Effective Single Phase Induction Motor Controller Based On Multi Objective Genetic Algorithm MOGA Using Green Plug Compensator Schemes

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Abstract – The paper presents a family of novel switched smart filter compensated devices using Green Plug Smart Filter Soft Starter GP-SF-SS devices for small single phase induction motors used in air-conditioning, ventilation and water pumping. GP-SF-SS devices are equipped with a dynamic online error driven optimally tuned modified PID controller that ensures improved power factor, reduced feeder losses, stabilized voltage, minimal current ripples and efficient energy utilization/conservation with minimal impact on the host electric grid security and reliability. The family of Green Energy devices and filters is based on concept of avoiding cyclical variations and transients in voltage and current to ensure uniform quasi steady state power and energy load demand. The outcome is improved power quality, efficient utilization and reduced KWh energy consumption. The family of Green Plugs, Smart Filters and Soft Starters are all low cost additions with an estimated cost of S10-15/KVA ratings and with payback periods ratings from 6-12 months at most.

Key words: Efficiency Optimization, Energy Conservation, Single-Phase Induction Motors Drives (SPIMs), Power Quality, Switched/Modulated Power Filters, Multi Objective Optimization MOO, and Genetic Algorithm GA.

I. INTRODUCTION

Small scale induction motors drives consume over 50% of the total electrical energy generated in the developed countries [1]. The electric utility industry and consumers of electrical energy around the world are facing new challenges for cutting electric energy cost, improving energy utilization, enhancing energy-efficiency, demand-side management, improving supply waveform-power quality, reducing safety hazards to personnel and protecting sensitive computer and automatic-data processing networks [2-3]. There is a mushrooming use of nonlinear electric loads especially in large motor drives, are furnaces and power electronic converter loads. All these nonlinear loads are byproduct of analog (saturation or Limiter type) or Digital (converter, solid state switching type) nonlinearities [4-5]. Nonlinear type loads cause severe waveform distortion, power quality problems interference and extra feeder losses due to excessive inrush currents and severe voltage sags. The extended use of power electronic switching conveyers and devices in motor drives, process-industries: Mining. Oil and Gas Industries and industrial DC and AC arc type furnaces have resulted in a polluted grid and unreliable radial distribution/utilization system with serious inherent voltage and power quality problems [6-7]. These nonlinear type electric loads are used with ventilation, air conditioning, water pumping and low power factor industries such as sewing, printing, shear and press machinery and food processing plants. These nonlinear loads also fall in the category of inrush or arc type motorized loads and combined with fluorescent lighting can cause waveform distortion, harmonic interference and voltage flickering [8-9]. Generally, direct online motor starting is an economical method for starting induction motors. But direct starting will result in severe voltage sags and extra heating. When starting large induction motors, excessive voltage dips result in overheating and loss of motor life expectancy [10]. In this paper, a family of novel switched filter devices using Green Plug Smart Filter Soft Starter GP-SF-SS devices equipped with a dynamic online error driven and optimally tuned modified PID controller that can ensure improved power factor, reduced feeder losses, reduced voltage and current ripples, efficient energy utilization/conservation with minimal impact on the electric grid security and supply continuity for single phase induction motor loads. The need for an on-line gains adaptation or self tunable control mechanism is highly needed in the control of any nonlinear systems with un-modeled dynamics. Several AI-related soft computing techniques, such as Genetic Algorithms and Particle Swarm Optimization PSO are emerging as valuable, robust, simple and effective tools in industrial process automation and on-line control adaptation. The Proposed tri loop dynamic error driven self tuned modified PID controller are also used to ensure energy efficiency, control loop decoupling, stability and system efficient utilization while maintaining full voltage stability capability. The paper presents a novel application of Multi Objective Genetic search Algorithms MOGA optimization and search techniques for online tuning are used to optimally tune the gains of modified PID controller. The smart filter/energy conservation devices ensure for single phase induction motor loads: supply power quality PQ enhancement, enhanced electric energy efficiency, extended life span of the induction motor, Reduced KWh consumption and electricity billing, minimized switching transients and load excursions, Maximized power/energy utilization under unbalanced load conditions, and Reduce THD.

II. GENETIC ALGORITHM GA

Genetic algorithm is an optimization method inspired by Darwin’s reproduction and survival of the fittest individual [11]. This algorithm looks for the fittest individual from a set of candidate solutions called population. The population is exposed to crossover, mutation and selection operators to find the fittest individual. The fitness function assesses the quality of each individual in evaluation process. The selection operator ensures the fittest individuals for the next generation. The crossover and mutation operators are used for variety of populations. Fig. 1 shows the general flow chart of the GA algorithm based on total error iterative minimum search. The steps of genetic algorithm are depicted as follows:
1. **[Start]** Generate random population of n chromosomes (suitable solutions for the problem)
2. **[Fitness]** Evaluate the fitness $f(x)$ of each chromosome $x$ in the population
3. **[New population]** Create a new population by repeating following steps until the new population is complete
   a. **[Selection]** Select two parent chromosomes from a population according to their fitness (the better fitness, the bigger chance to be selected)
   b. **[Crossover]** With a crossover probability cross over the parents to form a new offspring (children). If no crossover was performed, offspring is an exact copy of parents.
   c. **[Mutation]** With a mutation probability mutate new offspring at each locus (position in chromosome).
   d. **[Accepting]** Place new offspring in a new population
4. **[Replace]** Use new generated population for a further run of algorithm
5. **[Test]** If the end condition is satisfied, stop, and return the best solution in current population
6. **[Loop]** Go to step 2

The Non-Dominated Sorting Genetic Algorithm (NSGA) is a multi-objective genetic algorithm that was developed by Deb, et al. [12]. This algorithm has been chosen over a conventional genetic algorithm for three principal reasons: (a) no need to specify a sharing parameter, (b) a strong tendency to find a diverse set of solutions along the Pareto optimal front, and (c) the ability to specify multiple objectives without the need to combine them using a weighted sum. The basic idea behind NSGA is the ranking process executed before the selection operation, as shown in Fig. 1. This process identifies non dominated solutions in the population, at each generation, to form non dominated fronts [13], after this, the selection, crossover, and mutation usual operators are performed. In the ranking procedure, the non dominated individuals in the current population are first identified. Then, these individuals are assumed to constitute the first non dominated front with a large dummy fitness value [13]. The same fitness value is assigned to all of them. In order to maintain diversity in the population, a sharing method is then applied. Afterwards, the individuals of the first front are ignored temporarily and the rest of population is processed in the same way to identify individuals for the second non dominated front. A dummy fitness value that is kept smaller than the minimum shared dummy fitness of the previous front is assigned to all individuals belonging to the new front. This process continues until the whole population is classified into non dominated fronts. Since the non dominated fronts are defined, the population is then reproduced according to the dummy fitness values.

### III. SAMPLE STUDY MOTORIZED SYSTEM

Figure 2 depicts the block diagram of the utilization (single-phase induction motor SPIM) and the connection of the Green Plug-Smart Filter-Soft Starter GP-SF-SS and the speed control drive system to the SPIM Load. Figures (3-4) show the proposed tri-loop dynamic tracking controller to ensure both objectives of (energy/power) saving as well as power quality enhancement of the supply system current and load bus voltage. The novel GA self tuned multi regulators and coordinated controller are used for the following purposes: (1) Green plug filter compensator GPF-SPWM regulator for pulse width switching scheme to regulate the DC bus voltage and minimize inrush current transients and load excursions and (2) The SPIM drive with the speed regulator that ensure speed reference tracking with minimum inrush currents and ensure reduced voltage transients and improved energy utilization. Figures (5-12) depict the proposed family of Green Plug-Smart Filter-Soft Starter GP-SF-SS schemes. All filters objectives can be either: (a) Harmonic reduction and power quality (PQ) enhancement; or (b) Electric power/energy savings and dynamic reactive compensation for the single phase induction motor loads. The Proposed utilization scheme is fully validated using the Matlab/Simulink software environment under normal conditions, load excursion, SPIM motor torque changes to assess the control system robustness, effective energy utilization and speed reference tracking. The common concerns of power quality are the long duration voltage variations (overvoltage, under-voltage, and sustained interruptions), short duration voltage variations (interruption, sags, and swells), voltage imbalance (voltage unbalance), waveform distortion (DC offset, harmonics, inter-harmonics, notching and noise), voltage fluctuation (voltage flicker) and power frequency variations. To prevent the undesirable states and to reduce the power consumption, a GPF scheme is used to stabilize the system. The proposed control system comprises two sub-regulators or controllers named as DC side Green Plug Filter Compensator GPF-SPWM regulator and the SPIM drive speed controller. Figures (3-4) depict the proposed multi-loop dynamic self regulating controllers based on Multi Objective Optimization search and optimization technique based on soft computing GA. The global error is the summation of the three loop individual errors including voltage stability, current limiting and synthesize dynamic power loops. Each multi loop dynamic control scheme is used to reduce a global error based on a tri-loop dynamic error summation signal and to mainly track a given speed reference trajectory loop error in addition to other supplementary motor current limiting and dynamic power loops are used as auxiliary loops to generate a dynamic global total error signal that consists of not only the main loop speed error but also the current ripple, over current limit and dynamic over load power conditions.

The global error signal is input to the self tuned modified PID controller shown in figure 6.

A number of conflicting objective functions are selected to optimize using the GA algorithm. These functions are defined by the following:

- **J1** = Minimize the Total Harmonic Distortion of the Load current (THDi) 
- **J2** = Minimize the Total Harmonic Distortion of the Load Voltage (THDv)
- **J3** = Maximize the electric energy efficiency
- **J4** = Maximize the Power factor
- **J5** = Minimize the KWh Consumption
The dynamic error driven controller regulates the controllers’ gains using GA to minimize the system total error and the selected objective functions. The proposed dynamic Tri Loop Error Driven controller, developed by the First Author, is a novel advanced regulation concept that operates as an adaptive dynamic type multi-purpose controller capable of handling sudden parametric changes, load and/or source excursions. By using the Tri Loop Error Driven controller, it is expected to have a smoother, less dynamic overshoot, fast and more robust controller when compared to those of classical control schemes. In the Tuned modified PID controller proposed controller scheme, an optimally tuned modified PID controller for the SPIM motor drive systems is developed using the Genetic Algorithm GA, where the additional integral of the squared system error is implemented in this modified PID controller as shown in Eq. (13),

\[ u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} + K_v v(e(t)) \]  

The modified PID controller gains (K_p, K_i, K_d) are tuned using the GA searching algorithm to minimize the selected objective functions (J_1 - J_5).

IV. DIGITAL SIMULATION RESULTS

Matlab-Simulink Software was used to design, test, and validate the effectiveness of the (GP-SF-SS) devices for small motors used in household appliances, washers, dryers, fans, water pumps, ventilation systems, air-conditions and other applications in dispersing machines, actuators and small converters with induction motor size up to 5-25 KVA. The digital dynamic simulation model using Matlab/Simulink software environment allows for low cost assessment and prototyping, system parameters selection and optimization of control settings. To compare the global performances of modified PID controller, the Normalised Mean Square Error (NMSE) deviations between output plant variables and desired values, and is defined as:

\[ \text{NMSE}_{Vs} = \frac{\sum (V_s - V_{s-ref})^2}{\sum V_{s-ref}^2} \]  
\[ \text{NMSE}_{\omega_m} = \frac{\sum (\omega_m - \omega_{m-ref})^2}{\sum \omega_{m-ref}^2} \]  
\[ \text{NMSE}_{i_s} = \frac{\sum (i_s - i_{s-ref})^2}{\sum i_{s-ref}^2} \]  

The control system comprises the three dynamic multi loop error driven regulator is coordinated to minimize the selected objective functions. SOO obtains a single global or near optimal solution based on a single weighted objective function. The weighted single objective function combines several objective functions using specified or selected weighting factors as follows:

\[ \text{weighted objective function} = \alpha_1 J_1 + \alpha_2 J_2 + \alpha_3 J_3 + \alpha_4 J_4 + \alpha_5 J_5 \]

Where \( \alpha_1 = 0.20, \alpha_2 = 0.20, \alpha_3 = 0.20, \alpha_4 = 0.20, \alpha_5 = 0.20 \) are selected weighting factors. J_1, J_2, J_3, J_4, J_5 are the selected objective functions. On the other hand, the MO finds the set of acceptable (trade-off) Optimal Solutions. This set of accepted solutions is called Pareto front. These acceptable trade-off multi level solutions give more ability to the user to make an informed decision by seeing a wide range of near optimal selected solutions.

Table 1 shows the System behavior Without (GP-SF-SS) Schemes while table 2 shows the system behavior using traditional modified PID controller with constant controller gains for the (GP-SF-SS) eight schemes. In addition, table 3 shows System behavior comparison using the SOGA based Tuned modified PID controller and table 4 shows the system behavior comparison using the MOGA based Tuned modified PID controller. Comparing the system dynamic response results, it is quite apparent that the GA tuning algorithm highly improved the system dynamic performance from a general power quality point of view. The GA tuning algorithm had a great impact on Motor RMS voltage (PU) is improved from 0.8782 (without the (GP-SF-SS) device), 0.9448 (constant gains controller), to around 0.9851 (SOAGA based tuned controller), 0.9917 (MOGA based tuned controller). Motor RMS current (PU) is reduced from 0.8576 (without the (GP-SF-SS) device), 0.6845 (constant gains controller), to around 0.6406 (SOAGA based tuned controller), 0.6239 (MOGA based tuned controller). Maximum Transient Motor Voltage Over/Under Shoot (PU) is reduced from 0.1597 (without the (GP-SF-SS) device), 0.0938 (constant gains controller), to around 0.0469 (SOAGA based tuned controller), 0.0427 (MOGA based tuned controller). Maximum Transient Motor Current – Over/Under Shoot (PU) is reduced from 0.1775 (without the (GP-SF-SS) device), 0.0949 (constant gains controller) to around 0.0386 (SOAGA based tuned controller), 0.0325 (MOGA based tuned controller). The system efficiency is improved from 0.8145 (without the (GP-SF-SS) device), 0.9020 (constant gains controller), to around 0.9377 (SOAGA based tuned controller), 0.9325 (MOGA based tuned controller). Moreover, the Normalized Mean Square Error (NMSE-V) of the Motor voltage is reduced from 0.3293 (without the (GP-SF-SS) device), 0.04393 (constant gains controller), to around 0.008807 (SOAGA based tuned controller), 0.003610 (MOGA based tuned controller). In addition the (NMSE-\omega_m) of the SPIM motor is reduced from 0.5093 (without the (GP-SF-SS) device), 0.05909 (constant gains controller), to around 0.002576 (SOAGA based tuned controller), 0.001543 (MOGA based tuned controller). The (NMSE-I) of the Motor current is reduced from 0.2398 (without the (GP-SF-SS) device), 0.06488 (constant gains controller) to around 0.003525 (SOAGA based tuned controller), 0.002727 (MOGA based tuned controller). Total Harmonic Distortion THD (%) of the supply voltage is reduced from 17.486 (without the (GP-SF-SS) device), 6.6869 (constant gains controller), to around 5.1191 (SOAGA based tuned controller), 5.7369 (MOGA based tuned controller). THD (%) of the supply current is reduced from 19.475 (without the (GP-SF-SS) device), 6.8468 (constant gains controller) to around 3.6054 (SOAGA based tuned controller), 5.3255 (MOGA based tuned controller). THD (%) of the
Motor voltage is reduced from 16.456 (without the (GP-SF-SS) device), 6.9072 (constant gains controller), to around 4.3007 (SOGA based tuned controller), 3.4279 (MOGA based tuned controller). THD (%) of the motor current is reduced from 18.465 (without the (GP-SF-SS) device), 7.5903 (constant gains controller), to around 4.4072 (SOGA based tuned controller), 5.1945 (MOGA based tuned controller).

Motor power factor is improved from 0.7516 (without the (GP-SF-SS) device), 0.9004 (constant gains controller), to around 0.9354 (SOGA based tuned controller), 0.9350 (MOGA based tuned controller). Reduction in KWh Consumption (%) is reduced from 0.000 (without the (GP-SF-SS) device), 13.0035 (constant gains controller), to around 17.8021 (SOGA based tuned controller), 17.9411 (MOGA based tuned controller).

Fig. 1: Flow chart of NSGA.

Fig. 2 The proposed Green Plug-Smart Filter-Soft Starter GP-SF-SS for Single Phase Induction Motor SPIM drive system

Fig. 3 Tri-loop error driven self regulating dynamic controller for control of Single Phase Induction Motor SPIM drive

Fig. 4 Tri-loop error driven self regulating dynamic controller for the Green Plug-Smart Filter–Soft Starter GP-SF-SS Scheme

Fig. 5 Economic Tuned-Arm Power Filter and Capacitor Compensator Scheme-A

Fig. 6 Low Cost Tuned-Arm Power Filter / Capacitor Compensation Scheme-B

Fig. 7 Low Cost Tuned-Arm Power Filter and Capacitor Compensation Scheme-C
**9. CONCLUSION**

The paper presents a family of novel low cost green plug electricity saving device/Smart Filter/Soft Starter (GP-SF-SS) devices developed by the First Author and equipped with a dynamic online error driven optimally tuned modified PID controller using a dynamic online error driven optimally modified tuned PID controller. The (GP-SF-SS) device uses a smart dynamic error driven tracking controller to ensure combined functions of speed reference tracking and efficient utilization. This ensures of reduced electricity consumption, efficient operation, reduced motor losses, motor extended life span, enhanced AC supply operation with minimal voltage and current excursions, harmonics, voltage sags, inrush currents and severe excursions that cause voltage flickering, notching and spikes.

**REFERENCES**


Table 2 System dynamic behavior comparison using the constant parameters modified PID controller

<table>
<thead>
<tr>
<th>Scheme</th>
<th>RMS Motor voltage (PU)</th>
<th>RMS Motor current (PU)</th>
<th>Maximum Transient Voltage</th>
<th>Maximum Transient Current</th>
<th>System Efficiency</th>
<th>NMSE_V&lt;sup&gt;10&lt;/sup&gt;</th>
<th>RMS Current (PU)</th>
<th>Maximum Over/Under Shoot</th>
<th>Over/Under Shoot</th>
<th>THD&lt;sub&gt;v&lt;/sub&gt; Bus L (%)</th>
<th>THD&lt;sub&gt;i&lt;/sub&gt; Bus M (%)</th>
<th>Motor Power Factor</th>
<th>Reduction in KWh Consumption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP-SF-SS</td>
<td>0.9448 0.9353 0.9337 0.9352 0.9410 0.9468 0.9343</td>
<td>0.6845 0.7002 0.7127 0.6670 0.7371 0.7504 0.7125</td>
<td>0.0938 0.0903 0.0902 0.0913 0.0876 0.0934 0.0928</td>
<td>0.0949 0.0946 0.0934 0.0908 0.0867 0.0947 0.0879</td>
<td>0.0920 0.8864 0.9021 0.8765 0.8663 0.8555 0.8618</td>
<td>0.4393 0.8723 0.4597 0.4333 0.1873 0.9501 0.8982</td>
<td>0.5909 0.5238 0.9598 0.1338 0.3333 0.3910 0.2167</td>
<td>0.6488 0.2796 0.5075 0.3387 0.1149 0.2106 0.5887</td>
<td>0.6869 9.0298 7.4214 8.9958 7.3315 8.9853 6.5877</td>
<td>0.7487 0.5903 9.6865 6.7759 8.0481 7.9518 7.8722</td>
<td>6.7063 6.9072 9.2573 8.8022 6.8610 7.4883 8.7586 9.7237</td>
<td>0.9037 7.5903 9.6865 6.7759 8.0481 7.9518 7.8722 6.7063</td>
<td>13.0035 12.8073 12.9952 13.2836 13.7859 13.5407 12.7883 12.2191</td>
</tr>
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</table>

Table 3 System dynamic behavior comparison using the constant parameters modified PID controller

<table>
<thead>
<tr>
<th>Scheme</th>
<th>RMS Motor voltage (PU)</th>
<th>RMS Motor current (PU)</th>
<th>Maximum Transient Voltage</th>
<th>Maximum Transient Current</th>
<th>System Efficiency</th>
<th>NMSE_V&lt;sup&gt;10&lt;/sup&gt;</th>
<th>RMS Current (PU)</th>
<th>Maximum Over/Under Shoot</th>
<th>Over/Under Shoot</th>
<th>THD&lt;sub&gt;v&lt;/sub&gt; Bus L (%)</th>
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<th>Motor Power Factor</th>
<th>Reduction in KWh Consumption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP-SF-SS</td>
<td>0.9851 0.9933 0.9714 0.9894 0.9537 0.9945 0.9587</td>
<td>0.6406 0.6662 0.5973 0.5900 0.6309 0.6672 0.5821</td>
<td>0.0469 0.0270 0.0321 0.0474 0.0362 0.0244 0.0423</td>
<td>0.0386 0.0485 0.0329 0.0422 0.0409 0.0409 0.0275</td>
<td>0.9377 0.9301 0.9341 0.9182 0.9394 0.9635 0.9293</td>
<td>0.8807 0.7089 0.3113 0.5636 0.7984 0.7089 0.1122</td>
<td>0.2576 0.2852 0.1926 0.1449 0.4474 0.3110 0.2079</td>
<td>0.3525 0.8410 0.1416 0.9499 0.9267 0.9517 0.8104</td>
<td>0.5119 5.3982 3.6842 5.5626 5.2495 5.3935 4.4520</td>
<td>3.1943 3.6054 5.6580 4.4314 3.9182 3.1457 0.5392 3.5325</td>
<td>6.0698 3.4007 3.4859 4.3528 5.3305 4.5255 5.7485 3.5200</td>
<td>3.7695 4.4072 3.4605 4.8632 5.0777 5.3225 5.9297 4.8935</td>
<td>3.1822 0.9354 0.9250 0.9228 0.9264 0.9482 0.9587</td>
</tr>
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</table>

Table 4 System dynamic behavior comparison using a selected solution from the MOGA Pareto Front based Tuned modified PID controller

<table>
<thead>
<tr>
<th>Scheme</th>
<th>RMS Motor voltage (PU)</th>
<th>RMS Motor current (PU)</th>
<th>Maximum Transient Voltage</th>
<th>Maximum Transient Current</th>
<th>System Efficiency</th>
<th>NMSE_V&lt;sup&gt;10&lt;/sup&gt;</th>
<th>RMS Current (PU)</th>
<th>Maximum Over/Under Shoot</th>
<th>Over/Under Shoot</th>
<th>THD&lt;sub&gt;v&lt;/sub&gt; Bus L (%)</th>
<th>THD&lt;sub&gt;i&lt;/sub&gt; Bus M (%)</th>
<th>Motor Power Factor</th>
<th>Reduction in KWh Consumption (%)</th>
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<tbody>
<tr>
<td>GP-SF-SS</td>
<td>0.9917 0.9875 0.9692 0.9654 0.9923 0.9711 0.9741</td>
<td>0.6239 0.6693 0.6136 0.6278 0.5963 0.6252 0.6180</td>
<td>0.0427 0.0323 0.0345 0.0229 0.0372 0.0322 0.0440</td>
<td>0.0325 0.0289 0.0314 0.0488 0.0352 0.0321 0.0431</td>
<td>0.9325 0.9373 0.9441 0.9465 0.9524 0.9356 0.9460</td>
<td>0.3610 0.7281 0.2009 0.9099 0.5032 0.9540 0.4650</td>
<td>0.1543 0.6375 0.4557 0.6252 0.3093 0.8199 0.1710</td>
<td>0.5227 0.9220 0.1698 0.4907 0.2897 0.8010 0.5422</td>
<td>0.5736 4.2281 3.5144 4.1456 4.9191 4.9395 4.9103</td>
<td>4.6154 5.3255 4.3269 5.5017 5.5565 3.6072 5.4936 3.6072</td>
<td>4.9569 3.4279 3.2190 4.2872 3.4098 3.7474 5.0843 3.1952</td>
<td>3.3427 5.1945 5.8020 3.6985 4.3412 3.1218 5.1064 5.4246</td>
<td>4.4830 0.9350 0.9283 0.9556 0.9484 0.9400 0.9213 0.9595</td>
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