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# Optimal Single Point Injection of PV based DG Maximizing Technical, Social and Environmental Benefits in Radial Distribution Systems using JAYA Algorithm

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## Abstract

Power crisis is becoming a major challenge in modern day world due to ever increasing load demand leading to fast depletion of energy resources. As the number of loads connected to the distribution network increase, maintaining the voltage profile of the distribution network is becoming increasingly difficult for the network operator. The pollutants from a fossil fuel based power plant have adverse effects on the environment. This paper presents a comprehensive study on the technical, economic and environmental impacts on single point optimal allocation of DG on a radial distribution network. The test systems considered are standard IEEE 33 bus, 69 bus and 85 bus test systems.

**Keywords:** Benefit Cost Ratio (BCR), Distribution Network, Emission Cost Benefit Index (ECBI), Renewable Energy, Voltage Profile Enhancement Index (VPEI), Voltage Stability Index (VSI)

## 1. Introduction

An electric distribution network is characterized by high R/X ratio because of their radial nature. As a result, the load flow methods for transmission network viz. Gauss-Seidel, Newton-Raphson etc. do not work in case of radial networks. The active power losses in the distribution networks are higher as compared to distribution networks. Power crisis is one of the major challenges faced by distribution network operator. Due to ever-increasing load demand, the natural resources of energy are getting depleted. So, the network operators have to rely on renewable energy based DGs (eg. PV, Wind etc.) to save fossil fuel as much as possible. Further the harmful pollutants due to emission from fossil-fuel based plants lead to green-house effect and global warming. Increase in load growth leads to increase in size of distribution network causing voltage stability issues. For the past one decade, several researchers across the globe have addressed the aforementioned issues and gave solutions through their research works. Alam, Muttaqui and Bouzerdoum[1] investigated the voltage swell/dip characteristics in a DG integrated distribution network during islanding, post islanding and grid reconnection process. An intelligent computational algorithm has been developed by Anilkumar, Devriese and Srivastava[2] for Volt/VAR controlto maximize the energy savings in a wind integrated standard IEEE 13 & IEEE 37 distribution networks. A comprehensive optimisation model formulated as a second order conic programming problem by Erdinç et al.,[3] for optimal sizing and allocation of

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DG along with energy storage systems. Ettehadi, Ghasemi and Vaez-Zadeh[4] have performed a voltage stability analysis due to DG allocation on a standard IEEE 33 bus radial distribution network. An improved analytical method for optimal DG sizing & placement for loss reduction has been developed by Hung and Mithulananthan[5]. Gandomkar, Vakilian and Ehsan[6] have presented a genetic based Tabu-search for loss reduction in active distribution networks. Kansal, Kumar and Tyagi[7] have proposed optimal placement of different types of DGs for minimising power loss in distribution network using PSO technique and the optimal power factor is obtained. Hedayati, Nabaviniaki and Akbarimajd[8] have analysed the continuity of power flow and voltage sensitivity of buses of a distribution network those are prone to suffer a voltage collapse on optimal DG injection. Iqbal, Khan and Siddiqui[9] have proposed a scheme for reduction of power loss in a radial active distribution network and improvement of voltage profile by optimally placing DG & DSTATCOM. Singh and Mishra[10] have performed a survey on how performances of radial distribution networks enhance on optimal DG injection and different obtained performance parameters like voltage profile, active power losses, System Average Interruption Duration Index (SAIDI), Customers Average Interruption Duration Index (CAIDI) etc. have been discussed.Yuvaraj and Ravi[11] have applied Cuckoo Search Algorithm (CSA) to a multi-objective problem for simultaneous optimal allocation of DG and DSTATCOM to a radial distribution network and calculated the Voltage Stability Index (VSI) and loss sensitivity factor (LSF) for a standard IEEE 33 and 136 bus radial distribution network. Ghatak, Sannigrahi and Acharjee[12] have done a comparative performance analysis of a radial distribution network on optimal allocation of DG and DSTATCOM using improved PSO based on success rate.

# 2. Cost Modelling, Problem Formulation and Operating Constraints

## 2.1 Voltage Profile Enhancement Index (VPEI)

The voltage profile ($V_p$) needs to be investigated by the network operator during power flow process. The nominal voltage ($V_{nominal}$) should not violate the upper ($V^{upper}$) & lower ($V^{lower}$) limits. The allowable voltage limits are restricted to ± 10%.

$$V_{normal} = \frac{(V^{upper} + V^{upper})}{2} \qquad (1)$$

For a kth bus, VP is given by

$$V_{pk} = \frac{4(V_k - V^{lower})(V^{upper} - V_k)}{(V^{upper} - V^{lower})} \qquad (2)$$

For a radial distribution network, the Voltage Profile Index (VPI) is given by

$$VPI = \frac{1}{N_c}\sum_{k=1}^{N_c} V_{pk} \qquad (3)$$

$N_c$ is the number of loads connected to the distribution network.

The Voltage Profile Enhancement Index (VPEI) for a distribution network is given by

$$VPEI = \frac{(VPI)_{with\ DG}}{(VPI)_{without\ DG}} \qquad (4)$$

For voltage stability to be achieved, the value of VPEI should be greater than one. A value of unity indicates that the network after DG injection is marginally stable or may become unstable. If VPEI is less than unity, it indicates that the network is unstable.

## 2.2 Benefit Cost Ratio (BCR)

The benefit in terms of cost savings obtained after installing one or more DG/DGs is indicated by Benefit Cost Ratio (BCR). The total cost of DG is segregated into three components i) Investment Cost (INVC) ii) Hourly Working Cost (HWC) & iii) Annual Maintenance Cost (AMC). The cash flow for the newly placed DG/DGs in the coming future must be considered. The Inflation Rate (IFLR) & the interest rate (INTR) are necessary in order to predict its Current Price (CP). It is calculated as

$$CP = \frac{1 + \frac{IFLR}{100}}{1 + \frac{INTR}{10}} \qquad (5)$$

The Cumulative Current Price (CCP) for a specific Year-span (YRspan), is calculated as follows

$$CCP = \frac{1 - CP^{YR_{span}}}{1 - CP} \qquad (6)$$

The cost of PV based DG is calculated as given in the following equation.

$$DG_{cost} = INVC * P_{DG} + HWC* P_{DG} * PLF * YR_{span} * 8760 * CCP + AMC * CCP + YR_{span} \quad (7)$$

PLF is the plant factor. DG installation results in reduction of consumption of power from the main grid which, in turn, reduces active and reactive power losses of the distribution network. The benefit of installing DG is calculated by the following equation

$$DG_{benefit} = \{P_{DG} * PLF + (PLOSS_{\frac{W}{O}} - PLOSS_{W})\} * YR_{span} * 8760 * C_h * CCP \quad (8)$$

$C_h$ is the cost of power generation, $PLOSS_{\frac{W}{O}}$ is the power loss of the distribution network without any DG & $PLOSS_W$ is the power loss of the distribution network after DG installation.

Finally, the BCR of the DG/DGs is

$$BCR = \frac{DG_{benefit}}{DG_{cost}} \quad (9)$$

A value of BCR greater than 1 means that cost saving is generated after DG installation. If BCR equal to 1, it means that there is no benefit obtained in terms of cost after DG installation. A value of BCR less than 1, will reveal that a financial loss is incurred after DG installation.

### 2.3 Emission Benefit Cost Index

The 21st century an era of green energy when all the countries, across the globe, are trying to get rid of fossil fuel based power. It is due to the emission from fossil fuel which is rich in COx, NOx, particulate matter etc. Targets for all the countries are set for zero fossil fuel energy. Renewable energy based DG injection on a distribution network will reduce power consumption from fossil fuel. In order to ascertain the benefit of a DG with respect to environmental emission, ECBI is formulated as follows

$$E = E_{grid} * GP \quad (10)$$

$$EC = \sum_{t=1}^{YR_{span}} E * E_c * \frac{1}{(1+d)^t} \quad (11)$$

$$ECBI = \frac{EC_{without\ device} - EC_{with\ device}}{EC_{without\ device}} \quad (12)$$

E, $E_{grid}$ and GP represent the amount of $CO_2$ emission, emission factor and power generated by the main grid respectively. The variables d and t represent the rate of discount/interest and the number of years taken in planning the horizon. If ECBI, after DG injection, turns out to be greater than 0, it indicates that there is reduction in emission due to lower fossil fuel consumption. If ECBI is equal to zero, then there is no change in terms of emission after DG installation.

### 2.4 Formulation of the Objective Function

The Objective Function (OF) is formulated as a maximizing function, keeping equal weightage on the above three indices namely, VPEI, BCR and ECBI. The values of all the parameters have been taken from 7.

$$OF = \lambda_1 \times VPEI + \lambda_2 \times BCR + \lambda_3 ECBI \quad (13)$$

$$\sum_{k=1}^{3} \lambda_k = 1 \quad (14)$$

$$\lambda_1 = \lambda_2 = \lambda_3 = 0.333 \quad (15)$$

## 3. Operational Constraints

The objective function should not violate the constraints which are discussed below.

Voltage Constraint: The operating voltage of each node of a radial distribution network must lie within the upper and lower limits. $V_j$ is the operating voltage at the jth node of the network. $V_j^{mn}$ & $V_j^{mx}$ are the maximum & minimum voltage limits of the line.

$$V_j^{mn} \le V_j \le V_j^{mx} \quad (16)$$

Line Power Flow Limit: The distribution network must not carry power beyond its power carrying capacity. $PLF_{mn}$ is the power flow between the points m & n of the network and $PLF_{mn}^{mx}$ is the maximum power flow limit between the same points.

$$PLF_{mn} \le PLF_{mn}^{mx} \quad (17)$$

Active Power Flow Limit: The power output from the main generator must not exceed its specified limits. The power output of the main generator is given by $P_G$. $P_G^{min}$& $P_G^{max}$ are the minimum & maximum limits of the main generator.

$$P_G^{min} \le P_G \, P_G^{max} \quad (18)$$

## 4. Jaya Algorithm and its Application to the Problem of PV based DG Allocation

Jaya is a very simple but powerful algorithm proposed by R. Venkata Rao in 2015. It can be applied on both constrained and unconstrained optimization problems due to its fast convergence characteristics. It is based on the fact that the obtained solution for a specific problem will move towards the best value & move away from the worst value. The effectiveness of the algorithm has been shown for 24 standard constrained benchmark functions[13]. The algorithm has been proved to be promising and effective. Let g(x) is an objective function which is subjected to several constraints. Let 'v' (j=1, 2...m) indicate the design variables. The size of the population is denoted by '$n_{pop}$' (k=1, 2...n). The best and worst valued candidates are indicated by $g(x)_{best}$ and $g(x)_{worst}$ respectively at the $i^{th}$ iteration. Suppose, if, $X_{j,k,I}$ indicates the value of the $j^{th}$ variable of the kth candidate for the $i^{th}$ population, then its updated value as per Jaya Algorithm is given by the following equation. $c_{1,j,i}$ and $c_{2,j,i}$ are randomly generated values that lie between zero and unity. The term $c_{1,j,i} *(X_{j,best,i}-|X_{j,k,i}|)$ makes the candidate move towards the best solution and the term - $c_{2,j,i}*(X_{j,worst,i}-|X_{j,k,i}|)$ deviates the candidate away from the worst solution. The flowchart of Jaya Algorithm is illustrated in Figure 1.

$$X'_{j,k,i} = X_{j,k,i} + c_{1,j,i}*(X_{j,best,i}-|X_{j,k,i}|) - c_{2,j,i}*(X_{j,worst,i}-|X_{j,k,i}|) \quad (19)$$

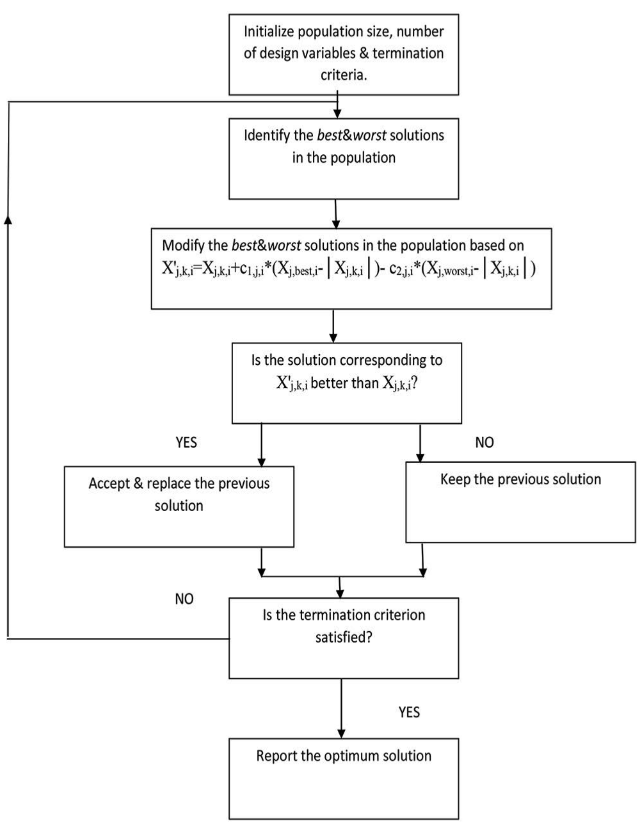


**Figure 1.** Flow chart of Jaya algorithm.

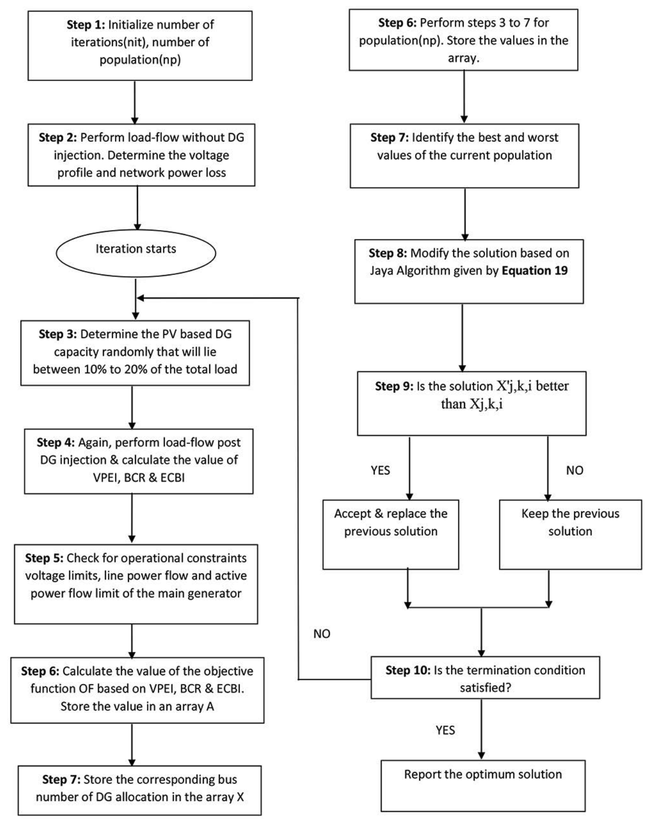


**Figure 2.** Flow chart of Jaya algorithm applied to the problem.

## 5. Simulation Results

The simulation work has been carried out in PC having configuration INTEL(R) Core (TM) i3-7100 CPU@ 3.90 GHz using MATBLAB 2014b MATPOWER v 6.0. The program is coded as per the flowchart given in Figure 2. The algorithms taken into consideration are RPSO, LPSO, PSO-SR, CSA-LF & Jaya. The number of iterations (nit), population (np) and trials are 100, 25 & 15 respectively. The convergence characteristics for standard IEEE 33, 69 and 85 bus systems are shown in Figure 3, 5 and 7 respectively. The VSI characteristics pre & post DG injection for standard IEEE 33, 69 and 85 bus systems are shown in Figures 4, 6 and 8 respectively The convergence rate for the said algorithms for standard IEEE 33, 69 and 85 bus systems are shown in Tables 1, 3 and 5 respectively. Calculation of the performance parameters viz. VPEI, BCR, ECBI, active power losses before and after DG injection, optimal points of DG injection are shown in Tables 2, 4 and 6 respectively. The data related to economic and emission parameters are taken from Table 7.

**Test System 1: IEEE 33 bus**

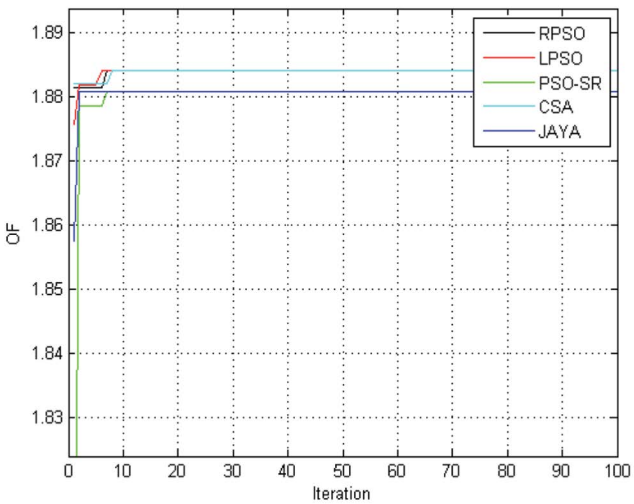


**Figure 3.** Convergence characteristics of standard IEEE 33 bus radial test system.

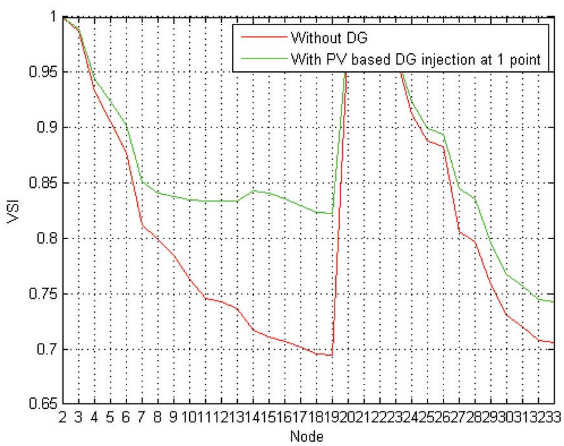


**Figure 4.** VSI characteristics of standard IEEE 33 bus radial test system.

**Table 1.** Rate of convergence for standard IEEE 33 bus test system

| IEEE 33 bus | RPSO | LPSO | PSO-SR | CSA-LF | JAYA |
|---|---|---|---|---|---|
| No of Iterations taken to converge | 7 | 6 | 7 | 8 | 2 |

### Test System 2: IEEE 69 bus

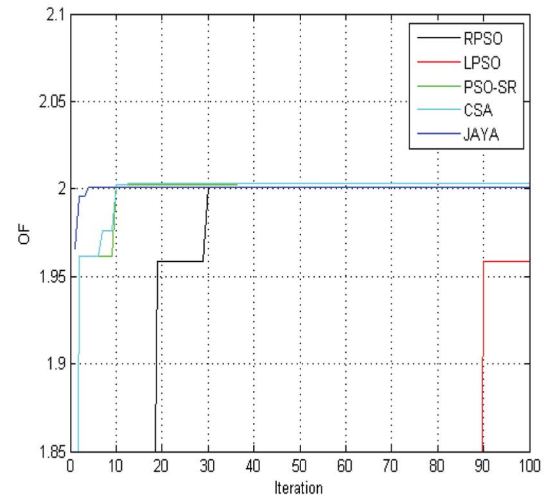


**Figure 5.** Convergence characteristics of standard IEEE 69 bus radial test system.


**Figure 6.** VSI characteristics of standard IEEE 69 bus radial test system.

**Table 3.** Rate of convergence for standard IEEE 69 bus test system

| IEEE 69 bus | RPSO | LPSO | PSO-SR | CSA-LF | JAYA |
|---|---|---|---|---|---|
| No of Iterations taken to converge | 30 | 111 | 37 | 13 | 4 |

**Table 2.** Results post DG injection in case of standard IEEE 33 bus test system

| IEEE 33 bus | VPEI | BCR | ECBI | OF | P_Loss before injection (kW) | P_Lossafter injection (kW) | Optimal point of injection |
|---|---|---|---|---|---|---|---|
| | 1.2763 | 4.1758 | 0.2063 | 1.8842 | 202.67 | 137.64 | 14 |

**Table 4.** Results post DG injection in case of standard IEEE 69 bus test system

| | |
|---|---|
| IEEE 69 bus | Optimal point of injectionP_Loss after injection (Kw)P_Loss before injection (Kw) OFECBIBCRVPEI |
| | 61130.152252.00850.21244.74471.0745 |

**Test System 3: IEEE 85 bus**

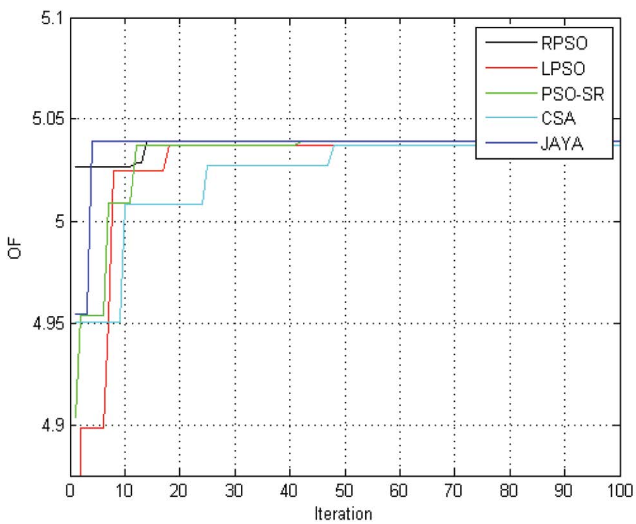


**Figure 7.** Convergence characteristics of standard IEEE 85 bus radial test system.

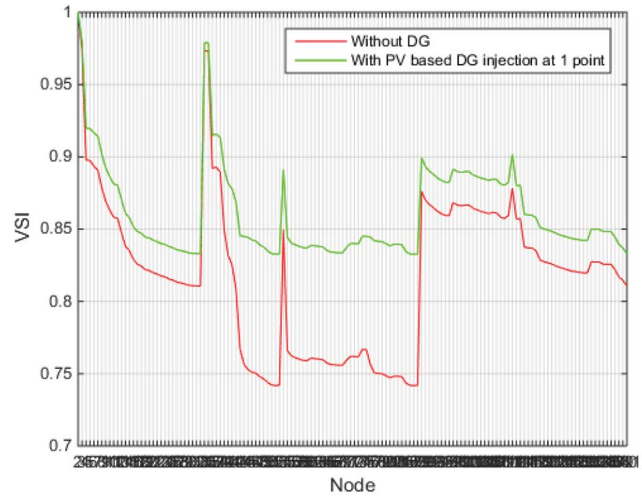


**Figure 8.** VSI characteristics of standard IEEE 85 bus radial test system.

**Table 5.** Rate of convergence for standard IEEE 85 bus test system

| IEEE 85 bus | RPSO | LPSO | PSO-SR | CSA-LF | JAYA |
|---|---|---|---|---|---|
| No of Iterations taken to converge | 14 | 18 | 42 | 48 | 4 |

**Table 6.** Results post DG injection in case of standard IEEE 85 bus test system

| IEEE 85 bus | VPEI | BCR | ECBI | OF | P_Loss before injection (Kw) | P_Loss after injection (Kw) | Optimal point of injection |
|---|---|---|---|---|---|---|---|
| | 11.5252 | 3.4032 | 0.2044 | 5.0392 | 316.13 | 240.29 | 52 |

**Table 7.** Economic and emission data for optimal DG allocation

| Parameter | Values |
|---|---|
| INVC of DG | $3 090 000 |
| HWC of DG | 0 |
| AMC of DG | 1% of IC |
| IFLR | 3% |
| INTR | 10% |
| YRspan | 10 |
| Ch | 120$/MW-h |
| PLF | 0.25 |
| Egrid | 910 kgCO2 /MWh |
| Ec | 10$/ton CO2 |

## 6. Discussion

The optimal injection points in case of IEEE 33, 69 & 85 bus systems are 14, 61 & 52 respectively. It is observed from the VSI characteristics that voltage profile in case of all the three test systems got improvement post DG injection which is shown by "green" line. In all the three cases, the active power loss got reduced after DG injection. For all the test systems, VPEI came out to be greater than unity, BCR greater than unity and ECBI greater than zero. This shows that the distribution networks under consideration have gained technical, social and economic benefits post DG injection. From the convergence characteristics, it is evident that JAYA is taking significantly less number of iterations with respect to RPSO, LPSO, PSO-SR and CSA-LF. Thus it is faster and robust than the other algorithms in comparison.

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