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# RESEARCH ARTICLE

# NONLINEAR SLIDING MODE CONTROL DESIGN FOR A MULTIMACHINE SYSTEM COMPOSED BY FOUR MARINE TURBINE SYSTEM

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**ABSTRACT**

In this paper, we deal the control problem for marine turbine systems in multimachine configuration. For this, we are modelling four interconnected marine turbine system and connected to an infinite bus by taking into account the multimachine interactions and the marine current dynamics. This multimachine system modelling is made through a transmittance matrix which uses the voltages and currents at each nodes of interconnection network. A decentralized sliding mode control is designed by using this multimachine model with taking into account the marine current constraints and multimachine interactions. Our proposed control law is applied on our multimachine marine turbine system in simulation under Matlab/Simulink environment with mechanical and electrical perturbations. The electrical perturbation is a short circuit of 200ms duration and the mechanical perturbation is the mechanical power drop of 50% of its value. The obtained simulation results prove that the proposed decentralized sliding mode control is able to well regulate our multimachine marine turbine system and preserves its performances despite the hydrodynamic perturbations and multimachine interactions. These results are compared to obtained results by the classical AVR-PSS (Automatic Voltage Regulator, Power Systems Stabilizer). The robustness test reveals that the proposed control law is better than AVR-PSS in precision terms and oscillation damping after perturbations.



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# INTRODUCTION

The actual challenge is to produce more energy while preserving environment, this implies the renewable energy systems development. In order to increase the renewable energy production, it will be interesting to associate several production unities, consequently, the renewable energy systems development in multimachine configuration becomes unavoidable. Another challenge is the renewable energy systems integration into electrical grid which has not initially designed to receive this energy form with intermittent and unpredictable character. To ensure the electrical grid connection, it will be necessary to regulate the terminal voltage and the frequency (or speed) of each production unit before the grid connection. Marine currents are predictable and vary slowly, this offers to the marine turbine system a connection facility to electrical grid compared to other renewable energy production sources. Some study have been made on the multimachine systems but very little on the marine turbine in multimachine configuration. To my knowledge, only authors of (1-2) have developed a marine turbine system in multimachine configuration. Authors of (1) use a feedback linearization technique to stabilize the distributed marine power generation units, this linearization technique is restrictive and supposes that the nonlinear system can be considered as linear around the equilibrium point. In paper (2), authors develop a new decentralized sliding mode for an electrical network composed by two marine turbine interconnected with grid connection possibility. The obtained results are satisfactory, only, this study does not applies to a larger size network. One has to mention that the network size augmentation implies the multimachine interaction increase which can reduce the proposed control performance. Authors of (3,4,5,6,7,8) have developed methods for marine turbine systems in monomachine configuration. These methods are focused on the control strategy development, the experimental validation of marine turbine, the comparative study between two controls strategies and two marine turbine driven by different generators, only, these study are not applied to marine turbine systems in multimachine configuration. Other studies have been done on the multimachinepower systems control and transient regime stabilization (9,10,11,12,13,14,15), the obtained results are satisfactory, only, they don't take into account the marine environment dynamics. The environment challenges require the multimachine marine turbine systems of larger size while developing the nonlinear control strategies to ensure their connection into electrical grid. In this paper, a nonlinear sliding mode controlis proposed to simultaneously regulate frequency and voltage of multimachine system composed of four marine turbines connected between them and connected to an electrical grid.

In section 2, the model of marine turbine multimachine system and the control strategy are presented. The simulation results and discussion are given in section 3 and a conclusion is made in section 4.

# METHODOLOGY

The marine turbine system used in this paper is illustrated as follows:

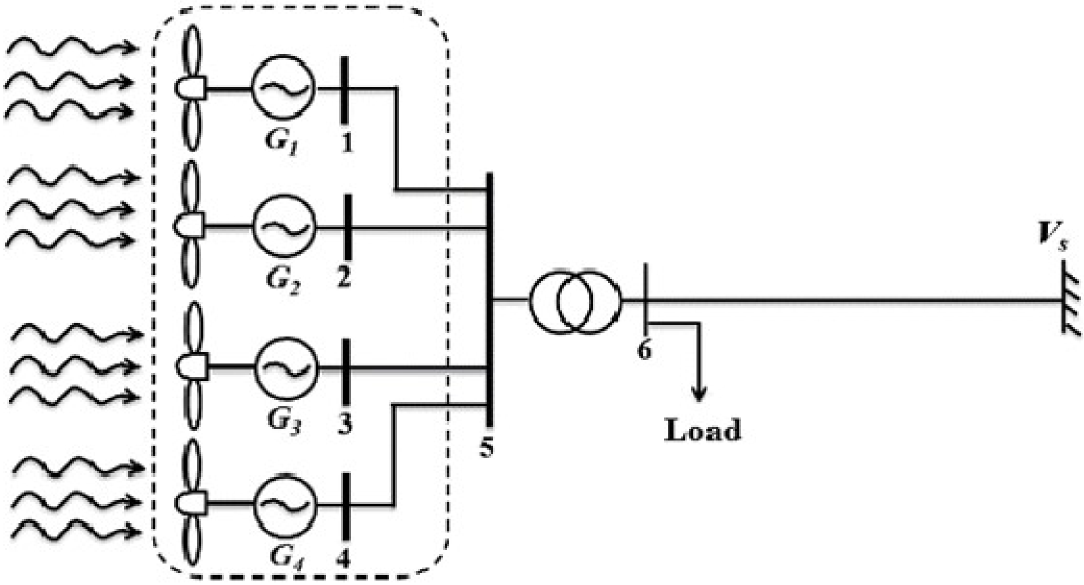



**Fig.1 Multimachine marine turbine system connected to infinite bus**

**Marine turbine modeling:** The extracted power for i-th marine turbine is modeled as follows (2,8,16):

$\rho$, $S_i$, $C_{p_i}$, are respectively the water density, the cross-sectional area of the i-th marine turbine and the power extraction coefficient.

$V_{t_i}$ is a speed tide and the chosen model which is more detailed in (2) is given as it follows:

$$V_{t_i} = V_{nt_i} + \frac{C_i - 45}{95 - 45}(V_{st_i} - V_{nt_i})$$

$V_{st_i}$, $V_{nt_i}$, $C_i$ are respectively the spring and neap tide current velocities and the tide coefficient.

**Multimachine power system modeling:** The multimachine model chosen is more described in paper(17,19), this model for i-th interconnected generators is given by.

$$\dot{\delta}_i = \omega_i$$

$$\dot{\omega}_i = -\frac{D_i}{H_i}\omega_i - \frac{\omega_s}{H_i}(P_{e_i} - P_{m_i})$$

$$\dot{P}_{e_i} = -\frac{1}{T'_{do_i}}P_{e_i} + \frac{1}{T'_{do_i}}\left\{ I_{q_i}\left[E_{f_i} - (X_{d_i} - X'_{d_i})I_{d_i}\right] + V_s\frac{T'_{do_i}E'_{q_i}\omega_i}{X'_{d_i}}\cos\delta_i \right\}$$

$$I_{q_i} = G_{ii}E'_{q_i} + \sum_{j=1 \quad j\neq i}^{n} E'_{q_j}\left\{G_{ij}\cos(\delta_j - \delta_i) - B_{ij}\sin(\delta_j - \delta_i)\right\}$$

$$I_{d_i} = -B_{ii}E'_{q_i} - \sum_{j=1 \quad j\neq i}^{n} E'_{q_j}\left\{G_{ij}\sin(\delta_j - \delta_i) + B_{ij}\cos(\delta_j - \delta_i)\right\}$$

with $\omega_i = \omega_{g_i} - \omega_s$ et $0 < \delta < \pi$ where

$I_{di}(t)$, $I_{qi}(t)$, $E'_{qi}(t)$ are respectively currents in direct and quadrature axis, transient EMF in the quadrature axis of i-th generators; $G_{ij}$ and $B_{ij}$ respectively integer and imaginary part of i-th row and j-th column elements of nodal admittance matrix whose synthesis technique is more detailed in (18).

$\delta_i(t)$, $\omega_{gi}(t)$, $P_{ei}(t)$, $H_i$, $D_i$, $T'_{d0i}$ are respectively power angle, electrical angular speed, active electrical power, inertia constant, damping constant and direct axis transient short circuit time constant of the i-th machine. $V_s, \omega_s$ are respectively voltage of infinite bus and synchronous machine speed $E_{fi}(t)$. is equivalent EMF in the excitation coil $X_{di}$, $X'_{di}$, $X_{dsi}$, $X'_{dsi}$ Are respectively direct axis reactance, direct axis transient reactance, synchronous global reactance, and transient global reactance of the system's direct axis (i-th machine to infinite bus). The multimachine system modeling which is more detailed in (18, 19) allows to obtain the final admittance matrix as follows:

$$Y_f = \begin{bmatrix} 0.1761-0.5379j & 0.1272+0.3215j & 0.0204+0.0121j & 0.0204+0.0121j \\ 0.1272+0.3215j & 0.1761-0.5379j & 0.0204+0.0121j & 0.0204+0.0121j \\ 0.0204+0.0121j & 0.0204+0.0121j & 0.2218-0.6423j & 0.1729+0.2171j \\ 0.0204+0.0121j & 0.0204+0.0121j & 0.1729+0.2171j & 0.2218-0.6423j \end{bmatrix}$$

This matrix establishes a link between the currents and voltage at the generator nodes (1, 2, 3, 4 on Fig.1).

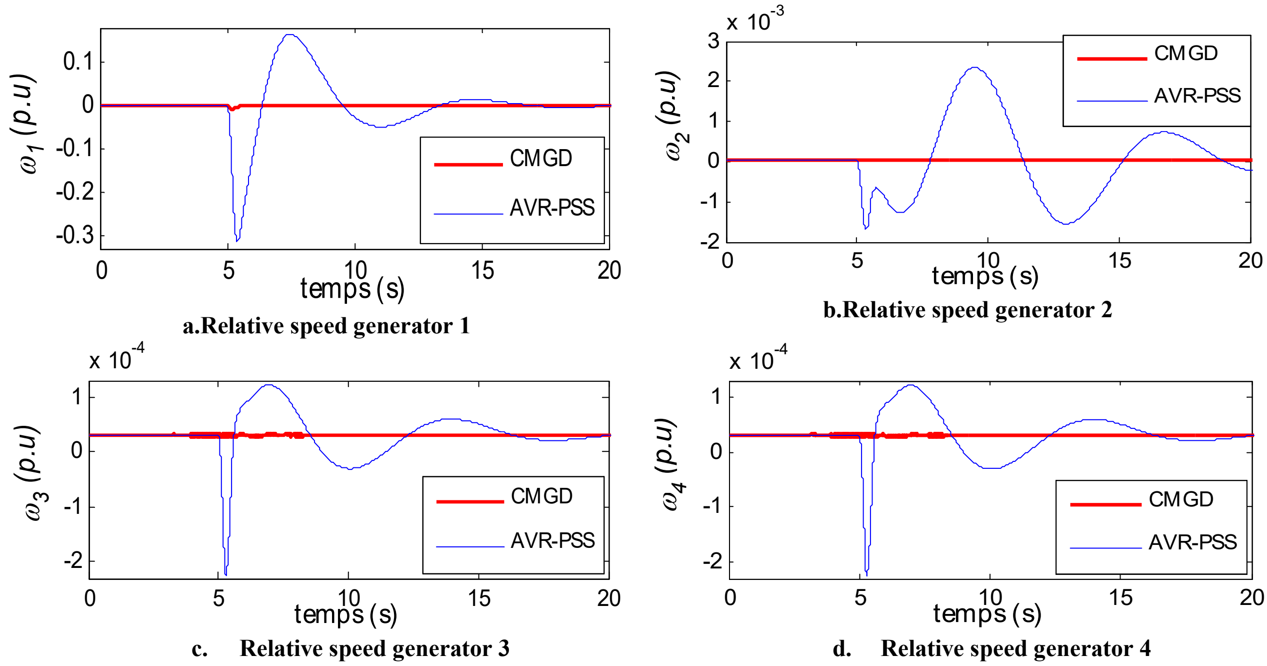
***Control law:*** The proposed control law is inspired of the developed technique in (19), it allows to synthetize the controller by using sliding mode technique and the Lyapunov method to ensure the control stability. The proposed control law is given as follows:

$$E_{f_i} = \frac{1}{I_{q_i}} \left\{ \begin{array}{l} -T'_{d0_i}\left[ \dfrac{a_i^2 H_i}{\lambda_{0_i}\omega_s} T_i + \dfrac{1-\dfrac{\lambda_{0_i} D_i}{H_i}}{\lambda_{0_i}\omega_s}\left(D_i\omega_i + \omega_s(P_{e_i} - P_{m_i})\right) \right] + P_{e_i} \\ -V_s \dfrac{E'_{q_i}\omega_i \cos\delta_i}{X'_{ds_i}} + (X_{d_i} - X'_{ds_i}) I_{d_i} - T'_{d0_i}\left[ K_i \mathrm{sign}(P_{e_i} - P_{eref_i}) \right] \end{array} \right\}$$

This control law objectives are to simultaneously regulate the terminal voltage and frequency via the generator speed. The generator speed must converge towards the network synchronous speed this implies the convergence towards 0 of relative speed which is the difference between the generator speed and the network synchronous speed. The terminal voltage must converge towards the network voltage which is equal to $1p.u$ in per unit coordinates.

# RESULTS AND DISCUSSION

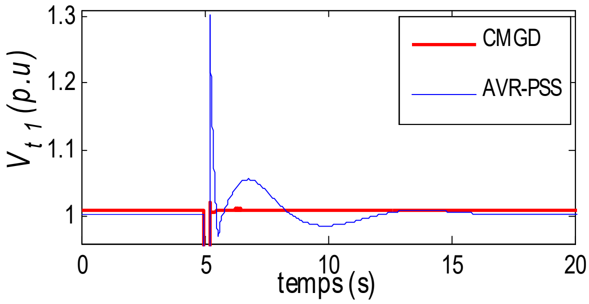
The proposed multimachine marine turbine system controlled is simulated in Matlab/Simulink environment with two perturbation types: the electrical perturbation which consists to realize a short circuit of 200ms duration and the mechanical perturbation consists to make a drop of 50% of its value.



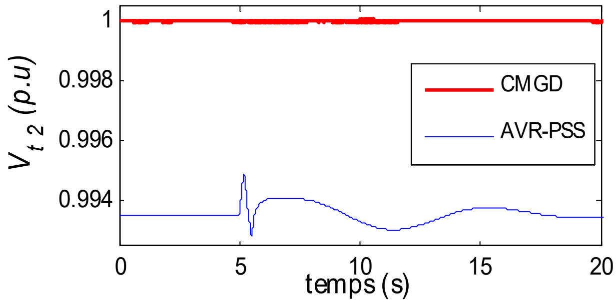

**a.Relative speed generator 1** **b.Relative speed generator 2**

**c. Relative speed generator 3** **d. Relative speed generator 4**

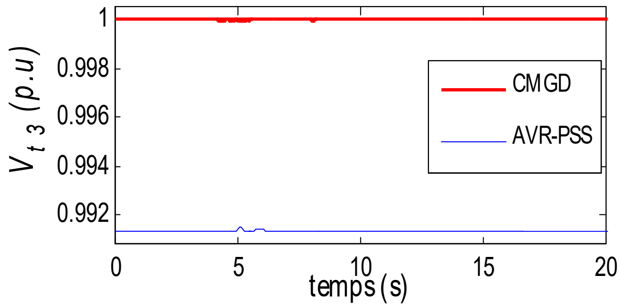
**Fig. 2. Generators relative speed for a short-circuit of 200ms duration after 5s**



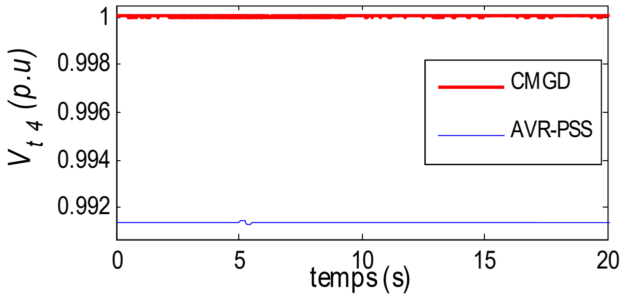

**a. Terminal voltage generator 1**




**b. Terminal voltage generator 2**

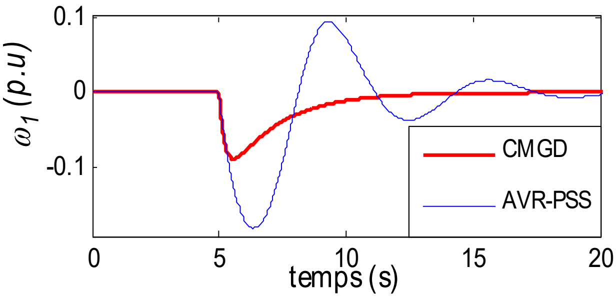



**c. Terminal voltage generator 3**

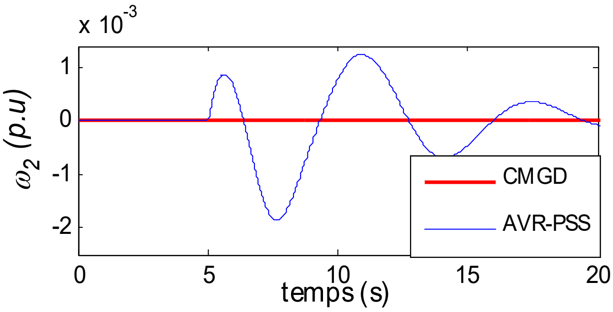



**d. Terminal voltage generator 4**

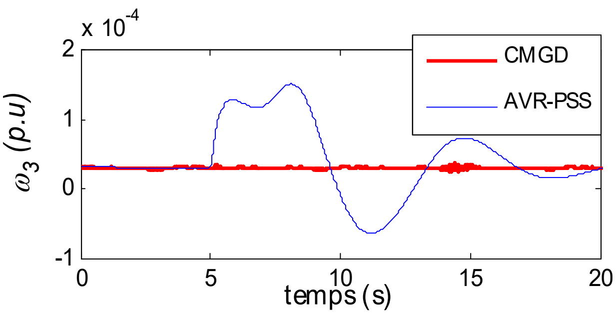
**Fig. 3. Generators terminal voltage for a short-circuit of 200ms duration after 5s**



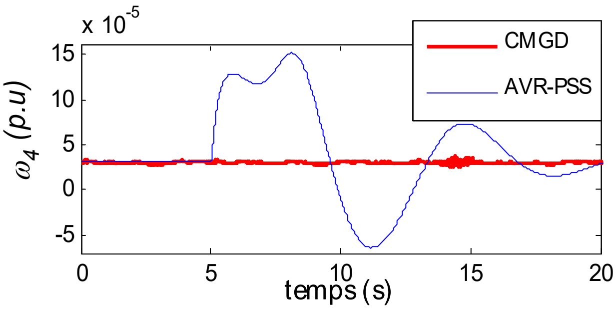

**a. Relative speed generator 1**




**b.Relative speed generator 2**



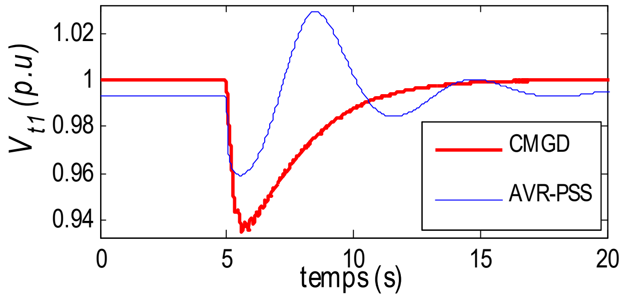

**c. Relative speed generator 3**



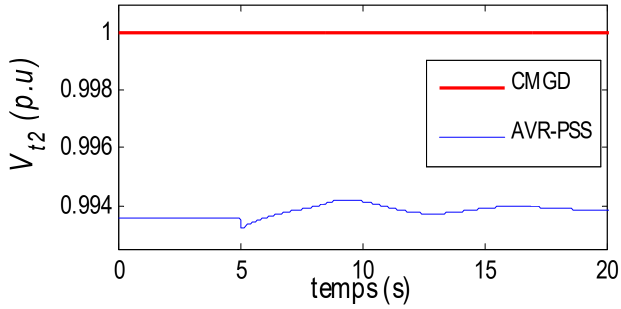

**d. Relative speed generator 4**

**Fig.4. Generators relative speed for mechanical power drop of 50% of its value**

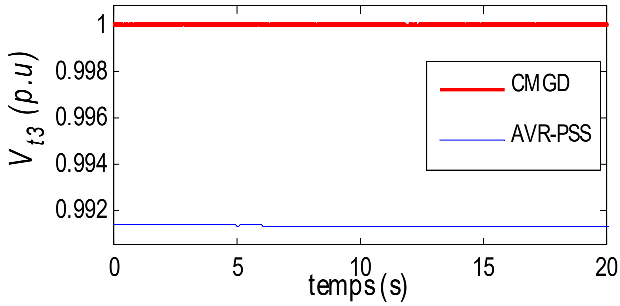
The proposed control method, named CMGD is compared to AVR-PSS and the obtained simulation results are shown on the following figures: The obtained results prove that the proposed controller well regulates the terminal voltage and relative speed despite the mechanical and electrical perturbations. It regulates with precision the terminal voltage and relative speed, reduces the overshoots values and attenuates the oscillation after perturbations. The perturbations are realized on the generator 1,consequently, they effects are more important on this generator and more and more attenuate when we move away from this generator. On all simulations figures, we remark that the proposed controller regulates the terminal voltage and frequency with a better precision compared to AVR-PSS and more attenuates the oscillation after perturbations. This fact can be explained by the taking into account of multimachine interactions into proposed controller design, this is not case of AVR-PSS. After the short circuit, the overshoots values with AVR-PSS achieve 15% for relative speed and 30% for terminal voltage on generator 1, this can carry the generator stall phenomena to electrical grid which can imply the energy production drop. After mechanical perturbation, the oscillation and overshoots values on generator 1 are greater with AVR-PSS compared to proposed controller, these oscillations can be carry a system instability. Globally, the proposed controller is better than AVR-PSS in terms of precision, overshoots values attenuation and damping oscillation.



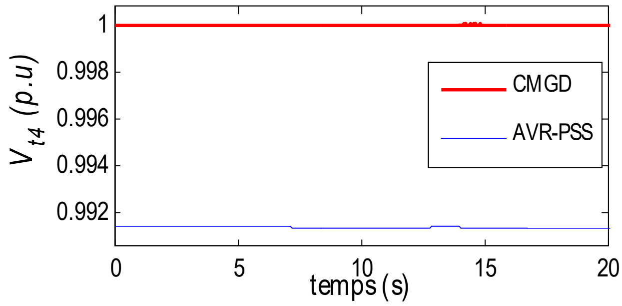

a. **Terminal voltage generator 1**




b. **Terminal voltage generator 2**




c. **Terminal voltage generator 3**




d. **Terminal voltage generator 4**

**Fig. 5. Generators terminal voltage for mechanical power drop of 50% of its value**

# CONCLUSION

In this paper, we have developed a model of multimachine marine turbine system composed by four marine turbines interconnected and connected to an infinite bus. The taking into account of multimachine interactions is realized via an admittance matrix which establishes a link between each generator nodes and terminal voltage of interconnection network. Then, we have proposed a nonlinear sliding mode control for regulating simultaneously terminal voltage and relative speed to ensure the electrical grid connection of proposed multimachine system. Finally, we have tested in simulation the proposed multimachine system controlled under mechanical and electrical perturbations and compared the obtained results to the classical AVR-PSS. The obtained results with proposed controller prove that this controller regulates efficiently voltage and frequency of each production system, even in perturbation presence. The comparative study reveals that the proposed controller presents the performance, effectiveness and robustness criteria better than AVR-PSS after and before perturbations.

**Appendix: System parameters**

| | |
|---|---|
| Synchronous speed | $\omega_s$=314.159 rad $s^{-1}$=1 *p.u* |
| Damping constant | $D_i$=0.1 *p.u* |
| Inertia constant | $H_i$=0.576 s |
| Generator direct axis reactance | $X_{di}$=0.894 *p.u* |
| Generator direct axis transient | $X'_{di}=0.620$ *p.u* |
| Direct axis transient open circuit time constant | $T'_{d0}=0.44$ s |
| Transmission line reactance | $X_L$=0.294 *p.u* |
| Control parameters | $K_i$=2, $\lambda_{0i}$=0.25, $a_i$=0.5. |

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