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INFLUENCE OF ELECTRIC MOBILITY ON MEDIUM- AND LOW-VOLTAGE POWER GRIDS

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ABSTRACT

Due to the political goals the amount of electric vehicles will increase in the future in Germany. To evaluate the future impacts of electric vehicles as a load on medium- and low-voltage power systems a representative power distribution system has been chosen and modeled. The investigation of different future electric vehicle penetrations based on simulation scenarios for Germany has been done. The outcomes of the scenarios will be described in the paper to lead to final conclusions and remarks with scope on network elements and voltage characteristics.

Index Terms – distribution grid, electric vehicle, load profile, benchmark, security of supply

1. INTRODUCTION

The German government has set an objective of one million electric vehicles (EV) within Germany by 2020 [1]. This ambitious goal aims to reduce local emissions by means of renewable energies applied to EVs and the dependency on fossil fuels and focuses further on the development of new concepts for mobility. In this respect issues of interests include possible impacts of charging EVs on the power distribution systems. Furthermore, the future energy and peak power demand of simultaneous charging EVs and its forecast might be investigated in more detail. Nowadays EVs are mostly single-phase charged on the low voltage grid. Thus, high amounts of instantaneously charging EVs could exceed certain limits of transformers or cables within the distribution power systems. Further aspects like power quality and security of supply could become more important as the amount of EVs increases. The electric mobility could take part within the development of shifting ancillary services. Therefore, communication infrastructure has to be built up. Furthermore, battery chargers could cause negative reactions through current harmonics with regard to other system parts or devices.

Various studies and scenarios have forecasted specified future amounts of EVs. The amounts, which are going to be investigated, are shown in Table 1. The future EV market penetration was calculated based on a amount of 50 million passenger cars, which was projected constant from 2020 till 2030 [2].

Table 1 Forecasted amounts and calculated penetrations of EVs in Germany [1], [2], [3]

Year	No. of EVs [mil.]	Penetration [%]
2020	1.0	2
2030	4.0	8

This proposal contributes to a simulative investigation about specified percentages (cp. Table 1) of single-phase charged EVs within a distribution medium- and low-voltage power system with the use of an exemplary EV. Hence, future possible impacts on power distribution systems will be studied by means of developed scenarios in relation to the driving and charging behavior of EVs for individual transport. Load profiles of EVs for medium-voltage (MV) and low-voltage (LV) power systems will be developed by means of a single-phased medium power charged EV. Further simulations will be used to investigate certain impacts with regard to compliance of standardized voltage characteristics [4] and power transformer loadings.

2. MODELING OF THE MEDIUM- AND LOW-VOLTAGE POWER NETWORK

2.1. Medium-voltage power network

The modeled power network consists of a medium-voltage rural distribution benchmark network, which was developed as a representative real network [5]. The modeled medium-voltage power system in Figure 1 consists of two sub networks, which have a rated voltage level of 20kV. This network structure has rural attributes, which means it is a distribution system of a small town and their surrounding area including industries and villages. The sub-networks are supplied from two 110/20 kV transformers, which are indicated as TR1 and TR2 in Figure 1. Sub-network 1 was defined within this paper as a supplying structure for urban areas and sub-network 2 for suburbs and villages.

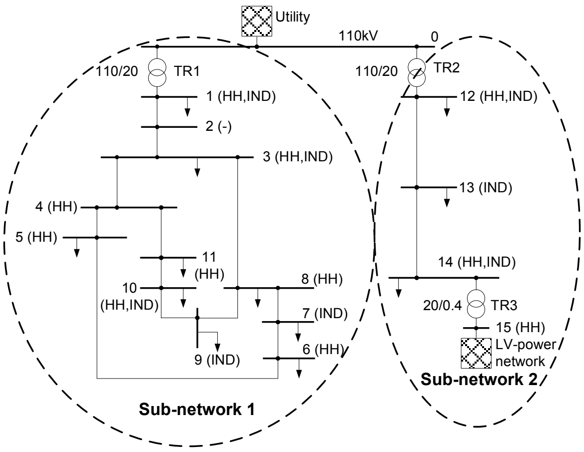

Figure 1 Medium-voltage rural distribution benchmark network, cp. [5]

Most of the connections are represented by cables, whereby some overhead lines are installed within the MV-power system. The detailed cable and line parameters of the power system are shown in Table 2.

Table 2 Parameters of network elements, cp. [5]

Node from	Node to	R' [Ω/km]	X' [Ω/km]	C' [nF/km]	Length [km]
1	2	0.579	0.367	9.93	2.82
2	3	0.164	0.113	413	4.42
3	4	0.262	0.121	405	0.61
4	5	0.354	0.129	285	0.56
5	6	0.336	0.126	343	1.54
6	7	0.256	0.130	235	0.24
7	8	0.294	0.123	350	1.67
8	9	0.339	0.130	273	0.32
9	10	0.399	0.133	302	0.77
10	11	0.367	0.133	285	0.33
11	4	0.423	0.134	310	0.49
13	8	0.172	0.115	411	1.30
12	13	0.337	0.358	10.18	4.89
13	14	0.202	0.122	299	2.99

To take designated differing loads for industries (IND) and households (HH) into consideration each node except node 2 in Figure 1 was connected to specified loads profiles as shown in Figure 2 [5].

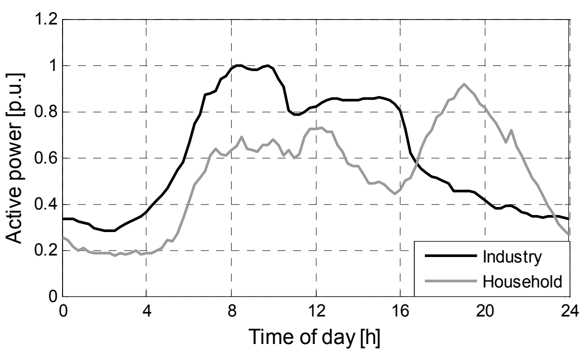

Figure 2 Typical load profiles for household and industries, cp. [5]

The typical load profiles for industries and households within this benchmark net are shown below in. Hence, the peak demand is expected between 6 a.m. and 4 p.m. for industrial loads and between 4 and 10 p.m. for household loads. The scaling parameters of active and reactive power for each node and load type are also given by [5]. Thus, the composition of households and industries is already specified while the amount of EV power still needs to be ascertained. For consideration of charging EVs a third type of load for was connected to each node which contains households. This type of load represents aggregated loads of EVs within the MV-power system and single charging EVs within the further modeled LV distribution power system (see node 15 in Figure 1).

2.2. Low-voltage power network

The chosen LV power network is modeled by means of a power supply structure for multiple blocks of houses which can be seen typical within suburbs of rural urban areas. The low-voltage grid supplies seven buildings of each 35 residential units. The LV distribution network shown in Figure 3 consists of 7 lines, which supply each multiple households (HH) or rather 35 residential units [7] and an electric vehicle load (EV). It should be mentioned that one residential unit can contain more than one household. Thus, in 2006 there were 39.55 million residential units in Germany [8] and 39.77 million households [9]. As described in [7] a NAYY-J 4x150 SE (see Table 3) cable was chosen to model the lines within the LV power distribution system.

Table 3 Parameters of NAYY-J 4x150 SE cable

In [kA]	R' [Ω/km]	X' [Ω/km]	C' [µF/km]
0.275	0.206	0.080	0.830

The distribution network was connected to node 14 within sub-network 2 to preserve the suburban character of this network topology. The scaling of active and reactive power for each load of households will be described in the following section.

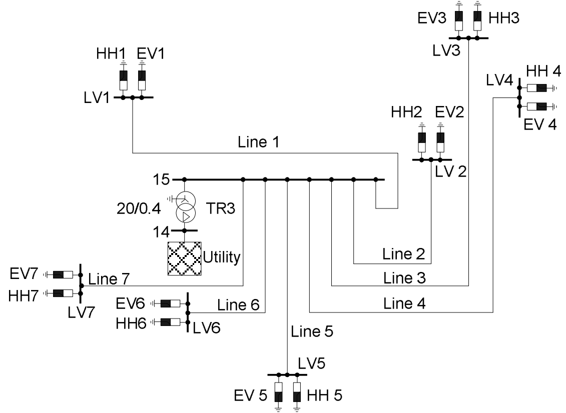

Figure 3 Modeled low-voltage distribution network with loads for electric vehicles, cp. [7]

3. EV PENETRATION SCENARIOS

3.1. General remarks

The possible future EV penetrations as determined in Table 1 were adapted to the modeled distribution power system. Therefore, the estimated amount of households within the power system is essential for calculating the amount of passenger cars under the scope of different EV penetrations.

3.2. Determination of EV amounts

To set a defined amount of EV in relation to each household-supplying node the quantity of households can be estimated by the energy consumption during a day. The average energy consumption of one household with two persons during a year amounts to 3100 kWh [10]. Hence, the amount of energy consumed during a day at nodes connected to households (cp. [5], [6]) reveals the number of households considered for the determined annual consumption. The ratio of passenger cars per household of 57% (cp. [2]) was used to calculate the amount of EVs for each node in Table 4.

Table 4 Calculated amounts of EVs

Node	Households	Passenger cars	EVs (2%)	EVs (8%)
1	22.088	26187	524	2.095
3	406	482	10	39
4	636	754	15	60
5	1068	1266	25	101
6	810	960	19	77
8	866	1027	21	82
10	702	833	17	67
11	487	578	12	46
12	22.088	26187	524	2.095
14	305	362	7	29

With regard to the LV distribution network the scaling of active and reactive power for each household load in Figure 3 was set to 23.9kW und 6kVAr. These parameters ensure the amount of 35 households per node, whereas the residual load of 59 households was connected to the MV-node 14.

4. MODELING EV CHARGING

4.1. Charging profile of EV

A measured charging profile for an exemplary small EV (see Figure 4) was used to integrate a realistic charging behavior as simultaneous charging EVs. The manufacturer lists the energy content of the installed lead acid traction battery at about 10kWh. The range of the car amounts to 64.5km. Thus, the charging profile and the actual charging power depend on the previously covered distance.

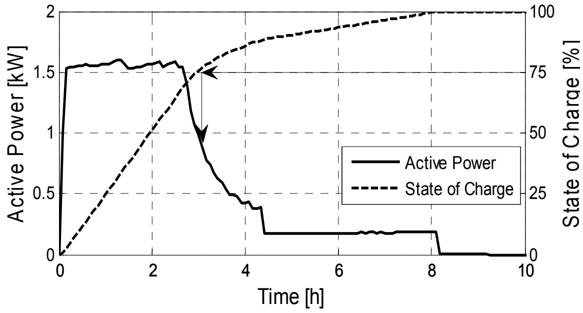

Figure 4 Measured charging profile of exemplary EV

The relationship between the covered distance and the resulting charging profile and its charging time can be expressed through the State of Charge (SoC) of the battery. The SoC in Figure 4 was calculated using the amount of energy charged during EV charging. This approach assumes a similar behavior of the energy content and the state of charge during charging. For example, 75% SoC needs about 5 hours to reach the fully charged state, whereby the initial point of load profile is derived from the clarifying arrows in Figure 4. The resulting charging profile and the corresponding SoC are the starting point for computing load profiles computation for simultaneous charging EVs with respect to the distribution of covered distances.

5. MODELING OF EV LOAD PROFILES

5.1. Aggregated load profiles

Aggregated load profiles make it possible to take a high amount of charging EVs at one node into consideration. Hence, different starting times and covered distances of EV can be modeled within aggregated load profiles, whereby the accuracy could be elevated by means of actual nonexistent diversity factors for EVs. The basis of load the profile computation is the distribution of average covered distances and starting times of private motorized transport. Distributions of percentages for 10km-range classes of passenger cars [11] were used to define 6 different range classes for EVs (see Table 5).

Table 5 Determined range classes and percentages

Range class [km]	Percentage [%]	SoC [%]
5	62.0	92
15	20.0	77
25	9.0	62
35	4.7	47
45	2.2	31
>60	2.1	7

The defined range classes in Table 5 are used to determine the SoC and the starting times of EVs for each range class. This is done by a statistical analysis of the starting times and driving distances of mobile persons [11], [12]. The percentage of the mobility class of interest that contains trucks, passenger cars and motorcycles is 43% (cp. [12]) of all travel and is indicated as mobilized individual traffic (MIT). The amount of travel of cars in Figure 5 was calculated using the composition of the MIT-group, whereby 87% of passenger cars are present (cp. [13]).

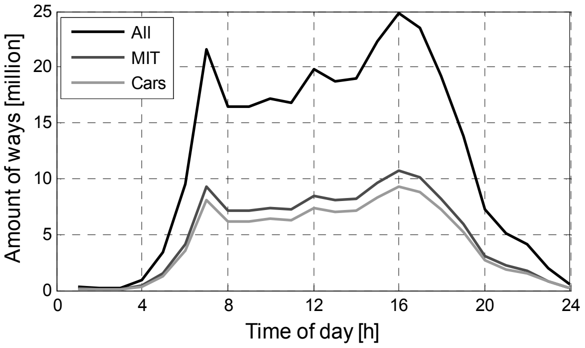

Figure 5 Starting time of travel (working day) [12]

The amount of travel was divided by 41.74 million, the number of registered passenger cars in Germany [13]. Accordingly, a distribution of start times for one representative passenger car was calculated, whereby one car covers averaged 2.54 trips during a working day. Furthermore, the calculated distribution was used to compute the amount of starting EVs in Figure 6 in respect to the determined range classes.

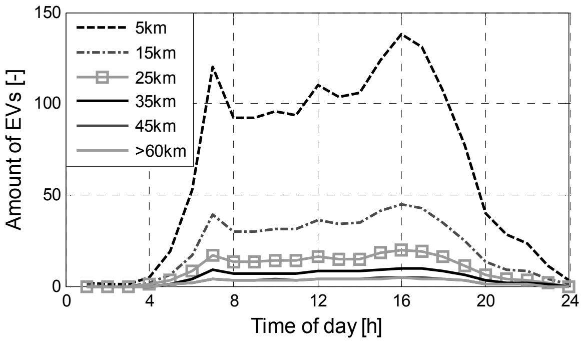

Figure 6 Start times of EVs during a working day for 6 range classes (computed for 1000 EVs), cp. [12]

5.1.1. Temporally distributed EV charging

The distribution of starting times for EVs makes it possible to compute the load profile. For each sub-network different average speeds of EVs were assumed according to urban and suburban driving characteristics. The average speed of passenger cars for urban areas was set to 20km/h and for suburban areas to 50km/h corresponding to [14]. To estimate the arrival times and the starting times for charging EVs each range class was divided by the defined average speeds. The calculated driving times of the range classes were used to shift the amount of starting EVs in Figure 6 the estimated arrival times (starting times for EV-charging). The resulting load profiles are computed by means of the measured charging characteristic of an exemplary EV (see Figure 4) with regard to the determined SoC of each range class. According to this, all individual load profiles for different charging time and SoC were added to an aggregated load profile. Figure 7 show the aggregated load profiles for the defined sub-networks with regard to the average speeds.

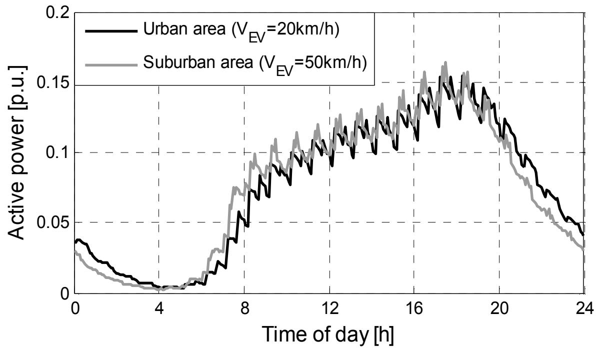

Figure 7 Computed aggregated load profiles for EVs

The computed load profiles in p.u. can be adapted to a certain amount of EVs by multiplying the profiles by the amount of EVs and the maximum charging power of one EV (1.6kW).

5.1.2. Maximal EV charging

The maximal load caused by simultaneous charging EVs was assumed with one range class (>60km).

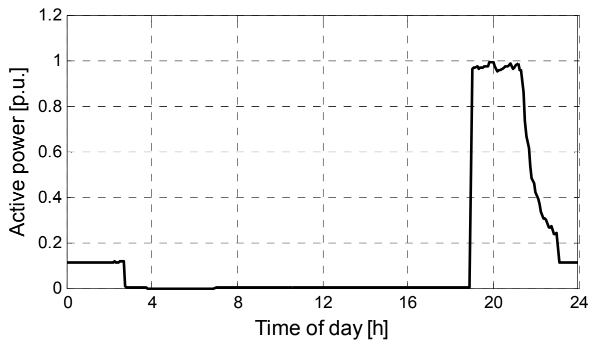

Figure 8 Load profile of worst case scenario

Hence, the total amount of EV recharge with maximum power from 92% SoC at the same time. The most critical time was set to 7 p.m., where the households induce a significant peak demand (cp. Figure 2). Thus, the computed load profile in Figure 8 leads to the worst case scenario.

5.2. Load profiles for low-voltage power network

The modeled LV distribution power network in Figure 3 was allocated for different EV penetrations with randomized charging EVs. The specified amount of EVs was randomly distributed to all households taking into consideration of the boundaries in Table 5. The starting times of the specified EVs at the MV-node were downscaled in relation to the EV amounts in Table 4.

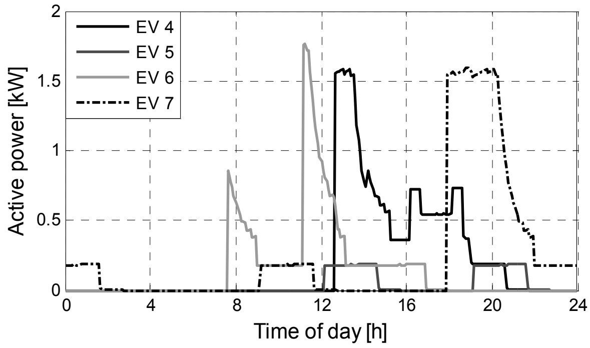

Figure 9 EV load profiles for 2% of EVs (7EVs)

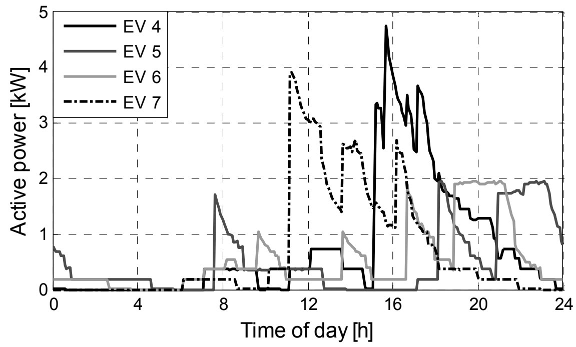

Figure 10 EV load profiles for 8% of EVs (35EVs)

Furthermore, the randomized algorithm leads to a computation that adds the different charging profiles to a resulting load profile for each node. Figure 9 and Figure 10 show the computed load profiles.

6. SIMULATION RESULTS

6.1. Background of the simulations

The load profiles developed above were implemented within simulation software PSS NETOMAC to study e.g. voltage profiles of the most affected nodes and transformer loadings of an MV- and LV-transformer.

6.2. Voltage profiles

Despite the high amounts of maximal charging EVs within the worst case scenario the simulations disclosed that the MV-network seems to be robust (see Figure 11). 2% of EV penetration does not significantly reduce the voltage in comparison to the reference scenario without EVs. Within the LV-distribution network the impact of the different scenarios in Figure 12 causes voltage drops at the same level regarding to the MV-power network.

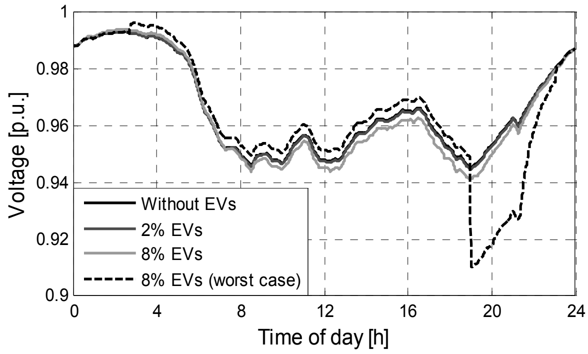

Figure 11 Voltage profiles at MV-node 6

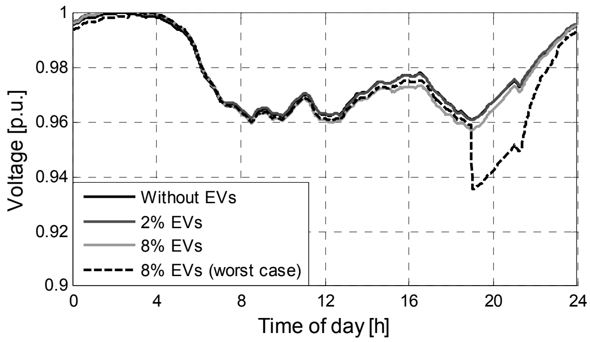

Figure 12 Voltage profiles at LV- node LV4

In comparison to the MV-grid the LV-network is less affected by voltage drops because different nodes were studied and each was in another sub-network. Never the less defined limits of voltage characteristics (0.9p.u.) were not exceeded by means of the simulated scenarios (cp. [4]).

6.3. Transformer loading

The worst case scenario in Figure 13 and Figure 14 causes a comparatively higher apparent power flow through the transformer TR1, which exceeds the rated apparent power of 25MVA for 7 minutes. Thus, the MV-transformer could be a limiting network element concerning its rated power. With regard to the LV-power distribution network the rated power of the transformer about 400kVA (cp. [7]) was not exceeded in Figure 14.

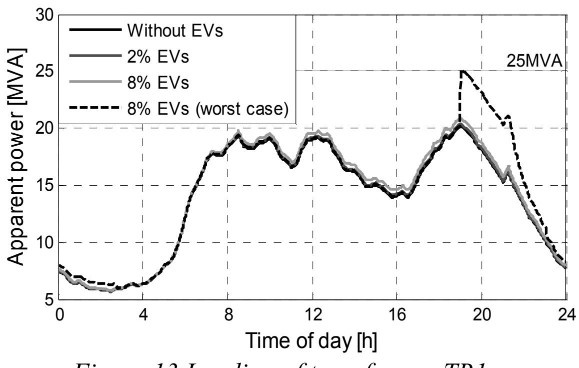

Figure 13 Loading of transformer TR1

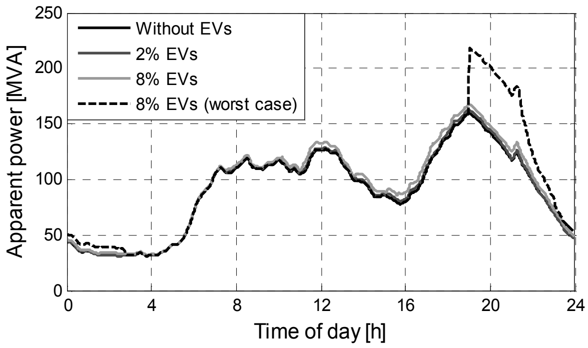

Figure 14 Loading of transformer TR3

All of the presented simulation results have shown marginal differences between voltage and loading profiles except for the worst case scenario. Accordingly, the specified amounts of EVs could not compromise the modeled power system within the defined boundaries represented by residential and industrial loads as well as network elements.

7. CONCLUSION

Future impacts of multiple charging EVs on voltage characteristics and network elements were investigated. Different scenarios for 2% and 8% of EV penetration as well as the worst case condition with maximal power charging of all EVs modeled and simulated. A previously proposed MV-benchmark power network was used under consideration of an additionally integrated LV-distribution network.

Charging EVs were modeled by means of aggregated load models for the MV-power network based on distributions for starting times for travel for mobile persons and the range classes of cars. Within the LV-distribution network charging EVs were randomly allocated to household loads.

Voltage profiles simulated for the chosen MV- and LV-nodes showed that the proposed scenarios can not exceed defined voltage characteristic limits, whereas the LV-distribution network seems to be less affected due to the location within the second sub-network. Furthermore, the simulated scenarios could not exceed the rated apparent power of the LV-transformer. However, the MV-transformer that interconnects the MV-grid to the superordinated transport system ran above its rated apparent power for a few minutes.

In summarizing it can be stated that the modeled MV- and LV-power system seems to be robust in the case of the simulated scenarios, whereby the MV-transformer could be a limiting network element given a maximal EV penetration of 8% and simultaneously maximal charging EVs. To finally verify these outcomes higher charging power of EVs as well as fast charging concepts should be take into consideration because of the relatively low charging power of the modeled EV. Furthermore plug-in hybrid electric vehicles should also be considered.

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