

Advanced Control Techniques: Super-twisting Controller Applications and Insights

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Abstract

Sliding mode control (SMC) provides robust control for uncertain systems. This study focuses on the Super-Twisting Controller (STC), a powerful SMC technique known for its finite-time convergence and robustness. Its importance is to provide chatter-free control and robustness against uncertainty, and make it suitable for systems with nonlinear dynamics and disturbances. The advantages of STC are faster speed, more accurate control actions, and enhanced system stability, though may require careful parameter tuning and is sensitive to parameter changes. Furthermore, the study examines various applications of STC in various technical fields, demonstrates its effectiveness in implementation problems, and finally we establish possible future research directions for further development and advancement of STC technologies.

Keywords: Sliding mode controller, super-twisting controller, robust controller

INTRODUCTION

The Super-Twisting Controller (STC) is a robust control technique that is particularly effective for systems with uncertain dynamics, disturbances, and non-linearities. It is known for its fast convergence, chattering-free control, and ability to handle complex systems. STC is built to withstand systemic uncertainties and disruptions.

It can handle parameter variations, modeling errors, and external disturbances effectively. STC is well-suited for controlling nonlinear systems where traditional linear control techniques may not be effective. It can handle nonlinearities in the system dynamics, making it applicable to a wide range of systems. STC is a type of sliding mode control (SMC), which is based on the concept of creating a sliding surface where the system dynamics are governed by a different set of equations. This sliding surface helps in achieving robust and precise control. The design of an STC involves tuning parameters such as the sliding surface gains, reaching law gains, and observer gains (if used with state observers). Proper tuning is essential to achieve desired performance and stability in the controlled system.

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Droop control in inverters can be improved by super-twisting algorithm for robustness. A disturbance rejection control approach for droop-controlled inverters is proposed in this study.

The study demonstrated strong robustness to parameter uncertainties and improved power sharing performance. Faster load power sharing was achieved compared to traditional multi-loop control. By integrating the Super twisting algorithm with sliding mode controllers, the research aims to achieve superior dynamic response characteristics, such as faster transient response, reduced settling time, and improved disturbance rejection [1]. Li *et*

al. focused on the sensor-less control of Permanent Magnet Synchronous Linear Motors (PMSLMs), aiming to enhance motor performance and reduce system complexity [2]. The implementation includes a Super-Twisting Sliding Mode Controller (ST-SMC), known for its robustness and chattering-free control, to achieve improved motor performance in terms of speed regulation and position accuracy. Additionally, a state observer is employed to replace traditional speed sensors, reducing cost and complexity while maintaining control accuracy. Furthermore, adaptive sliding mode control techniques are utilized to enhance system robustness against parameter variations and external disturbances, ensuring stable and reliable operation of the PMSLM system. In the paper by El-Sousy and Alenizi, an Optimal Adaptive Generalized Super-Twisting Sliding Mode Controller (OAGSTSMC) scheme is proposed for presenting a significant advancement in Permanent Magnet Synchronous Motor (PMSM) control performance, particularly in mitigating the effects of disturbances [3]. The OAGSTSMC demonstrates superiority in minimizing tracking errors and chattering compared to other control schemes, offering improved precision and smoother operation in PMSM control applications. This innovative approach not only enhances control performance but also showcases the potential of combining advanced control algorithms with machine learning for superior control outcomes in dynamic and uncertain environments. The Super-Twisting Nonlinear Gain Sliding Mode Controller (STNGSMC) is introduced as a method to enhance the position control of PMSM while reducing chattering, a common issue in sliding mode control. By incorporating a nonlinear gain in the STSMC (Super-Twisting Sliding Mode Controller), the control scheme achieves improved position tracking performance. The stability of the closed-loop system is demonstrated using the Lyapunov theorem, that ensures robust and reliable operation [4]. In the present research by Gao *et al.*, a novel enhanced state observer (ESO)-based Adaptive Super-Twisting Non-Linear Fractional-Order PID Sliding Mode Control Strategy (ASTNLFOPIDSMC) for the speed operation of a PMSM (permanent magnet synchronous motor) is proposed [5]. In the sliding mode phase, the control approach guarantees rapid convergence, great resilience, and little steady-state loss; in the achieving phase, the Adaptive Super Twisting Reaching Law (ASTRL) reduces chattering and offers strong robustness and high precision. The goal of an ESO is to create a continuous feedback correction for disturbances from outside sources.

The conventional Super-Twisting (ST) Second-Order Sliding Mode Control (SOSMC) has limitations, including chattering phenomena and a relative degree equal to two in SSMR systems. The Higher-Order Super-Twisting control (HOST) control reduces chattering and achieves finite-time convergence, making it more robust than the conventional ST-SOSM. The performance of the HOST controller has been experimentally validated on a Pioneer P3AT SSMR robot, showing good performance under parametric uncertainty variations and external disturbance [6]. The paper by Alhassan *et al.* discusses the challenges of operating bridge cranes under large amplitude cargo sways, particularly when the payload develops a double-pendulum effect [7]. A modified sliding mode observer (SMO) with uncertainty compensation is proposed to predict the unavailable states of the system, allowing for simple implementation, noise resiliency, and bounded-time convergence. A composite SMO-based modified super-twisting control technique is designed to achieve rapid and precise trolley placement and suppress cargo swing. The proposed control system maintains the system's asymptotic stability using a strict quadratic Lyapunov function. In their study, Ullah *et al.* employed the non-singular terminal super twisting sliding mode control method suggests an adaptive resilient formation and trajectory tracking control strategy for a leader-follower formation of Unmanned Aerial Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs) [8]. Here, numerical simulations are used to examine two variations of the control schemes: Adaptive Super Twisting SMC (AST-SMC) and Adaptive Non-Singular Terminal Super Twisting SMC (ANSTS-SMC). Comparing the ANSTS-SMC control strategy against the AST-SMC approach, the former performs better with fewer tracking mistakes. The proposed control algorithm demonstrates enhanced robust behavior to acceleration type disturbances and parametric uncertainties compared to AST-SMC algorithms. The paper by Dai *et al.* presents a longitudinal tracking control approach for a morphing wave-rider aircraft using an adaptive super twisting sliding mode controller [9]. The morphing wave-rider is designed for optimal flight performance in various mission scenarios, and its aerodynamic performance and dynamic model are

discussed. In comparison to conventional sliding mode control, the suggested controller reduces the mean tracking error of the pitch angle by 25% while still being able to monitor the optimal trajectory during the morphing process. The adaptive super twisting algorithm based sliding mode controller is shown to have good adaptability to the nonlinear and uncertain aerodynamic characteristics of morphing aircraft. The study by Yessef *et al.* proposes an intelligent super-twisting sliding mode control (STSMC) strategy using neural networks to enhance the control of a wind turbine system with a dual induction generator [10]. The proposed strategy overcomes the drawbacks of the traditional Direct Power Control (DPC) strategy by combining the robustness of the STSMC technique with the adaptability and accuracy of neural networks. This combination reduces energy ripples, increases the quality of the current, and improves the overall performance of the system. The implementation of the proposed strategy is validated through experimental results using the dSPACE 1104 Card, demonstrating its effectiveness and ability to enhance the control of the wind turbine system.

THEORETICAL FRAMEWORK OF SUPER-TWISTING CONTROLLERS

On Different Applications

Droop Controlled Inverters in Distributed Generation System

The Super-twisting algorithm (STA) is a control strategy proposed for droop-controlled inverters in distributed generation systems. It is based on a sliding mode control technique for uncertain nonlinear systems. The control law of STA involves a sliding variable, representing the deviation between the desired and actual system outputs, and a control input determined by the sign function applied to the sliding variable and other parameters. This control law ensures that the sliding variable converges to zero in finite time, leading to a fast and accurate control response. The stability of STA controllers can be proven using Lyapunov functions, demonstrating the convergence of the system to a desired equilibrium point [1].

Permanent Magnet Synchronous Motor (PMSM)

A self-adaptive super-twisting sliding mode controller is proposed by Li *et al.* for sensor-less vector control of a permanent magnet synchronous linear motor (PMSLM) [2]. This controller is based on the second-order sliding mode control theory and utilizes a super-twisting algorithm. The design includes components such as a sliding mode observer, low-pass filter, position angle, and speed estimation. In the study by El-Sousy and Alenizi, the super-twisting sliding-mode control (STSMC) is a technique used to reduce chattering and stabilize the drive system of a PMSM [3]. It is based on control laws designed using the sliding surface and control gains. Proper selection of control gains is crucial to avoid chattering and achieve optimal control performance. Various methods are employed for STSMC, including Lyapunov-based adaptive control, second-order sliding-mode observer, variable-gain algorithms, and composite control approaches. A super twisting-based nonlinear gain sliding mode controller (STNGSMC) is employed for position control of PMSMs by Gil *et al.* [4]. This controller incorporates a nonlinear gain to enhance position tracking performance compared to a standard STSMC. The proposed method addresses chattering caused by unmodeled dynamics such as quantization effects, sensor resolution, and pulse-width modulation (PWM) switching noise in PMSM position control systems. Using an Extended State Observer (ESO), a unique Adaptive Super-Twisting Non-Linear Fractional-Order PID Sliding Mode Control Strategy (ASTNLFOPIDSMC) is proposed by Gao *et al.* [5]. The plan makes use of a brand-new sliding surface with nonlinear integral, differential, and proportional terms called Non-Linear Fractional Order PID (NLFOPID). In the reaching phase, exceptional control performance is attained by applying an ASTRL.

Skid Steered Mobile Robot (SSMR)

The limitations of conventional super twisting control (STC) in skid-steered mobile robot (SSMR) systems, particularly focusing on chattering phenomena and a relative degree equal to two in such systems. To address these drawbacks a higher-order version of STC called Higher-Order Super Twisting Control (HOST) is proposed by Matraji *et al.* [6]. The HOST algorithm is based on Higher-Order Sliding Mode Control (HOSMC) and represents a higher-order version of the conventional ST

algorithm. HOST control exhibits improved robustness and convergence properties compared to STC, making it suitable for trajectory tracking control of SSMR systems.

Trajectory Tracking Control Scheme for UAVs and UGVs

Using the Non-Singular Terminal Super Twisting Sliding Mode Control (ANSTS-SMC) Method, an adaptive robust formation and trajectory tracking control strategy for a leader-follower formation of UAVs and UGVs is presented by Ullah *et al.* [8]. This control technique is appropriate for high-precision group tasks because it seeks to assure minimal tracking errors and quick state convergence. Through numerical simulations, the paper assesses two variations of the control schemes: Adaptive Super Twisting SMC (AST-SMC) and ANSTS-SMC.

SUPER-TWISTING CONTROLLER DESIGN

Super-twisting sliding mode control is derived from the second-order sliding mode control theory of high-order sliding mode. Super-twisting cannot only maintain the fastness and robustness of first-order sliding mode control, but also effectively reduce the chattering generated by the sliding mode observer in vector control and enhance the stability of the system.

Consider an uncertain non-linear system:

$$\dot{x}=f(t, x)+b(t, x)u \quad (1)$$

$$y=s(x, t)$$

where, $x \in \mathbb{R}^n$, $u \in \mathbb{R}$ represent a state vector and a control function, respectively; $f(t, x) \in \mathbb{R}^n$ represents a differentiable vector-field; and $s(x, t)$ represents a sliding variable [1].

The input-output dynamics of system in Eq. (1) can be expressed as:

$$\dot{s}(t, x) = \frac{\partial}{\partial t} s(t, x) + \frac{\partial}{\partial x} s(t, x) [f(t, x) + b(t, x)u] \quad (2)$$

$$\ddot{s}(t, x) = \frac{\partial}{\partial t} \dot{s}(t, x, u) + \frac{\partial}{\partial x} \dot{s}(t, x, u) [f(t, x) + b(t, x)u] + \frac{\partial}{\partial u} \dot{s}(t, x, u) \dot{u} = \chi(t, x, u) + \varphi(t, x, u) \dot{u} \quad (3)$$

Where, $\chi(t, x, u)$ and $\varphi(t, x, u)$ are bounded but unknown, there are positive constant values X , ϕ_{\min} and ϕ_{\max} .

$$0 < \phi_{\min} < \varphi(t, x, u) < \phi_{\max} X < \chi(t, x, u) < X \quad (4)$$

Here the derivative can be obtained as:

$$\ddot{s} \in [-X, X] + [\phi_{\min}, \phi_{\max}] \dot{u} \quad (5)$$

Where, $s = \dot{s} = 0$

Then the control law based on Super Twisting algorithm is:

$$u = -\lambda |s|^{\frac{1}{2}} \text{sign}(s) + v \quad \dot{v} = -\alpha \text{sign}(s) \quad (6)$$

When the system is in the sliding state, the uncertainty and disturbance of the matching are invariant. In order to getting a good control effect, the switching term gain needs to be adjusted when the system boundary changes, so the adaptive sliding mode algorithm has stronger anti-interference performance. According to particular system of equations, the controlled system that is disturbed is:

$$\ddot{x} = F(t, x) + B(t, x)u_1 + \varphi(t) \quad (7)$$

Where, $\varphi(t)$ is a continuous random disturbance with no defined boundary, and u_1 is the control law of the Super-twisting algorithm. The second-order sliding mode speed controller based on the Super-twisting algorithm can be designed as:

$$\dot{i}_q = -k_p |s_\omega|^r \tanh(s_\omega) + i_{q1} \quad \dot{i}_{q1} = -k_i \tanh(s_\omega) \quad (8)$$

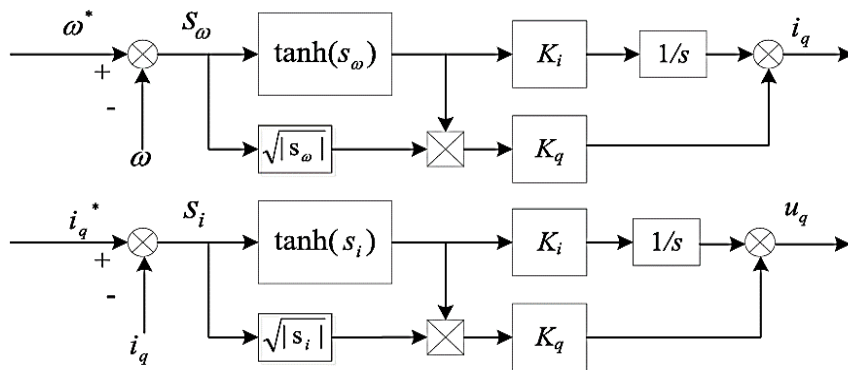


Figure 1. Super-Twisting sliding mode controller.

And

$$u_q = -k_p |s_\omega|^r \tanh(s_\omega) + u_{q1} \quad \dot{u}_{q1} = -k_i \tanh(s_\omega) \quad (9)$$

Where $k_p > 0$, $k_i > 0$, are the parameters designed in super-twisting control algorithm. Suppose the interference $\varphi(t)$ is differentiable, and $|\dot{\varphi}(t)| \leq \delta$, $\forall t \geq 0$, where δ is a normal number. We have to design a suitable adaptive control strategy to derive k_p and k_i such that \dot{x} and \ddot{x} converge to zero in a finite time. The adaptive laws for designing k_p and k_i are:

$$\dot{k}_p = \begin{cases} w_1 \sqrt{\frac{y_1}{2}}, & x \neq 0 \\ 0, & x = 0 \end{cases} \quad (10)$$

$$k_i = x + \frac{\eta^2}{4} + \frac{k_p \eta}{4} \quad (11)$$

The block diagram of the Super-twisting sliding mode controller designed according to Eqs. (8) and (9) is shown in Figure 1.

The Super Twisting algorithm and the second-order sliding mode speed controller are designed to stabilize the system and achieve desired control objectives. The Super Twisting algorithm adjusts the control input based on the sliding variable to handle uncertainties and disturbances. The Super Twisting algorithm adjusts the control input based on the sliding variable to handle uncertainties and disturbances.

FUTURE SCOPE AND DISCUSSION

Further research can focus on exploring the application of the super-twisting algorithm in various types of droop-controlled inverters including LCL-type grid-connected inverters [1]. This review can assess the algorithm's performance and effectiveness in different system configurations, providing insights into its adaptability and suitability for diverse power distribution setups. Additionally, there is potential to optimize and fine-tune the super-twisting algorithm to enhance its robustness and performance, especially in the presence of model uncertainties and parameter perturbations. Extending the implementation of the algorithm to multi-phase or three-phase droop-controlled inverters can further evaluate its applicability and benefits in more complex power distribution systems. The proposed self-adaptive super-twisting sliding mode controller has shown promising results in the sensor-less vector control of Permanent Magnet Synchronous Linear Motors (PMSLMs) [2–4].

By integrating a state observer based on the sliding mode state observer (SMO) with the super-twisting sliding mode controller, the system effectively reduces chattering and improves control precision. In future there is scope for further optimization and fine-tuning of the controller parameters to enhance the overall performance of the PMSLM system. Additionally, the controller design could be extended to other types of linear motors or different applications requiring high-speed positioning and precise control.

The study by Yessef *et al.* proposes an intelligent super-twisting sliding mode control (STSMC) strategy using neural networks for wind turbine systems, demonstrating enhanced control performance and reduced energy ripples [10]. Future research in this area could focus on advancing the integration of neural networks with control algorithms, exploring real-time adaptation mechanisms, and addressing challenges related to system scalability and robustness. Overall, the future scope for all the areas includes advancing adaptive control techniques, integrating artificial intelligence and machine learning approaches, and addressing practical implementation challenges to further improve control performance and system efficiency in aerospace and renewable energy applications.

CONCLUSION

The review focuses on advanced control strategies for various applications such as UAVs, UGVs, PMSMs, morphing aircraft, bridge cranes, wind turbines, and mobile robots. Adaptive Super Twisting SMC (AST-SMC), Higher-Order Super Twisting Control (HOST), Super Twisting Sliding Mode Control (STSMC), and Adaptive Non-Singular Terminal Super Twisting SMC (ANSTS-SMC) are a few of these systems.

The research on control strategies has demonstrated significant advancements in various applications. The integration of the Super Twisting algorithm with sliding mode controllers has shown superior dynamic response characteristics, including faster transient response, reduced settling time, and improved disturbance rejection. Furthermore, adaptive and intelligent control techniques, such as neural network-based strategies and higher-order sliding mode control, have proven effective in enhancing control performance, reducing chattering, and improving robustness against uncertainties and disturbances. Looking ahead, further research could focus on fine-tuning and optimizing these control strategies for even better performance and robustness. Additionally, exploring advanced control algorithms, integrating machine learning techniques, addressing specific application challenges, and validating control strategies through extensive experimental studies are areas of potential future research.

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