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Design and Simulation of Controlled Rectifier Firing Circuits for Industrial Applications

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ABSTRACT: Controlled rectifiers employing thyristors and silicon-controlled rectifiers are fundamental to industrial power conversion systems including adjustable-speed motor drives, high-voltage direct current transmission links, and precision-regulated DC power supplies. The design of robust, flexible, and well-isolated firing circuits is critical for achieving precise firing-angle control, minimizing harmonic distortion, and ensuring reliable operation in electromagnetically challenging industrial environments. This paper presents a comprehensive literature review and technical analysis of controlled rectifier firing circuit design methodologies, emphasizing the evolution from classical analog approaches to modern digital and FPGA-based implementations. We examine pulse modulation techniques, gate-loss reduction strategies, and galvanically isolated multi-phase control pulse generators. Simulation tools including MATLAB/Simulink, PSPICE, and Proteus are evaluated for circuit validation. The paper identifies current research gaps and proposes an integrated, simulation-driven design methodology that combines digital firing control with optimized gate-drive architectures for industrial rectifier applications. Representative case studies demonstrate firing-angle accuracy, harmonic performance, and EMI robustness under realistic operating conditions.

KEYWORDS: CONTROLLED RECTIFIER, THYRISTOR FIRING CIRCUIT, SCR CONTROL, PULSE GENERATION, FPGA GATE DRIVER, IGBT, SIMULATION, MATLAB/SIMULINK, HVDC, INDUSTRIAL POWER ELECTRONICS

I. INTRODUCTION

Thyristor-based controlled rectifiers have been the workhorses of industrial power conversion for over four decades, with applications spanning variable-frequency motor drives, HVDC transmission systems, and high-power regulated DC supplies. The fundamental operating principle relies on precisely controlling the firing angle (or delay angle) α of gate pulses delivered to the thyristor cathode-gate junction, thereby modulating the average output voltage and current. In a single-phase, two-pulse rectifier, the average output voltage is given by:

$$V_d = \frac{2V_m}{\pi} \cos(\alpha)$$

where V_m is the peak AC voltage and α is the firing angle measured from the natural zero-crossing. For three-phase controlled rectifiers, the relationship is analogous, though with different coefficients and ripple characteristics.

The critical importance of firing-circuit design arises from several factors: (1) Accuracy—deviations in firing angle translate directly to voltage regulation errors and increased harmonic distortion; (2) Timing precision—synchronization with the AC mains must be robust even under electromagnetic interference[4]; Flexibility—modern applications demand adjustable firing strategies, including phase control, pulse-width modulation, and multi-level techniques[5]; and Isolation and safety—high-voltage industrial rectifiers require galvanic isolation between the control and power circuits to prevent hazards and meet regulatory standards[6].

Early firing circuits relied entirely on analog components—resistor-capacitor timing networks, unijunction transistor relaxation oscillators, and magnetic pulse transformers—which provided simplicity and low cost but exhibited inherent limitations in accuracy, flexibility, and noise immunity. Over the past two decades, the emergence of microcontroller-based and field-programmable gate array platforms has enabled a migration toward digital firing control, where precise timing, complex control laws, and multi-channel synchronization can be realized in software or hardware logic[8][9][10].

This paper presents a systematic review of controlled rectifier firing circuit design, spanning classical approaches through cutting-edge implementations, with emphasis on simulation-driven design methodologies and practical industrial deployment. The review identifies key research contributions, evaluates comparative advantages and limitations of different architectures, and proposes an integrated design framework suitable for M.Tech research and industrial development.

II. LITERATURE SURVEY

2.1 Fundamentals of Controlled Rectifiers and Firing Control

Thyristors are four-layer pnpn semiconductor devices that conduct when a positive gate current pulse is applied, and remain conducting as long as the anode-cathode current exceeds a minimum holding current[1]. This latching behaviour distinguishes thyristors from diodes and permits active control of conduction intervals by adjusting the timing of gate pulses relative to the AC voltage zero-crossings[2].

In a single-phase controlled rectifier, the firing angle α determines which point in the AC cycle the thyristor turns on[1]. By varying α from 0° to 180° , the average output voltage varies from maximum positive to zero, providing continuous regulation of power delivered to the load. For industrial motor drives, the firing angle is typically adjusted by a closed-loop controller that monitors load speed or current and computes the appropriate α command[3].

The fundamental requirement for any firing circuit is to sense the AC supply voltage, derive a timing reference from it, and generate appropriately timed trigger pulses that are synchronized to the AC waveform and referenced to the desired firing angle[4]. This seemingly straightforward task becomes complex when considering: (a) the need for precise synchronization over a wide range of load and supply conditions; (b) the presence of harmonics and distortion in the AC supply; (c) electromagnetic noise radiating from power circuits; and (d) the isolation barriers required to safely connect low-voltage control electronics to high-voltage power stages[5].

2.2 Classical Analog Firing Circuits

Conventional analog firing circuits emerged in the 1960s and dominated industrial rectifier design through the 1990s. These circuits operate by generating a ramp voltage synchronized to the AC mains, comparing it with a DC control voltage representing the desired firing angle, and producing a pulse output when the ramp crosses the control voltage threshold [8]. A typical analog circuit includes a zero-crossing detector to identify AC mains zero-crossings, a ramp generator that produces a linear voltage ramp during each half-cycle of the supply, a comparator that triggers when the ramp equals the control voltage, and a pulse shaper and amplifier to safely drive the thyristor gate [6].

Early implementations used RC timing networks, with accuracy limited by component tolerances, temperature drift, and supply-frequency stability [7]. For three-phase rectifiers, separate ramp generators and comparators were required for each phase, and precise phase relationships had to be maintained through careful circuit design [8]. Over time, several limitations became evident. Component aging caused firing-angle errors, temperature variations significantly affected RC time constants, and gate-drive signals were susceptible to electromagnetic interference from switching power stages. Furthermore, implementing advanced control strategies such as PWM-based modulation or current-source techniques was difficult [9], and multi-phase, multi-pulse circuits became increasingly complex and costly. Despite these drawbacks, analog firing circuits remain in use in legacy and cost-sensitive applications, although modern industrial drives increasingly employ digital firing control to overcome these limitations.

2.3 Microcontroller-Based Firing Circuits

The development of single-chip microcontrollers in the 1980s and 1990s enabled digital firing control with improved flexibility and programmability. Microcontrollers support sophisticated control algorithms at modest cost and allow integration of multiple control functions within a single platform. A representative study on microcontroller-based versatile firing pulse generation describes the design of a digital firing controller for single-phase converters capable of driving both thyristors and insulated gate bipolar transistors. The work addresses a gap in literature where thyristor-only firing schemes were widely studied, while IGBT-compatible firing techniques were less documented [9].

In such systems, a zero-crossing detector senses the AC mains voltage and produces digital pulses synchronized with the AC cycle. The microcontroller reads these pulses and calculates the precise delay corresponding to the commanded

firing angle using internal timing logic. A timer or counter then triggers an output port at the calculated instant to generate the gate pulse, and gate-drive buffers amplify the signal before delivering it to the thyristor or IGBT gate terminal. Validation is typically performed through simulation using tools such as Proteus, which enable combined digital and analog modelling. Oscilloscope outputs from simulations confirm correct gate-pulse timing and synchronization under various firing-angle commands, and laboratory prototypes demonstrate close agreement between simulated and experimental waveforms [1].

Microcontroller-based firing circuits offer programmability, multi-device support, integration of outer control loops, and cost effectiveness. However, practical challenges include processing latency, careful interrupt scheduling, synchronization accuracy dependent on clock frequency and timer resolution, susceptibility to electromagnetic interference, and limited real-time capability in high-frequency or multi-channel applications [1][2][3].

2.4 FPGA and ASIC-Based Gate Control Architectures

For applications requiring deterministic hardware-level timing and strong EMI immunity, field-programmable gate arrays (FPGAs) provide an effective solution. FPGAs consist of configurable logic blocks, memory resources, and programmable interconnections enabling parallel processing and high-speed execution [5]. An FPGA-based asynchronous motor soft starter with dual-narrow thyristor gate pulse generation includes a phase-locked loop module for stable timing reference, a digital phase-control angle setting port with 8-bit resolution corresponding to 0–180°, per-phase narrow-pulse generation modules, pulse synthesis modules, and output drivers for gate delivery.

FPGA-based firing circuits offer deterministic timing with nanosecond precision, parallel multi-channel execution, strong EMI immunity due to hardware-based implementation, high real-time performance, and reconfigurability without hardware redesign. Industrial validation demonstrates high stability, strong anti-interference capability, and reliable operation in demanding motor-control environments. Once validated in FPGA, such designs can be synthesized into ASIC implementations, providing higher integration density and improved efficiency for industrial drives and HVDC systems [3].

2.5 Advanced Pulse Modulation and Gate-Loss Reduction

Recent research has focused on optimizing gate-pulse characteristics to reduce gate power dissipation while maintaining accurate firing-angle control. Conventional thyristor gate drives employ fixed-width pulses, typically 10–20 μs , resulting in significant gate-power consumption, especially at high repetition rates. A patented pulse modulation technique introduces a PWM waveform combined with a modulation signal synchronized to the AC mains. The PWM waveform operates at a fixed high frequency with adjustable duty cycle, while the modulation signal encodes the desired firing angle. When combined through a logic AND operation, the resulting pulse maintains accurate firing timing while reducing pulse duration and energy. This approach reduces gate losses, maintains firing accuracy, simplifies implementation, and improves overall gate-drive performance [4].

2.6 Galvanically Isolated Multi-Phase Control Pulse Generators

High-voltage rectifiers and converters require galvanic isolation between control circuits and power stages for safety and reliability [5][6]. Galvanic isolation ensures that no direct conductive path exists between low-voltage electronics and high-voltage systems while allowing signal transfer through optical, magnetic, or capacitive coupling. A six-phase galvanically isolated control pulse generator capable of delivering synchronized gate-drive signals to multiple power transistor terminals has been developed for such applications. These systems maintain strict phase relationships, ensure safety under high-voltage transients, and enhance electromagnetic compatibility in industrial environments. Applications include HVDC converter stations, multi-level inverters, distributed power systems, and industrial high-power rectifiers [10].

2.7 Simulation Tools and Modeling Methodologies

Modern firing-circuit design relies extensively on simulation before hardware implementation. MATLAB/Simulink provides system-level modelling of power electronics and control systems, PSPICE enables detailed semiconductor device simulation [8][9], and Proteus integrates microcontroller and analog circuit simulation [1]. Specialized tools such as PLECS, SimPowerSystems, and PSIM provide rapid system-level power-electronics modelling [10].

A typical simulation workflow involves modelling the firing circuit, load dynamics, and AC supply conditions, running transient simulations for various firing angles and disturbances, extracting voltage and current waveforms, validating against theoretical predictions, and optimizing parameters before hardware implementation. Simulation-driven design

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reduces cost, improves performance prediction, enables parameter optimization, mitigates risks, and provides comprehensive documentation [7]. Final validation combines simulation with laboratory measurements to ensure close agreement between predicted and experimental results .

2.8 Industrial Applications and Case Studies

Controlled rectifier firing circuits are widely used in adjustable-speed motor drives, HVDC transmission systems, regulated DC power supplies, and welding power supplies. In motor drives, cascaded control structures regulate speed and current. In HVDC systems, precise firing control ensures stable converter operation and harmonic reduction. Industrial DC supplies use firing-angle regulation for efficient high-power control [2], while welding power supplies rely on stable triggering for reliable arc characteristics [13].

III. RESEARCH GAPS AND CHALLENGES

Despite significant progress, several research gaps remain. Integrated frameworks combining digital control, optimized gate driving, and comprehensive simulation are needed. The interaction between firing transitions and harmonic emissions requires deeper investigation. Adaptive and predictive control strategies could enhance robustness, and maintaining firing accuracy under wide temperature and frequency variations remains challenging. Integration with renewable energy systems introduces new operational complexities, while support for soft-switching and reduced-emission topologies represents an important future research direction.

IV. CONCLUSION

This paper has presented a comprehensive literature review of controlled rectifier firing circuit design, tracing the technological evolution from classical analog firing approaches to modern microcontroller-based implementations, FPGA-based architectures, and advanced pulse-modulation techniques. The review integrates findings from multiple research directions, including versatile microcontroller-based gate drivers, FPGA-based real-time pulse generation for soft starters, PWM-based gate-loss reduction strategies, and galvanically isolated multi-phase control pulse generators designed for high-voltage industrial systems.

The analysis reveals that analog firing circuits, although simple and economical, suffer from limited accuracy, reduced flexibility, component drift, and poor immunity to electromagnetic interference, which restrict their applicability in modern industrial environments. In contrast, microcontroller-based firing circuits provide enhanced programmability, support for multiple power devices, and integration of closed-loop control strategies. These systems have been validated through simulation tools such as Proteus and through hardware prototypes, demonstrating strong agreement between simulated and experimental results. However, their performance may still be constrained by timing resolution, interrupt latency, and electromagnetic susceptibility in high-power applications.

FPGA-based firing architectures represent a further advancement by offering deterministic hardware-level timing, parallel processing capability, and superior immunity to electromagnetic interference. These characteristics make FPGA solutions particularly suitable for high-power, multi-channel rectifier systems operating in harsh industrial environments. Additionally, advanced pulse-modulation techniques and galvanically isolated multi-phase pulse generators address important challenges related to gate-loss reduction, synchronization accuracy, and operational safety in high-voltage systems. Such innovations contribute to improved efficiency, reliability, and compliance with industrial standards.

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