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Development Trends and Optimization Approaches in Switched-Mode Power Supplies

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ABSTRACT Analysis of more than 1,200 scientific and technical articles devoted to Switched-Mode Power Supplies, which have now become fundamental components of power systems for modern electronic devices across all spheres of human life demonstrates that the development of these supplies still proceeds empirically. The practice of improving their basic topologies is largely based on intuitive-heuristic combinations of established circuit design solutions and does not exhibit tendencies toward forming universal methodological foundations for realizing the existing innovative potential. Moreover, the absence of a theory of systemic development, built on a generalized model of the regularities of basic topology modifications, and the lack of tools for predicting efficiency lead to the fact that design solutions are evaluated only post factum, based on the results of full-scale experiments, instead of prior analytical validation to ensure predictability and reduce time and costs of design. This situation restrains systemic structural-functional optimization of circuit solutions and complicates achieving higher levels of scalability and energy efficiency. An additional obstacle is the insufficient integration of digital tools and intelligent control methods to ensure the ability of supplies to adapt to variable and random operating conditions. Unlike numerous routine reviews of the accumulated array of circuit solutions, a concept is proposed to overcome these limitations, based on a set of formalized transformation operators for circuit design solutions. Such an approach not only elevates the systematization of known solutions to a new level but also creates conceptual foundations for the transition from design based on intuitive-heuristic assumptions to ensuring reproducible and predictable results. Promising directions for further development include expanding the functional capabilities of pulse-width modulation and stepwise energy accumulation in inductive and capacitive elements, which opens the way to integrating the analog diversity of circuit solutions of supplies with the transformational potential of digital intelligence, aimed at adaptability to changing operating conditions and optimization of operating modes in real time. All this together forms the conceptual foundation of the synthesis methodology, which will contribute to the systematization of accumulated experience and implementation of established promising directions of development for creating next-generation supplies, capable of ensuring high energy efficiency, scalability, and flexible and profound integration into modern technological platforms of various purposes.

KEYWORDS basic topologies, energy accumulation structures, empirical improvement approaches, conceptual foundations of synthesis methodology, system optimization.

I. INTRODUCTION

Switched-Mode Power Supplies (SMPS) evolve into integral components of modern electronic devices, which are the cornerstone of technical progress in all areas of human activity – from household appliances and healthcare to defense and renewable energy systems.

The principle of operation of the SMPS is founded on accumulating and converting energy from the primary power source in the inductive element (L) and regulating the output voltage formed in the capacitive element (C) using pulse-width modulation (PWM).

The advancement of SMPS has largely been driven by an empirical approach involving the combination and experimental testing of solutions derived via an intuitive–heuristic path. The modeling and optimization of their operating modes are based primarily on classical methods for determining the duration of transient processes and resonance conditions in uncontrolled circuits. Innovative solutions that go beyond the scope of uncontrolled models remain sporadic. In particular, as the method considered in [1], which involves accumulating energy in a parallel LC circuit and utilizing it in a series RLC circuit. In this case, both circuits operate in an aperiodic mode, whereas they are typically considered to be oscillatory.

Although SMPS are integral to newest technologies, they themselves have the lowest level of implementation of digital tools and intelligent control methods among all branches of electronics. But these tools and methods are crucial to ensure adaptive operation SMPS in changing conditions, ranging from internal stochastic factors such as load dynamics and battery discharge rate, to external factors including seasonal and weather fluctuations in wind speed and solar radiation that affect the power output of generators and photovoltaic panels.

Given this context, as well as the growing demands for scalability and adaptability of modern technology components, the strategy for developing SMPS should focus not only on improving their circuit architecture and operating modes, but also on reorienting the methodology of projecting from empirical research toward the systemic synthesis of a new generation of solutions.

Accordingly, unlike the numerous routine reviews and systematizations of the collected array of modifications to basic SMPS topologies, in particular [2-19], the aim of this work is to identify promising directions to improve and develop the conceptual foundations of a methodology for integrating known and synthesizing new solutions, as well as criteria for evaluating their potential with the goal of creating a new generation of SMPS.

II. DEVELOPMENT TRENDS

Depending on whether the L element is employed as an inductor or a pulse transformer, SMPS topologies are classified into non-isolated and isolated types.

The non-isolated topologies include Boost, Buck, and Buck-Boost. The following isolated topologies have been derived from them: Flyback, originating from Buck-Boost, for low-power applications; Forward, derived from Buck, for medium power with improved efficiency; Push-Pull, based on Buck, symmetrical for medium and high power levels; Half-Bridge, evolved from Push-Pull, efficient and simple for micro grids and low-voltage systems; and Full-Bridge, also evolved from Push-Pull, for high-power applications.

Summarized in the form of hierarchical trees in Figs. 1-5, the results of the analysis of review articles [2-19] for the period from 2008 to 2026, whose combined bibliographies exceed 1,200 sources, indicate that in the early stages of development, SMPS modification occurred by duplicating basic topologies.

The sequence of their emergence is as follows: Series – used to increase voltage without a transformer; Parallel – for high power and improved thermal performance; Interleaved – a phase-shifted parallel connection to reduce ripple and enhance efficiency; Multiphase – an extension of Interleaved to three or more phases for high-current applications; Bridge-based – combinations of Half-Bridge and Full-Bridge for high power; Stacked/Multicell – cascaded multilevel structures for inverters and battery cell balancing systems; Dual – symmetrical for reducing voltage ripple; Modular/Matrix – matrix scaling for high voltage and power.

An analysis of modifications to basic topologies reveals a gradual transition: from the use of separate L and C elements to perform functions determined by their dual properties (L for voltage amplification and C – for current), to structures of L and C elements designed for energy accumulating and voltage/current conversion. This transition encompasses both classical LC circuits and specialized network cells, including structures such as Switched Capacitor (SC), Switched Inductor (SI), and hybrid combinations (SC+SI). The development proceeds sequentially: from simple series and parallel LC structures to cells of the Ćuk, SEPIC, and Zeta types; from switching structures SC, SI, SC+SI, and Series/Parallel Resonant LLC schemes to topologies with enhanced conversion ratios such as Voltage Lift, Quadratic, and Multiple Lift. The current stage of development is characterized by convergence into complex LC networks – Multicell, Multilevel, Interleaved, Cascaded, Coupled, and Hybrid. A separate direction of progress is the integration of Z-source and quasi-Z-source topologies.

In Fig. 4, a tree illustrating the evolution of structures for energy accumulation and voltage/current conversion is presented. These structures combine integrated solutions with improved adaptability, functional integration, and system optimization, thereby providing power scalability, high energy density, extended voltage regulation range, increased conversion ratio, and low losses.

In addition to SMPS topologies and structures for energy accumulation and conversion, the characteristics of voltage rectifiers must be considered. Although they serve only a matching function – forming DC voltage from a pulsed signal – their parameters significantly affect overall SMPS efficiency. Functionally, rectifiers act as universal autonomous modules: the same circuit solution can be integrated into different topologies. To avoid re-considering identical rectifiers within various topologies of other structural-functional components, their evolution should be analyzed separately.

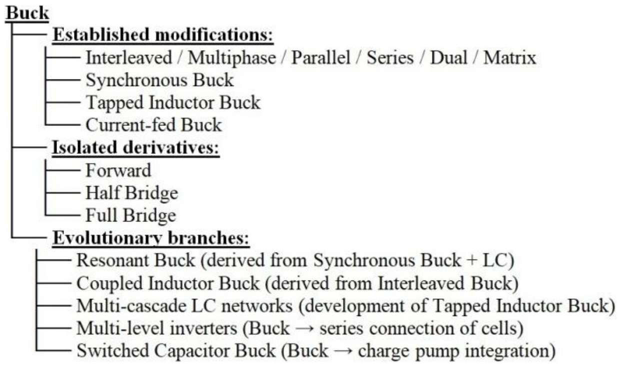

FIG. 1. Tree based on Buck topology modifications.

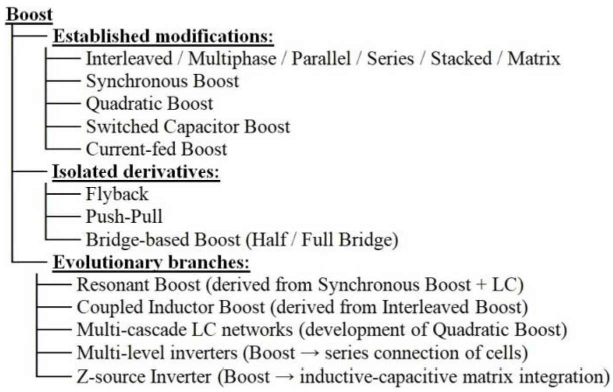

FIG. 2. Tree based on Boost topology modifications.

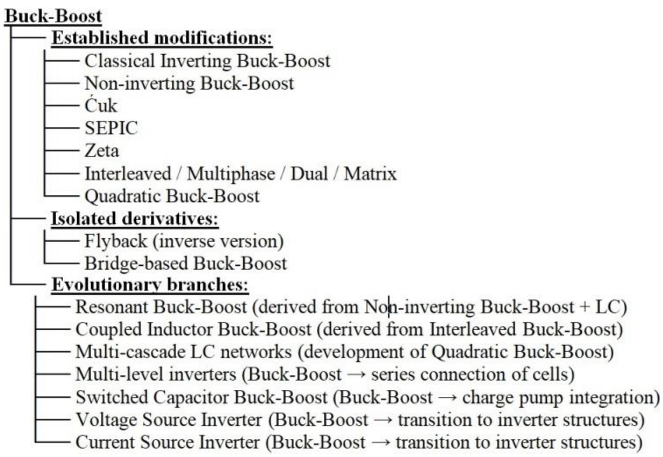

FIG. 3. Tree based on Buck-Boost topology modifications.

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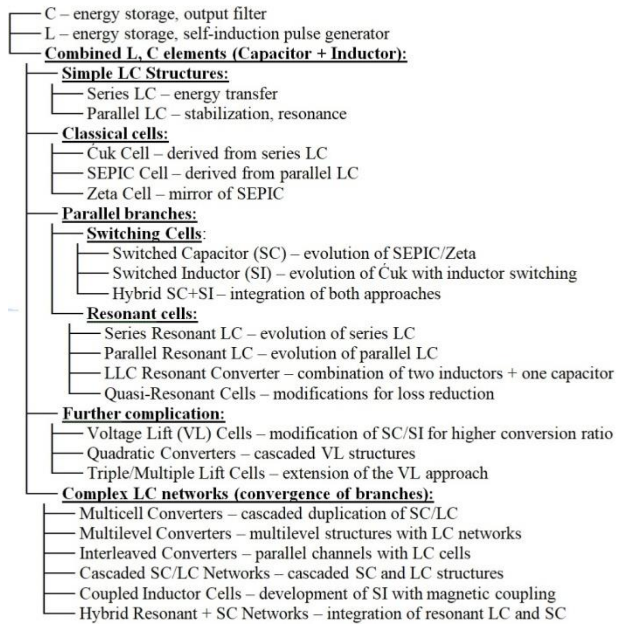

FIG. 4. Tree of development the energy accumulation and conversion structures.

Fig. 5 shows the rectifier evolution tree: from classical diode circuits, through synchronous MOSFET rectifiers, to actively controlled structures and matrix solutions. Similar to energy accumulation and conversion structures, the evolution of rectifiers reflects the transition from passive elements to controlled multifunctional systems. This transition meets modern requirements for integration with diverse signals and sources, ensuring circuit-level scalability and enhanced energy efficiency.

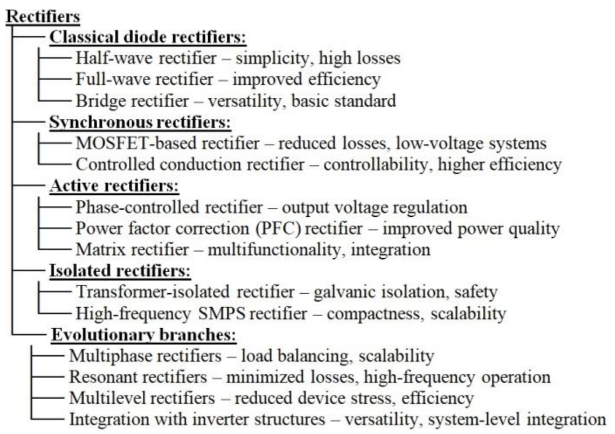

FIG. 5. Tree of development the rectifiers.

The analysis of decision trees presented in Figs. 1-5 shows that, among all branches of electronics, the design of SMPS exhibits the greatest diversity of circuit and structural-functional approaches to performing the same tasks. Meanwhile, none of these approaches supports the integration of digital technologies or the deployment of intelligent control strategies. This highlights the need for a paradigm shift in power electronics aimed at uniting the richness of switched analogue diversity – systems that, while operating in discrete modes akin to digital devices, contain no inherent prerequisites for digital control – with the transformative potential of digital intelligence.

III. EMPIRICAL IMPROVEMENT APPROACHES

The results of the analysis demonstrate that, despite significant progress, improvements to SMPS have largely been achieved empirically – through intuitional-heuristic configurations and integrations of pre-developed design solutions, along with the selection of favorable outcomes during full-scale laboratory experiments.

A representative example of such practice is the hybrid SMPS [20], obtained as a result of the sequential integration into the basic Boost topology of three circuit solutions differing in construction principles and functional purpose, as shown in Fig. 6 (taken from [20]).

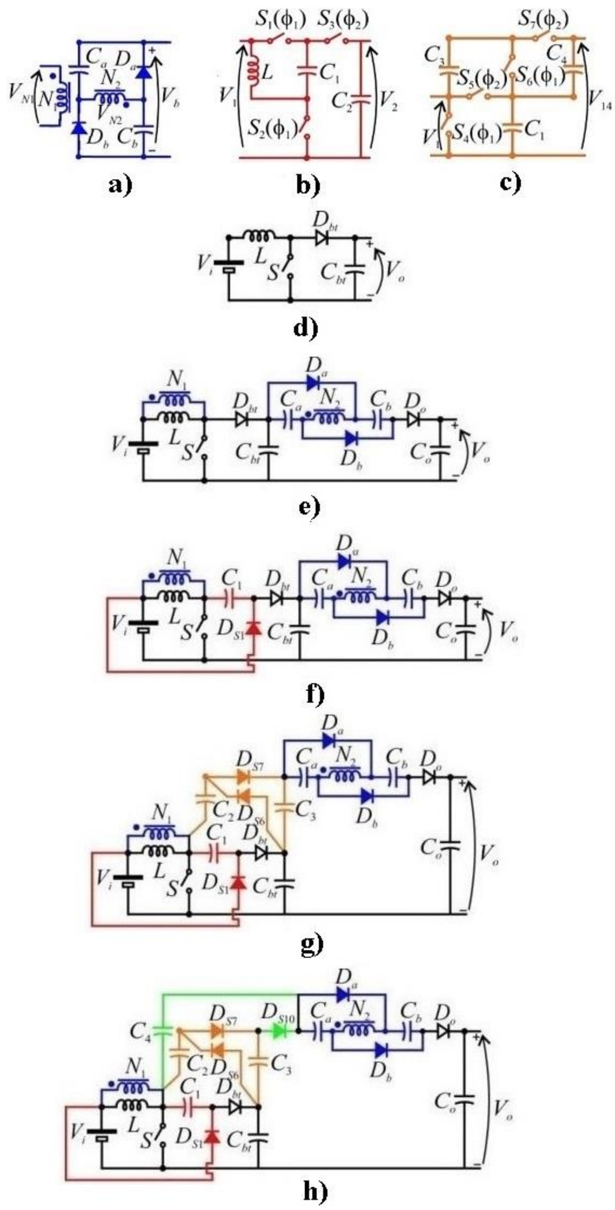

FIG. 6. Circuit solutions forming the hybrid SMPS [20]: coupled inductors with a voltage multiplier (a); step-up switched capacitor (b); switched capacitors (c), and the sequence of their integration into the Boost topology (d-h).

As a result, without any justification of feasibility, the number of elements increases significantly, while the number of operating modes per switching period rises from two to four.

In general, the results of the analysis indicate that all modifications of SMPS topologies, as summarized in [2-18], were obtained by combining empirical approaches with intuitive-heuristic methods.

IV. PROMISING DIRECTIONS AND METHODS OF REFINEMENT

An example that transcends established approaches is the method of converting DC voltage into pulses, whose implementation is discussed in [1].

This method gives the element L a new functional role: without additional energy input, the electromotive force of self-induction automatically reconfigures the parallel connection of the elements L and C, in which energy is accumulated in the electric and magnetic fields, to their series connection with the active load R, thereby ensuring controlled energy transfer and utilization.

Modeling and analyzing the efficiency of topologies transformed from basic ones using this method, denoted by the prefix LC and presented in Fig. 7, goes beyond classical approaches. In particular, traditional methods for determining the duration of transients in RL and RC circuits, as well as the analysis of the resonant state in ideal LC and real RLC circuits, according to which such circuits are considered uncontrolled, prove insufficient.

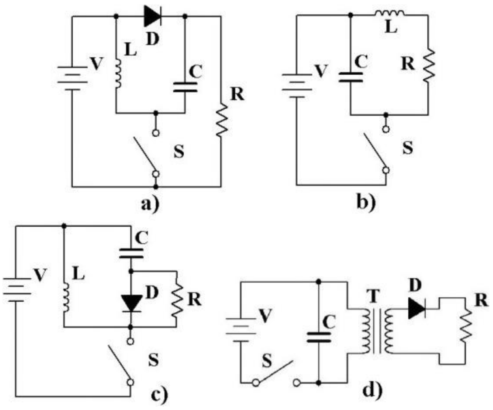

FIG. 7. Modifications of basic topologies according to method [1]: LC-Boost (a), LC-Buck (b), LC-Buck-Boost (c), LC-Flyback (d).

Moreover, method [1] enables optimization of known solutions, particularly topology SMPS [21] presented in Fig. 8 (adapted from [13, p. 9157, Fig. 18c]).

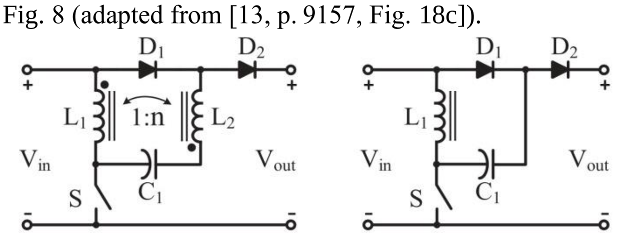

FIG. 8. Topology [21] – left, and its simplification – right.

This topology was obtained as an integration of a switched C element and coupled L elements. It is reported that a prototype based on topology [21] delivers a power of 250 W with an efficiency of 97.2%, which decreases to 93.6% under full load.

The topology [21] can be considered redundant and simplified to the LC-Boost topology in Fig. 7a, as shown on the right in Fig. 8. This should prevent the efficiency reduction reported in [21], since the dissipation losses in coupled L elements are inherently greater than in a single L element.

Also, the method [1] makes it possible to consolidate approaches aimed at reducing peak currents and losses in C elements through stepwise energy accumulation, as discussed in [22, 23]. In addition, it is possible to propose an inversion and extension of the approaches [22, 23] and apply them simultaneously to L elements, which has not yet been described in the known literature. This will allow for the control of energy storage in several C- and/or L-elements using separate switches and several sources.

Such an approach creates prospects for extending the 'single channel' PWM, in which voltage regulation is performed by varying the duration and repetition period of control pulses for commutation of only one L element. Fig. 9 illustrates an example of separate control of L and C element commutation by pulses and repetition periods of different and variable duration.

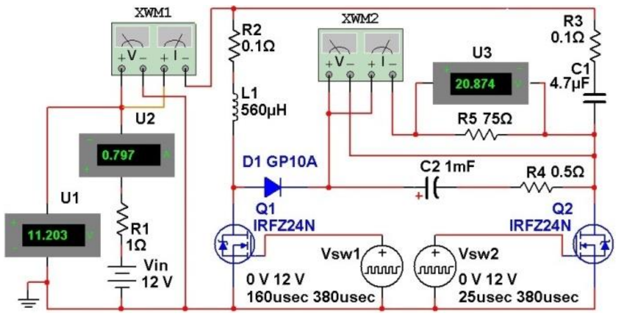

FIG. 9. A circuit diagram for studying the LC-Buck-Boost topology in the Multisim simulator environment, which contains independent switches Q1 and Q2 for elements L1 and C1, respectively.

As the switch count increases, the circuit shown in Fig. 9 is equivalent to synchronous MOSFET rectifiers (in the tree shown in Fig. 5) [24], which lower voltage drop compared to diode rectifiers. However, such rectifiers do not offer the same opportunities for PWM development as the method described in [1].

In addition to improving the controllability of energy accumulation and voltage/current conversion, LC-Buck-Boost topology in Fig. 9 creates the conditions for integrating digital tools and intelligent methods for SMPS control and operating-mode optimization.

For example, Fig. 10 illustrates a circuit diagram for stepwise accumulation of energy from a single battery in three C elements in the order C1 to C3. Fig. 11 illustrates stepwise energy accumulation in a single C element from three battery cells, sequentially connected in the order V1 to V3. This provides a radically new way to interact with digital intelligence to control the performance of SMPS under changing conditions in real time.

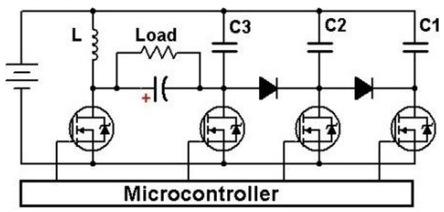

FIG. 10. LC-Buck-Boost topology illustrating stepwise energy accumulation in three C elements from a single battery.

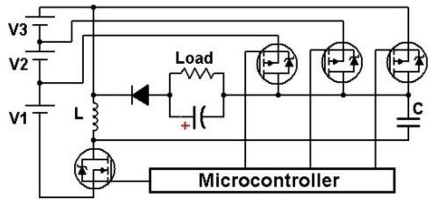

FIG. 11. LC-Buck-Boost topology illustrating stepwise energy accumulation in a single C element from three battery cells.

V. CONCEPTUAL FOUNDATIONS FOR A METHODOLOGY OF SOLUTION SYNTHESIS

Analysis of the sequential process of modifications of SMPS topologies and L and C element structures has made it possible to identify and formalize operators that reflect established approaches to their transformation:

1. Combination – sequential and/or parallel connection of basic topologies and L and/or C elements to form new functional units;
2. Cascading – sequential or parallel duplication of basic topologies and L and/or C elements for scaling power and voltage ratings;
3. Switching – introduction of additional switching elements to implement new or extend existing principles and operating modes;
4. Resonance – creation of conditions and modes for utilizing resonance phenomena by adding extra L and/or C elements;
5. Coupling – application of inductive, capacitive, optical, or wave coupling between elements and/or subsystems to transfer energy and signals without galvanic contact;
6. Integration – merging of topologies and/or their structures into networks and systems with enhanced interaction;
7. Hybridization – combination of heterogeneous design and control principles, as well as physical media, into multifunctional, highly efficient, and adaptive systems.

This set of operators provides a tool for the purposeful design of innovative solutions through the transformation of L and/or C element structures. For example:

– Series LC + Switching → Ćuk;
– Parallel LC + Switching → SEPIC;
– SEPIC + Cascading → Quadratic SEPIC.

Fig. 12 presents a hierarchical tree of these operators along with examples of their application. In this tree, the new operators ‘Self-Reconfiguration’ and ‘Step-By-Step Charging,’ highlighted in red, represent the method [1] and the approaches [21, 22]. Unlike operators that reflect existing practices, solutions on the ‘Self-Reconfiguration’ operator with independent energy accumulation control offer fundamentally unprecedented prospects for realizing the benefits of digital intelligence.

This tree constitutes both a conceptual framework and a foundation for the systematic analysis of patterns in the purposeful development of innovative solutions in SMPS topologies and L and/or C element structures.

The deployment of this conception into a rigorous methodology for the synthesis of new solutions requires a deeper elaboration of the initial set of operators, the development of a formalized database of known solutions, and the systematization of physical phenomena and technical principles – both those already applied and those that may be utilized. It further necessitates the definition of criteria for evaluating the resulting circuit solutions in terms of transient process dynamics, energy indicators, and loss magnitudes, which ultimately determine their efficiency.

Avoiding empirical practice will ensure the systematic and reproducible nature of solutions obtained through consistent and well-grounded transformations, rather than accidental intuitive-heuristic conjectures. It will also open the way to predicting promising topologies and operating modes of structures for energy storage and voltage conversion, while expanding the research space for practical applications.

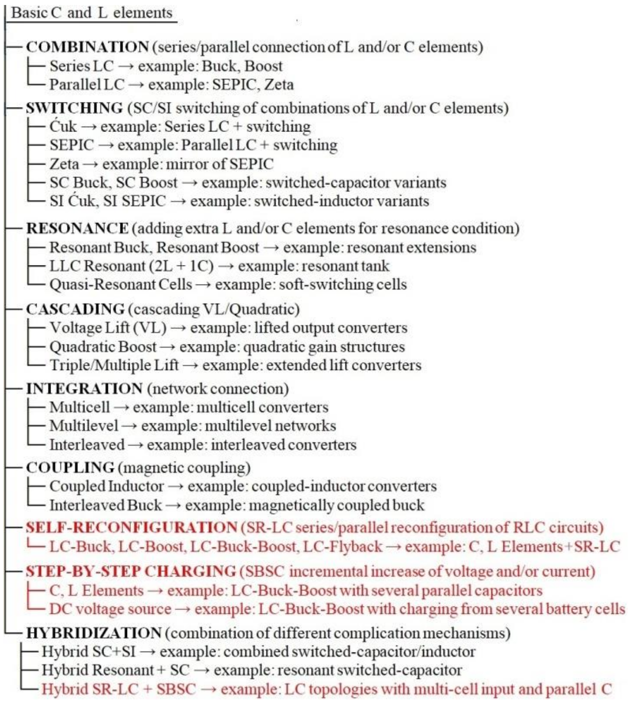

FIG. 12. A hierarchical tree of transformation operators that reflects established and news approaches.

VI. CONCLUSION

The predominant reliance on empirical, intuitive, and heuristic practices in SMPS design and refining hinders the full realizing of untapped innovative potential inherent in the diversity of existing solutions and promising trends.

The proposed framework of formalized operators for consolidating and transforming circuit design solutions constitutes a methodological foundation for systematic structural-functional optimization of existing topologies and for the purposeful development of new modifications. This methodological tool further underpins the search for innovative solutions, while laying the groundwork for a future methodology of synthesis.

A promising direction for advancement emerges from the convergence of independent switching control with stepwise energy accumulation in inductive and capacitive elements. This convergence expands the functional scope of classical PWM and provides a solid foundation for integrating modern digital and intelligent control systems into SMPS. In combination, these innovations advance the efficiency of SMPS and augment their adaptability under variable operating conditions in renewable energy networks and energy-saving technologies.

AUTHOR CONTRIBUTIONS

P. B. – conceptualization, methodology, data analysis, manuscript preparation, peer review and editing, data visualization.

COMPETING INTERESTS

The author declares no conflict of interest.

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Тенденції розвитку та підходи до оптимізації імпульсних джерел живлення

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АНОТАЦІЯ Аналіз матеріалів понад 1200 науково-технічних статей, присвячених імпульсним джерелам живлення, які нині стали фундаментальними компонентами систем живлення сучасних електронних пристроїв для всіх галузей людського життя – від побутової техніки та охорони здоров'я до оборони та відновлюваної енергетики, засвідчує, що їх розвиток досі відбувається емпіричним шляхом. Практика вдосконалення базових топологій імпульсних джерел живлення здебільшого ґрунтується на інтуїтивно-евристичних комбінаціях усталених схемотехнічних рішень, і не демонструє тенденцій формування універсальних методологічних засад для реалізації існуючого інноваційного потенціалу. Водночас, відсутність теорії системного розвитку, побудованої на узагальненій моделі закономірностей модифікації базових топологій, й нестача інструментів прогнозування їх ефективності призводять до того, що проектні рішення оцінюються лише постфактум, за результатами натурних експериментів, замість попередньої аналітичної валідації для забезпечення їх передбачуваності й скорочення часу та витрати на проектування. Така ситуація стримує системну структурно-функціональну оптимізацію схемотехнічних рішень і ускладнює досягнення вищих рівнів масштабованості й енергоефективності джерел живлення. Додаткову перешкоду створює недостатня інтеграція цифрових засобів та інтелектуальних методів керування для забезпечення здатності джерел живлення адаптуватися до змінних і випадкових умов експлуатації. На відміну від численних рутинних оглядів накопиченого масиву схемотехнічних рішень, запропоновано концепцію подолання цих обмежень, яка базується на наборі формалізованих операторів трансформації схемотехнічних рішень. Такий підхід не лише виводить систематизацію відомих рішень на новий рівень, а й створює концептуальні засади переходу від проектування шляхом інтуїтивно-евристичних припущень до забезпечення відтворюваних і передбачуваних результатів. Перспективними напрямами подальшого розвитку є розширення функціональних можливостей широтно-імпульсної модуляції та покрокового накопичення енергії в індуктивних і ємнісних елементах, що відкриває шлях до інтеграції аналогового різноманіття схемотехнічних рішень імпульсних джерел живлення та трансформаційного потенціалу цифрового інтелекту з метою адаптивності джерел живлення до мінливих умов експлуатації та оптимізації режимів їх роботи в реальному часі. Усе це разом формує концептуальну основу методології синтезу, яка сприятиме систематизації накопиченого досвіду і реалізації встановлених перспективних напрямів розвитку для створення імпульсних джерел живлення наступного покоління, здатних забезпечити високу енергоефективність, масштабованість та гнучку і глибоку інтеграцію у сучасні технологічні платформи різного призначення.

КЛЮЧОВІ СЛОВА базові топології, структури накопичення енергії, емпіричні підходи до вдосконалення, концептуальні засади методології синтезу, оптимізація систем.