

A Review of Cuckoo Search Algorithm Based Optimal Siting and Sizing of Shunt Capacitors in Radial Distribution Systems

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Abstract: Compensating reactive power deficiency on power grids is a central concern in the distribution of energy management systems. Several approaches have been adopted over time to minimize the total real power loss and enhancing bus voltage profile. Shunt capacitor has been used from time immemorial for addressing issue of reactive power compensation at the distribution end of power systems, and the extent of benefits derivable from its usage depend solely on correct siting and sizing. To this effect, meta-heuristic algorithms are promising optimization tools for achieving these objectives. This paper, therefore, presents a comprehensive review of cuckoo search algorithm based on optimal siting and sizing of shunt capacitors in radial distribution systems. The suitability, in addition to strengths and weakness of each approaches reported in the reviewed articles have been painstakingly x-rayed. Based on the review, it was observed that a two-stage approach is always adopted in the compensation process: the pre-selection of potential or sensitive nodes and the optimal sizing of shunt capacitors needed for the compensation. For the pre-location, Voltage Stability Index and Loss Sensitivity Factor were found to be comparatively less complex and highly suitable techniques. Another cogent discovery from this review is that less attention has been drawn to the use of cuckoo search algorithm by Nigerian researchers. Therefore, regarding Nigerian electric grid system, the use of cuckoo search algorithm in reactive power support presents a research gap for further investigations.

Keywords: Capacitor Cost Saving, Cuckoo Search Algorithm, Power Factor, Radial Distribution Systems, Real Power Loss, Shunt Capacitor, Voltage Profile

I. Introduction

In recent times, electrical distribution networks are comparatively becoming larger and complex daily and the aftermath effects of this geometrical expansion in distribution network paved way for overshoot in systems real power losses and severe deviation in system voltage profile [1]. It has been established that the

amount of real power loss in radial distribution systems is about 13% of the total power generated [2, 3]. Fundamentally, real power losses are a product of inadequate reactive power supply, therefore if the system losses are to be adequately curtailed; a means of supplying reactive power locally is highly imperative [4]. One of the most cost-effective approaches to compensate for lagging reactive power in a radial distribution system is the use of shunt capacitors. It does this compensation by reducing the current and MVA in the lines [5]. When shunt capacitors are optimally sited and sized, a significant reduction in system losses coupled with good voltage profile maintenance within

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the statutory limits is guaranteed [6]. Other miscellaneous merits derivable from the optimal placement of shunt capacitors in radial distribution systems (RDS) include the appreciable release of the thermal capacities of distribution lines, feeders and transformers, in addition to enhanced power factor [4, 7].

With these benefits, system security and reliability will be sustained and, consequently, as much power as feasible can be transmitted through the transmission line without fear of severe depreciation [8]. In the last few decades tide has turned in favor of artificial intelligence (IA) for optimal siting and sizing of shunt capacitor in RDS, since the problem of shunt capacitors placement is not an online action for distribution systems, but rather a computational solution methodology [4].

Generally, all categories of AI, whether heuristics or meta-heuristics possess good processing speed, less computational complexity and less computational time, only that the degree of the possessions varies[9,10]. Advancement in computational intelligence has really enhanced the performance of population-based meta-heuristics algorithms with its variants flooding the intellectual community daily as tools for addressing complex engineering optimization problems. One of the newest members is the cuckoo search algorithm (CSA) that was developed by Yang and Deb in 2009 [11].

The algorithm combines the good quality of three different algorithms: differential evolution (DE), particle swarm optimization (PSO) and simulated annealing (SA) [11, 12]. Additionally, CSA uses a lévy flight approach for exploration and exploitation of search space, as against isotropic random walk used by other members of the family [11].

In this present study, a comprehensive review of CSA-based optimal siting and sizing of shunt capacitors in radial distribution systems is presented. The rest of this paper is organized as follows: Section 2 presents the problem while Section 3 gives an overview of the CSA. In Section 4, related works on the use of the algorithm are presented, and Section 5 provides the conclusion and future recommendation on the study.

II. Problem Formulation

The central emphasis, when it comes to placement of reactive power compensators in the radial distribution system (RDS), is to minimize real power loss and enhance the voltage profile of the system. A two-stage approach is usually adopted in the process of siting and sizing shunt capacitors for the purpose. The first stage entails pre-determination of the candidate or potential/sensitive node(s) where shunt capacitors are to be installed.

The essence of this stage is to reduce the exploration and exploitation of search space by the algorithms to be employed in deciding the optimal size of shunt capacitors that are required to be installed in the predetermined locations, in the second stage [11]. Optimal siting and sizing of shunt capacitors in RDS is a multi-objective optimization problem. Although a single objective function can be formulated, in which case a weighted value is assigned to every single objective function formulated. This is a way of dealing with multi-objective function formulation [13]. The common objective functions for this type of research are minimization of real power losses, minimization of bus voltage deviation and minimization of cost of shunt capacitors.

The total real power loss in all branches is given as;

$$P_{T\text{ loss (m,m+1)}} = \sum_{m=1}^n P_{\text{Loss}}(m, m+1) \quad (1)$$

and, P_{Loss} is given as;

$$P_{\text{Loss}} = \left(\frac{P_m^2 + Q_m^2}{|V|^2} \right) \times R_m \quad (2)$$

also, the total voltage deviation is given as;

$$\text{TVD} = \sum_{m=1}^n |1 - V_m| \quad (3)$$

where P_{Loss} is real power loss; P_m is real power loss at busm; $P_{T\text{ loss}}$ is total power loss of the system; Q_m is reactive power loss at busm; R_m is resistance of the line section between buses m and m + 1; and TVD is total voltage deviation.

The cost of shunt capacitors as presented by Yang and Deb (2010) is;

$$\text{Capacitor Cost} = X_i C_{0i} + Q_{ci} C_{1i} + B_i C_{2i} T \quad (4)$$

where, $X_i = 0/1$, 0 means no capacitor installed at bus; C_{0i} is installation cost; C_{1i} is per kVar cost of capacitor bank; Q_{ci} is capacitor bank size in kVar; B_i is number of capacitor bank; C_{2i} is operating cost of per bank per year; and T is planning period.

If f_1 , f_2 and f_3 represents equations (2), (3) and (4) respectively; also, if W_1 , W_2 , and W_3 are the weighted valued assigned to the three equations respectively on the basis of relative importance of each objective function, then a multi-objective functions is given thus;

$$F = (f_1 \times W_1) + (f_2 \times W_2) + (f_3 \times W_3). \quad (5)$$

The central aim of the objective function regarding shunt capacitor siting and sizing is to minimize the real power loss, minimize bus voltage deviation and cost of shunt capacitors to be installed, this is could be expressed as;

$$F_{\min} = (f_1 \times W_1) + (f_2 \times W_2) + (f_3 \times W_3) \quad (6)$$

and,

$$W_1 + W_2 + W_3 = 1; \quad 0 < W \leq 1 \quad (7)$$

The system constraints to which the objective functions are to be subjected are inequality and equality constraint. The non-linear real and reactive power flow equations constitute the equality constraints given as;

$$P_m = |V_m| \sum_{m=1}^n |y_{mn}| |V_n| \cos(\delta_m - \delta_n - \theta_{mn}) \quad (8)$$

$$Q_m = |V_m| \sum_{m=1}^n |y_{mn}| |V_n| \sin(\delta_m - \delta_n - \theta_{mn}) \quad (9)$$

where P_m denotes real power flowing out of bus m; Q_m stands for reactive power flowing out of bus m; $|y_{mn}|$ and θ_{mn} respectively represent the size and angle of admittance; while δ_m and δ_n connote the angles of voltage at buses m and n respectively.

The system inequality constraints are the limits placed on the bus voltage magnitude and the sizes of reactive power to be supplied by the shunt capacitors to be installed is given as;

$$V_m^{\min} \leq V_m \leq V_m^{\max},$$

$$V_m^{\min} = 0.95 \text{ p.u and}$$

$$V_m^{\max} = 1.05 \text{ p.u} \quad (10)$$

$$Q_c^{\min} \leq Q_c \leq Q_c^{\max} \quad (11)$$

The commonest techniques for determining the locations where shunt capacitors are to be installed are Voltage Stability Index (VSI), Loss Sensitivity Factor (LSF), Power Loss Index (PLI) and Index Vector Method (IVM). These approaches are used to reduce the computational time as the potential buses or sensitive nodes are identified before sizing which is normally done with the aid of optimization algorithms. The

nodes with the least value of VSI are identified as potential buses where shunt capacitors are to be installed. It is computed from the base caseload flow using;

$$VSI_{(m+1)} = |V_m|^4 - 4[P_{m+1,eff} \times X_m - Q_{m+1,eff} \times R_m]^2 - 4[P_{m+1,eff} \times R_m + Q_{m+1,eff} \times X_m]|V_m|^2 \quad (12)$$

where, V_m stands for bus m voltage magnitude; X_m connotes line reactance between section m and $m + 1$; R_m represents the line resistance between section m and $m + 1$; $Q_{m+1,eff}$ is the total effective reactance power load through the bus $m + 1$; and $P_{m+1,eff}$ stands for total effective real power load fed through the bus $m + 1$.

In LSF, bus whose normalized voltage magnitude values are less than 1.01 are treated as the sensitive nodes where shunt capacitors are to be installed to achieve greater loss minimization. It is computed from the base case load flow as;

$$\begin{aligned} LSF &= \frac{\partial P_{line\text{loss}}(k)}{\partial Q_{eff}(k)} = \frac{(2 \times Q_{eff}(k)) \times R(j)}{(V(k))^2} \\ &= \frac{\partial Q_{line\text{loss}}(k)}{\partial Q_{eff}(k)} = \frac{(2 \times Q_{eff}(k)) \times X(j)}{(V(k))^2} \end{aligned} \quad (13)$$

The normalize voltage magnitude is obtained using equation (13), thus;

$$\text{norm}[i] = \frac{|V[i]|}{0.95} \quad (14)$$

Obtaining the sensitive node using the IVM from the based caseload flow by calculating the reactive component of current in the branches and reactive power load concentration at each node is by using;

$$\text{Index}[n] = \frac{1}{V_n^2} + \frac{I_q(k)}{I_p(k)} + \frac{Q_{eff}(n)}{\text{total } Q} \quad (15)$$

where V_n is bus voltage at n^{th} ; $I_q(k)$ is imaginary component of current in k^{th} branch; $I_p(k)$ stands for real component in k^{th} ; and total Q is the total reactive load of the given distribution systems.

The PLI is another approach to identify where capacitors are to be placed, in which buses having higher PLI and lower bus voltage values of 0.95 p.u are considered as the potential buses for the location of shunt capacitors. At m^{th} node, the PLI value is computed using equation (16);

$$PLI = \frac{LR_m - LR_{min}}{LR_{max} - LR_{min}} \quad (16)$$

where LR stands for loss reduction at node m^{th} .

III. Cuckoo Search Algorithm

CSA was developed using the parasitic brooding attributes of a bird called cuckoo [11]. The algorithm is a unique hybridized version of three different algorithms namely DE, PSO and SA [12]. Aside from having fewer parameters, it utilizes the lévy flight approach used by some birds and fruit flies in locating their foods, to explore and exploit the search space against the isotropic random walk approach used by other population-based algorithms [12].

CSA is endowed with fascinating features; it has only fewer parameters making the computational task easier to implement, the use of lévy flight approach guaranteed efficient and effective exploitation and exploration of search space which invariably give rise to its capability of achieving good convergence characteristics, its ability to efficiently combined both random walks and global explorative random walk give rise to enhanced adaptability for handling complex engineering optimization problems [11,12].

The three basic idealize rules formulated for CSA are; each cuckoo lays one egg (a design solution) at a time and dumps its egg in a randomly chosen nest among the fixed number of available host nests, the best nests with high a quality of egg (better solution) will be carried over to the next generation and the number of available host nests is fixed, and a host can discover an alien egg with a probability $p_a \in [0, 1]$. In this case, the host bird can either throw the egg away or abandon the nest so as to build a completely new nest in a new location.

The parameters of CSA that have to be defined prior to the simulation are the number of nests (N_p), iteration maximum no ($Iter_{max}$) and the probability of an alien egg to be discovered (p_a) can have its value chosen in the range $[0, 1]$. Also, the solution quality of the algorithm depends largely on the number of nests and the higher number of is chosen the higher probability for a better optimal solution to be obtained [14].

IV. Related Works

Authors in [15] applied LSF to pre-determine sensitive buses requiring reactive power compensation, while the optimal sizes of the required shunt capacitors were evaluated using CSA. Both IEEE 15 and IEEE 34 bus RDS were used as the test case systems and the proposed approach was implemented on MATLAB 7.12. The load flow analysis on the test case systems was done using the branch current load flow approach and the results obtained were validated with results from DE using real power loss and system voltage profile as performance metrics. It was concluded, by these authors, that this approach placed capacitors at less number of sites, and with optimal sizes. It also offers relatively higher savings in the costs of capacitors, compared to

GA and PSO. However, the work would have been more robust if the proposed approach was implemented on real practical RDS.

The use of CSA for the allocation of static shunt capacitors on RD networks is also presented by authors in [16]. A multi-objective function consisting reduction of system peak losses, enhancement of system voltage profile, and improvement of overall system power factor was formulated. A two-staged approach was adopted, in which the power loss index was used to identify the potential buses, while CSA was then used to optimally size the shunt capacitor required for the compensation. IEEE 33 bus and IEEE 69 bus systems were employed for test cases, and the proposed approach was implemented in MATLAB.

The obtained result was validated with Fuzzy Harmony Search (FHS) algorithm and Ant Bee Colony (ABC) optimization, based on the stated performance metrics. It is found that the CSA competes outstandingly with FHS and ABC and so the authors concluded that CSA produces a quality solution with smooth convergence characteristics. Nevertheless, the real practical distribution system was not used for the analysis as this has a high resistance to the reactance ratio. Likewise, the work revealed that PLI may not always indicate the appropriate sites for siting the shunt capacitors.

As a means of compensating for reactive inadequacy in RDS, a CSA-based optimization approach for allocation and sizing of shunt capacitor was discussed by [17]. PLI was used to determine the suitable locations for the installation of reactive power supports, while CSA was employed to determine the optimal sizes required. This approach was implemented in MATLAB and tested on IEEE 69 bus test system, with the minimization of real power loss

and improvement in system voltage profile as performance metrics. The results obtained were validated using Fuzzy-HS and Plant Growth Simulation Algorithm (PGSA). The percentage real power loss for CSA, FHS and PGSA are 34.36%, 32.58% and 26.90% respectively, also, the system overall power factor for each approach are 0.95, 0.94 and 0.96 respectively, while the minimum system voltage profile for each approach respectively are 0.9285, 0.931426 and 0.9287 p.u. It is also found that CSA exhibited high computational time compared to FHS and PGSA in addition to the fact that PLI is not relatively suitable in pre-determination of suitable locations for siting shunt capacitors.

Capacitor allocation and sizing on IEEE 69 bus test system was investigated by authors in [18] using real power loss, voltage enhancement and cost saving under different loading condition as the performance metrics. PLI was used to pre-determine the potential buses where capacitors were to be installed, after which CSA was employed to size the capacitors required optimally. The results of the CSA sizing was validated with PSO, DE and DE-PSO, in which the obtained results indicated that the CSA caused appreciable reduction both in real power loss and annual energy consumption. The major drawback in this work is that the PLI used is grossly inadequate, compared to VSI and LSF, for pre-determination of buses where shunt capacitors are to be placed.

Authors in [19] reported a methodology for finding optimal siting and sizing of capacitors on RDS, with a view to improve system voltage profile and reduce the real power loss. In the study, loss sensitivity approach was used to find potential buses for the installation of reactive power support, while CSA was used to find the optimal sizes. IEEE 15 bus, IEEE 34 bus and IEEE 69 bus RDS were employed as test case

systems, with minimization of real power loss, bus voltage enhancement and cost saving as performance metrics, while the implementation tool was MATLAB. Based on the result obtained, it was concluded by the authors that CS algorithm is less complex since it has fewer parameters compared to other algorithms.

CSA for optimal sizing of shunt capacitor under different load condition on IEEE 33-bus test system was presented by authors in [20]. The performance metrics used are minimization of total real power loss and voltage profile enhancement. The proposed approach was implemented in MATLAB environment. Although the system loss got reduced appreciably and voltage profile was enhanced, yet the pre-determination of candidate buses needing capacitor placement was not done, coupled with the fact that the method employed for the load flow studies was not stated. In addition, no evidence of results validation with other meta-heuristics algorithm was reported in the presentation.

Authors in [21] examined effective of CSA in the allocation of switching capacitor in RDS. The optimum capacitor siting solution was evaluated for a system of feeders that are fed through their transformers. West Algerian network was used as the test case system, in which CSA was employed to determine the optimal allocation of the capacitors downstream of the transformers and in the feeders. However, the candidate buses for the allocation of the shunt capacitors were not identified in the report, aside the fact the process of load flow studies was not clearly stated. Also, the result of the proposed approach was not validated with other meta-heuristics algorithm.

Researchers in [22] used the CSA to decide both the optimal location and size of shunt capacitors.

The BFS load flow technique was used for the flow studies, while the test case systems were IEEE 33 bus and IEEE 69 bus RDS. The validation of the result of the proposed approach was done using PSO, On the IEEE 33 bus system, CSA improved power loss by 34.50%, compared to PSO approach that recorded 34.48% improvement. But on the IEEE 69 bus system, CSA recorded 32.13%, while PSO produced 35.43% reduction in real power loss. The installation of shunt capacitor using CSA also reduced appreciably compared to what was obtained using PSO. The authors, therefore, concluded that CSA has the capability to produce consistent result with 30 independent fair trials.

Another approach for optimal sizing and placement of shunt capacitor using CSA is presented by [23]. VSI was used to pre-determine the potential buses where capacitors were to be installed and thereafter the optimal sizes required were determined using CSA. BFS load flow technique was employed. A multi-objective function capturing real power loss minimization and voltage profile enhancement, which was converted into single objective function using weighted approach, was formulated.

The proposed approach was tested on IEEE 33 bus and IEEE 69 bus RDS using different load factors implemented using MATLAB software. The results of the proposed approach was validated with results obtained via PSO, Teaching Learning Base Optimization (TLBO), Direct Search Algorithm (DSA) and GA. Based on the result comparison, the proposed approach achieved the least real power loss, enhanced system voltage profile and best net cost saving. The authors concluded that unlike GA, PSO and DSA, CSA requires less

computational effort in addition to possession of fewer control parameters.

In [24], CSA based optimal allocation and sizing of shunt capacitor is implemented on IEEE 33 bus test systems and two practical RDS of 22 bus and 29 bus. The shunt capacitor was placed at 50% loading with a view to minimizing system real power loss and improving system voltage profile. The results obtained using the proposed approach was validated with GA, PSO and HAS. Based on the performance metrics used, CSA outsmarted other proposed approach. On the practical RD network, appreciable reduction in system network losses was achieved alongside improved system voltage profile. The major drawback with the work was that the potential buses where shunt capacitors were to be installed were not pre-determined. This definitely must have affected the computational time during the exploration and exploitation of the search space.

V. Discussion of Findings

On pre-determination of potential buses or sensitive nodes prior sizing of capacitor bank, VSI, LSF, IVM and PLI are found to be the major tools reported in the surveyed literatures. In terms of the computational complexity, PLI is grossly too complex and cumbersome as reported by researchers [16, 17]. In addition, the load flow has to be repeated severally before the potential buses can be identified. It is also reported that IVM too suffered the same major drawback as the PLI.

Both the VSI and LSF are, however, less complex and so give adequate suggested buses where shunt capacitors are to be installed to achieve minimized real power loss and enhanced bus voltage profile as well as attaining greater cost saving. Contrary to the submissions made by other authors who present CSA as a suitable and power tool in reactive power compensation,

Table1: A Summary of Application of CSA for Siting and Sizing of Shunt Capacitors in Radial Distribution System

Author's Names and ear of Publication	Algorithm Employed	Algorithms used for Validation	Test Case Systems	Inference Drawn	Performance Metrics
Reddy and Manohar, (2013)	LSF CSA	GA and PSO	IEEE 15 and 34 bus RDS	i. Places capacitors at less number of sites with optimal sizes, ii. It offers relative higher saving in cost of capacitors	i. Minimization of real power loss ii. Voltage profile enhancement
El-Fergany and Abdelaziz, (2013)	PLI CSA	FHS and ABC	IEEE 33 and 69 bus RDS	i. CSA produced quality solution with smooth convergence characteristics ii. PLI may not always indicate the appropriate sites for capacitor siting	i. Reduction of system peak losses, ii. System voltage profile enhancement iii. Overall system power factor
El-Fergany, and Abdelaziz, (2014)	PLI CSA	PGSA FHS	IEEE 69 bus RDS	i. CSA exhibited high computational time compared to PGSA and FHS ii. PLI is not a suitable for predetermination of potential buses	i. Reduction of system peak losses, ii. System voltage profile enhancement iii. Overall system power factor
El-Fergany and Abdelaziz, (2014)	PLI CSA	PSO, DE and DE-PSO	IEEE 69 bus RDS	i. CSA caused appreciable reduction both in real power loss and annual energy consumption ii. PLI is grossly inadequate as the load flow has to be repeated severally to get potential buses. CS algorithm is less complex due to its fewer parameter	i. Reduction of system peak losses, ii. System voltage profile enhancement iii. Overall system power factor
Dinakara and Gunaprasad, (2014)	LSF CSA	No validation was made	IEEE 15, 34 and 69 bus RDS		i. Minimization of real power loss, ii. Bus voltage enhancement iii. Cost saving
Deepthi <i>et al.</i> (2015)	LSF CSA	No evidence of results validation	IEEE 33-bus system	i. Potential buses were not previously determined.	i. Minimization of total real power loss ii. Voltage profile enhancement
Hamzi and Meziane (2015)	CSA	No evidence of results validation	West Algerian Network	i. Newton Raphson used for the load flow is grossly not adequate for distribution load flow analysis. ii. Potential buses were not previously determined.	i. Minimization of total real power loss ii. Voltage profile enhancement
Idris and Zaid (2016)	LSF CSA	PSO	IEEE 33 and 69- bus RDS	i. CSA has the capacity to produce consistence result	i. Minimization of total real power loss
Devabalaji <i>et al.</i> (2016)	VSI CSA	PSO, GA, TLBO, DSA	IEEE 33 and 69-bus RDS	i. CSA achieved the least real power loss, enhanced system voltage profile and best net cost saving ii. CSA requires less effort computational effort.	i. Minimization of real power loss, ii. Bus voltage enhancement iii. Cost saving
Priyadarshini, Prakash, and Rekha (2017)		GA, PSO and HAS	IEEE-33, Real RDS of 22, 29 Bus	The major drawback with the work was that the potential buses where shunt capacitors are to be installed are not predetermined this would affected the computational time	i. Minimization of real power loss, ii. Bus voltage enhancement

the report in [16] deviates by describing the algorithm as exhibiting too long computational time. It is noted, however, that the outcome of the work in [17] is influenced by the choice of PLI for the pre-determination of the candidate buses, a choice that is grossly inadequate, as noted even in the same work. Improper choice

of values for the control parameters could also be a major cause of the long computational time reported.

In general, a summary is presented in Table 1, which compares at a quick glance the methods, the test case systems and the performance

metrics used, as well as the inferences drawn in the literatures reviewed on the use of CSA for optimal siting and sizing of capacitor-based reactive power compensators.

VI. Conclusions

Presented in this paper is a comprehensive review of articles on CSA-based optimal siting and sizing of shunt capacitors in RDS. Suitability, in addition to strength and weakness, of the approach, as reported in the reviewed articles, is painstakingly x-rayed. It is established, in all the reviewed papers, that CSA-based optimal placement and sizing of shunt capacitors is a reliable tool for addressing the problem of reactive power support on RDS.

However, it is noted that even though the CSA-based approach has been shown to be a powerful tool for placement and sizing of shunt capacitors, the number of papers so far turned out on the concept is grossly scanty. Nevertheless, improved performance in the area of minimization of total real power loss, voltage profile enhancement, capacitor cost saving and improvement of overall system power factor, is a hallmark of the algorithm as found common to all the reviewed pieces of literature.

This review has also revealed that the use of CSA for addressing capacitor-based reactive power compensation has received very low attention on Nigerian RDS, as there is no account of the adoption of the approach found in the course of sourcing research papers on the concept. Meanwhile, the algorithm is robust and highly suitable for handling the problem of compensators placement and sizing, even on relatively large networks. This, therefore, opens up a research gap for Nigerian researchers that may be interested in undertaking such an investigation with reference to the Nigerian grid system.

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