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Selected topics of parameterization of circuit models of 25 kV 50 Hz traction supply networks with converter substations

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Abstract **-** Selected steps in determining peripheral structures and their parameters during simulating modeling of 25 kV 50 Hz traction networks with continuous power supply by inverter power stations are presented in the article. The purpose is to find a suitable methodology for creating the structure and parameterization of circuit models for pre-project preparation and parameterization of output characteristics of inverters in substations and parameterization of distance short-circuit protections. In particular, an analysis of the impact of respecting the capacities of the traction circuit is presented.

Keywords**:** converter power supply station, track parametrization, traction power network 25 kV 50 Hz, distance protection

1. Introduction

The technical solution for the electrification of lines using a 25 kV 50 Hz system with converter substations and continuous power supply has a number of differences from the conventional concept. It is no longer about supplying one isolated section of the line with one transformer, but it is about parallel supply of the network with voltage sources that have a controllable voltage hardness in normal operating mode. This significantly expands the number of scenarios and operational situations that can occur in the defined area.

When preparing electrification with this technology, it is therefore necessary to perform a series of pre-project calculations and simulations to verify the power, energy, voltage and short-circuit conditions. From these calculations based on the topology of the tracks, their operational load and the parameters of the supply infrastructure, the materials for dimensioning and parameterization the technologies of traction power stations and other requirements associated with their management, protection, etc. are obtained. The methodology of creating the structure and parameterization of the circuit models of catenary networks is of fundamental importance for performing these calculations.

2. Approaches to parameterization of 25 kV 50 Hz traction supply circuits

Approaches to parameterization differ in terms of the nature of the parameters and their adaptation, in terms of the purpose of the calculations and the simplifications and influences considered, and also in the type and structure of the circuits.

Most technical publications focus on the investigation of the parameters of a 1x 25 kV 50 Hz traction supply network with converter substations under steady-state continuous power supply conditions and also using the structure of a circuit model of a line section with distributed parameters (MTL - Multiconductor transmission-line). [1][2]

In the models, to simplify simulations and calculations, the number of conductors considered is reduced to the messenger wire, contact wire and rails.

The analysis of the influence of ground return is the subject of publications [3],[4], Current AC railway power systems consist of several conductors with different interconnections. The ground return is shared between the rails, the ground conductors connected to the rails and the ground.

The topic of the influence of the short-circuit behaviour of the traction power system is addressed by authors in publications [5],[6]. In [8], the authors analyzed and modeled a 2x 25 kV 50 Hz traction power system in the time domain to simulate short-circuit conditions and to obtain a practical method to identify the short-circuit behavior of the traction system.

In particular, the possibility of neglecting capacity parameters due to the difficulty in assessing track rail parameters, which depend mainly on changing environmental conditions, was analysed.

In publication [7] presents an electromagnetic field model for the identification of equivalent multi-conductor railway transmission lines with distributed self and mutual series impedances, which is used to represent the parametric behaviour of the impedance of a single track with respect to current, frequency, track material properties and earth conductivity. The paper presents a two-dimensional finite element mesh for the optimized solution of eddy currents on an electrified overhead line, FE models of rails, sleepers.

MATLAB, MATLAB Simulink and Modelica are the most commonly used applications for computer modelling and simulation in the publications.

3. Parameterization strategies for selected purposes

The 25 kV converter power supply is a new technology that has a number of specifics – mainly continuous double-sided power supply of line sections, adjustable output characteristics of inverters (basically adjustable hardness) and a new approach to the solution of short-circuit protection (distance protection, division of the protected circuit into several zones with predetermined selectivity of protection). In the preparation of projects, it is necessary to perform a series of model calculations and simulations of the entire continuous system in order to set the distance protections and to set the output characteristics of the inverters delta/P (voltage phase shift/active power) and Q/U (effective voltage/reactive power).

In order to perform the calculations efficiently with sufficient accuracy and at the same time with adequate calculation times, it is necessary to build an appropriate topology of the traction network circuit model and its parameterization. For distance protection, the accuracy of the setting of the settings is required. up to 20%, while the safe function is also ensured by the corresponding safety coefficients respecting the inaccuracies of the calculations. To set the distance protections of a traction circuit, a large number of repeated calculations must be performed, combining different locations of short-circuit switches and short-circuit points. Therefore, less time consuming calculations are necessary.

At the Faculty of transport engineering of the University of Pardubice, a large number of sensitivity analyses were performed to test the influence of the topology and parameterization of the traction power circuit on the accuracy of the calculation of selected variables in the traction circuit. Some of the results have been published in [11] and [12], other results are reported in internal research documents. The basic assumption of all calculations was to solve linear circuits in harmonic steady state with a current and voltage frequency of 50 Hz. In particular, the following alternatives were examined:

Effect of localizing the impedance of the return path in the traction power circuit: The possibility of adding the impedance of the return path to the impedance of the catenary was verified computationally in five traction circuit structures. This would allow calculations to be performed voltage referenced to a single common reference node on the power traction network, significantly reducing the number of equations to solve the circuit. The values of currents, voltages, active and reactive powers of power substations and trainsets were compared in test calculations in both alternatives. The results varied in the order of tenths of a percent, so this simplification is acceptable.

Effect of the ground return through the rail/ground: The results of calculations of voltages, currents and powers of substations and trains were compared for 5 sample circuits considering the path of return current through the rail or ground. The deviations of the results were up to 3%, in rare cases up to 4%.

Effect of mutual inductances of tracks on multi-line tracks: The results of calculations of voltages, currents and powers of substations and trains while respecting and neglecting mutual inductances of traces in multi-line tracks were compared for 5 sample circuits. Furthermore, the output impedances of the power substations during short circuits in the traction circuit were compared. Neglecting mutual inductances brings a calculation error of up to over 10%, mutual inductance must be respected in the calculations.

Effect of traction circuit capacities: The effect of respecting the capacities of the traction circuit on the accuracy of the calculations is presented in more detail in this paper.

Comparison of calculation results with measurements: According to the described concept, a model of the real traction power circuit of the line section Přerov Břeclav on the 2nd railway corridor in the Czech Republic was built. It is a section of continuous traction power supply with two converter and one conventional substation. The measured and calculated output impedances of the substations were compared, i.e. their module and angle during short circuits in the traction circuit. The measurement was carried out by the company Electrification of Railways Prague a.s.. For distant short-circuits (more than 5 km) the deviation of measured and calculated values of impedance modules up to 10%, impedance angles up to 13% was recorded. These deviations are quite acceptable for setting the distance protections using model calculations. Deviations of up to 20% have been recorded for close short circuits, rarely up to 30%. These are accuracy limits and other activities of the faculty are focused on refining the calculations.

3.1. Principles of distance protections and their settings in continuous power traction networks

The greatest use of distance protections is in the protection of lines at voltage levels *ehv* (extra high voltage from 300kV to 800k) and *vhv* (very high voltage from 52kV to 300kV) but they are also widely used to protect overhead lines of the 25 kV 50 Hz system. Protection of the overhead line is mainly done by distance protections or Delta I protections (reacting to fast current changes: di/dt).

The distance protection measures the phase of the current and voltage at the place of its installation. From the voltage and current phasors, it then obtains the impedance phasor via Ohm's law. During a short circuit, the calculated impedance value is lower than the impedance measured under load. The basic principle of short-circuit evaluation follows from this consideration: if the measured impedance is lower than the operating impedance and at the same time is within the set protection area of the complex R-X plane of the distance protection, then the protection sends a trip pulse to the appropriate switch at its output.

As mentioned, when a short circuit occurs on the line, the measured impedance is reduced from the value of the load impedance to the lower fault impedance. The fault impedance (ZF1, ZF2) consists of two components. The first component is the impedance of the traction line between the protection and the short circuit (ZLF1 and ZLF2). The second component is the short circuit impedance (RF), which is purely resistive and includes arc resistance.

When setting the short-circuit distance protection, it is necessary to respect the separation of the load impedance area from the fault impedance area in the complex plane. The fault area is then always divided into several graded areas or so-called zones, which differ in their range in the traction circuit. By range is meant the maximum value of the short-circuit resistance (RF) and maximum distance at which impedance phase of the fault is still within the area of the protection zone.

Distance protection is a stepped protection in which selectivity is achieved by graduated time delays of the equipment. Protections (and therefore protection zones) further away from the short circuit have a longer protection level time set. It is necessary that the protection closest to the short circuit always reacts. In the event of a switch or protection failure, the nearest other protection (back-up) switches off the short circuit with a set delay.

3.2. Characteristics of distance protection

The characteristics of distance protections are formed by curves drawn in the Gaussian impedance plane (complex plane R-X), which divide the plane into the area of load or blocking protection and the area of protection equipment (fault area) [11]. In order to set the protections appropriately, it is necessary to perform simulation calculations to identify the impedance parameters of the real traction circuit during short-circuits so that the protection settings provide adequate protection for short-circuit tripping in the monitored section of the traction circuit with the specified selectivity.

4. Output characteristics of the converter power station

Converter substations offer more options in terms of control.[13] Output characteristics are provided for controlling power substations. In the case of converter substations, these characteristics can be influenced and set in user interface of the converter. Settings can be fixed as well as variable with the possibility of reconfiguration during operation. The characteristics of the converter then influence the energy performance of the operation at any given moment. [14]

The first of the two output characteristics is the dependence of the active power and the phase shift of the output voltage, i.e. the angle δ (P/δ characteristic). For a converter station, the characteristic can be modified. The characteristic can be used to control the active power by shifting the angle δ. One scenario for which the characteristic can be used is to load two substations more equally than conventional substations. [15]

Another output characteristic is the dependence of reactive power and output voltage of the substation (U/Q characteristic). An example of the characteristic configuration in practice is available in [15].

The methodology for calculating the characteristics with better performance is not yet known and the optimum setting of the characteristics will vary depending on the given track structure, its load and the complete train driving scenario that will regularly occur on the route. The appropriate setting of converter output characteristics has a major impact on the power ratios in the traction network and on the overall energy consumption. [16], [17]

5. Verification of the influence of traction circuit capacities on the accuracy of the calculation of selected quantities

Calculations were carried out at the Faculty of transport engineering of the University of Pardubice, the aim of which was to verify the influence of the implementation of capacities in the simulation model of the 25 kV 50 Hz traction circuit on the accuracy of the determination of the selected quantities. In terms of the focus of the research activities, the effects of capacity implementation in simulation models were investigated for the case of a standard operating scenario on the railway line and for the case of the solution of the traction circuit ratios during a short circuit. To verify the effect of the implementation of the traction circuit capacities on the accuracy of the calculations, a model of the traction circuit was created according to Fig. 1.

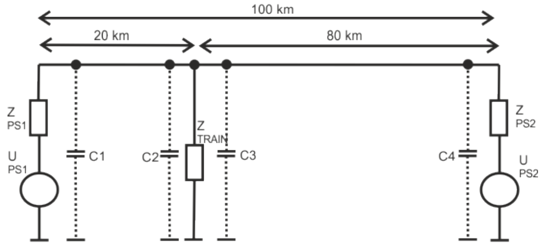

Fig. 1: Circuit for verifying the influence of the implementation of traction circuit capacities on the accuracy of calculations.

The simulated circuit consists of a single-track track section with a length of 100 km. There are power substations at both ends of this section. The effective voltage value of the power substations is $U_{PS1} = U_{PS2} = 27$ kV, the internal impedance of the power substations is $Z_{PS1} = Z_{PS2} = 0 + 7j$ Ω. The impedance of the traction circuit without capacities is considered $Z_{RL} = 0{,}26 + 0{,}55j$ Ω/km. The above parameters are taken from internal documents of the railway infrastructure manager in the Czech Republic. The parallel capacity of the traction circuit corresponds to the usual value in the conditions of the Czech railway network $Z_C = 20$ nF/km. In km 20, the load of the train set is taken into account in the calculations within the standard operating scenario. All comparative calculations of the traction circuit quantities in the standard operating scenario were performed depending on the actual value of the input active power of the train from 0 to 6000 kW with a step of 50 kW. In order to compare the effects of the implementation of the traction circuit capacities on the accuracy of the calculation of selected quantities, three variants were considered:

- Traction circuit is completely without capacities (variant marked RL),
- Capacities are considered according to Fig. 1 with values C1 = C2 = 200 nF, C3 = C4 = 800 nF – concentrated capacity, variant marked RLC,
- Capacities are concentrated in elementary capacitors CC = 200 nF, which are located along the track for 10 km, variant marked RLCCC.

Test calculations were carried out in SW for solving traction circuits, which was developed at the Faculty of Transport Engineering of the University of Pardubice in the Matlab environment.

Fig.2 shows a comparison of the values of the calculated values of the selected traction circuit values for the mentioned three calculation variants (RL, RLC, RLCCC) for the case of train power factor cosφ = 0.99. The values of the active powers of the power stations PS1 and PS2, the reactive powers of PS1 and PS2 (negative sign = inductive reactive power) and the effective values of the currents of the power stations PS1 and PS2 are compared.

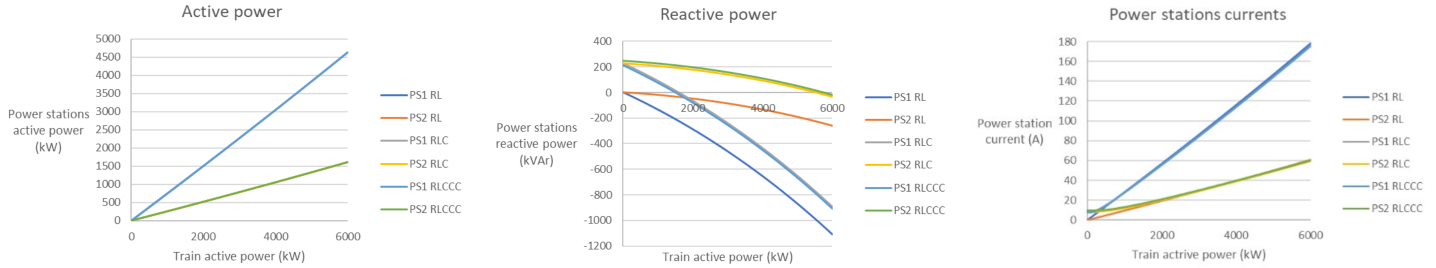

Fig. 2: Comparison of active power, reactive power and current of PS1 and PS2 for three calculation variants.

From Fig. 2, it is clear that the implementation of capacities in the calculation has no effect on the calculation of active power ratios. The significant influence of the capacity implementation is visible when calculating the reactive power of PS1 and PS2 in the entire train power range. The difference in reactive power values for the calculation case with concentrated capacities and with capacities evenly distributed over 10 km is very insignificant. Similar conclusions were found when calculating the voltage ratios in the traction circuit. On the graph on the right in Fig. 2 is a comparison of the rms values of the PS1 and PS2 currents. Here it is clear that the differences in the calculations with and without capacity consideration apply in the area of lower train power up to about 1000 kW and only for PS2, which is more distant from the train. During the test calculations, the influence of the implementation of the traction circuit capacities was verified even for the case of a train with cosφ = 0.8. Practically the same conclusions apply to this case as for the presented results valid for a train with cosφ = 0.99.

In further calculations, the effect of the implementation of traction circuit capacities on the accuracy of the calculation of circuit quantities for the case of short circuits was tested. Short-circuits were considered instead of the train set at the same place on the track according to Fig. 1. Calculation cases for resistive character circuits with $R_{SC} = 1\ \Omega$ a $R_{SC} = 12\ \Omega$ resistances were tested. In the short-circuit calculations, a combination of the conventional power station PS2 and the inverter power station PS1 was considered, and the short-circuit calculations take into account the switching of the inverter substation to the 800 A current limiting mode. Only the RL and RLC calculation variants were compared. The results of these comparative calculations are shown in Table 1.

Table 1: Comparison of selected calculation results for short-circuits (P = active power, Q = reactive power, I = current RMS)

	P_{PS1}	P_{PS2}	Q_{PS1}	Q_{PS2}	I_{PS1}	I_{PS2}	$\cos\varphi_{PS1}$	$\cos\varphi_{PS2}$
$R_{SC} = 1\ \Omega$, RL	4116	5013	-6691	-10165	800	472	0,524	0,442
$R_{SC} = 1\ \Omega$, RLC	4119	5029	-6691	-10052	800	467	0,524	0,447
$R_{SC} = 12\ \Omega$, RL	12493	4191	-4720	-5940	800	286	0,935	0,576
$R_{SC} = 12\ \Omega$, RLC	12507	4231	-4671	-5792	800	282	0,936	0,590

It is clear from Table 1 that the implementation of the traction circuit capacities does not have a significant effect on the accuracy of the traction circuit fault calculations. Table 1 shows that the highest deviation occurs in the case of a 12 Ω short circuit for reactive power and cosφ PS2, however, even here the deviation is about 2.5%, which represents sufficient accuracy in terms of calculating the short circuit protection parameters, since sufficient amplitude and phase margin is always considered when setting the short circuit protection parameters.

6. Effect of capacity on output characteristics

The simulations to determine the effect of capacities are based on a model adapted from [15]. However, capacity is considered in the catenary section block. The specific capacity of the catenary per kilometer is set as 20 nF/km. [1]

6.1. Criteria

Four criteria were used to evaluate the simulations:

- Lowest loss criterion - achieving minimum losses in the traction circuit for selected operating scenarios
- The criterion of equal distribution of power - achieving a balanced power load on the substations
- Voltage stability criterion - minimization of local voltage drops in the traction network
- Criterion of the lowest consumption from the distribution network - minimum total energy consumption from the distribution network, consumption of maximum recuperated energy inside the traction network

6.2. Characteristic P/δ

In the simulation of the active power characteristic, the already mentioned voltage phase shift angle of the converter δ acts as an action control. It takes values of -10° to 10°. For each simulation, the angle at the point where the criterion is best matched is then searched.

The graphs in Fig. 3 show how the operating points for the loss and voltage criteria have changed. Points without considering capacities in the power line are plotted in red, while points that account for capacities in the power line are plotted in green. The first plot shows the characteristic for the loss criterion. Here no continuous deviation is seen with and without considering capacities. The green points practically overlap the red ones, and hence are not visible in the graph.

On the other hand, for the voltage criterion, the red and green points already deviate systematically from each other. The deviation is not always regular, however, it can be said that when considering the capacities in the traction line, the operating points shift to slightly lower control angles.

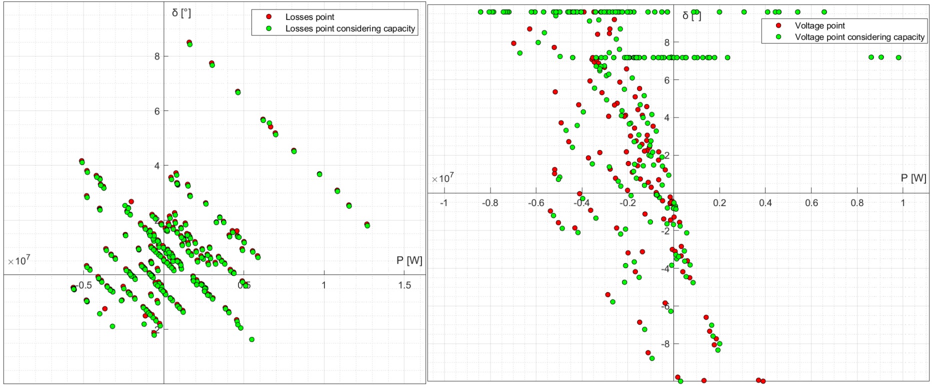

Fig 3: Effect of capacity on the P/δ characteristic for the loss criterion and for the voltage criterion

6.3. Characteristic U/Q

The characteristic of reactive power and output voltage was simulated with variable output voltage of the converter substation instead of variable voltage phase shift angle δ as in the previous case. Two sets of simulations were performed, and the angle δ that now enters the simulations as a constant was chosen to be 0° for the first set of simulations and 2° for the second set of simulations.

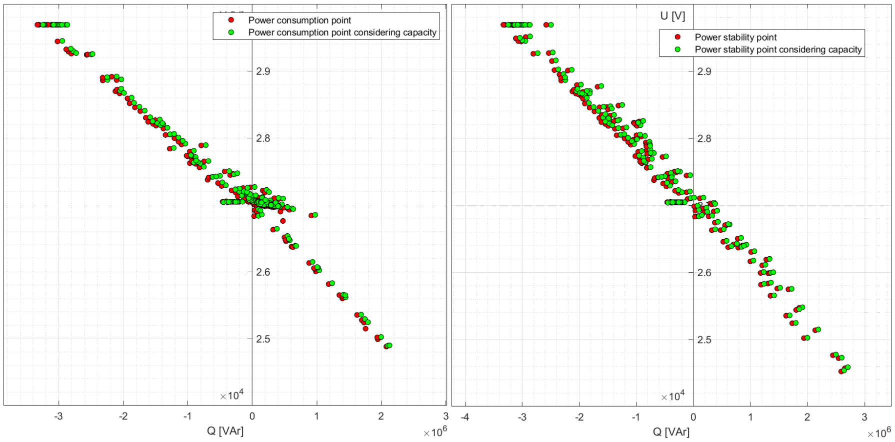

Fig. 4: Effect of capacity on the U/Q characteristic for the power criterion and the power distribution criterion at a phase shift of 0°

The first graph shows the U/Q characteristic for the lowest loss criterion, the second shows the criterion of an equal power distribution. As in the previous graphs, points without considering capacities are marked in red and points that take capacities into account are marked in green. The difference of these points can be seen for both selected criteria. Similarly, for both criteria a systematic deviation between the two groups of points can be observed. Thus, the effect of capacities will cause the operating points to tend towards higher reactive power when capacities are considered. However, the deviation of the points is not large and there would be a slight shift within the modelled characteristic.

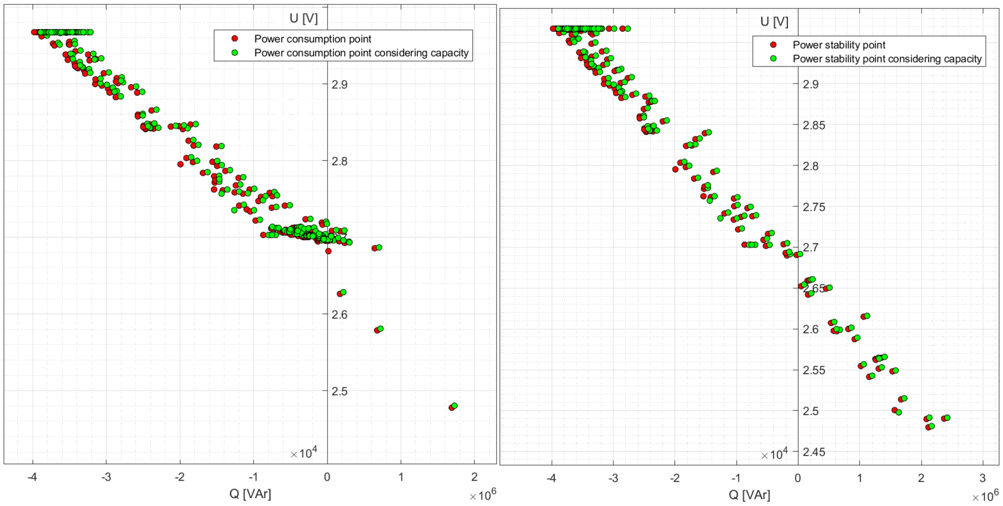

Fig. 5: Effect of capacity on the U/Q characteristic for the power criterion and the power distribution criterion at a phase shift of 2°

For a set of simulations with a voltage phase shift angle of 2°, a systematic deviation can also be observed. Thus, the capacity does not only have a significant effect on the grouping of points in one region or on one part of the output characteristic, but it affects the characteristic as a whole, with the whole imaginary curve slightly shifted towards a higher reactive power. The different voltage phase shift angle constants for these simulations have a more significant impact on the characteristic than considering capacity. The deviation of the relative operating points when considering capacities and without them, appears to be the same for both values of the phase shift angle δ.

7. Conclusion

In the presented paper, the influence of the capacity behaviour in the circuit model of the traction grid of 25 kV 50 has been analysed. It is clear that in the case of analyses and methods used for simulations of standard operation (e.g. purpose of setting the output characteristics of converter substations) it is appropriate to respect capacity. It has been that it is sufficient to consider capacities by concentrating them in existing circuit nodes (parallel to track nodes, and trains). Such an implementation ensures sufficient accuracy of the results, while not increasing the number of nodes the circuit, which would cause a significant increase in computation times. In the case of simulations of traction circuits short circuits, it is not necessary to include capacity in the calculation, especially if the calculations are oriented towards the parameterisation of distance short-circuit protections.

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