-output isolated flyback (110 V → 24 V/5 V)	PI closed-loop	Complete design + simulation framework, 85–90% efficiency	Cross-regulation and practical losses remain open considerations

VIII. Research Gaps and Future Directions

The reviewed literature demonstrates significant individual progress in multi-output flyback design, closed-loop control and efficiency-enhancement techniques. However, relatively few published studies combine, within a single design framework, (i) a complete mathematical design methodology for a specific locomotive-relevant input/output specification such as 110 V DC to 24 V/5 V DC, (ii) PI-based closed-loop control implemented and validated in MATLAB/Simulink, and (iii) discussion of practical hardware realization considerations such as PCB layout, thermal behaviour and electromagnetic interference. Future work identified from this review includes the application of wide-bandgap devices and active-clamp techniques to further raise efficiency and power density for railway-grade auxiliary modules, the use of advanced control (sliding-mode, model-predictive, adaptive) to improve cross-regulation between unequal loads, and long-duration reliability testing under railway environmental conditions (vibration, temperature cycling, electromagnetic interference).

IX. Conclusion

This paper has reviewed converter topologies, control techniques and efficiency-improvement methods relevant to the design of auxiliary DC power supplies for DC and AC locomotives. The flyback converter emerges from the literature as the preferred topology for compact, multi-output, isolated auxiliary supplies at the power levels typically required by locomotive control electronics, primarily because a single high-frequency transformer can supply several isolated outputs with a low overall component count. PI closed-loop voltage control remains the dominant practical control method, while active-clamp circuits, regenerative snubbers and wide-bandgap devices represent the principal routes to higher efficiency. The comparative analysis and research gaps identified in this review directly motivate the design, simulation and validation of the multi-output isolated flyback converter reported in the companion paper by the same authors.

References

[1] R. W. Erickson and D. Maksimović, Fundamentals of Power Electronics, 2nd ed. New York, NY, USA: Springer, 2001.

[2] N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics: Converters, Applications and Design, 3rd ed. Hoboken, NJ, USA: Wiley, 2003.

[3] M. H. Rashid, Power Electronics Handbook, 4th ed. Oxford, U.K.: Butterworth-Heinemann, 2018.

[4] C.-H. Cheng, C.-J. Chen, and S.-S. Wang, "Small-signal model of flyback converter in continuous-conduction mode with peak-current control at variable switching frequency," IEEE Trans. Power Electron., vol. 33, no. 5, pp. 4145–4156, May 2018.

[5] A. Thangavelu, V. Senthilkumar, and D. Parvathyshankar, "Zero voltage switching-PWM technique-based interleaved flyback converter for remote power solutions," IET Power Electron., vol. 9, no. 7, pp. 1381–1390, 2016.

[6] M. Bączek, "Small-signal transmittances of the non-ideal flyback switch-mode converter," Arch. Elect. Eng., vol. 73, no. 1, 2024.

[7] M. Tahan, D. Bamgboje, and T. Hu, "Compensated single input multiple output flyback converter," Energies, vol. 14, no. 11, art. 3009, 2021.

[8] C.-M. Leng and H.-J. Chiu, "Three-output flyback converter with synchronous rectification for improving cross-regulation and efficiency," Electronics, vol. 10, no. 4, art. 430, 2021.

[9] P. Granello et al., "Modeling and experimental validation of dual-output flyback converters with capacitive coupling for improved cross-regulation," Electronics, vol. 13, no. 17, art. 3503, 2024.

[10] C. Mullett, "Improving the regulation of multi-output flyback converters," Power Integrations, Appl. Note.

[11] B. King, "Adding a single capacitor to improve cross-regulation in dual-output flyback power supplies," Texas Instruments, Tech. Article, 2024.

[12] S. Kapat, "Control techniques for DC-DC converters," IEEE Ind. Electron. Mag., vol. 14, no. 2, pp. 16–29, 2020.

[13] K. Ogata, Modern Control Engineering, 5th ed. Upper Saddle River, NJ, USA: Prentice Hall, 2010.

[14] Y. Yu, M. Kong et al., "Optimization strategy for output voltage of CCM flyback converter based on linear active disturbance rejection control," Appl. Sci., vol. 13, no. 23, art. 12786, 2023.

[15] L. Xue and J. Zhang, "Highly efficient secondary-resonant active clamp flyback converter," IEEE Trans. Ind. Electron., vol. 65, no. 2, pp. 1236–1243, Feb. 2018.

[16] G. Balbayev, "A novel regenerative snubber circuit for flyback topology converters," 2020.

[17] W. Haider and Q. P. Ha, "A lossless passive snubber for soft-switching of flyback converters," 2024.

[18] F. Cacciotto, A. Cannone et al., "Analysis and optimization of a regenerative snubber for a GaN-based USB-PD flyback converter," Electronics, vol. 13, no. 6, art. 1045, 2024.

[19] S. Dey, M. B. Ray, H. Soni, R. Ghosh, and M. Shah, "Comparison between quasi-resonant and active-clamp flyback topologies for GaN-based 65 W wall charger application," in Proc. IEEE Appl. Power Electron. Conf. (APEC), 2021.

[20] Y. Huang et al., "Very-high-frequency resonant flyback converter with integrated magnetics," Electronics, vol. 13, no. 22, art. 4363, 2024.

[21] B. Devee and V. Pathak, "Design and implementation of a DC power supply for locomotive application," Int. J. Eng. Appl. Sci. Manage., vol. 7, no. 5, Aug. 2026.