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Real-Time Ton/Toff adjustment and fault prediction in high-voltage IGBT serial switch for pulsed power applications

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***Abstract*—This paper presents a control architecture for dynamic voltage balancing in high-voltage IGBT stacks, addressing transient overvoltage phenomena during switching transitions. The system integrates a three-layer protection scheme - local RC snubbers, TVS diodes, and a global snubber - with adaptive gate timing correction at 20 ns resolution. Real-time edge control is performed locally for each device, based on optical feedback and independent Ton/Toff adjustment. A reduced 14-dimensional control space is achieved by anchoring a reference transistor, ensuring temporal stability and synchronization. The operational behavior of TVS devices under burst-mode stress is characterized as transitional buffering during system tuning. Additionally, methods for predictive degradation analysis-based on $U_{CES(on)}$, Ton/Toff drift, thermal trends, and correction statistics - are outlined, supporting fault diagnostics and preventive maintenance strategies. Preliminary results obtained from the prototype system indicate that it is feasible to develop an algorithm that exhibits desirable trends in adaptive regulation, supporting the overall concept of closed-loop switching control in stacked HV structures.**

***Keywords*—microwave klystron modulator; HV pulse switch; adaptive regulation; pulse slope correction; series transistor HV ballancing**

I. Introduction

THE Institute of Nuclear Chemistry and Technology (INCT) provides radiation sterilization services for single-use medical devices to over forty manufacturers of disposable medical equipment, as well as four tissue banks from across the country. The range of sterilized products currently includes several dozen items such as surgical garments, catheters, bacteriological containers, eye droppers, pipettes, biomaterials, wound dressings, implants, and biostatic transplants (e.g., bone and skin grafts). The annual sterilization capacity of the Radiation Sterilization Station for single-use medical products approaches 100 million units.

Radiation sterilization is an environmentally friendly method that poses no health risk to operators or the natural environment and, most importantly, ensures user safety. The accelerator is currently operated for approximately 2,500 hours annually under an electron beam. A major issue limiting further operation relates to the availability, cost, and quality of spare parts imported from Russia — particularly the MI-470 magnetron.

Therefore, a key objective is to commission an accelerator equipped with a new microwave energy source. The MI-470 magnetron is planned to be replaced with a TH-2158 klystron, offering a guaranteed service life of 4,000 hours and an operational lifespan of up to 10,000 hours. The change of the microwave power source will enable stable operating conditions for the sterilization process. Furthermore, it will significantly extend the service life of the high-frequency (RF) power system and ultimately reduce the operating costs of the facility.

To implement this upgrade, it is necessary to use auxiliary equipment adapted to the technical parameters of the klystron, including a pulsed modulator, microwave transmission line, and accelerating section. Once these components are modified, the accelerator will ensure the required quality of radiation processing by achieving nominal parameters (energy and power levels), along with the operational reliability necessary for the provision of services to the healthcare sector. The accelerator installation intended for industrial and service applications consists of several subsystems, each fulfilling a specific function, as shown in Fig. 1.

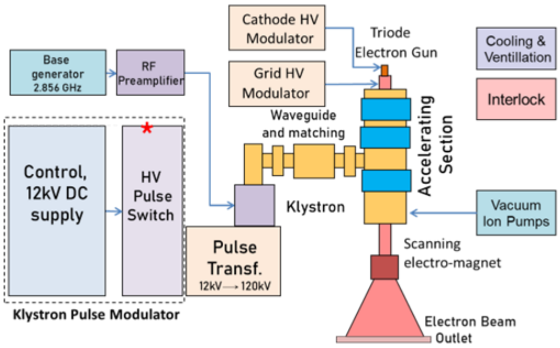

Fig.1. Supporting infrastructure of a 10 MeV linear accelerator used in radiation processing applications.

II. The concept of a high-voltage pulse switch for klystron modulator

The linear accelerator used in this process requires a microwave power source capable of delivering a peak power of 5 MW (average power approximately 20 kW). This role is fulfilled by the microwave klystron. The klystron is powered by high-voltage pulses supplied through a power pulse transformer from a system that essentially operates as a high-voltage switch, generating short (10 µs), rectangular-shaped pulses of 12 kV at approximately 1 kA.

This system, referred to as the klystron modulator, is typically designed as a pulse-forming network (PFN) consisting of an LC line discharged into a matched load through a gas-filled switching tube (thyratron).

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An alternative modulator concept is based on a partial discharge circuit. In this approach, a large electrical capacitance CB acts as an energy bank that supplies the klystron with short pulses formed by a high-voltage switching device.

Advancements in semiconductor device technology have enabled the development of switching systems based on thyristor and subsequently transistor technologies. The limitation imposed by the maximum voltage ratings of individual switching elements has necessitated the adoption of series configurations incorporating multiple devices within a single switch. A critical challenge in protecting transistors against overvoltage conditions lies in ensuring uniform voltage distribution across all elements during dynamic transitions between conducting and blocking states. To address this, measures are implemented at several key levels:

- selection of active switching elements with closely matched electrical characteristics and operation under similar thermal conditions;
- introduction of passive voltage suppression networks (RC snubbers and Transient Voltage Suppressor, TVS diodes);
- dynamic adjustment of control parameters for each individual switching element.

The latter strategy is currently the subject of ongoing research aimed at enhancing the reliability of high-voltage switches, particularly under off-nominal load conditions, as well as improving energy efficiency by significantly reducing or eliminating the need for RC snubber networks. Real-time, adaptive adjustment of the switching timing for each individual element can be achieved through a computing unit executing control algorithms based on data acquired by a parallel signal acquisition system monitoring all switching elements simultaneously.

The proposed method for achieving and maintaining appropriate dynamic voltage sharing involves software-based regulation of switching time delays, informed by data collected across the entire switching assembly. For the adopted switch architecture, this requires the development of a numerical model, the definition of an acquisition data profile from selected circuit nodes, and the design of a control algorithm that ensures conservative behavior of the model within a specified range of operating conditions (e.g., varying load parameters, ambient or junction temperatures).

The concept of dynamic voltage balancing during on/off commutation in series-connected IGBT power transistor stacks takes into account the roles of both snubber networks and TVS protection devices. In series configurations of IGBT power transistors designed for switching high voltages on the order of tens of kilovolts, the behavior of each individual device is critical to the safety and stability of the entire stack. Variations in the parameters of individual transistors, including turn-on (Ton) and turn-off (Toff) times, can lead to nonuniform voltage distribution U_{CE} during switching events — a phenomenon referred to as dynamic voltage imbalance.

A. Control space analysis and the role of reference transistor anchoring

In a series-connected system composed of eight IGBT power transistors, each device can be independently controlled by adjusting its turn-on and turn-off times. The total decision space of the system can be described as:

$$X = [Ton_1, Toff_1, Ton_2, Toff_2, ..., Ton_8, Toff_8] \in \mathbb{R}^{16}$$

Each coordinate of this vector corresponds to a timing edge for an individual transistor. In an ideal case, these parameters could be corrected independently; however, the physical behavior of the system introduces strong couplings between dimensions.

1) Primary coupling

Shared load current - all transistors are connected in series and conduct exactly the same pulsed current (on the order of 1 kA). This implies that:

- Accelerating the turn-on or delaying the turn-off of a single transistor results in an overvoltage burden on the remaining devices,
- Overvoltage on one transistor must be mitigated by its snubber and TVS protection components.
- This coupling is neither local nor weak. It is immediate, strong, and system-wide.

2) Topological problem: system drift.

If timing corrections are introduced relative to previous values (e.g., +20 ns) without anchoring any element, the entire system may experience a global temporal shift without violating local constraints. Such drift may lead to:

- Reaching the physical limits of delay adjustment circuitry,
- Losing synchronization with the klystron and other components of the accelerator system.

3) Solution: reference transistor anchoring.

Introducing a fixed temporal reference by permanently setting Ton_1 and $Toff_1$ (for transistor T_1) eliminates the drift and stabilizes the system's temporal topology. T_1 is located closest to the ground potential, making it the most suitable candidate for this role. Anchoring this parameter pair reduces the decision space to:

$$X' = [Ton_2, Toff_2, ..., Ton_8, Toff_8] \in \mathbb{R}^{14}$$

The correction system now operates relative to a fixed temporal pattern, which:

- Facilitates synchronization with a reference signal from the overarching Master Generator,
- Enables degradation trend tracking without absolute time drift,
- Allows deterministic planning of corrections without cumulative timing errors.

4) Control strategy in the reduced space.

In the $\mathbb{R}^{14}$ space:

- Corrections are performed iteratively and selectively,
- Decisions are based on observed overshoots and undershoots in the U_{CE} (Ton/Toff) waveforms,
- The correction vector $K = [\Delta Ton_2, \Delta Toff_2, ..., \Delta Ton_8, \Delta Toff_8]$ is updated only in response to threshold violations.

Due to the anchoring mechanism, the system maintains temporal coherence, eliminates drift, and allows for precise cause-effect mapping between corrective actions and observed switching behavior.

This model serves as the foundation for all dynamic correction algorithms, adaptive control strategies, and predictive diagnostics in systems employing multi-element high-voltage stacks.

B. Analysis of the neural control concept

At the conceptual stage, the use of an artificial neural network (ANN) was considered as a decision-making element for correcting the Ton/Toff timings of individual transistors. The network would receive data from the U_{CE} (Ton/Toff) channels of all eight transistors and, based on voltage patterns and trends, would make decisions regarding timing corrections, warnings, or shutdown requirements.

Theoretical advantages:

- The network could identify nonlinear relationships between switching times and voltage levels.
- It would be capable of predicting transistor degradation or failure based on long-term changes in signal characteristics.
- In complex scenarios where conventional threshold-based logic is insufficient, the network could make context-aware decisions.

Despite these potential benefits, the concept was deliberately rejected due to the inability to guarantee full diagnostics and predictable behavior of the neural network under conditions critical to system safety.

Key concerns:

- Lack of decision transparency: As a black-box system, a neural network does not allow verification of why a particular corrective action was taken — or not taken.
- Inability to validate extreme scenarios: The network may react unpredictably to new combinations of input data that were not encountered during the training phase.
- Testing difficulties: It is impossible to perform deterministic unit or functional tests due to the non-deterministic nature of network inference.
- No independent fallback mechanism: Overriding or replacing the network with a simpler backup logic in emergency conditions is difficult to implement.

<u>In a system where a single incorrect switching decision may result in damage to a complex assembly of high-cost, high-voltage power transistors, it is essential to preserve a deterministic and auditable control logic.</u>

C. Algorithmic control approach to voltage balancing in pulsed power switches

This approach enables not only safe correction of switching parameters but also full control over debugging, testing, and certification of the system in high-voltage applications requiring increased reliability.

1) Problem statement and its importance

During commutation as shown in Fig. 2, each transistor in the series-connected stack should ideally share the voltage in proportion to its position. However, differences in switching times cause certain transistors to temporarily experience excessive voltage — often significantly exceeding their nominal U_{CE}max — for fractions of a microsecond. In the worst-case scenario, this may lead to internal breakdown and catastrophic failure of the system.

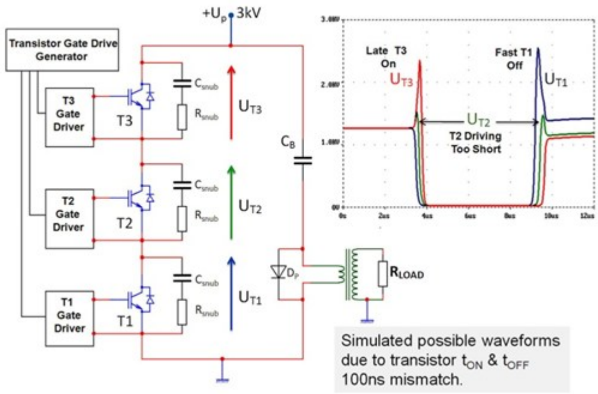

Fig. 2. Simulated impact of a 100 ns Ton/Toff mismatch on voltage distribution in a series IGBT stack.

2) Role of local snubbers.

Each transistor is equipped with a local RC snubber, whose primary function is to absorb energy resulting from transient overvoltage and to limit du/dt. Properly selected snubber fixed [1] capacitances combined with resistors form a low-pass filter with a relaxation time matched to the average switching duration. In the event of a sudden U_{CE} surge, the snubber absorbs a portion of the excess energy. However, it does not provide effective protection against voltage spikes if the mismatch exceeds a certain threshold (e.g., >100 ns).

III. DYNAMIC SWITCHING TIME CORRECTION SYSTEM

A. Role of TVS Diodes

TVS (Transient Voltage Suppressor) diodes are responsible for clamping peak voltages during sudden imbalances. These devices can absorb single pulses in the range of several tens of joules with pulse durations of ~100 ns without damage. Connected in parallel to each transistor, a series TVS assembly clamps the voltage above a predefined threshold (e.g., 2.5 kV), protecting the transistor from breakdown. A key advantage of modern TVS components based on diffused silicon structures (e.g., 5KP, 15KP series) is their sub-nanosecond response time (~1 ns), provided they are correctly mounted with minimal stray inductance.

B. Switching Time Correction

A cornerstone of the entire system as shown in Fig. 3 is the individual control of Ton/Toff timing for each transistor. Corrections are performed in discrete steps (e.g., 20 ns), and overvoltage detection is achieved through an analog optical link that transmits U_{CE} (Ton) and U_{CE} (Toff) signals from each transistor to a central analysis unit.

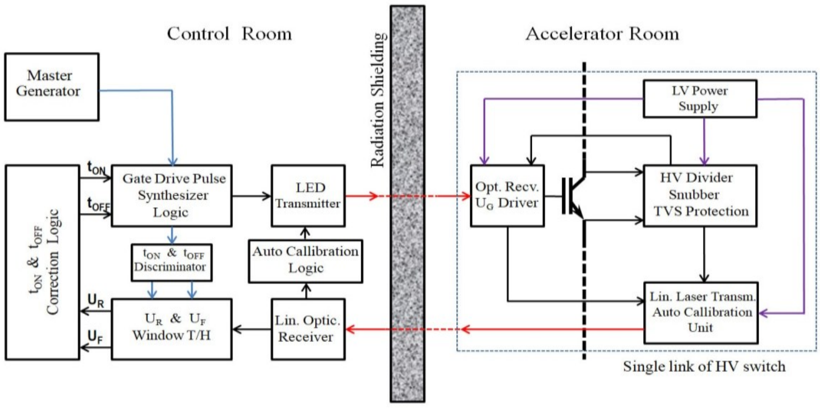

Fig. 3. Split architecture of switch control system

C. *Ground-Level Analysis Unit*

All U_{CE} signals from the transistors are transmitted via analog optical links, unlike to [2], to a shared analysis module referenced to ground potential. This module divides the commutation period into two phases: Ton (rising edge) and Toff (falling edge). For each phase, the instantaneous collector-emitter voltage U_{CE} is recorded and stored (shown in Fig. 4) for later comparison and analysis.

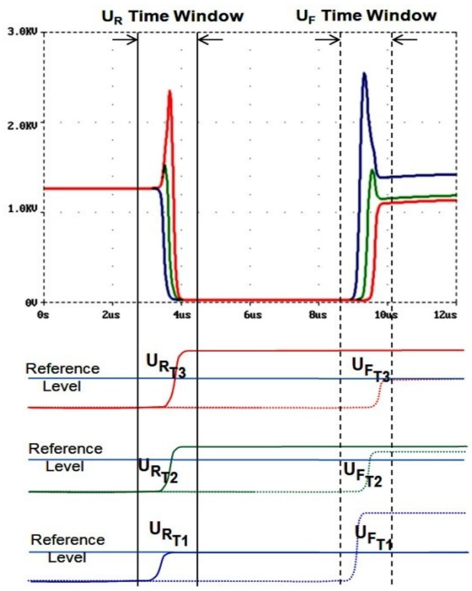

Fig. 4. T/H captured instantaneous collector-emitter U_{CE} voltage of each transistor

Based on deviations from a reference level U_{REF}, the system applies a three-threshold decision algorithm, for example:

- Timing correction: If $U_{CE} > U_{REF} + 30\%$, the system introduces a 20 ns timing correction for the next pulse.
- Warning: If $U_{CE} > U_{REF} + 45\%$, a 30 ns correction is applied, and a diagnostic warning is triggered.
- Alarm state: If $U_{CE} > U_{REF} + 75\%$, an immediate shutdown of the entire switching system is issued due to compromised operational safety.

Typical disturbances identified by the system (as it is shown in Fig. 2):

- Late turn-on: A delayed turn-on results in excessive voltage on the transistor (U_{CE} overshoot).
- Early turn-off: Premature switching off causes a rise in the transistor's collector-emitter voltage.
- Pulse too short: Insufficient conduction time leads to voltage stress during both the rising and falling edges.

This decision-making structure enables not only real-time system adjustments but also facilitates observation and reporting of phenomena related to component degradation, system aging, or unexpected disturbances in control signals.

D. *Gate Pulse Synthesis Unit*

Gate pulse synthesis for each transistor is performed locally, using a primary reference signal and an individual timing correction stored in a register or latch. The system features two independent control paths:

- A delay path for the rising edge (Ton),
- A delay path for the falling edge (Toff).

Each path is equipped with a dedicated programmable timer to adjust the corresponding edge. The synthesizer receives analog signals proportional to U_{CE} at the Ton and Toff moments via local ADCs, sampled during the previous switching cycle. Based on the stored correction parameters, it generates a local GATE_OUT pulse with a defined phase and duration.

This architecture allows independent control of each pulse edge, enabling precise fine-tuning without time-shifting the entire gate signal. Such granularity helps isolate and identify the causes of overvoltage stress, thereby improving diagnostic accuracy.

E. *TVS Operation Under Real Conditions*

Although a single overvoltage pulse can exceed 1 kA within 100 ns, the total energy dissipated is typically only around 0.04 J. The TVS diode has approximately 2 ms to dissipate this heat before the next pulse occurs. A sequence of 5–6 such pulses during the tuning phase does not exceed the Safe Operating Area (SOA) of the device. Therefore, the TVS acts as a transient buffer during the system's adaptation process.

As a conclusion - the combination of three protection layers — local RC snubbers, TVS diodes, and a global snubber — together with an adaptive switching time correction system, forms an effective dynamic voltage-balancing strategy for IGBT stacks. The system does not require perfectly matched transistors; instead, it relies on accurate observation, detection, and correction with a time resolution of 20 ns. TVS elements do not operate continuously but serve as fast-response fuses, activated only during critical dynamic events.

F. *Alternative Methods for Predicting Component Degradation*

To monitor and anticipate progressive degradation (e.g., from radiation or temperature stress) in power transistors and other components within a series-connected system, data-driven and physics-based modeling methods can be used instead of neural networks. Effective and transparent strategies include:

- Monitoring long-term changes in U_{CE}(on) : A gradual increase in the saturation voltage during conduction is indicative of junction degradation, such as increasing thermal resistance or damage to the power channel. Data collected from each pulse can be used to build trend graphs.
- Analyzing Ton and Toff as functions of temperature and duty cycle: Changes in the U_{CE} slope during switching events may reveal deteriorating transition characteristics or issues with the gate drive circuitry.
- Detecting minor overshoots in previously stable sequences: Even below alarm thresholds, recurring micro-deviations — so-called micro-anomalies — may suggest microcracks or parameter drift.
- Analyzing timing correction statistics: For each transistor, a histogram of applied corrections (magnitude and direction) can be maintained. A trend of unidirectional corrections may indicate a permanent timing drift (e.g., Ton consistently shifting later).
- Correlating local temperature measurements with correction trends: A local rise in temperature that coincides with an increased need for corrections may point to heat dissipation issues or degradation of the silicon structure.
- Comparing relative changes across transistors at the same voltage level: Assuming identical devices, any significant behavioral divergence may signal the onset of failure in a specific transistor.

All of the above methods rely on simple numerical data (voltages, timings, temperature, correction frequency) and can be processed using standard deterministic algorithms, allowing full traceability and validation. Integrating these techniques creates a predictive-diagnostic layer that supports operators or enables automated, condition-based maintenance decisions.

The described approach integrates the precision of optical diagnostics, adaptive timing control, and analog pulse protection, providing a modern method for voltage management in high-voltage (HV) systems requiring critical reliability.

IV. Experimental

Modulator based on partial capacitor discharge [3] architecture was applied as the linac klystron pulse power source. Fig. 5 shows charge/discharge path with indicated circuits preventing resonant oscillations.

A capacitor energy bank C_B consisting of three capacitors, each rated at 10 µF and very low parasitic inductance, connected in parallel, was used. During the pulse duration, the voltage amplitude decreases from approximately 126 kV to 122 kV. According to specifications provided by the klystron manufacturer, such a change in voltage amplitude results in a variation of klystron output power from 5.2 MW to 4.6 MW. A 3% change in voltage amplitude corresponds to a 13% variation in output power.

A complete pulse transformer with a voltage ratio of 1:10 — comprising the pulse transformer itself, oil tank, klystron filament transformer, choke, capacitive voltage divider, and coupling capacitors. Owing to its innovative design and precisely wound windings, the transformer achieves a voltage rise time of approximately 1 µs, even for relatively long pulse durations reaching 16–18 µs.

In the setup described and shown in Fig. 5, the primary winding inductance of the pulse transformer is 2.4 mH. This limits the expected current rise rate of the high-voltage switch to approximately 46 A/µs during the initial voltage rise across the klystron. Such a constraint benefits the dynamic voltage balancing process across U_{CE} junctions via the RC snubber branches.

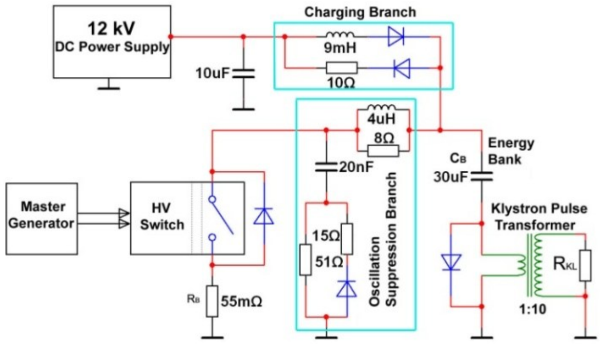

Fig. 5. Simplified schematic of charge/discharge path in the klystron modulator including Global Snubber preventing U/I resonant oscillations.

A. *Global Snubber*

In addition to local snubbers and TVS diodes, a global snubber is implemented across the entire series-connected switch assembly. The snubber consists of a (22 nF + 51 Ω) network in parallel with a diode and a 15 Ω resistor.

Its function is to absorb energy from the shared stray inductance (from both the circuit and the transformer) and to suppress high-frequency oscillations arising from the tendency of discharge circuit components to enter local resonance with parasitic capacitances.

V. Results

The experimental setup shown in Photo. 1. was temporarily assembled using a PC-based platform as the central analysis and decision-making unit. This configuration serves as a development environment for implementing and testing control algorithms prior to the final integration of the switching system into its target high-voltage klystron modulator device.

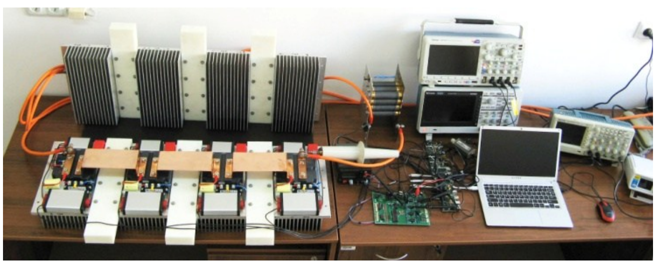

Photo. 1. Experimental setup based on PC.

Preliminary results of adaptive gate timing regulation for a four-transistor configuration are presented in Fig. 6.

The control system is under active development and will be transitioned to a dedicated embedded computing platform featuring real-time diagnostics, fail-safe mechanisms, and operator communication interfaces.

The proposed solution, once finalized and implemented, will open new opportunities in the design of high-power pulse switches for mission-critical equipment.

Such systems are essential in applications requiring high reliability and precise timing control—particularly in areas like pulsed accelerators, radiation processing systems, electromagnetic launchers, or advanced plasma generators—where fault tolerance and dynamic switching integrity are paramount.

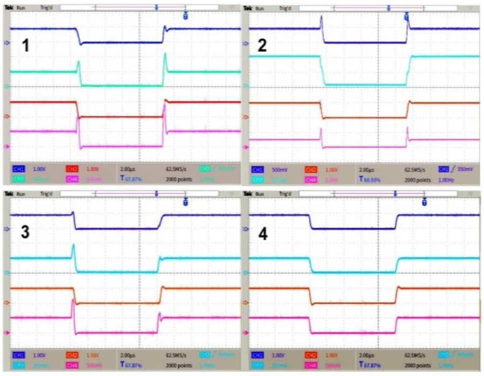

Fig. 6. Oscilloscope image showing successive stages of iterative overvoltage regulation in the system.

VI. CONCLUSIONS

This work demonstrates a novel approach to dynamic voltage balancing and real-time control in high-voltage IGBT switching systems. By integrating adaptive Ton/Toff correction algorithms, multilayer overvoltage protection, and optical feedback diagnostics, the proposed architecture achieves precise timing regulation without requiring perfectly matched semiconductor devices.

A key contribution of this system is its modular and scalable design, which enables individualized gate control and deterministic timing corrections with sub-20 ns resolution. The introduction of a reference-anchored decision space eliminates timing drift, while the use of optical signal acquisition allows non-intrusive, high-speed monitoring of switching behavior.

Experimental validation of a four-transistor prototype confirms the effectiveness of the adaptive regulation strategy, which will be further developed on a dedicated embedded platform with diagnostic and communication interfaces.

The proposed concept lays a foundation for the next generation of high-reliability, pulse-mode switching systems used in specialized high-voltage applications, including radiation processing, accelerator technology, and industrial pulsed power. Its ability to predict and compensate for component degradation in real time makes it particularly suitable for systems where failure tolerance and service continuity are critical.

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