Power Quality Event Analysis in 25 kV 50 Hz AC Railway System Networks

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***Abstract*—Power quality (PQ) phenomena characterizing the voltage and current signals of railway electricity networks differ from those present in transmission and distribution electricity grids. Presently, there are no standardized procedures focused on PQ measurement techniques explicitly for railway applications. This paper evaluates whether the standard power quality measurement algorithms used in monitoring 50 Hz electrical grids are sufficient for an accurate evaluation and classification of PQ parameters of voltage dips, swells and interruptions present in 25 kV AC railways. An algorithm is presented to better characterize different types of interruption, distinguishing between causes due to network configuration or by other factors. For voltage dips and swells it is also shown that a smaller window size (less than 1 cycle) produces a more accurate estimate of the disturbance magnitude and duration. The two methods are verified against recorded signals of pantograph voltage and current. Recommendations are therefore provided for PQ measurement algorithms for AC railways.**

***Index Terms*—Railway transportation power systems, power quality, power system transients, voltage interruption**

I. Introduction

Power quality (PQ) phenomena superimposed on voltage and current signals of transmission and distribution electricity grids, due to their non-stationary characteristics and random nature, introduce challenges in measurement, monitoring and characterisation. Although complex, established approaches in international standards define PQ indices, testing and measurement methods, e.g. IEC 61000-4-30 [1], IEC 61000-4-7 [2] and IEEE Std. 1159 [3]. For the European public electricity networks, EN 50160 [4] defines a minimum set of characteristics that electrical utility companies should guarantee to customers. While in fixed conventional electricity grids PQ disturbances are well known and have been extensively researched [5] [6], including the definition of quantities and indexes, for AC traction systems these issues are still under consideration and have been only preliminarily considered in the literature [7] [8]. There are no standardized procedures for measurement and evaluation of PQ for railway applications: EN 50163 [9] determines the voltage and frequency characteristics of the railway traction supply, whereas EN 50388 [10] deals with some quality requirements at the interface between the traction unit and fixed installations, focusing on the train power factor and giving only guidelines for the assessment of harmonics, in particular in relation to voltage instability. Some literature deals with PQ issues of AC 50 Hz traction systems, focusing on the statistics of harmonics along a network and for different operating conditions [8] [11]. Such literature proposes and discusses measurement solutions, including practical aspects [12] [13], and considers solutions to PQ compensation, especially for the interface with the utility [14] [15]. However, no standards focus on PQ measurement techniques for railway applications, either for DC or AC systems. Railway electric supply networks are characterized by peculiar PQ phenomena [16]: trains are a moving source, interacting with traction substations (TSs), overhead contact lines (OCLs) and other trains within the same supply section. Trains continuously exchange power during acceleration, coasting and notably during regenerative braking [6], giving rise to an energy flow that deviates from the most intuitive process from TS to the train, but may be in the opposite direction (back to the TS), or directly exchanged between trains. This producer-consumer behaviour of the locomotive with the rest of the system is characterized by harmonics, interharmonics, dips, swells, oscillatory transients and arcing, which further deteriorate the power quality of the railway grid. It is observed that electric signals of railway networks are characterised by short variations in voltage magnitude and frequent periodic voltage interruptions due to specific characteristics of the network (e.g. "phase separation sections", also named as "neutral sections"), and specific operating conditions (e.g. pantograph detachment from the OCL). Dips and swells shorter than 1 cycle are not accurately characterised by the measurement methods proposed in IEC 61000-4-30 [1]; hence methods using shorter calculation intervals are needed for a closer tracking of the voltage dips and swells and to further understand the phenomena. In general, an analysis technique is needed regarding voltage interruptions, differentiating those caused by the network configuration from other voltage variations.

This paper aims to verify whether standardized PQ measurement methods defined in IEC 61000-4-30 [1], and used in monitoring of PQ parameters of 50 Hz electrical grids, are sufficient for accurate evaluation and classification of the PQ parameters of phenomena, such as voltage dips, swells and interruptions, present in 25 kV AC traction systems. The paper is structured as follows: Section II presents an overview of the general characteristics of the voltage and current signals captured in 25 kV 50 Hz AC railway networks. Section III considers voltage interruption, its sources and a method for classification of the events caused by different factors. Section IV considers voltage dip and voltage swell parameters in AC traction systems and explores the effect of the window size. Section V provides conclusions to the paper.

II. Typical voltage and current signals

This section presents the main characteristics of the pantograph voltage and current signals recorded at various European 25 kV railway networks. Voltage and current signals, presented and used for the analysis of the PQ parameters, are part of the waveform database of the 16ENG04 MyRailS project [17]. Fig. 1 and Fig. 2 represent the voltage and current waveforms acquired at a pantograph during a train journey of approximately 18.5 minutes. Small variations of the envelope characterize the voltage. This journey spans over all the possible running modes of a train: acceleration (100–300 s), coasting/cruising (600–680 s and 700–870 s), braking (320–330 s, 540–550 s and 860–950 s) and stationary (0–100 s and 320–450 s) to refer to the most evident time intervals, where each is characterized by a different current absorption pattern. During normal operation conditions, the voltage level at the OCL is different from the nominal voltage for AC 50 Hz systems set out in EN 50163 [9] and reported in Table I. The OCL voltage is normally ranging between U_{min1} and U_{max1}, and may be as low as U_{min2} or as high as U_{max2} for limited periods of time (e.g. 2 and 5 minutes, respectively). This voltage is affected by the voltage changes at the primary side of the TS, those due to voltage regulation mechanisms and caused by traffic overload (when an unusual number of trains occur in the same supply section with significant power absorption). Fig. 3 represents the root mean square (rms) values of voltage and current magnitudes, measured over a 10-cycle time interval, as recommended by [1]. Fig. 4 represents the dynamic impedance at the locomotive pantograph, defined as Z = V/I, and calculated for the fundamental phasors. As can be seen, the voltage remains above the nominal value of 25 kV and close to the highest permanent voltage U_{max1} (this is quite a common phenomenon in railways, where system parameters are sized for the largest traffic load attainable), whereas a clear dependence in the current on the running mode of the train can be seen in the time domain plots. Additional recordings on 25 kV systems are planned, in addition to those performed on DC 3 kV systems, using a data acquisition system (DAQ) installed on-board.

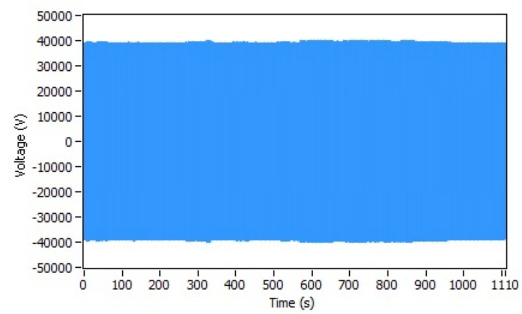

Fig. 1. Instantaneous voltage at the pantograph

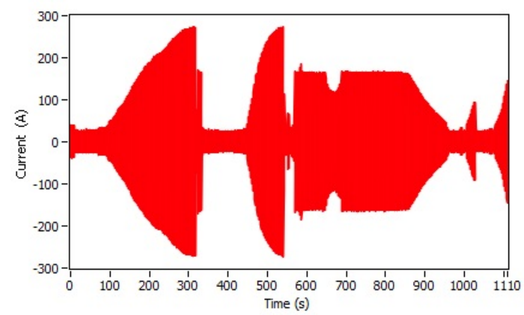

Fig. 2. Instantaneous current at the pantograph

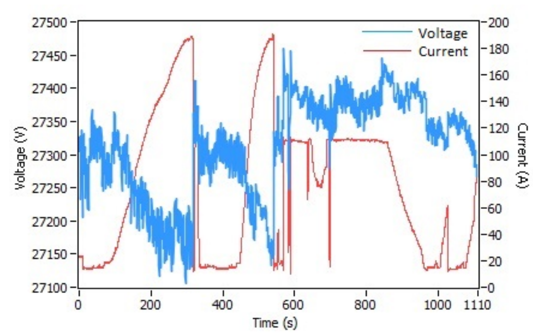

Fig. 3. r.m.s value of voltage and current at a pantograph level

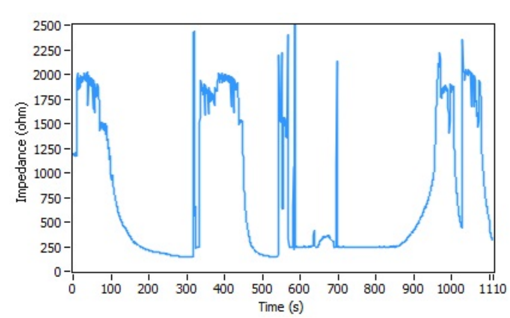

Fig. 4. Dynamic impedance of the traction unit

TABLE I
NOMINAL VOLTAGE AND THEIR PERMISSIBLE LIMITS IN TRACTION SYSTEMS (EN 50163, [9])

Electrification system	Nominal voltage and their permissible limits				
	Lowest non-permanent voltage U_{min2} (V)	Lowest-permanent voltage U_{min1} (V)	Nominal Voltage U_n (V)	Highest perma-nent voltage U_{max1} (V)	Highest non-permanent voltage U_{max2} (V)
AC (r.m.s value)	17500	19000	25000	27500	29000

III. SUPPLY VOLTAGE INTERRUPTION

Supply interruption in transmission and distribution grids is a phenomenon caused by faults in the system, failure of equipment and tripping of protection devices installed in the network. In AC traction systems, supply interruption of the locomotive is periodically caused due to the phase separation sections, as part of the power supply network, and is disciplined by EN 50388 [10]. The measurement method specified in IEC 61000-4-30 [1] is normally used to detect and measure voltage interruptions in electricity grids. Although it is a standardized and broadly used method, it is not suitable for the typical disturbances experienced in AC railways and will not be able to discriminate between events caused by neutral sections and by other sources.

This section proposes an algorithm for voltage interruption discrimination, applied to AC 25 kV 50 Hz systems. Fig. 5 represents a simplified version of a common power supply configuration, where TSs are more or less evenly spaced along the railway line to feed independent supply sections [14] [15]. To reduce the unbalance on the three-phase power supply system, caused by single phase loads, each TS is connected to different pairs of the utility phases and this requires the electrical isolation of the various supply sections by means of phase separation sections. During the journey, the train passes under several phase separation sections from which the frequent supply interruptions are observed at the locomotive pantograph.

By definition, a supply interruption is the condition when the voltage magnitude at the supply terminal becomes less than 1% of the nominal value, shown in Table I [9]. Fig. 6 and Fig. 7 represent examples of two voltage interruptions for two successive phase separation sections. The events are characterized by a time duration of about 7-8 seconds. According to EN 50388 [10], the power consumption of the train must be brought to zero before the train passes under a phase separation section to avoid arcing. The time domain signals show that the current magnitude was reduced to zero before the train enters the phase separation section. Fig. 8 and Fig. 9 show both voltage and current behaviour respectively for the first voltage interruption seen in Fig. 6 and Fig. 7. This event occurs when a locomotive is leaving one section of the network supplied by one phase and preparing to enter the next section supplied by another phase. The same behaviour is common to other waveforms of the database. It is important that the proposed algorithm considers not only the voltage, but also the current, as a supplementary piece of information to determine the cause of the event. Fig. 10 presents the flow chart of the proposed technique; the algorithm steps are given below:

1) Extraction of 1 cycle of voltage and 1 cycle of current from the database is performed;
2) Voltage and current rms values are calculated;
3) Voltage magnitude is compared with the interruption threshold;
4) If the voltage magnitude is below the set threshold, the current magnitude of the previous cycles is checked;
5) If the current magnitude on each of the previous 5 cycles is less than 1A the voltage interruption is attributed to phase separation section; otherwise the voltage interruption is caused by other factors;
6) The algorithm iterates by sliding the window along the signal by 1 cycle until the end of the record is reached.

The proposed new algorithm is tested with voltage and current records taken from the said project database. It is observed that this algorithm can differentiate voltage interruptions based on their cause, i.e. due to network configuration (namely phase isolation) or other phenomena.

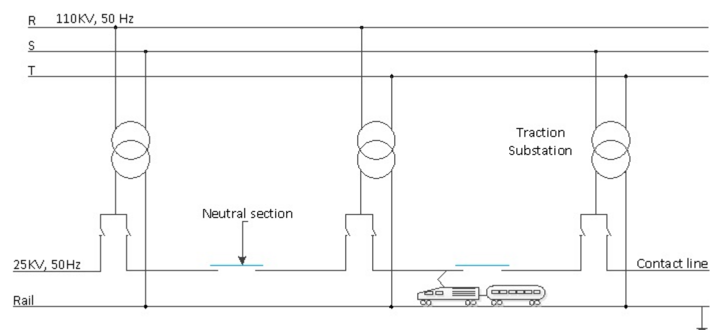

Fig. 5. Power supply network example in AC traction systems

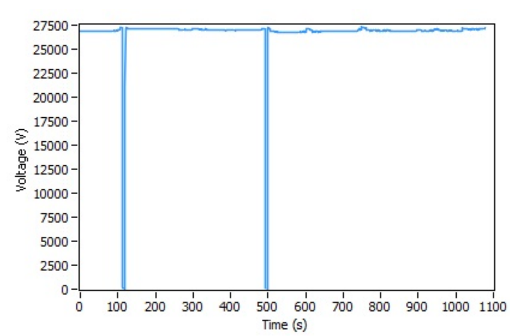

Fig. 6. Supply voltage interruptions registered in segment 1 of the network

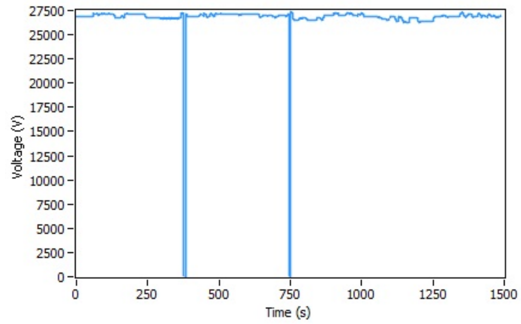

Fig. 7. Supply voltage interruptions registered in segment 2 of the network

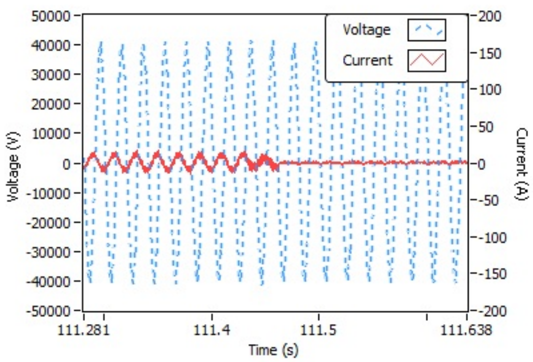

Fig. 8. Voltage and current before the interruption 1 in the segment 1

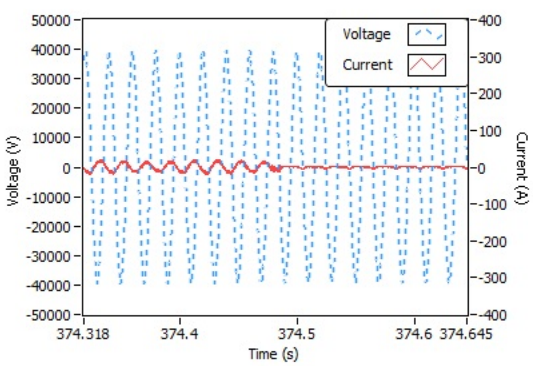

Fig. 9. Voltage and current before the interruption 1 in the segment 2

IV. Voltage dip and voltage swell

All railway electrification systems are characterized by short variations of the voltage magnitude. Dips and swells of less than 1 cycle and frequent transients shorter than half a cycle affect the waveform and the rms value of the measured quantity. Because of such short durations, the measurement method proposed in the IEC 61000-4-30 [1], i.e. rms voltage measured over 1 cycle, does not accurately characterize these phenomena in 25 kV AC traction systems. For this reason, methods using shorter calculation intervals for closely tracking short variations of the voltage magnitude are needed. This section considers using a half-cycle window length and analyses the

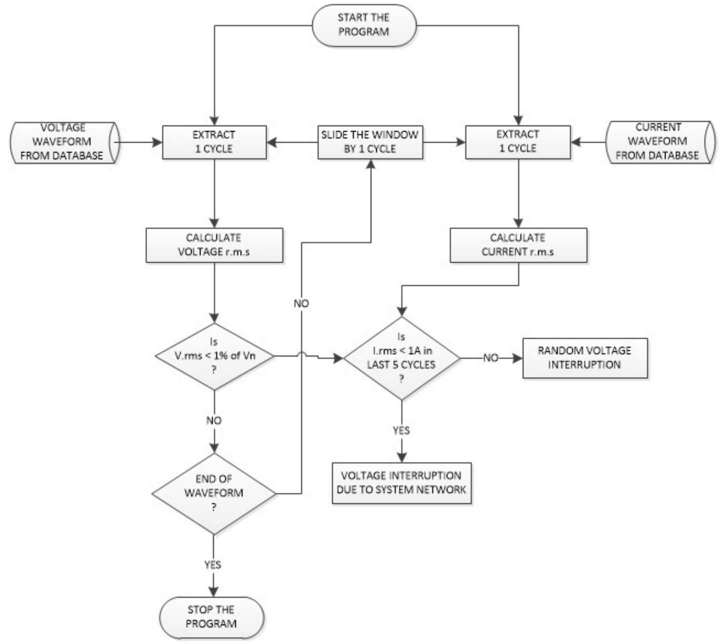

Fig. 10. Flowchart of the proposed measurement technique for classification of voltage interruptions

impact that it has on calculation of the rms value for dips and swells and proposes recommendations for the method to be used by PQ monitoring instruments designed for AC electric railway applications. In AC traction systems voltage dips are also caused by switching on large loads simultaneously, such as when several locomotives are starting to run at the same time or when passing under a phase separation section and connecting to the same supply section. The latter may also cause voltage swells, depending on the position along the line, as demonstrated in [18], due to resonance phenomena. In general voltage swells and slower voltage rises are mainly associated with regenerative braking and switching off of locomotive onboard loads. With a behaviour similar to MV distribution networks, a voltage dip may be also caused by faults in other sections of the network, where a sudden voltage reduction before the fault is cleared is coupled through the high voltage feeding network (often arranged as a HV bus feeding some TSs in parallel).

By definition, voltage dips and swells are temporary reductions or increases of the voltage magnitude below 90% or above 110% of the nominal voltage, respectively [18]. Dips and swells are characterized by residual voltage and maximum swell voltage, respectively, and by time duration. Both phenomena are classified according to these characteristics, by referring to Tables 5 and 6, and to [4]. Thus, correct classification requires a high level of accuracy.

Methods based on rms calculation, fundamental extraction and estimate, or more directly on processing of the instantaneous peak value are reviewed in [19], although the definition of swell or sag is still based on the rms value as per standards.

The work in [20] well represents performance and accuracy of algorithms based on rms calculation (both sliding window and synchronized versions) used to estimate voltage dips, including frequency deviation among the considered sources of error. It is observed that AC railway systems may show significant variations of the instantaneous fundamental frequency, especially for those weakly connected or completely separated from the national grid, such as 16.7 Hz systems [21], much less for 25 kV 50 Hz systems, at least in the examined European networks [22].
Methods based on a half-cycle and 1-cycle window for rms value calculation are considered. Even though both methods are standardized [1] [23], the method proposed in [1] (using a 1-cycle window) is mostly used by instruments for measuring PQ indices and to interpret the results in electricity grids. The effects of the window size are evaluated in terms of accuracy of the measured quantity and estimated time duration of the event; results are shown in Figs. 11 to 13, for some events captured within the recordings. In the case of voltage swells shown in Figs. 12 and 13, both events are followed by interruptions, therefore the recovery of the signal does not occur after the swell. Such events correspond to the overvoltage's observed in [18]. Fig. 11 shows the difference in magnitude for a voltage dip event using a 1-cycle and a half-cycle window. Strictly speaking, this event cannot be classified as a dip because the reduction in magnitude does not go below 90% of the nominal voltage; the same may be observed for the two swells, shown in Fig. 12 and 13.
All examples highlight the clear difference that the time window size has on the accuracy of the estimate. In terms of time duration, dip and swell events with fractional cycle duration will be rounded up to one cycle, or to an integer number of cycles; the characterization using half cycles is more accurate (by a factor of two) yet could not be calculated over a shorter window in order to preserve the significance of rms concept. Since the accuracy is improved, then also the classification of the event according to Table 5 and 6 of EN 50160 [4] is improved. The event presented in Fig. 12 will not be considered a voltage swell if measured in 1 cycle, because the swell voltage will be slightly less than 110% of the nominal value, whereas using a half-cycle window, it will be registered as a swell and with a voltage larger than 120% of the nominal value.
This analysis has shown that the measurement method using a half-cycle window produces more accurate results in terms of magnitudes and time duration for characterizing dips and swells in AC railway systems. It is of course possible to push the reduction of the time window even further, going to quarter-cycle estimates. To this aim it is necessary to assume a symmetry of the quarter-cycle type, that has as a precondition that even harmonics are negligible, as it is in reality for AC railways in general [8]. This may represent the further improvement in measurement accuracy, whilst preserving the rms concept.

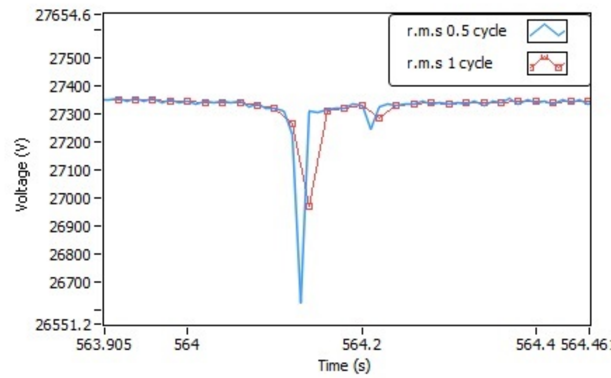

Fig. 11. Voltage dip measured as r.m.s value over 1 cycle and half cycle

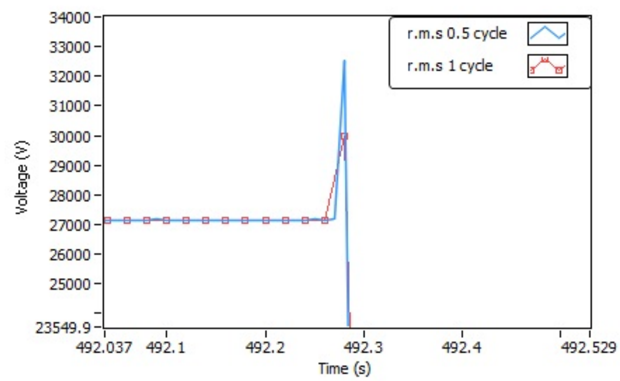

Fig. 12. Voltage swell measured as r.m.s value over 1 cycle and half cycle

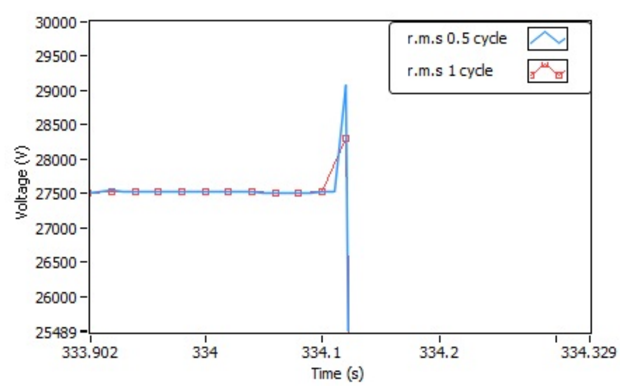

Fig. 13. Voltage swell measured as r.m.s value over 1 cycle and half cycle

V. Conclusions

This paper has evaluated whether or not the standard power quality measurement algorithms used to monitor 50 Hz electrical grids are sufficient for an accurate evaluation and classification of power quality parameters of voltage dips, voltage swells and voltage interruptions in 25 kV AC traction systems. Some characteristics of the signals and possible network configurations have been presented and discussed, in order to understand the sources behind the events.

For voltage interruptions an improved estimation technique (including a cross check of the absorbed current behaviour) allowing understanding and classification of different phenomena on the network related to voltage interruption has been presented and discussed. This technique is able to identify voltage interruptions related to the network configuration, and specifically due to phase separation sections.

Due to the characteristics of the signals present in railway systems, it was observed that the measurement methods for the characterization of dip and swell phenomena proposed by the IEC 61000-4-30 standard are not sufficiently accurate for 25 kV AC traction systems. The risk is an underestimate of amplitude and time duration, for which the use of shorter integration intervals has shown better accuracy.

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