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Vasyl Tarasiuk[1], Oleksiy Gorodny[2]

[1]Phd Student of the Department of Electrical Engineering and Information and Measurement Technologies
Chernihiv Polytechnic National University (Chernihiv, Ukraine)
E-mail: vasyltarasiuk.ua@gmail.com. **ORCID:** https://orcid.org/0009-0003-5310-9202

[2]PhD in Technical Sciences, Associate Professor of the Department of Electronics, Automation, Robotics and Mechatronics
Chernihiv Polytechnic National University (Chernihiv, Ukraine)
E-mail: aleksey.gorodny@gmail.com. **ORCID:** https://orcid.org/0000-0001-5303-9564

ADAPTIVE CONTROL TO ENHANCE ENERGY EFFICIENCY IN QUASI-RESONANT SWITCHED-MODE CONVERTERS UNDER DYNAMIC LOADS

Modern demands for energy efficiency and power density are stimulating the transition to quasi-resonant converters capable of minimizing switching losses. This article systematizes the limitations of both classical linear regulators and common nonlinear approaches to power switch control. To increase the energy efficiency of quasi-resonant converters, a hybrid control architecture based on artificial intelligence is proposed. The task of an artificial intelligence control system is to ensure stability and increase the energy efficiency of switched-mode voltage converters. AI-based control options are considered, namely: neural networks, fuzzy logic, and reinforcement learning.

Keywords: *quasi-resonant converter; zero-current switching; zero-voltage switching; artificial intelligence; pulse-width modulation; energy efficiency; switched-mode voltage converter.*
Fig.: 4. Table: 4. References: 21.

Relevance of the research. Modern energy efficiency standards impose strict requirements on switched-mode voltage converters, demanding high power conversion efficiency (PCE) not only in nominal mode but across the entire range of load parameter variations. For classical converters with pulse-width modulation (PWM), this task is challenging, as their PCE significantly decreases at light loads due to the dominance of switching power losses inherent to PWM converters at high operating frequencies. A promising alternative is quasi-resonant converters, which, by implementing zero-current switching (ZCS) or zero-voltage switching (ZVS), can minimize switching losses.

The main obstacle limiting their application is a systemic problem: the primary control method–pulse-frequency modulation (PFM), used to maintain the zero-current or zero-voltage switching mode of the power switches as the load changes–itself becomes a source of significant losses. The physics of the process is that to increase the energy transferred to the load, the system reduces the on-time of the power switch, while the duration of the resonant process remains constant, leading to a sharp increase in operating frequency. Such an increase in frequency negates the advantages of operating with ZVS and ZCS by activating other loss mechanisms: gate drive losses and core losses in magnetic components increase. Thus, a fundamental contradiction exists between the necessity of maintaining zero-current or zero-voltage switching modes and the reduction in efficiency due to the side effects of traditional control methods, which necessitates the search for new intelligent approaches.

Target setting. The drawback of classical approaches to controlling quasi-resonant converters, including industrial controllers and PID (Proportional-Integral-Derivative) based regulators, is their optimization for a narrow operating region. When operating beyond its boundaries, these systems are unable to adapt to a wide range of loads and other factors, which manifests in the loss of the zero-current or zero-voltage switching mode and, as a consequence, a significant drop in efficiency. The analysis of existing research shows that a key gap remains as follows: the absence of comprehensive solutions that simultaneously optimize integral efficiency, dynamic regulation performance, and compliance with electromagnetic compatibility (EMC) standards.

In this context, the research objective is to create an adaptive control method capable of calculating optimal switching instants in real-time for the guaranteed maintenance of the zero-current or zero-voltage switching mode. This controller must not only stabilize the output voltage but also minimize total power losses (conduction, switching, and control), considering hardware limitations and requirements for the level of electromagnetic interference. The idea is that combining a model-oriented part to guarantee stability with intelligent methods (neural networks, reinforcement learning) will make it possible to solve this complex problem.

Actual scientific researches and issues analysis. Over the last decade, power electronics has seen a steady transition towards quasi-resonant and switched-mode voltage converters. Fundamental research has substantiated the advantages of using quasi-resonant converters, which have enabled increased power density and efficiency compared to classical converters with PWM [1]. These solutions are enhanced by the introduction of wide-bandgap semiconductors (GaN, SiC), which, thanks to their high-speed operation, allow for raising operating frequencies into the megahertz range, imposing even stricter requirements on the accuracy and adaptability of control systems [2].

The implementation of wide-bandgap semiconductor power switches (GaN, SiC) is a promising direction for the development of switched-mode voltage converters. The ability to operate at frequencies measured in units and tens of megahertz allows for achieving high power density, but at the same time, it reduces the time windows for decision-making to nanoseconds. Under these conditions, traditional controllers based on discrete calculations with a fixed clock cycle prove to be too slow. Their limited speed does not allow for tracking instantaneous changes in the resonant circuit, leading to the inevitable loss of the soft-switching mode, a sharp increase in dynamic losses, and potential loss of stability. Thus, the transition to GaN/SiC transforms the task of adaptive control from a desirable optimization into a critically necessary condition for realizing the potential of the modern component base.

Systems based on Fuzzy Logic Control (FLC) have proven their effectiveness in controlling complex nonlinear quasi-resonant converters, demonstrating improved transient responses without the need for a precise mathematical model [3]. The latest research demonstrates the potential of Deep Reinforcement Learning (DRL), which has been successfully applied to create a fully autonomous [4], model-dependent control system for a complex three-level Neutral-Point-Clamped (NPC) inverter, showing results that surpass even Model Predictive Control (MPC) [5].

However, the analysis reveals key gaps, including: most works on DRL concern simple PWM topologies, while for more complex switched-mode voltage converters, they are limited to simulation. There is a lack of comprehensive solutions that simultaneously optimize integral efficiency, dynamics, and EMC indicators, and that have been brought to experimental proof on real equipment.

The aim of the research is to develop an experimental validation of a hybrid adaptive control method that solves the problem of efficiency drop under dynamic load changes and ensures consistently high integral energy efficiency. The key objectives to achieve this goal are increasing integral energy efficiency and complying with strict constraints on the level of electromagnetic interference and the thermal management of the switched-mode voltage converter elements. Moreover, the synthesized controller must be oriented towards practical implementation with a minimal set of required sensors and acceptable computational costs for microcontrollers or Field-Programmable Gate Arrays (FPGAs) [6]. The effectiveness of the proposed approach must be proven through comparative simulation and experimental research on a test bench using the proposed control strategies.

The statement of basic materials. For decades, converters with PWM have been the foundation of power electronics, which was fully justified by their simplicity and reliability. However, the technological revolution, driven by the rapid development of very-large-scale integrated circuits, has fundamentally changed the requirements for energy efficiency. The transition to compact and increasingly powerful digital systems has brought entirely new priorities for power supplies to the forefront, namely: maximum power density and high energy efficiency across different load levels. It is under these new conditions that classical PWM topologies require significant improvement.

The main drawback of PWM converters lies in high switching losses, which arise from the simultaneous presence of high voltage and current on the switching element during switching transients. These losses, dissipated as heat, become excessive as the operating frequency increases. Thus, high switching losses impose a strict upper limit on the operating frequency, which, in turn, limits the achievable power density. In practice, this limits the power density of PWM converters. In addition to losses, the high rates of change of current (di/dt) and voltage (dv/dt), characteristic of hard switching, generate significant electromagnetic interference (EMI), which complicates the design and requires additional filters [7].

Table 1 presents a comparative analysis of two fundamental approaches to designing switched-mode voltage converters, namely: traditional PWM with hard switching and modern quasi-resonant converter topologies with soft switching. The table systematizes the key differences across five criteria. Switching losses are the main drawback of PWM, whereas quasi-resonant converters minimize them by switching at zero current or zero voltage. This, in turn, allows for a significant increase in the operating frequency in quasi-resonant converter systems, which is limited in PWM systems due to rising losses. Consequently, quasi-resonant converters have a much lower level of electromagnetic interference. The final row highlights the trade-off: although quasi-resonant converter technologies are generally more efficient, their efficiency can decrease during rapid changes in load parameters not using complex adaptive control algorithms [8].

Table 1 – Comparison of PWM and quasi-resonant converters

Characteristic	PWM converters (hard switching)	Quasi-resonant converters (soft switching)
Switching losses	High, dominant	Minimal (theoretically zero)
Operating frequency	Limited by losses	High (allows for smaller component sizes)
EMI level	High (due to sharp di/dt and dv/dt)	Low (due to sinusoidal current or voltage waveforms)
Efficiency	Decreases at high frequencies and light loads	High over a wide range, but can decrease under variable loads without adaptive control

Source: developed by the authors.

Soft switching is a key technology that allows overcoming the limitations of PWM converters. Its fundamental principle consists of using a resonant circuit–a network of inductors and capacitor–to shape the voltage and current signals in such a way as to avoid their simultaneous presence on the power switch during switching. This is achieved through two main mechanisms: zero-current switching or zero-voltage switching.

Zero-voltage switching: This mechanism ensures that the voltage across the switching element is zero immediately during its turn-on or turn-off. This effectively eliminates the losses associated with recharging the power switch's capacitances, which are dominant at high frequencies. This is typically achieved using a resonant capacitor connected in parallel with the power switch.

Zero-current switching: This mechanism guarantees that the current flowing through the switch is zero during its turn-on or turn-off. This minimizes the losses associated with breaking an inductive circuit. It is implemented using a resonant inductor connected in series. The schematic of a parallel quasi-resonant converter with zero-current switching and its timing diagrams are shown in Figure 1 and Fig. 2, respectively.

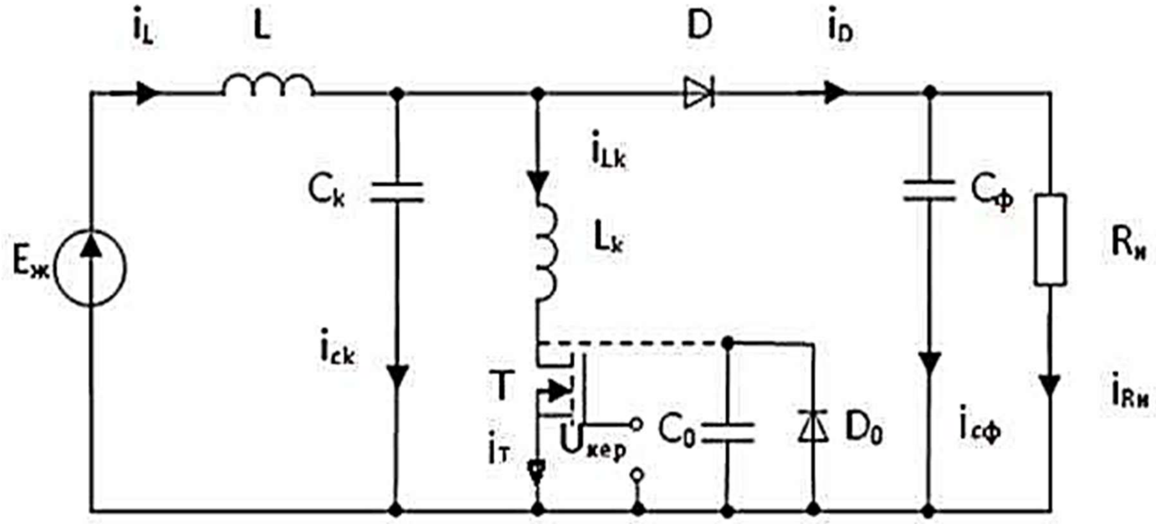


Fig. 1. Schematic of a parallel ZCS quasi-resonant converter

Source: [9].

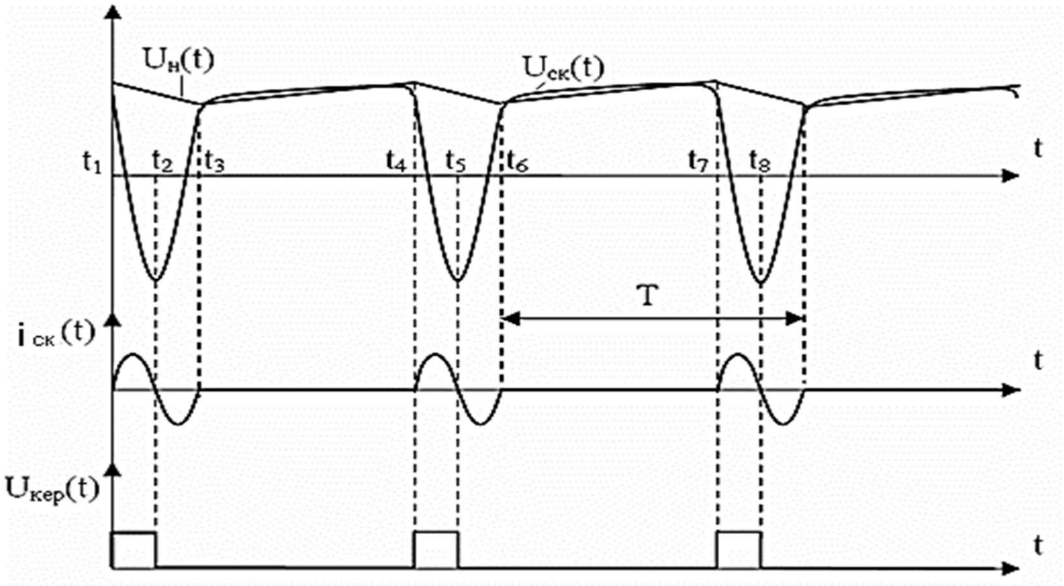


Fig. 2. Timing diagrams of the ZCS quasi-resonant converter

Source: [9].

The advantage of zero-current or zero-voltage switching is the ability to significantly increase the operating frequency of the switched-mode voltage converter without a substantial increase in switching losses. High-frequency operation, in turn, allows using smaller electronic components, leading to a significant increase in power density and overall system efficiency.

Table 2 details the two main mechanisms underlying soft-switching technology, namely: zero-current and zero-voltage switching. For each mechanism, the table explains the principle of operation–the condition under which the power switch is turned on. It then identifies the specific type of loss that is eliminated: for zero-current switching, it is the losses from recharging the power switch's output capacitance, which is critical at high frequencies, and for zero-voltage switching, it is the losses associated with breaking an inductive circuit. This table serves to clearly distinguish between these two fundamental principles.

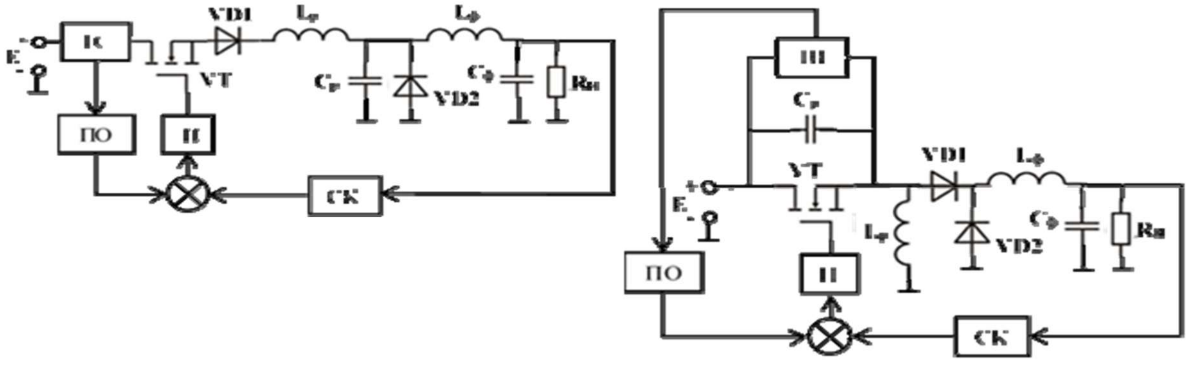
Table 2 – Main mechanisms of soft switching

Principle of operation	Type of loss eliminated	Key resonant element
Switching occurs when the voltage across the switch is zero	Losses from recharging the power switch's output capacitance	Capacitor connected in parallel with the power switch
Switching occurs when the current through the switch is zero	Losses associated with breaking the inductive circuit	Inductor connected in series with the power switch

Source: developed by the authors.

Figure 3 shows the functional schematics for implementing the quasi-control mode in quasi-resonant converters: a – ZCS quasi-resonant converter, b – ZVS quasi-resonant converter. In the initial stage of operation, the control system generates a short pulse that turns on the power switch. Subsequently, on the secondary windings of the current transformer (for a ZCS quasi-resonant converter) or voltage transformer (for a ZVS quasi-resonant converter), signals appear that are proportional to the resonant current or resonant voltage, respectively. The resulting signals are amplified by a threshold amplifier and converted into control pulses for the power switches, creating a local positive feedback loop that holds the transistors in the on state. At this point, the initial pulse from the control system is no longer needed; during the subsequent on-state interval, the power switches operate directly from the feedback loop. This forms the basis of the quasi-control principle.

When the value of the resonant current (in the case of a ZCS quasi-resonant converter) or voltage (for a ZVS quasi-resonant converter) approaches zero, the positive feedback action ceases, and the power switches automatically turn off. The conditions for the emergence and cessation of the positive feedback are determined by the principles of automatic control theory for closed-loop systems [10].



a *b*

A – amplifier (- П – підсилювач)
AL – amplifier-limiter (ПО – підсилювач-обмежувач)
CT – current transformer (ТС – трансформатор струму)
VT – voltage transformer (ТН – трансформатор напруги)
CS – control system (СК – система керування)

Fig. 3. Functional schematics of the quasi-control mode implementation: a – ZCS quasi-resonant converter; b – ZVS quasi-resonant converter

Source: [10].

Equation 1 shows the calculation of energy losses in the power switch of a series of the quasi-resonant converter with zero-current switching. The approach consists of dividing the operating period of the switched-mode voltage converter into four characteristic intervals, for each of which the time dependencies $U_{TP}(t)$ and $i_{TP}(t)$ are determined. Based on these dependencies, the instantaneous power losses are calculated [10]:

$$P_n = \frac{1}{t_n - t_{n-1}} \int_{t_{n-1}}^{t_n} U_{TP}(t) \cdot i_{TP}(t) dt. \quad (1)$$

Sliding Mode Control (SMC) is a powerful nonlinear technique that has gained recognition for its energy efficiency in various operating modes. In many power electronics applications, SMC is considered a more appropriate and widely researched alternative to fuzzy and adaptive control [11].

Principle of operation: In a switched-mode converter that switches at zero current or zero voltage, the power switch is part of a resonant circuit with an inductor L and a capacitor C, in which energy is periodically exchanged between the magnetic field of the inductor and the electric field of the capacitor. When the power switch turns on, the current through it begins to rise not linearly, but according to a sinusoidal law. At the moment of switching, the control system waits for this sinusoidal current to naturally decrease to zero. It is at this moment that it turns off the transistor. "Sliding" is the process during which the controller "slides" along the curve of the falling current, awaiting the moment of zero crossing. It does not forcibly turn off the power switch when the current is still high but "allows" the oscillatory process to bring the current to zero on its own. This provides ideal conditions for turn-off. There are two main approaches to implementing SMC in converters:

- SMC based on hysteresis modulation: This is a classical approach that is simple to implement, but its main drawback is a variable switching frequency. This complicates the design of output filters and can create problems with electromagnetic compatibility.
- SMC based on fixed-frequency PWM: This more modern approach solves the problem of operating over a wide frequency range, making it significantly more effective in practical applications. General methods have been developed for synthesizing PWM control laws for switched-mode converters operating in both continuous and discontinuous current modes.

The application of SMC allows bridging the gap between control theory and the practice of power electronics, providing reliable and fast regulation for DC-DC converters.

Fuzzy logic-based control is another intelligent strategy that does not require a precise mathematical model. It is based on human experience and qualitative control rules in an "if-then" format, making it ideal for complex nonlinear systems, including quasi-resonant converters where linear PID regulators are challenging to apply.

The standard architecture of a traditional FLC includes three stages: converting crisp input values, such as the error and the change in error, into fuzzy sets; applying a rule base (e.g., a 7×7 table with 49 rules); and converting the fuzzy conclusion into a crisp control signal. However, this approach has significant practical drawbacks, especially for embedded systems: high computational complexity, substantial memory requirements for storing the rule base, and difficulty in tuning the scaling factors and the rules themselves. These limitations can reduce the maximum achievable switching frequency and complicate implementation on microcontrollers or digital signal processors.

To solve these problems, simplified fuzzy logic controllers (SFLC) have been developed. The innovation of SFLC lies in using a single input variable and a one-dimensional rule base. This significantly reduces memory requirements and computational complexity. As a result, the algorithm becomes simpler to implement and tune, and also increases performance speed, allowing it to be effectively used in high-frequency quasi-resonant converters for current or voltage regulation. The evolution from FLC to SFLC is a clear example of the engineering search for a compromise between energy efficiency, control system stability, and the complexity of its practical implementation [12].

A promising direction in the control of electronic power switches is the application of deep learning. Reinforcement learning is based on the purposeful acquisition of experience: the controller manages the power switch and the load, and through trial and error, learns to make better decisions.

The control task is conveniently formalized as a Markov Decision Process (MDP) [13], namely: "states – actions – reward function". The goal of the controller is to find an effective control policy, that is, a rule for selecting actions based on the current state. In deep reinforcement learning, deep neural networks are used to approximate the value function, which allows for handling diverse situations and preparing the control system for operation with a real device. The practical design of a DRL controller requires the careful definition of three main elements:

● State (st): This is a set of observable variables that fully characterize the current state of the system. For a power converter, this would include: the output voltage error, inductor currents, and capacitor voltages.

● Action (at): This is the set of possible control inputs. For switched-mode converters, this can be a discrete set corresponding to the permissible switching states of the power switches, or a continuous value such as the duty cycle or switching frequency. The choice of control algorithm depends on the capabilities of the quasi-resonant converter and the expected results.

● Target (reward) Function (rt): The design of the reward function is of paramount importance as it defines the control objective. A well-designed reward function allows for achieving minimization of the output voltage error, ensuring voltage balancing in the DC link of NPC inverters, and improving energy efficiency [14].

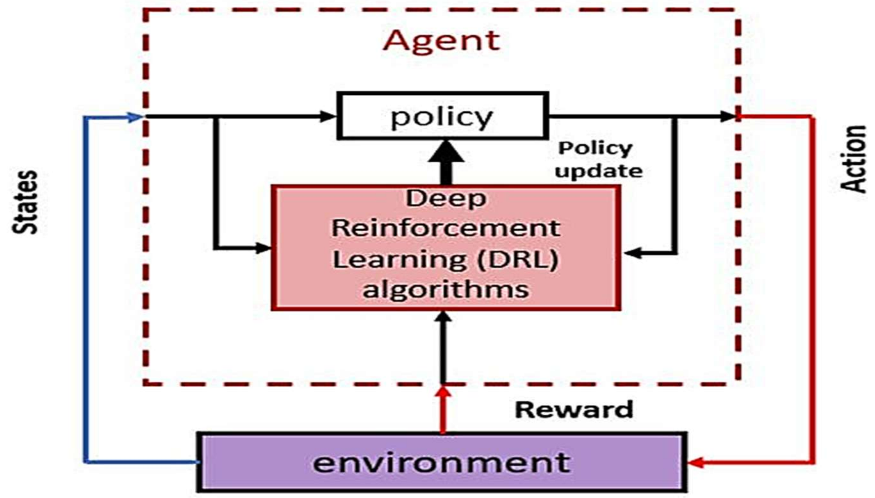


Fig. 4. Schematic of a DRL controller's operation

Source: [15].

The NPC inverter is a fundamental topology for low and medium-power switched-mode converters due to its reduction of total harmonic distortion, limitation of the rate of voltage change (dv/dt), and lower operating voltages across the power switches. At the same time, synthesizing a control system for this inverter is a complex task, as it requires simultaneously ensuring voltage balance on the DC-link capacitors and selecting optimal switching vectors from a set of permissible configurations, considering criteria for loss minimization and compliance with electromagnetic compatibility requirements.

DRL (specifically, a Deep Q-Network, DQN, agent) offers a model-free solution that can control the switching process to simultaneously regulate output parameters and balance the neutral-point voltage. This is achieved through a reward function whose goal is to maintain the system's stability and energy efficiency. The DRL approach compares favorably to traditional methods, including space-vector modulation [16)] or model predictive control [17], thanks to its ability to adapt to parameter changes and system uncertainties without requiring a precise mathematical model.

A critical problem for applying DRL in physical systems is the difference between simulation and real-world operation (the "sim-to-real" gap). DRL agents require millions of iterations for training, which is impractical and unsafe on real equipment. Therefore, training is conducted in a simulation environment. The problem is that control policies trained in an ideal simulation can show significantly worse results when deployed on a real system due to unmodeled dynamics, sensor errors, and parameter discrepancies. To overcome this gap, the following strategies are used:

- Environment randomization: Training the agent in various simulation environments with randomized physical parameters (inductance, capacitance, load) to force it to learn more robust methods for stabilizing the system's energy efficiency.
- System identification: Using experimental data to build a more accurate model of the real equipment, which is then used in the simulation.
- Fine-tuning on hardware [18]: After initial training in simulation, a short and safe stage of online training is conducted on the real switched-mode voltage converter to adapt the control policies.

Hardware-in-the-Loop (HIL) simulation: The use of HIL systems, such as Opal-RT, as an intermediate stage between pure simulation and a physical prototype is a key tool for verifying the effectiveness of the control method [19].

The success of DRL in power electronics depends not only on the algorithm itself but also on the parallel development of high-precision simulations and knowledge transfer methods. This changes the role of the control engineer—from a developer of mathematical models to a designer of training environments and reward function systems.

The practical implementation of advanced control systems requires consideration of two key aspects, namely: combining different methodologies to create synergistic hybrid systems and selecting the appropriate hardware platform (Digital Signal Processor (DSP) [20] or FPGA) for executing computationally intensive algorithms in real-time.

Modern control approaches do not require the complete replacement of old approaches with new ones. Instead, hybrid architectures allow for combining the effective aspects of different methods to achieve better results. In renewable energy systems, an artificial neural network [21] can predict the optimal operating point (e.g., the maximum power point), while SMC is used as a fast and reliable inner loop to track this reference point.

The main principle of these hybrid systems lies in functional distribution: the tasks of learning and adaptation are assigned to the artificial intelligence component (neural network/fuzzy logic), while guaranteed stability and energy efficiency are provided by the traditional component (SMC/PID). Executing complex control algorithms in real-time requires appropriate hardware platforms. The two main classes of devices used for these purposes are DSPs and FPGAs.

DSPs are specialized microprocessors optimized for the rapid execution of mathematical operations. They are programmed using high-level languages (e.g., C/C++), which provides flexibility and a relatively fast development cycle. DSPs are best suited for sequential, complex algorithms.

FPGAs are a configurable hardware platform. They do not execute program code but are configured to create specialized digital circuits. Their key advantage is the ability to perform a multitude of simple operations simultaneously with very low latency. This makes them effective for tasks that can be executed in parallel.

The choice between a DSP and an FPGA for implementing AI-based control systems largely depends on the structure of the algorithm itself. DSPs are well-suited for traditional control loops and more sequential AI algorithms. In contrast, FPGAs, thanks to their architecture that enables the massive parallel execution of a large number of tasks, are the appropriate choice for implementing neural networks, as quasi-resonant converter systems require processing a large amount of data in parallel. Modern FPGAs contain specialized tensor blocks to accelerate the matrix and vector operations that form the basis of AI algorithms, providing higher performance and energy efficiency for such tasks. The low latency of FPGAs is also critically important for high-frequency control loops.

To generalize and systematize the considered control methods, their key characteristics, advantages, and disadvantages are summarized in two comparative tables. This approach allows for a separate evaluation of the technical performance indicators and the practical aspects of implementing each control method.

Table 3 presents a comparison of the technical characteristics and performance indicators of the considered control methods. The analysis is conducted based on four key criteria. Model dependency shows how sensitive the method is to the accuracy of the system's mathematical description. Robustness to disturbances assesses the controller's ability to maintain stable operation during changes in load or parameters. Dynamic response characterizes the speed of reacting to changes, and computational complexity indicates the requirements for hardware implementation. The table demonstrates the evolution from simple (PID), but unstable, methods to complex intelligent methods (SMC, DRL), which offer high stability and speed at the cost of significant computational resources.

Table 3 – Characteristics and performance indicators of control strategies

Control Strategy	Model Dependency	Robustness to disturbances and parameter changes	Dynamic response	Computational complexity
Linear PID	High	Low	Slow	Low
Phase-shift	Medium	Low	Moderate	Low
SMC	Low	Very high	Very fast	Medium
FLC	Model-free	High	Fast	Medium-High
DRL	Model-free	Very high	Very fast	Very high
Hybrid (FNSM)	Low	Very high	Very fast	High

Source: developed by the authors.

Table 4 supplements the previous analysis, focusing on the practical aspects of the implementation and application of each control method. Design complexity assesses the effort required to develop and tune the controller. For each method, its key advantages and disadvantages are highlighted. The final column defines the primary application domain, which allows a developer to choose the optimal approach for a specific task, balancing performance and implementation complexity.

Table 4 – Practical aspects and application domains of control strategies

Control Strategy	Design Complexity	Key Advantage	Key Disadvantage	Primary Application Domain
Linear PID	Low (systematic tuning)	Simplicity	Poor performance for nonlinear systems	Simple DC-DC converters
Phase-shift	Low	Simple implementation of zero-current or zero-voltage switching	Limited control range, high circulating currents	Resonant inverters
SMC	Medium (requires expertise)	Guaranteed stability	Variable frequency (in hysteretic types)	Reliable industrial drives, DC-DC converters
FLC	High (requires expert knowledge)	Handles nonlinearities, intuitive	Computational cost, tuning complexity	Quasi-resonant converters, nonlinear systems
DRL	Very high (requires simulation and data)	Autonomous optimization, adaptability	Difference between ideal simulation conditions and the real device	Complex multi-objective systems, real-time system adaptation
Hybrid (FNSM)	High	Combination of learning (NN) and stability (SMC)	Implementation complexity	High-performance systems with uncertainties

Source: developed by the authors.

Conclusions. The analysis has shown that in quasi-resonant converters, energy efficiency can decrease during rapid changes in operating load due to the limitations of classical control methods. Modern power switches based on GaN and SiC have switching times measured in nanoseconds. Therefore, the future of power electronics lies in the realm of hybrid control architectures. The combination of existing control methods that guarantee stability with intelligent, AI-based control methods is the most promising path for creating switched-mode voltage converters capable of realizing their maximum efficiency under a wide range of changing external factors (e.g., changes in supply voltage, load parameters, temperature).

Future research directions. Future research should focus on creating a control model using AI; validating the results through simulation; and comparing the simulation results with experimental research.

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Василь Анатолійович Тарасюк[1], Олексій Миколайович Городній[2]

[1]аспірант кафедри електричної інженерії та інформаційно-вимірювальних технологій
Національний університет «Чернігівська політехніка» (Чернігів, Україна)
E-mail: vasyltarasiuk.ua@gmail.com. **ORCID:** https://orcid.org/0009-0003-5310-9202
[2]кандидат технічних наук, доцент кафедри електроніки, автоматики, робототехніки і мехатроніки
Національний університет «Чернігівська політехніка» (Чернігів, Україна)
E-mail: aleksey.gorodny@gmail.com. **ORCID:** https://orcid.org/0000-0001-5303-9564

АДАПТИВНЕ КЕРУВАННЯ ДЛЯ ПІДВИЩЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ У КВАЗІРЕЗОНАНСНИХ ІМПУЛЬСНИХ ПЕРЕТВОРЮВАЧАХ ЗА УМОВ ДИНАМІЧНИХ НАВАНТАЖЕНЬ

Актуальність дослідження зумовлена сучасними стандартами енергоефективності, які висувають жорсткі вимоги до імпульсних перетворювачів напруги, а саме: високого коефіцієнта корисної дії (ККД) у всьому діапазоні навантажень. Класичні перетворювачі з широтно-імпульсною модуляцією не задовольняють цим вимогам через підвищені комутаційні втрати. Перспективною альтернативою є квазірезонансні імпульсні перетворювачі (КРІП), що мінімізують втрати завдяки комутації при нульовому струмі або напрузі. Однак їхня ефективність може знижуватися через недоліки існуючих методів керування, зокрема частотно-імпульсної модуляції, яка при зміні навантаження призводить до швидкої зміни робочої частоти та збільшує комутаційні втрати. Постановка проблеми полягає в тому, що класичні підходи до керування КРІП, включно з ПІД-регуляторами, оптимізовані для вузької робочої області. Це може спричинити втрату режиму м'якої комутації та зменшення ККД. Перспективним є створення комплексних рішень, що одночасно оптимізують енергоефективність, якісні динамічні показники та відповідність стандартам електромагнітної сумісності (ЕМС). Метою дослідження є розробка гібридного адаптивного методу керування, здатного збільшити ККД при динамічній зміні навантаження та забезпечити стабільно високу енерго-ефективність. Контролер має в реальному часі обчислювати оптимальні моменти комутації, стабілізувати вихідну напругу та мінімізувати втрати. У статті проаналізовано переваги м'якої комутації над жорсткою, розглянуто механізми перемикання при нульовому струмі та напрузі. Систематизовано існуючі методи керування: від лінійних ПІД до нелінійних, таких як керування у ковзному режимі (SMC) та на основі нечіткої логіки (FLC). Особливу увагу приділено перспективним підходам на основі глибокого навчання з підкріпленням (DRL). Висновки підтверджують потребу в створенні гібридних систем керування на основі штучного інтелекту.

Ключові слова: *квазірезонансний перетворювач; комутація при нульовому струмі; комутація при нульовій напрузі; штучний інтелект; широтно-імпульсна модуляція; нечітка логіка; енергоефективність; імпульсний перетворювач напруги.*

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