10.48047/jocaaa.2024.32.02.74

RECENT ADVANCES IN FRACTIONAL-ORDER CONTROL SYSTEMS: THEORY, DESIGN, AND ENGINEERING APPLICATIONS

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Abstract Fractional-order control (FOC) has moved from a niche "better-than-integer" idea into a practical design option across power electronics, renewable-energy-integrated grids, robotics, and networked cyber-physical systems. The reason is simple: many real processes are not memoryless. Their dynamics depend not only on the present state but also on a history of states—through diffusion, viscoelasticity, electrochemical polarization, thermal accumulation, hysteresis, and unmodeled distributed parameters. Fractional calculus embeds this memory directly into models and controllers by allowing integrals and derivatives of non-integer order. Over the last few years, and especially in 2023, progress has accelerated in five directions: (i) application-driven fractional modeling and identification, (ii) robust fractional-order PID families and systematic tuning workflows, (iii) fractional sliding-mode, backstepping, and disturbance-observer designs that reduce chattering while improving disturbance rejection, (iv) fractional predictive control variants that better balance fast switching and constraint handling, and (v) stability/consensus tools for multi-agent and uncertain nonlinear fractional systems with event-triggered communication. This paper synthesizes these recent advances with an engineering emphasis: what changed in design practice, what worked in implementations, and where the hardest open problems remain—particularly around discretization, order selection, and verification. Two summary tables are included to (1) map controller families to their typical advantages and pitfalls and (2) link application domains to design objectives, common performance indices, and implementation constraints.

Keywords: fractional-order control; fractional calculus; FOPID (PI^λD^μ); fractional sliding mode control; active disturbance rejection control (ADRC); fractional extended state observer (FOESO); model-free predictive control; renewable energy and power electronics; multi-agent consensus; stability and robustness

1. Introduction Fractional-order control extends classical control by replacing integer-order operators with non-integer ones. In an integer-order PID, integration accumulates error with

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order 1 and differentiation anticipates change with order 1. In a fractional PID—commonly written as PI^λD^μ—both the integral order (λ) and derivative order (μ) become continuous design parameters. That one conceptual shift gives engineers two extra degrees of freedom, often letting a controller shape phase and gain more smoothly, improve robustness, and handle long-memory effects without inflating controller order through ad hoc filters.

In 2023, research momentum was strongly driven by application demands. Renewable energy and storage systems, for example, brought fast switching, high uncertainty, and grid-code constraints that stress classic tuning heuristics; survey work in 2023 consolidated these motivations and highlighted why fractional controllers can better handle the combined dynamics of power converters, machines, storage, and grid interactions (Alilou et al., 2023). In robotics, fractional modeling and control were reviewed with a hardware-aware lens, emphasizing hysteresis-like and memory-driven effects in joints, actuators, and flexible links, and showing where fractional dynamics improves tracking and disturbance handling (Bingi et al., 2023). In modern interconnected power systems, load-frequency control (LFC) has become harder because renewable intermittency changes the disturbance profile; in 2023, intelligent fractional-order LFC designs were proposed and evaluated with virtual inertia concepts and modern stability constraints (Zaid et al., 2023). Meanwhile, the theoretical base also matured: stability concepts for uncertain nonlinear fractional systems, fuzzy approximators, and observer structures were developed to make the designs less "hand-tuned" and more verifiable (Ma & Sun, 2023; Rhaima et al., 2023).

A recurring engineering question is: what exactly did "recent advances" add beyond "fractional PID is flexible"? The 2023 literature indicates five concrete advances that matter in practice:

1.1 **Controller families expanded beyond FOPID** into fractional backstepping with finite-time command filtering (Ma et al., 2023), fractional sliding-mode designs for robotics and actuators (Chaudhary & Kumar, 2023; Yang et al., 2023), and fractional disturbance-observer frameworks used inside larger controllers (Wang et al., 2023; Dou et al., 2023).

1.2 **Model-free and predictive frameworks began to adopt fractional operators** to improve robustness when plant models are uncertain or time-varying, particularly for inverter-based systems (Albalawi et al., 2023).

1.3 **Event-triggered and distributed control for fractional-order multi-agent systems** matured, targeting bandwidth reduction while guaranteeing Zeno-free operation and consensus (Jin et al., 2023; Ye et al., 2023).

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1.4 **Optimization-based tuning became more tool-like** (not only "use metaheuristics"), with new tuning tools and improved algorithms demonstrated on benchmark plants such as AVR and grid subsystems (Tumari et al., 2023; Mohd Tumari et al., 2023; Hongesombut et al., 2023).

1.5 **Survey consolidation** in 2023 helped unify terminology, application categories, and comparison baselines in fractional optimal control and energy systems (Abd-Elmonem et al., 2023; Alilou et al., 2023).

The remainder of this paper is organized into six major headings (including references). Within the major headings, short numbering is used only where it clarifies design steps or comparisons.

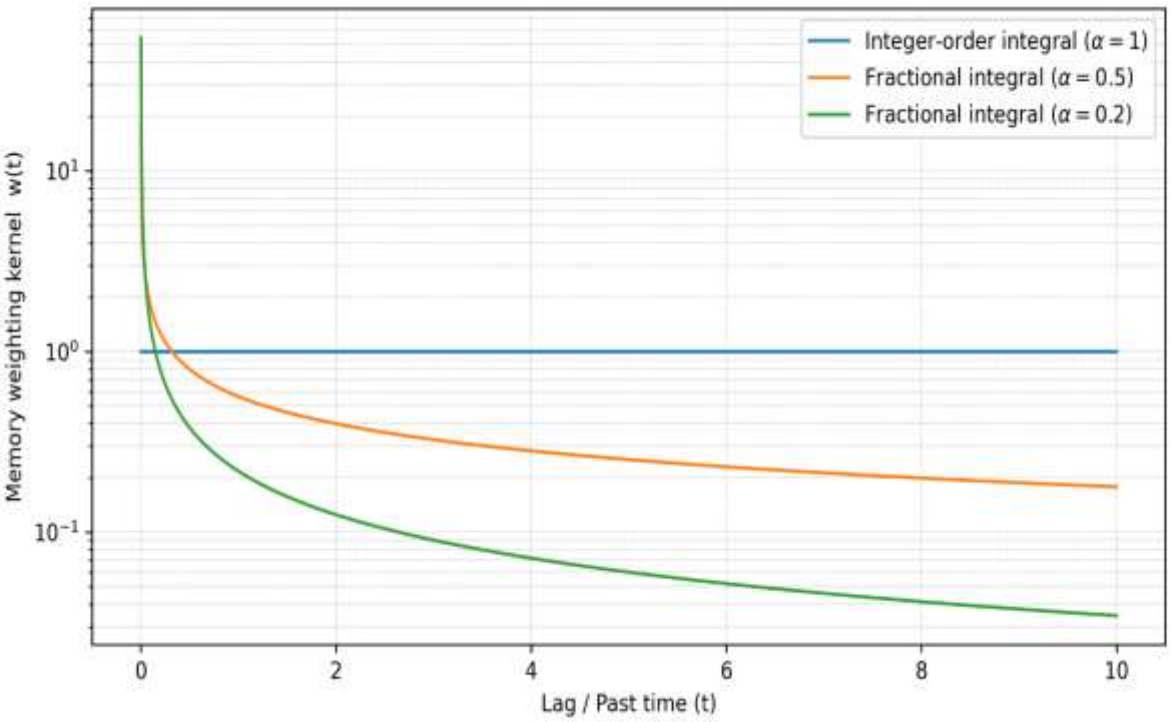

Figure 1. Conceptual comparison between integer-order and fractional-order differentiation and integration illustrating memory effects in dynamic systems.

2. Recent theoretical developments enabling better designs

FOC designs are only as trustworthy as the stability and robustness tools supporting them. A key 2023 trend was to move stability statements from informal frequency-domain intuition into more structured Lyapunov, Mittag–Leffler, and practical stability results—especially for uncertain nonlinear systems, fuzzy systems, and systems with disturbances.

2.1 **Stability notions aligned with "engineering reality" (practical stability)** Classical asymptotic stability (state → 0) is often too strict when disturbances, quantization, and unmodeled dynamics exist. A 2023 direction emphasized *practical* forms of stability that

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guarantee boundedness within a tolerable neighborhood. For example, practical Mittag–Leffler stability results for fractional-order nonlinear fuzzy systems formalized conditions under uncertainty that better resemble what engineers validate in experiments (Rhaima et al., 2023). This matters because many fractional designs are deployed in noisy industrial settings where exact convergence is unrealistic, but predictable bounded performance is essential.

2.2 Fractional observers and disturbance estimation as "core infrastructure"

In modern control practice, disturbance observers are often as important as feedback gains. Fractional extended state observers (FOESO) and related ideas appeared in 2023 as a strong theme: instead of treating disturbances as simple additive signals, FOESO variants aim to estimate disturbances in systems where the plant itself has memory. In 2023, active disturbance rejection control (ADRC) with fractional-order extended state observer mechanisms was explored to enhance estimation performance and improve disturbance rejection using additional plant information (Wang et al., 2023). In space or free-floating manipulator contexts, fractional disturbance-observer-based sliding mode approaches were developed for robust tracking under disturbances and uncertainty (Dou et al., 2023). The key "advance" is architectural: rather than tuning a fractional controller alone, researchers increasingly co-design estimation and control layers, using fractional operators where memory impacts both states and disturbances.

2.3 Distributed and consensus control for fractional multi-agent systems

Fractional-order multi-agent systems (FOMAS) are important in swarms, microgrids, and networked robotics. In 2023, several works gave sharper consensus conditions and protocol designs, including sampled-data consensus depending explicitly on the fractional order, coupling gains, and sampling period (Ye et al., 2023), and robust consensus for uncertain fractional-order agents using matrix existence conditions (Riazat et al., 2023). Event-triggered distributed sliding mode control was also proposed in 2023 to reduce communication while guaranteeing consensus and avoiding Zeno behavior (Jin et al., 2023). The design takeaway is that "fractional order" cannot be treated as a cosmetic modification; it changes convergence rates and stability regions, so network protocols must explicitly account for it.

2.4 Fractional optimal control as a bridge between theory and computation

While many controllers remain PID-like, optimal control offers a unifying design language, especially when constraints and cost trade-offs matter. A 2023 survey of fractional-order optimal control problems consolidated formulations, solution approaches, and modeling motivations (Abd-Elmonem et al., 2023). This is a practical enabler: predictive control and constrained designs often rely on optimal control machinery, and having a clearer fractional

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optimal control toolkit supports the move toward fractional MPC variants in power and motion systems.

3. Controller synthesis and tuning advances in 2023

This section focuses on what engineers actually build: controller structures, tuning strategies, and performance criteria. The "recent advances" are not just new equations; they are new combinations of structures (fractional operators + robust design motifs) and more systematic tuning/optimization workflows.

Table 1. 2023-era fractional controller families—what they are good at, and what can go wrong

Controller family	**Typical structure**	**Where it shines**	**Common pitfalls / cautions**
FOPID (PI^λD^μ)	5 parameters (Kp, Ki, Kd, λ, μ)	Smooth phase shaping, robustness margins, flexible transient response; widely validated in power/AVR/LFC tuning (Tumari et al., 2023; Mohd Tumari et al., 2023; Hongesombut et al., 2023)	Over-parameterization → tuning ambiguity; discretization error; derivative noise sensitivity if μ near 1
Fractional sliding mode (FO-SMC / terminal SMC)	Fractional reaching laws + robust switching	Strong robustness to uncertainty; reduced chattering with fractional dynamics; strong tracking in robotics (Chaudhary & Kumar, 2023) and actuator systems (Yang et al., 2023)	Implementation chattering still possible; needs careful boundary layers; numerical approximation affects stability

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Fractional ADRC / FOESO-based control	FOESO + disturbance compensation	High disturbance rejection when memory effects matter; improved estimation performance in 2023 designs (Wang et al., 2023)	Observer tuning becomes critical; sensitivity to sampling and discretization; validation complexity
Fractional backstepping with command filters	Backstepping + FO finite-time filters/observers	Handles nonlinearities and avoids "explosion of complexity"; good for marine/vehicle tracking examples (Ma et al., 2023)	Design complexity; parameter dependence; requires good state estimation
Model-free predictive control with fractional operators	MFPC + FOC in loop	Works when accurate models are hard; shown for inverter voltage control (Albalawi et al., 2023)	Stability proof may be harder; computational load; needs careful constraint handling
Distributed/event-triggered control for FOMAS	Event-triggered SMC/consensus	Reduces communication; consensus with Zeno-free behavior (Jin et al., 2023; Ye et al., 2023)	Trigger design is delicate; network delays and packet loss need explicit treatment

3.1 **FOPID became more "engineered": tuning tools, benchmarks, and reproducibility**

The FOPID is still the most widely deployed fractional structure because it is close to standard PID practice. But 2023 added maturity by producing tuning tools and benchmark-oriented studies rather than only theoretical claims. For automatic voltage regulator (AVR) systems, a 2023 tuning tool using the Marine Predators Algorithm (MPA) was introduced and demonstrated strong performance in terms of transient response and robustness measures (Tumari et al., 2023). Complementary 2023 work improved the MPA-based tuning approach and reinforced the idea that metaheuristic tuning is most valuable when it is packaged as a reproducible workflow with explicit objective functions and constraints (Mohd Tumari et al., 2023). In energy systems, fractional-order PID strategies were also applied to frequency-related

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problems such as pumped-storage regional frequency control (Gong et al., 2023) and broader renewable-energy-integrated contexts summarized in a 2023 review (Alilou et al., 2023). For power-system damping and stability, energy-focused studies used fractional controllers combined with optimization algorithms (Hongesombut et al., 2023). The practical "advance" is not the algorithm name; it is the clearer mapping between objective functions (ISE/ITAE/overshoot/settling time), robustness constraints, and the selection of λ and μ rather than treating them as arbitrary.

3.2 **Fractional sliding mode: robust tracking with less chattering, closer to hardware**

Sliding mode control (SMC) is known for robustness but also chattering. A strong 2023 advance was the use of fractional reaching laws and terminal sliding concepts to reduce chattering while retaining robustness, especially in robotics. A 2023 ISA Transactions study presented fractional order fast terminal sliding mode control for robot manipulator tracking, explicitly targeting the classic trade-off between fast convergence and control smoothness (Chaudhary & Kumar, 2023). Another 2023 ISA Transactions work combined fractional modeling with neural-network-based sliding mode control for piezoelectric actuators, a class of systems where hysteresis/memory effects are significant and integer-order models often underperform (Yang et al., 2023). These are not just conceptual extensions: they indicate a shift to actuator-level validation and model structures that reflect memory dynamics.

3.3 **Fractional backstepping and finite-time command filtering: nonlinear control without complexity blow-up**

Backstepping is powerful for strict-feedback nonlinear systems but can suffer from "explosion of complexity" due to repeated differentiation of virtual controls. In 2023, designs used fractional-order finite-time command filters and disturbance observers to estimate needed derivatives and disturbances without amplifying noise as much as integer-order differentiation. A 2023 Fractal and Fractional paper proposed a backstepping control strategy for an unmanned surface vehicle using fractional finite-time command filtering and a fractional finite-time disturbance observer to improve tracking while controlling chattering (Ma et al., 2023). The broader lesson is that fractional filters can play a dual role: they reduce derivative estimation noise and encode memory, improving robustness in nonlinear tracking.

3.4 **ADRC with fractional observers: "estimate-and-cancel" for memory systems**

ADRC is popular because it turns unknown dynamics and disturbances into an "extended state" estimated by an observer, then cancels it. In 2023, this idea was strengthened for systems where memory cannot be ignored. A 2023 ISA Transactions paper examined ADRC with fractional-order extended state observer enhancements, aiming to improve estimation performance and

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disturbance rejection by leveraging plant information (Wang et al., 2023). In parallel, disturbance observer based fractional-order sliding mode schemes were demonstrated for free-floating space manipulators—systems that are highly nonlinear and disturbance-sensitive—emphasizing finite-time disturbance estimation (Dou et al., 2023). Together, these works point to an important design shift: fractional control is increasingly built as a *system architecture* (observer + robust controller + filters), not as a single block.

3.5 Predictive and model-free frameworks adopting fractional operators

Predictive control is valued for constraint handling; model-free predictive control (MFPC) is valued when modeling is hard. A 2023 study proposed fractional-order model-free predictive control for voltage source inverters, improving performance in UPS-like inverter applications where nonlinearities and parameter variations are common (Albalawi et al., 2023). The point is not that "fractional MPC is better," but that fractional operators can reshape how predictive control handles dynamics that exhibit memory effects, especially where switching, thermal accumulation, and load variations interact.

3.6 Distributed and event-triggered control: communication-aware fractional control

In networked cyber–physical systems, continuous information exchange is often impractical due to bandwidth limits, energy constraints, and delays. Fractional-order dynamics complicate this further because memory effects make stability sensitive to sampling and communication policies. In 2023, **event-triggered distributed control strategies** for fractional-order multi-agent systems (FOMAS) gained significant attention. Instead of periodic updates, control actions are triggered only when a state-dependent condition is violated. Jin et al. (2023) proposed an **event-triggered sliding mode consensus control** framework that guarantees convergence while explicitly avoiding Zeno behavior. Their results showed that fractional dynamics can actually *benefit* event-triggered schemes by smoothing state evolution, thereby reducing triggering frequency.

Similarly, Ye et al. (2023) analyzed **sampled-data consensus protocols** for fractional-order agents and derived explicit stability conditions linking sampling period, coupling strength, and fractional order. These results are practically relevant for microgrids, vehicle platoons, and sensor networks, where communication schedules must be co-designed with control laws. The 2023 literature therefore marks a shift from centralized, continuously updated fractional controllers toward **communication-aware, distributed implementations**, making fractional control more realistic for large-scale systems.

4. Application-driven advances across engineering domains

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Recent advances are best understood through applications, because fractional control is rarely adopted for elegance alone—it is adopted when it solves a real performance limitation.

Table 2. Application domains and 2023 fractional-order control trends

Application domain	Control objectives	Fractional advantage observed in 2023 studies
Power systems & renewable energy	Frequency regulation, voltage stability, damping oscillations	Improved robustness under uncertainty and renewable intermittency; smoother dynamic response (Alilou et al., 2023; Zaid et al., 2023; Gong et al., 2023)
Power electronics & inverters	Voltage/current regulation, fast transients	Better handling of switching dynamics and load variations using FOPID and fractional MFPC (Albalawi et al., 2023)
Robotics & actuators	High-precision tracking, disturbance rejection	Reduced chattering and improved tracking with fractional sliding mode and neural-enhanced designs (Chaudhary & Kumar, 2023; Yang et al., 2023)
Marine & vehicle systems	Nonlinear trajectory tracking	Fractional backstepping with finite-time observers improves robustness and convergence (Ma et al., 2023)
Multi-agent & networked systems	Consensus, coordination, reduced communication	Event-triggered and sampled-data fractional control ensures stability with lower bandwidth (Jin et al., 2023; Ye et al., 2023)

In **power and energy systems**, 2023 work emphasized grid resilience under renewable penetration. Intelligent fractional-order load frequency control schemes demonstrated better damping and robustness than classical integer-order designs under stochastic disturbances (Zaid et al., 2023). Reviews consolidated how fractional controllers integrate naturally with virtual inertia and modern grid codes (Alilou et al., 2023).

In **robotics and smart actuators**, fractional-order sliding mode and neural-assisted controllers were shown to outperform classical designs when hysteresis, friction, and memory effects dominate. These studies reinforced the idea that fractional dynamics are not merely mathematical curiosities but physically meaningful representations of real hardware (Bingi et al., 2023; Yang et al., 2023).

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In **distributed systems**, fractional consensus control bridged control theory with communication constraints, aligning well with Industry 4.0 and smart infrastructure requirements. Overall, applications in 2023 demonstrated that fractional control is transitioning from laboratory demonstrations to **system-level solutions**.

5. Challenges, open problems, and research directions

Despite clear progress, several challenges remain unresolved and define the next research frontier.

5.1 Discretization and real-time implementation

Most fractional operators rely on numerical approximations (e.g., Grünwald–Letnikov, Oustaloup filters). In real-time embedded systems, memory length, sampling rate, and computational load remain limiting factors. Although 2023 studies demonstrated successful implementations, a unified guideline for balancing accuracy and efficiency is still lacking (Bingi et al., 2023).

5.2 Order selection and physical interpretability

Choosing fractional orders (λ, μ) is often optimization-driven rather than physics-driven. While optimization tools in 2023 improved tuning reproducibility (Tumari et al., 2023), the link between fractional order and underlying physical mechanisms remains an open question, especially for certification-critical applications.

5.3 Stability certification and standards

Although Lyapunov and practical stability results expanded in 2023 (Rhaima et al., 2023; Ma & Sun, 2023), industrial adoption requires clearer certification pathways comparable to classical control standards. Bridging theory with verification tools is a pressing need.

5.4 Integration with AI and data-driven control

Neural networks and learning-based methods increasingly appear inside fractional controllers (Yang et al., 2023). However, guaranteeing stability, interpretability, and safety remains challenging. Future research must integrate learning with fractional control without sacrificing analytical guarantees.

6. Conclusions

a **consolidation phase** for fractional-order control systems. Advances were not limited to new controller equations but extended to observer design, distributed architectures, optimization-based tuning, and application-driven validation. Fractional controllers demonstrated clear benefits in systems with memory, uncertainty, and strong nonlinearities—particularly in

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renewable energy, power electronics, robotics, and networked systems. At the same time, challenges related to discretization, order selection, and certification remain. Overall, recent advances indicate that fractional-order control is evolving from an academic alternative into a **practical, system-level design paradigm**, especially when combined with robust control, disturbance observers, and modern optimization techniques.

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