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Maximization of Wind Energy Utilization through Facts Devices

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***Abstract*— This paper proposes a method for maximizing capacity of wind generation by best location of FACTs devices. Initially capacities of the connected wind units are determined by industry. A probabilistic approach is applied for the day – ahead planning. It is used to find the maximum deployable wind sources. So that the prescribed wind spillage is not exceeded. This is done using the optimum power flow. Further it can be improved by installing FACTS devices.**

FACTS devices are used to enhance AC system controllability, stability and increase power transfer capability. Two ranking list are developed for SVC and TCSC and then they are combined into a unified method.

Keywords*— Wind generation utilization, contracted obligations, spillage prioritization, corrective scheduling, FACT devices, reliability, sequential Monte-Carlo simulation (SMCS).

I. INTRODUCTION

Connection of wind energy sources has continuously grown over the last decade, leading to saturation and deferral of new wind connections in some countries.

The size of wind capacity that can be accommodated is driven by thermal and voltage constraints, fault ride through and stability capabilities,[1] required spinning reserve etc.

Once wind units are connected, system operator needs to consider both network security and contractual obligations with generators; the latter is usually expressed in terms of maximum allowable wind curtailment or spillage.

II. OVERVIEW OF THE METHODOLOGY

Objectives of the probabilistic approach for day-ahead planning of systems with large penetration of wind are threefold: a) Maximize deployed wind generation to meet contractual obligations, b) Increase overall system reliability, c) Reduce system operation cost including costs of curtailed load and wind. [2]

The objectives are achieved by following corrective actions: a) Reschedule dispatchable generation, b) Curtail load and wind generation, c) Install SVCs and TCSCs, d) Deploy RTTR on overhead lines.[4]

The overall methodology consists of two simulation stages. The first$SMCS^1$ is preparatory and it delivers outputs, which are required by the second stage $SMCS^2$.

The main building blocks of the first stage are:

- ❖ Connection of wind generation using an industry method.
- ❖ Probabilistic analysis of the wind spillage contractual value.[5]
- ❖ Determining Base Expected Energy Not Supplied (BEENS), Base Expected Spillage (BESP), wind spillage cost coefficients, voltage histograms for ranking of SVCs, as well as BEENS and BESP increments for TCSC ranking.[3]
- ❖ Procedure for placement of SVC and TCSCs.

Maximum utilization of wind sources with different controls is investigated in the second simulation stage.

Two different methodological approaches are:

- ❖ The $SMCS^2$ procedure
- ❖ The state enumeration based on outages

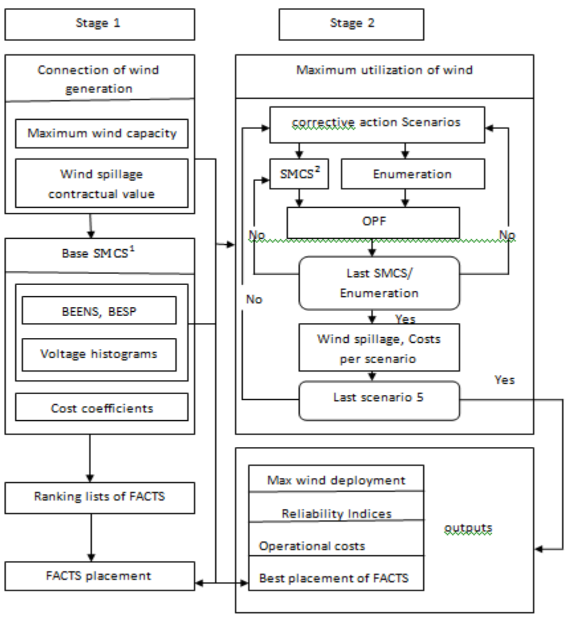

Fig: 1 Methodology for maximum utilization of wind generation

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The essential building blocks are same for both methodologies. The following corrective action scenario are executed in this stage.

1. Scheduling scenario: Generation rescheduling and curtailment of wind & load is considered to maximize wind utilization,[5] RTTR may also be included.
2. Scheduling and FACTS scenario: Generation and load rescheduling with placement of SVCs and/or TCSCs is done, RTTR may also be included.
3. Increased deployed wind scenario: This can be either 'scheduling' or 'scheduling & FACTS scenario' whereby wind capacities are increased until contract limits are met.

III. FIRST SIMULATION STAGE

The first $SMCS^1$ is preparatory and it delivers outputs, which are required by the second stage $SMCS^2$.

3.1 CONNECTION OF WIND GENERATION

To speed up connection process, utilities often provide developers with maximum permissible generation capacities that can be connected [6] at system nodes. The calculation can be done using either formula-based approach, or more complex iterative load-flow method.

The formula based approach is applied by the French transmission system. This approach is based on the first Kirchhof's Law, so[7] that maximum connection capacity P_{WGi}^{max} of *wind* generation at node *i* is:

$$P_{WGi}^{max} = (P_{Di}^{min} + pr_i . \sum_i S_i^{STR} - P_{Gi}^{up})/\beta \quad (1)$$

Where P_{Di}^{min} is minimum load, Pr_i is proportion of capacity, S_i^{STR} is seasonal thermal rating (STR) in MVA, P_{Gi}^{up} is existing generation and $\beta \varepsilon [0,1]$ is the ratio of the expected wind speed during summer minimum with respect to the winter maximum speed (typically *0.8*).

Empirical factor $\beta < 1$ is introduced because wind speeds are higher in wintertime. The total wind generation that can be connected at all nodes in the network is limited to:

$$\sum_i P_{WGi}^{max} \leq \delta . P_D^{peak}/wf \quad (2)$$

Where δ is percentage of peak demand that can be supplied by wind generation, P_D^{peak} is system peak demand and wfε [0,1] is wind factor indicating percentage of total wind capacity utilized to supply peak demand.

3.2 SEQUENTIAL MONTE CARLO SIMULATION

The basic features of the SMCS procedure are given below.

3.2.1 RANDOM SAMPLING, WIND GENERATION

The relevant chronological phenomena are wind generation, profiles, load curtailments with load recoveries and RTTR. All network components and generation units are modeled using the two-state Markov model. Load varies in a window around the forecast hourly loads, which is found using the neural network approach .

One SMCS period is equal to 24 hours and simulations are repeated until convergence is obtained.

All simulations are done for the winter peak and summer minimum days. All [9]results from the first stage $SMCS^1$ are denoted with a prefix '*B*' indicating 'base' values. They are used for prioritization of spillages, placement of FACTS, etc. in the $SMCS^2$.

3.3 PRIORITIZATION OF WIND CURTAILMENTS

All OPF calculations in the $SMCS^1$ are done with equal costs of wind spillages.

The cost coefficients should be proportional to appropriate reliability index, which reflects stochastic requirements for wind spillage at [10]different points. Wind spillages are classified as voluntary and involuntary. The cost coefficients are defined as:

$$\varepsilon_i = BESP_I^{rel} . \sigma \quad \text{Voluntary spillage} \quad (3)$$

$$\varepsilon_i = BESP_I^{rel} . \mu_i^p \quad \text{Involuntary spillage} \quad (4)$$

$$BESP_i^{rel} = \sum_{y=1}^{y} \sum_{t=1}^{T} \left(\frac{SP_i^{y,t}}{P_{WGi}^{up}}\right)/Y \quad (5)$$

Where ε_i is spillage cost, $BESP_i^{rel}$ is expected *relative* spillage in the first SMCS1, σ is contracted price, μ_i^p is *p-th* percentile of base marginal price, *Y* is total number of simulated days, *T=24h*. $SP_i^{y,t}$, is active power spillage, and P_{WGi}^{up} is (sampled) wind active power generation.

3.4 PLACEMENT OF SVCS AND TCSCS

Placement of FACTS is done in two stages: two ranking lists for SVCs and TCSCs are established first, and then an algorithm is developed to combine these two lists.

3.4.1 RANKING OF SVCs

Ranking of SVCs is based on the following assumptions:

a) SVCs are installed when violation of voltage constraints exists or when voltages are close to the limits,

b) SVCs are placed at nodes where the voltage problems are highest.

Essential indicators used to build the ranking list are expected curtailed loads BEENS and curtailed winds BESP. The corresponding daily nodal curtailments are $BEENS_i^{volt}$ and $BESP_i^{volt}$.

To consider feasible voltages close to the limits, voltage histograms $\gamma_i = \{V_i^l, \ldots, V_i^t, \ldots, V_i^{24Y}\}$ at nodes *i* are recorded and the following quantities computed:

$$\Delta\gamma_i^{v^{min}}(\varphi) = \frac{1}{Y} \sum_{v^{min}}^{v^{min}} + \varphi_{(\gamma_i - V^{min})} \quad (6)$$

$$\Delta\gamma_i^{v^{max}}(\varphi) = \frac{1}{Y}\sum_{v^{max}}^{v^{max}} + \varphi^{(V^{max}-\gamma_i)} \quad (7)$$

Which represent total daily nodal voltage deviations from the lower limit eqn(6) and upper limit eqn (7) in a pre-specified per unit region φ.

These deviations are then included into the developed criterion for ranking of nodes for SVC connection:

$$\rho_i = \left(\tau_1 BEENS_i^{volt} + \tau_2 BESP_i^{volt}\right)[1 + \Delta_{\gamma i}^{v^{min}}(\varphi) + \Delta_{\gamma i}^{v^{max}}(\varphi)] \quad (8)$$

Where $\tau 1$ and $\tau 2$ are weights showing relative importance of load curtailment compared to wind spillage.

3.4.2 RANKING OF TCSCs

Essential assumptions used for ranking of TCSCs are: a) TCSCs are installed when energy curtailments occur due to violation of capacity constraints, b) Numerical sensitivity analysis of OPF solutions is applied to define branches best candidates for TCSC installation, c) The initial set of branches candidates for TCSC placement is based on available thermal capacity margins of the branches.The main algorithmic steps are:

1) Consider a $SMCS^1$ OPF solution and find binding capacity constraints. If there are no such constraints, repeat step No. 1 for the next hourly period.

2) Find the set of branches $ij\ \varepsilon\ \beta_{br}$ which have sufficient capacity margin (typically, at least 20-30%). These branches will be further examined for TCSC installation.

3) Do two OPF runs with relaxed voltage constraints, the first with original reactances, whilst the reactance of the considered branch[11]$ij\varepsilon\,\beta_{br}$ is modified by pre-specified increment in the second run. The reduction in load and generation curtailments at node m is denoted by $\Delta BEENS_{ij,m}^{th}$ and $\Delta BESP_{ij,m}^{th}$..

4) Step 3 can also be done to include highly loaded branches into TCSC ranking, which is analogous to voltage interior regions.

5) Find the total weighted *daily* reduction in load and wind curtailments due to change in reactance x_{ij}.

$$\Delta BENSP_{IJ} = \tau_1 \sum_{m\epsilon\beta ENS} \Delta BEENS_{ij,m}^{th} + \tau_2 \sum_{m\epsilon\beta ESP} \Delta BESP_{ij,m}^{th} \quad (9)$$

which is used to find a TCSC ranking list in descending order.

3.4.3 ALGORITHM FOR PLACEMENT OF SVCs AND TCSCs

Expected daily load curtailments due to violation of voltage and thermal constraints are used to define the best location.

$BEENS^{volt}$ and $BEENS^{th}$, as well as expected daily spillages caused by voltage and thermal constraints, $BESP^{volt}$ and $BEENS^{th}$, are then used to define the best locations for placement for SVCs and TCSCs:

1)Where linear combination of curtailed wind and load due to voltage problems $ce^{volt} = (\tau_1.BEENS^{volt} + \tau_2.BESP^{volt})$ is greater than the curtailed energy due to thermal problems $ce^{th} = (\tau_1.BEENS^{th} + \tau_2.BESP^{th})$ a top-ranked SVC is installed and $SMCS^2$is run; otherwise, the highest ranked TCSC is placed and $SMCS^2$ is run.

2) The $SMCS^2$ results give a new set of load and wind curtailments $BEENS^{volt}$, $BEENS^{th}$, $BESP^{volt}$, $BESP^{th}$. They are used to determine whether a SVC or TCSC is installed.

3) The above procedure is repeated until:

- ❖ Either improvement in load and wind curtailments is considered insignificant, or,
- ❖ The FACTS investment budget is spent.

IV. NETWORK DATA

4.1. TEST NETWORK

The test network IEEE-24 bus system is used. Assume an increase in load by 1.31pu and an increase of 0.55pu and 0.6pu transmission capacity for the 138kV and 230kV levels, respectively.

To calculate power outputs of wind turbines (WTGs), it was assumed that cut-in, rated, and cut-out speeds are 14.4, 36, and 80km/h, respectively.

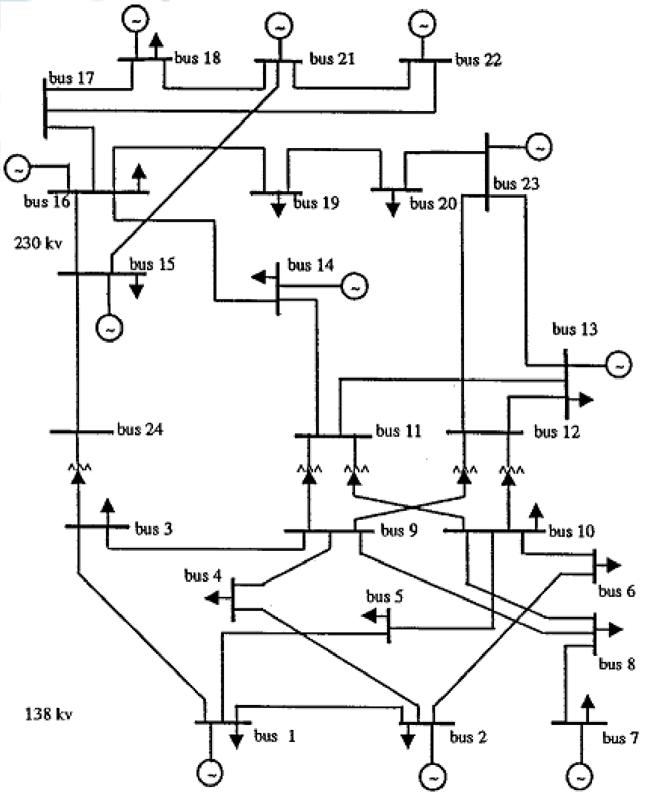

Fig. 2: Modified test network

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V. ANALYSIS

5.1 RANKING AND PLACEMENT OF SVC AND TCSC

The best locations are buses b18, b7, b19, b14, b8 and b1. The voltage spillages are very high at these buses, whilst $BEENS^{volt}$ is high only at b7 and b8. The lowest feasible internal voltages are at b13 and b15, whilst b18 has highest feasible voltages.

Table 1 – SVC Ranking List

Wind buses	ρ_i	$BESP_i^{volt}$	$BEENS_i^{volt}$	$\Delta\gamma_i^{v^{max}}$	$\Delta\gamma_i^{v^{min}}$
b18	14.129	27.82	0.02	0.008	0.007
b7	12.046	5.50	18.40	0.008	0
b19	11.441	22.66	0.04	0.008	0
b14	11.269	22.37	0.1	0.002	0.001
b8	10.922	9.52	12.38	0.001	0.001
b1	10.899	21.73	0.003	0.002	0.001
b13	3.701	7.07	0.2	0.018	0
b2	2.872	5.73	0	0.001	0.001
b15	2.069	3.87	0.16	0.017	0.001

Table 2 – TCSC Ranking List

Line	$\Delta BENS\&SP_{ij}$	$\Delta BESP_{ij}^{th}\,(MW)$	$\Delta BEENS_{ij}^{th}$(MW)
(15,24)	8.11	16.2	0.02
(7,8)	7.64	10.9	4.38
(8,9)	7.6	12.12	3.14
(15,16)	7.5	13.16	0.01
(2,6)	5.073	7.42	2.72
(13,23)	3.9	7.87	0.028
(8,10)	3.32	4.6	2.04
(14,16)	3.61	5.12	0.1

The thermal reductions $\Delta BEENS^{th}$ indicate that lines (7,8), (8,9) & (2,6) are the best locations, whilst lines (15,24), (8,9) and (15,16) give highest thermal spillage reductions $\Delta BESP^{th}$. The maximum spillage reduction of 13.16MW is for line (15, 16) where the initial $BESP^{th}$ was 58MW.

Best location of placement of SVCs and TCSCs are based on the comparison of wind and load curtailments due to voltage ce^{volt} and thermal constraints ce^{th}.

Table 3 – Best location for FACTS placement

Buses &Line	Ce^{volt}	> <	Ce^{th}	Buses &Line	Ce^{volt}	> <	Ce^{th}
Base SMC	88.74	<	104.1	b14	80.80	>	76.71
(15,24)	96,12	>	95.02	b8	76.01	<	76.93
b18	94.97	>	94.42	(15,16)	75.75	>	74.31
b7	89.05	<	93.82	(2,6)	74.08	>	70.28
(7,8)	88.58	>	86.01	b1	74.01	IS	70.12
b19	85.11	<	86.29	b13	74.99	IS	71.01
(8,9)	86.94	>	76.87	(13,23)	74.06	IS	70.03

Where $Ce^{th}>Ce^{volt}$ means the first TCSC from the ranking list is placed in line (i,j). Otherwise the first SVC is connected to bus 'b'. Every time an SVC or TCSC is installed, the difference in EENS and ESP is checked against the threshold value.

TCSC on line (15, 24) reduces Ce^{th} but increases Ce^{volt}. However the total curtailed energy Ce^{volt} plus Ce^{th} is always reduced. Nodes b18, b7, b19, b14 and b8 should be considered for SVC installation, whilst line (15,24), (7,8), (8,9), (15,16) and (2,6)) for TCSC placement.

5.2 PRIORITIZATION OF WIND SPILLAGES

Scenario *S1* with unit spillage costs in the OPF is used to evaluate base wind spillages BESP and marginal prices μ, required for the calculation of wind spillage cost coefficient that are used in the OPF for scenario *S2*.

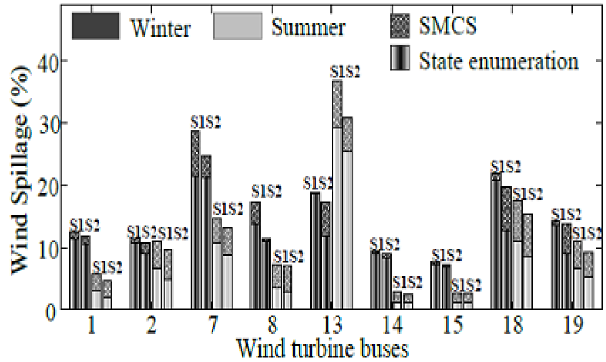

Fig. 3: Wind spillages under scenario *S1* and scenario *S2*

The largest decrease (33%) in spillage occurs at bus 8 in winter, whilst in summer, wind spillage decreases by 20% at bus 13. The $SMCS^2$reduces wind spillage in the total system by 10.8% in winter and 13.11% in summer.

5.3 MAXIMIZED DEPLOYED WIND CAPACITY

The initially installed wind capacity of 4470MW is used to calculate the optimal wind spillages. Spillages are higher in all cases in winter due to increased network stress.

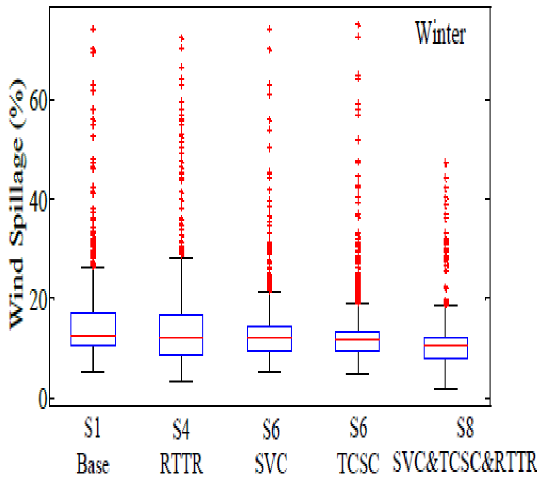

Fig 4: SMCS winter wind spillages for Scenarios S1, S4, S6 (f1), s6 (f2) & S8

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Scenario S8 with a combination of SVC, TCSC & RTTR gives the best minimized spillages, with a reduction of 31.65% in winter and 33.44% in summer.

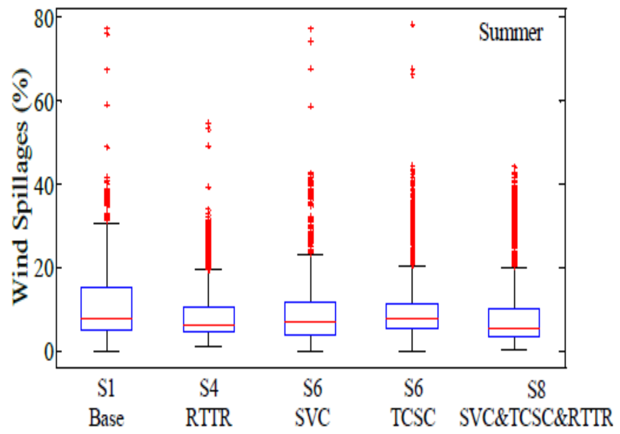

Fig 5: SMCS summer wind spillages for scenarios S1, S4, S6 (f1), s6 (f2) & S8

The second best spillage is for S6 (f2) giving reduction of 22.8% in winter and 22.3% for s6 (f1) in summer.

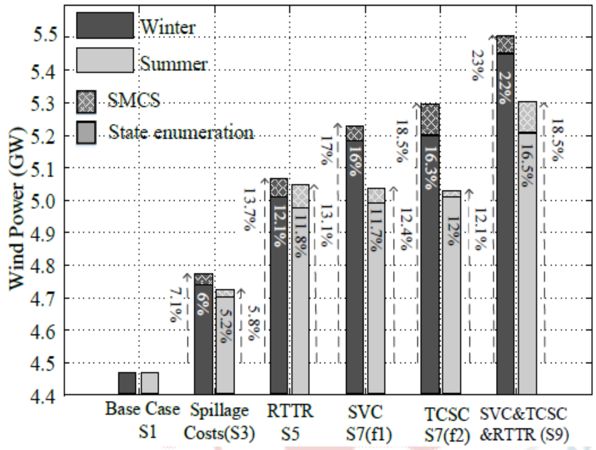

Fig 6: Maximum deployed wind capacity under scenarios S3, S5, S7, and S9

The maximum integrated wind power that meet contractual obligation is calculated using the following cases: a) S3 with prioritized spillage costs, b) S3 with RTTR, c) S7 with SVC, TCSC & RTTR.

In all cases, it was possible to deploy more wind in winter and summer days.

S8 is the most reliable both in terms of load and spillage indices. Reduction in EENS is 24% in winter and 79% in summer. The spillage indicators are also significantly lower. Non – zero spillage costs gives significantly reduced ESP and ESPF.

5.4 OPERATION COSTS

Operation costs for different scenarios and cost savings between the scenarios and base case S1 are quantified in terms of VaR matrices at different confidence levels α.

S8 (SVC, TCSC & RTTR) shows the highest savings compared to S1 by 45%.

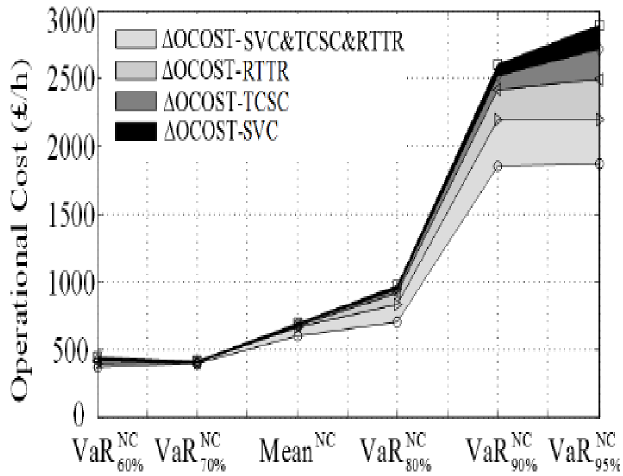

Fig 7: Operating costs

VI. CONCLUSIONS

Maximzation of wind energy utilization through best location of FACTS devices are obtained for IEEE 24 bus system. By this method wind spillages are also reduced.

Due to this method wind energy utilization increased. Operation costs are reduced. Relability also increased.

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