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Optimal fuzzy controller for speed control of DC drive using salp swarm algorithm

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ABSTRACT

The inherent non-linearity of the system being investigated highlights the limitations of traditional proportional integral or PI tuning approaches. Consequently, the primary objective of this study is to construct and refine the PI controller by leveraging the salp swarm algorithm, aiming to enhance the performance of the DC drive output. Through the application of the salp swarm algorithm, the fuzzy PI controller undergoes dynamic online modifications, leading to optimal results. The controller's superior performance is achieved by employing an optimization approach to identify the optimal set of solutions for the Fuzzy PI parameters. Rigorous simulations are conducted to comprehensively evaluate the proposed salp swarm algorithm technique, assessing its viability and efficacy in real-world. Thorough simulations assess the viability of the salp swarm algorithm, evaluating its effectiveness in real-world applications. The study demonstrates the methodology's reliability through comparative analyses of DC/DC converters against alternative methods. In non-linear systems like the DC drive, innovative optimization strategies are shown to significantly boost PI controller performance. The findings offer valuable insights for advanced control system design.

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1. INTRODUCTION

Control systems find extensive applications in various fields, such as information technology, industrial processes, and home appliances. As system complexities grow, characterized by nonlinearities, operating limits, time delays, and uncertainties, the need for more sophisticated control systems intensifies [1], [2]. Fuzzy controllers have gained significant interest in motion control systems due to their ability to handle nonlinear features and adapt to imprecise models. Artificial intelligence (AI) methods, particularly in fuzzy proportional integral (PI) tuning, are increasingly popular, promising advancements in performance and effectiveness across control systems [3]-[5].

Cutting-edge computational intelligence-based methods, such as genetic algorithm (GA) and particle swarm optimization (PSO), offer solutions to the fuzzy PI tuning problem [6]. GA, rooted in evolutionary biology, is known for approximating solutions to challenging optimization problems, making it a preferred choice in computer science and engineering [7]-[9]. Its adaptability and scalability, along with the capacity to handle nonlinearities and uncertainties, make GA an effective tool for optimizing control system issues. Leveraging the advantages of GA and PSO enables researchers and engineers to enhance the performance and stability of fuzzy PI controllers, pushing the boundaries of control and optimization methods [10], [11].

The introduction of a genetic fuzzy (GF) algorithm-based controller for Quasi-Resonant converters in drive applications brings various benefits, such as minimizing transient speed response, reducing switching stresses, and minimizing losses, especially within limited bandwidth ranges [12]. However, challenges include diminishing optimum stability with increasing convergent speed and the difficulty of managing dynamic datasets. Despite the strengths of GA, simpler algorithms may outperform it for specific optimization problems within the same computation time [13]-[17]. In the pursuit of more effective control solutions, this paper explores the utilization of the salp swarm algorithm for fuzzy controller parameter tuning in DC drives powered by DC/DC converters. The objectives are: i) Develop and refine a fuzzy PI controller for DC drives using the salp swarm algorithm; ii) Enable dynamic online modifications of the fuzzy PI controller to enhance DC drive output performance; iii) Evaluate the proposed salp swarm algorithm through rigorous simulations for real-world applicability; and iv) Compare the salp swarm algorithm's effectiveness in fuzzy PI tuning bacterial foraging algorithm.

The advantages of incorporating the salp swarm algorithm lie in its ability to efficiently handle complex optimization problems, offering improved convergence and effectiveness compared to traditional methods. This novel approach promises to advance the field of control systems by providing a robust and efficient technique for optimizing Fuzzy controller parameters in the context of DC drives.

2. PROBLEM FORMULATION

The goal of the ongoing research is to optimize the DC drive speed controller's parameters for minimal overshoot and reduced steady-state error, which are essential for high-performance applications [18]-[21]. The controller parameters must be changed in order to maintain desired performance because the plant transfer function varies with operating conditions. The system consists of two fuzzy PI type controllers, one for inner loop current control and the other for outer loop speed control [22]-[25]. Finding the ideal fuzzy PI controller parameters to reduce performance criteria is the goal. The objective function, which describes the performance of the fuzzy PI control system is defined in (1), uses key performance indicators of transient responsiveness.

$$Minimize = F = \{\int_0^{\infty} t|e(t)|dt \ + OS + t_s + t_r\} \tag{1}$$

The first term in the equation is the integral of time multiplied by integral time absolute error or ITAE, the second term is overshoot, the third term is settling time, and the last term is rise time. The fitness function is the inverse of the performance indices. We used the discrete form of ITAE in this paper. ITAE are considered performance indices, and the fitness function indicated by J can be defined as (2).

$$\boldsymbol{J} = \frac{\mathbf{1}}{(\mathbf{100} + \sum_{K=1}^{N}|\omega_{ref} - \omega_m|)} \tag{2}$$

To improve the performance of a PID-controlled system, the PID gains are changed to minimize a specific performance index. The performance index is determined over a time interval; T, which is typically in the neighborhood of $0 \leq T \leq t_s$ where ts is the system's settling time. The performance indices utilized were stated as integral of time multiplied by absolute error (ITAE) and described as (3).

$$ITAE = \int_0^T t|e\,(t)|dt \tag{3}$$

To identify the ideal fuzzy controller, salp swarm algorithm is used. In both methods, the populations are initialized within their bounds and the necessary parameters, such as speed error, change in speed error, and control outputs, are initialized in order to optimize the input scaling factors of the fuzzy PI controller. The fitness function, which is the objective function's inverse, is identified, and performance and fitness values for SSA are assessed using newly developed parameters. The process is repeated until the allotted number of iterations has been achieved if there are any problems, in which case the fitness function is given a negative value. As the ideal fuzzy controller, the choice with the highest fitness value is chosen.

The techniques utilized for this work are theoretical calculations based on analytical equations, figuring out the capacitance and inductance values for a particular switching frequency. The simulation program's design parameters are verified using these theoretical values. Throughout the process, assumptions and limitations are specified and followed. Using a simulation tool, specifically the MATLAB/Simulink software, the design is validated once the applied parameters yield results that match the theoretical ones. The experimental design is also evaluated by simulation prior to deployment.

3. FUZZY SALP SWARM ALGORITHM (FSSA)

In this study, the fuzzy salp swarm algorithm (FSSA) is employed to determine the parameters of the fuzzy logic controller, which are subsequently used to regulate the drive speed. These parameters encompass coefficients of linear output functions, input membership function parameters, and input scaling factors. The commands within an M-File written in MATLAB execute FSSA iterations, as illustrated in Figure 1. The optimized fuzzy speed controller's simulated structure for Quasi-Z-Source converter fed drives, is depicted in Figure 2. Furthermore, Figures 3 and 4 display the proportional-integral (PI) gains corresponding to speed and load torque.

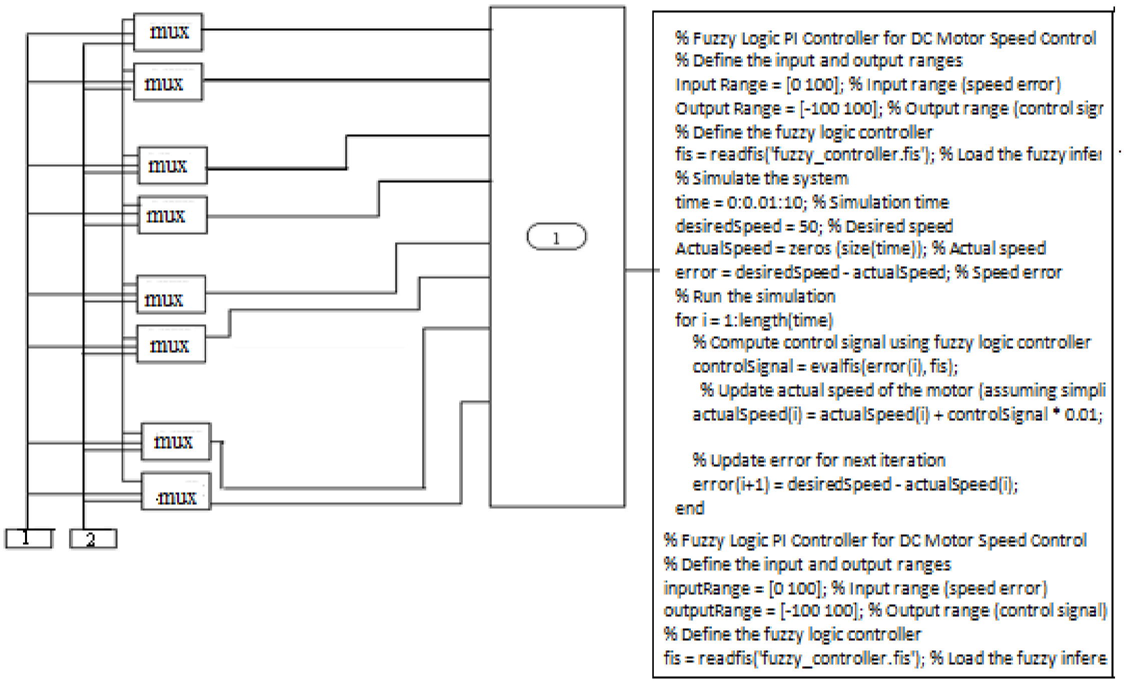


Figure 1. MATLAB commands in M-file

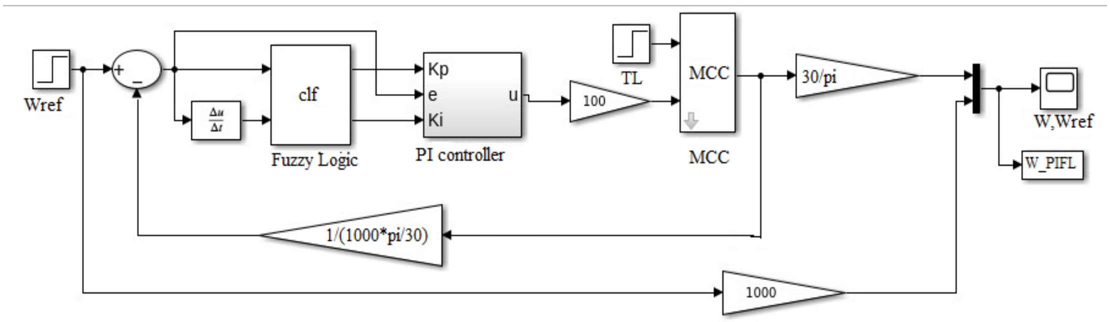
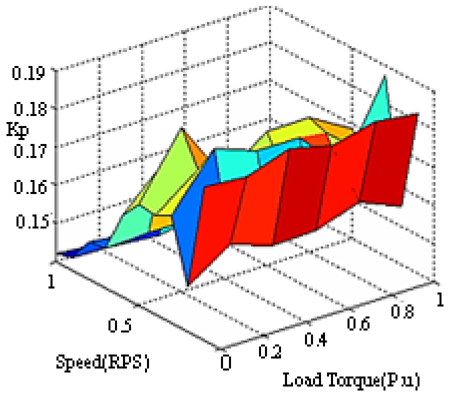


Figure 2. Simulated structure of optimized fuzzy speed controller

Figure 5 showcases the rule viewer and surface viewer of the fuzzy controller implemented using FSSA. The integration of FSSA enhances the optimization process, allowing for the effective tuning of fuzzy logic controller parameters for improved drive speed control. The FSSA algorithm, inspired by the swarming behavior of salps, optimizes the parameters through collaborative interactions among individuals in the swarm. The FSSA algorithm is known for its ability to efficiently explore the solution space and converge towards optimal or near-optimal solutions. It introduces a novel approach to parameter optimization, leveraging the collective intelligence of a swarm of salps to navigate the search space effectively. In the M-File for MATLAB, the FSSA iterations involve the adaptation and update of parameters, mimicking the social interactions observed in salp swarms. These iterations lead to the determination of optimal or near-optimal parameters for the fuzzy logic controller, thereby enhancing the overall performance of the drive speed control system. The utilization of FSSA in this context provides a robust and intelligent optimization technique, demonstrating its effectiveness in fine-tuning fuzzy logic controllers for complex systems such as those involving Z-Source and Quasi-Z-Source converters in drive applications.



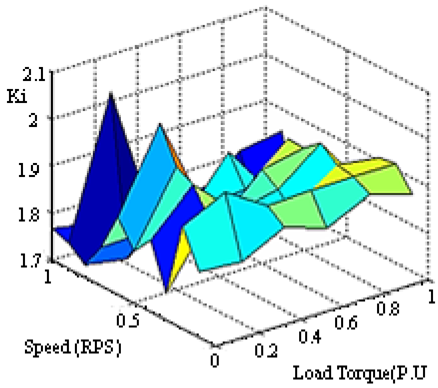


Figure 3. K_P corresponded with speed and load torque Figure 4. K_I corresponded with speed and load torque

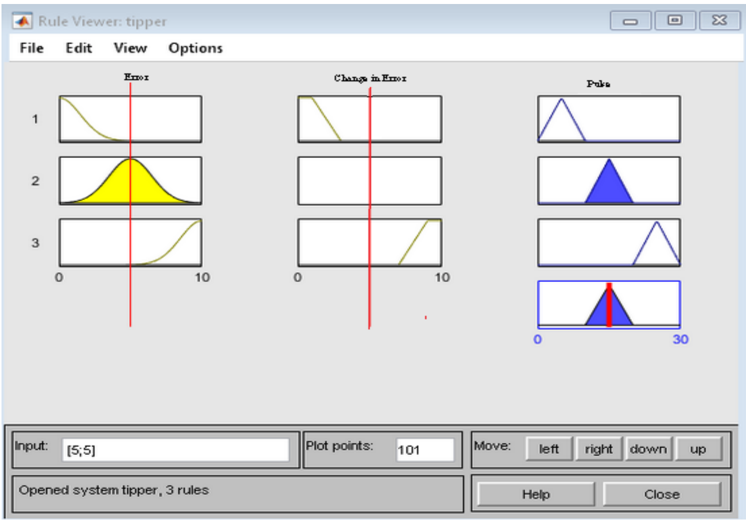


Figure 5. Simulink rule viewer for fuzzy logic controller

4. RESULTS AND DISCUSSIONS

For a drive powered by a quasi-Z source converter, the effectiveness of the suggested approach is evaluated. By comparing the outcomes of the suggested fuzzy optimized salp swarm optimization with those of the fuzzy optimized bacterial foraging algorithm FBFA controller, its efficacy is examined. The structure of the optimized fuzzy speed controller for a Quasi-Z-Source converter-fed drive is illustrated in Figure 6. This controller leverages fuzzy optimized salp swarm optimization to enhance its performance in the context of the quasi-Z source converter-driven system.

The effects of the models' performance based on varying input model parameters such as load torque and reference speed were assessed. The impact of these varied input parameters on system performance in terms of rise time, settling time, peak overshoot, and peak speed value were evaluated. A reference speed of 1200 rpm was randomly selected at no load. This selected reference speed was later repeated for a load torque of 7Nm. Their corresponding responses with fuzzy-optimized bacterial foraging algorithm (BOFA) and fuzzy-optimized salp swarm optimization were displayed.

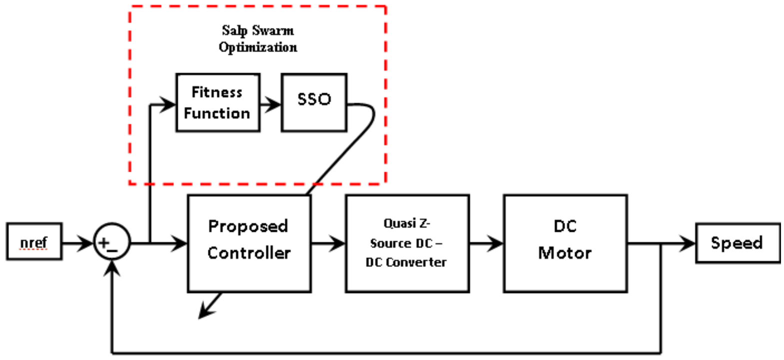


Figure 6. Structure of fuzzy optimized SSA for speed control of DC motor

4.1. System performance for reference speed of 1200 rpm at no load

The system's response and performance for a reference speed of 1200 rpm with the fuzzy-optimized bacterial foraging algorithm (BOFA) and fuzzy-optimized salp swarm optimization (SALP) at no load, are presented in Figures 7 and 8 respectively. The system performance for a reference speed of 1200 rpm at no load is summarized in Table 1. Table 1 provides a detailed overview of the system performance for a reference speed of 1200 rpm at no load, employing fuzzy-optimized bacterial foraging algorithm (BOFA). Noteworthy metrics include a rise time of 0.224 seconds, settling time of 1.387 seconds, a maximum overshoot of 18.3%, and a peak speed value of 1420 rpm.

The shorter rise time indicates a rapid initial response, but it comes at the cost of a higher overshoot and longer settling time. These characteristics suggest a trade-off between achieving quick initial response and the subsequent stabilization period. Engineers may weigh these factors based on the specific requirements of the DC drive system, balancing the need for speed response against overshoot considerations. With a rise time of 0.44 seconds, settling time of 0.781 seconds, a significantly reduced maximum overshoot of 4.3%, and a peak speed value of 1200 rpm, SALP demonstrates a different trade-off between response time and stability. While SALP exhibits a slightly longer rise time, it achieves faster stabilization and maintains a lower overshoot compared to BOFA. These attributes suggest that fuzzy-optimized salp swarm optimization may be a favorable choice for applications where minimizing overshoot and achieving quicker stabilization are critical performance factors. Ultimately, the selection between BOFA and SALP depends on the specific performance requirements of the DC drive system.

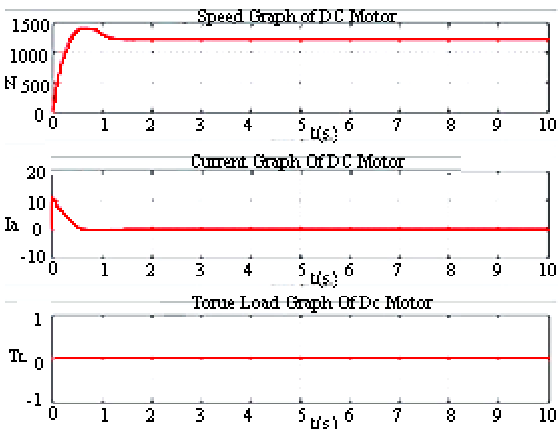


Figure 7. Response of system with FBFO

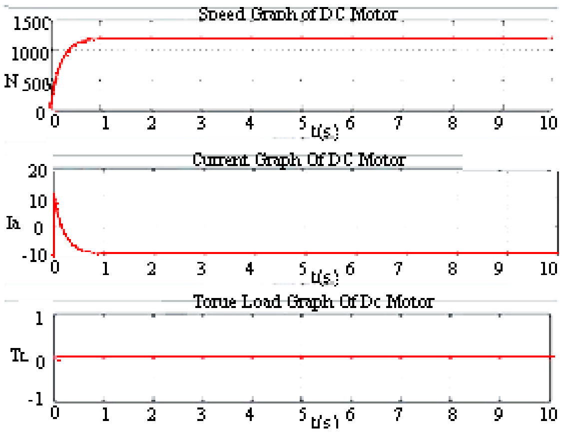


Figure 8. Response of system with FSSA

Table 1. Performance indices for the DC motor BOFA and SALP at no load and 1200 rpm reference speed

Parameters	Fuzzy-optimized bacterial foraging algorithm (BOFA)	Fuzzy-optimized salp swarm optimization (SALP)
Rise time (Tr)	0.224 seconds	0.44 seconds
Settling time (Ts)	1.387 seconds	0.781 seconds
Maximum overshoot	18.3%	4.3%
Peak speed value	1420 rpm	1200 rpm

4.2. System performance for reference speed of 1200 rpm at 7 Nm torque load

In this analysis, the system performance of a DC motor operating at a reference speed of 1200 rpm with a load torque of 7 Nm is examined using fuzzy-optimized bacterial foraging algorithm (BOFA) and fuzzy-optimized salp swarm optimization (SALP). Table 2 shows the performance indices for the DC motor with BOFA and SALP at load and 1200 rpm reference speed. The rise time (Tr), settling time (Ts), maximum overshoot, and peak speed value for each controller are as shown in Table 2.

Comparing the performance of the two controllers, it is observed that fuzzy-optimized salp swarm optimization (SALP) exhibits a longer rise time but achieves a faster settling time, lower maximum overshoot, and maintains a lower peak speed value compared to fuzzy-optimized bacterial foraging algorithm (BOFA) under the influence of a 7 Nm load.

a) Fuzzy-optimized salp swarm optimization (SALP) advantage:
  - Faster Stabilization: SALP demonstrates a significantly faster settling time, implying quicker adaptation to the applied load torque. This characteristic can be crucial in applications where rapid stabilization is essential.
  - Lower overshoot: SALP exhibits a lower maximum overshoot, indicating a more controlled and precise response to the load disturbance.

b) Fuzzy-optimized bacterial foraging algorithm (BOFA) characteristics:
  - Gradual Stabilization: BOFA, with a longer settling time, showcases a more gradual stabilization process. This behaviour might be advantageous in scenarios where a smoother response is preferred over quick adjustments.

c) The choice between the two controllers depends on the specific requirements of the DC drive system, considering factors such as overshoot tolerance, settling time, and peak speed constraints, especially in the presence of varying loads.

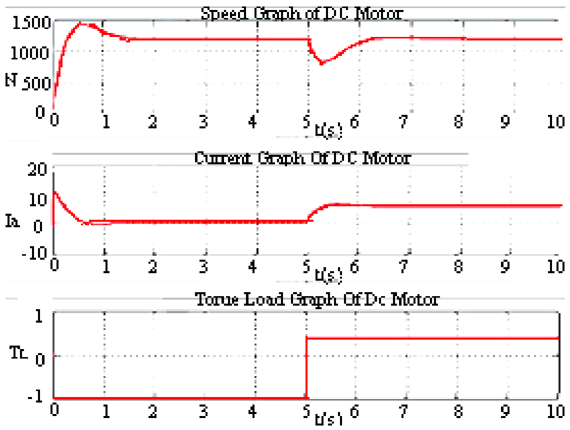


Figure 9. Response of system with FBFO at 7NM

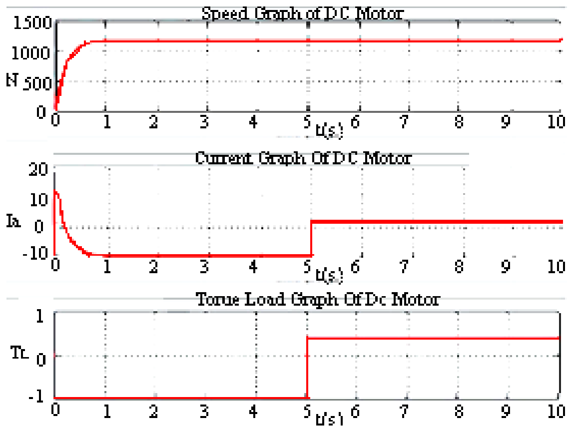


Figure 10. Response of system with FSSA at 7 NM

Table 2. Performance indices for the DC motor with BOFA and SALP at load and 1200 rpm reference speed.

Parameters	Fuzzy-optimized bacterial foraging algorithm (BOFA):	Fuzzy-optimized salp swarm optimization (SALP)
Rise time (Tr)	0.224 seconds	0.34 seconds
Settling time (Ts)	1.16 seconds	0.781 seconds
Maximum overshoot	17.7%	3.3%
Peak speed value	1420 rpm	1200 rpm

5. CONCLUSION

In conclusion, the comparative assessment of fuzzy-optimized bacterial foraging algorithm (BOFA) and fuzzy-optimized salp swarm optimization (SALP) controllers for a DC motor drive powered by a quasi-Z source converter reveals valuable insights. Under a reference speed of 1200 rpm at no load, BOFA exhibits a quicker rise time but at the expense of a higher overshoot and longer settling time. On the other hand, SALP showcases a slightly longer rise time but achieves faster stabilization, lower overshoot, and maintains a lower peak speed value. With a load torque of 7 Nm, SALP maintains its advantages, demonstrating faster stabilization, lower overshoot, and a lower peak speed value compared to BOFA. SALP's capacity for quicker adaptation and precise response makes it favorable for applications where rapid stabilization is crucial. Conversely, BOFA's gradual stabilization might be advantageous in scenarios where a smoother response is preferred over quick adjustments. The ultimate controller choice hinges on specific DC drive system requirements, encompassing factors like overshoot tolerance, settling time preferences, and peak speed constraints, particularly in the face of varying loads.

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