

## **Development of transmission voltage class, reconnectable 230 x 115 kV mobile transformers for improved reliability of power delivery**

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### **SUMMARY**

Uninterrupted power delivery is of utmost importance for electric power transmission companies. It is especially important for very large cities, such as Toronto, Ontario. Therefore, Hydro One Networks Inc (HONI), operating in Ontario, decided to develop a fleet of mobile transformers and substations to deploy these devices in emergency situations. This is especially important as an aging power transformer fleet resulted in eight major failures of Hydro One's transmission assets in the year 2018 alone; three of them being catastrophic. As several operating voltage levels are used in HONI stations, there was a need to design transformers with reconnection to different voltages on high voltage and low voltage sides, resulting in the following voltage combinations for four transformers: two units with 230 x 115 – 27.6 x 13.8 kV and two units with 230 x 115 – 44 kV. As a compromise between the weight allowed on public roads and the required power, the decision was made that the mobile units would have 30 MVA rating. The 230 kV bushings with polymeric insulation were used to reduce the weight and lower the risk of mechanical damage. The HV and LV reconnections were achieved through use of special winding configurations and very detailed dielectric design incorporating the externally operated switches to facilitate ease of reconnections. The forced cooling with directed oil circulation through windings (ODAF) with two coolers dissipating a total of 500kW were used. The units were designed with high temperature insulation to meet the weight and dimensional limits. Since a transformer was of 230kV class, the air cell conservator system was used to eliminate possibility of moisture ingress from the atmosphere.

### **KEYWORDS**

Power engineering, power delivery, high voltage engineering, mobile transformer, high temperature insulating system

**Introduction**

Mobile transformers are generally step-down units, typically rated up to 60 MVA, with HV ratings up to 245 kV. Based on the application and power system in which the mobile substations are used, these transformers may have multiple voltage connections on HV and/or LV side. Series-parallel switches are generally used to achieve different voltage connections. Series-parallel switches were preferred by Hydro One instead of internal link-board, to simplify transformer construction, improving ease of operation and increasing overall reliability. Delta/woye re-connection can also be a separate feature by using a special de-energized switch connection.

In order to reduce the size and weight of the mobile units, their design has higher current densities and resulting higher power loss, as well as lower insulation levels than the conventional units. Moreover, these transformers – as typically not being used for continuous operation - are designed with high impedance to reduce short circuit forces and this helps to reduce the weight of unit. High value of voltage regulation, being consequence of high impedance, is a compromise for obtaining a high power, light weight unit.

As the transformer and associated cooling system has the significant impact on the transportability of the mobile substation unit, the manufacturer and user need to work closely to evolve an agreeable set of parameters that meets the expectations of user and also result in overall acceptable size and weight of the mobile substation. These requirements are often conflicting, such as a redundancy of the cooling equipment versus the size and weight reduction.

Since the main objective is to lower the active part weight, these are designed with less conductor cross-sections at increased winding temperatures, requiring use of high temperature insulation materials. Maximum temperature rise limits for various insulation systems in mineral oil are shown in table below. Higher oil temperatures are possible for ester and silicon liquid systems. These values are published in IEEE C57.154 standard [1].

| Temperature limits               | Standard system | Mixed Hybrid system | Fully Hybrid system |       |       |
|----------------------------------|-----------------|---------------------|---------------------|-------|-------|
| Average winding rise             | 65°C            | 65°C                | 75°C                | 85°C  | 95°C  |
| Winding hottest-spot rise        | 80°C            | 90°C                | 90°C                | 100°C | 115°C |
| Maximum ambient temperature      | 40°C            | 40°C                | 40°C                | 40°C  | 40°C  |
| Winding hottest-spot temperature | 120°C           | 130°C               | 130°C               | 140°C | 155°C |
| Top oil temperature rise         | 65°C            | 65°C                | 65°C                | 65°C  | 65°C  |
| Maximum Top oil temperature      | 105°C           | 105°C               | 105°C               | 105°C | 105°C |

To optimize the weight and size of the unit, a fully hybrid system with the 95°C average winding rise was used in this design. These units are generally specified with lower insulation levels to keep active part weight as low as possible. The major insulation is the same as any other transformer. But the main difference is in the minor insulation where high temperature materials are used. Conductors are covered with high temperature insulation and based on type of thermal system, high temperature materials are used for other parts of the minor insulation as well.

Cooling is provided by high efficiency, compact ODAF coolers with finned tubes, fans and pumps. Two coolers of 50% capacity each are used and are arranged in horizontal or vertical orientation based on type and lay out of trailer. With these coolers there is no ONAN rating available, there is also no overload operating mode. The power supply to the cooling equipment is provided by an auxiliary transformer whose HV bushing is connected to the LV of the main transformer.

**Development of transmission voltage class, reconnectable 230 x 115 kV mobile transformers**

The following section covers details of the development of 230kV Mobile substation [2]. The development had many challenges since it is the first time we have developed a mobile unit with

reconnectable capability for 230 kV voltage application. The most important aspect of the development is to achieve compact light weight high performance EHV unit without compromising quality [3-5]. The special features of the units were as follows:

- Compact core design,
- High temperature aramid insulation for winding conductors and insulation parts adjacent to windings, such as duct sticks and key spacers,
- Special Continuously transposed cable with high temperature enamel and epoxy for LV windings,
- High temperature aramid insulation of stranded cables for the leads,
- Compact ODAF coolers,
- Series-parallel switch and LTC on LV side,
- Special, two-part series parallel switch on HV side,
- Light-weight bushings with composite insulation,
- Compact tank layout,
- Specially designed oil preservation system with a conservator,
- Use of analytical tools to achieve compact design
- Use of 3D modelling software for Transformer and Mobile substation design

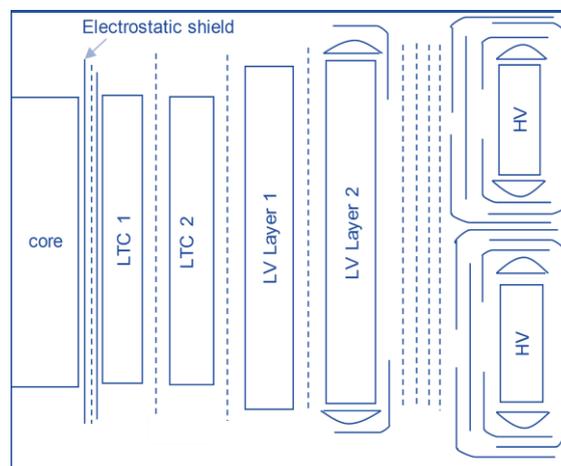
The development involved two designs with two units of each design as per Table I below.

**Table I Basic design parameters**

|                   | Design1, LV=44kV      | Design2, LV=27.6 x 13.8kV   |
|-------------------|-----------------------|---|
| Power Rating, MVA | 30                    | 30  |
| HV Voltage, kV    | 230 X 115 Delta       | 230 X 115 Delta   |
| LV Voltage, kV    | 44 Wye                | 27.6 X 13.8 Wye   |
| HV BIL, kV        | 750 X 550             | 750 X 550   |
| LV BIL, kV        | 250                   | 170 X 95  |
| LV LTC            | +/-20% in +/-16 steps | +/-20% in +/-16 steps for 27.6 kV connection<br>+/-20% in +/-8 steps for 13.8 kV connection |
| Impedance [%]     | 13.5                  | 13.5  |

Since Design 2 is more complex with reconnection on both HV and LV side, the paper would focus more on the development of this design.

Core was designed as a three-phase three-legged configuration with the step-lap mitred joints. The focus was to use optimum flux density in core in order to reduce weight and dimension of the core. The material of the core lamination was M4-grade, grain-oriented silicon steel. Winding disposition starting from the core outward is as shown in the figure below.



*Fig.1. Layout of the windings*

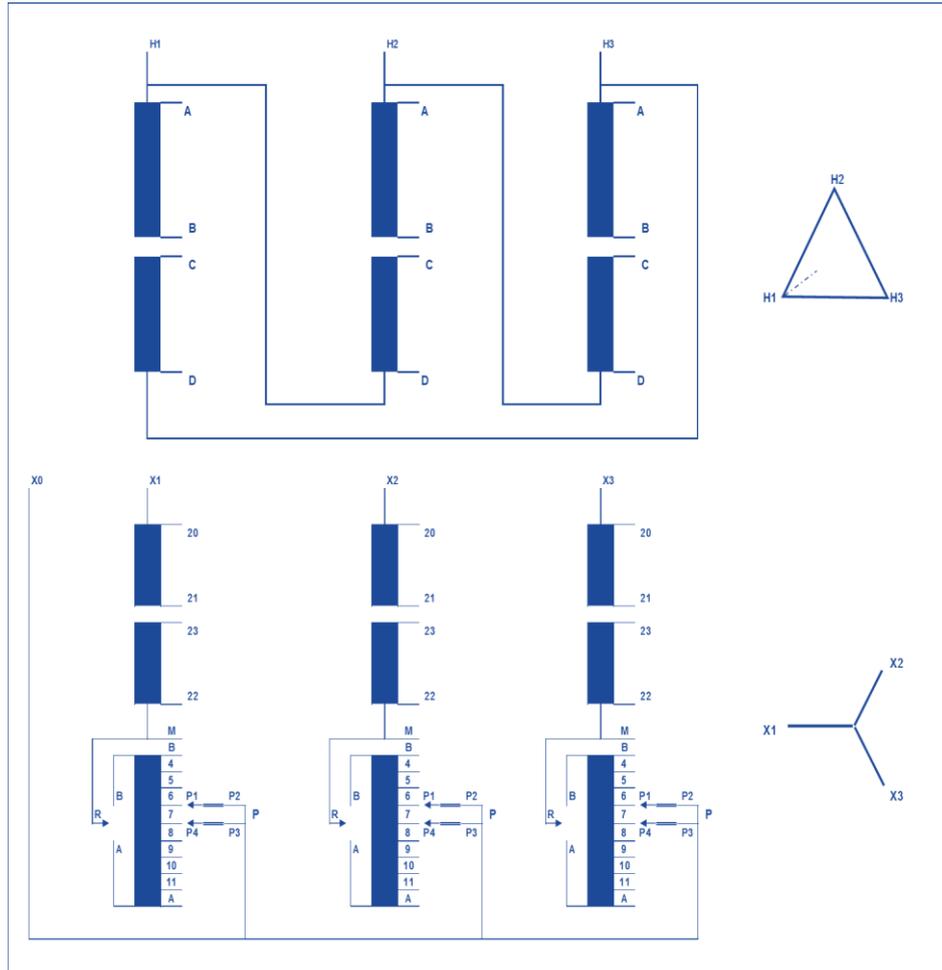


Fig.2. Nameplate schematics for 230x115 – 13.8x 27.6 kV mobile transformer

The LV LTC tap winding was positioned next to the core and was designed as a two-layer multi-start winding to provide high series capacitance and to reduce eddy and/or circulating current effects in the neighboring magnetic parts. High thermal class aramid-paper covered magnet wire was used for conductor material.

The LV winding was designed as a single layer helical winding using special high thermal class CTC conductor to optimise space, control the eddy current loss and to reduce the hotspots due to the radial component of leakage flux. The epoxy and enamel of CTC was also of high thermal class. The LV winding was wound in two parts as a two-layer (Jones-type) construction, in order to connect the two halves either in series or in parallel to achieve two different voltages in LV circuit.

The HV winding was designed as an end-fed, fully interleaved disc winding to provide high series capacitance and near linear transient voltage distribution across HV winding. High thermal class aramid-paper covered magnet wire was used for conductor material. The winding is made in two parts with a gap at the center to enable series and parallel connection. The center gap insulation design was very critical, as the 550kV BIL for the 115kV connection would appear across the gap during the parallel connection with 550 kV FW and 605 kV CW.

Hybrid insulation system was used in which only those parts that are directly in contact with the winding conductor, such as winding duct stick and key spacers, were made of high thermal class aramid insulation. Cellulose based insulation was used for all other parts of the winding assembly.

The voltage at various points within, between and at the end of windings was calculated using an advanced transient voltage program using complex L-C network with several hundreds of nodes– see an example of transient calculations in Fig.3.

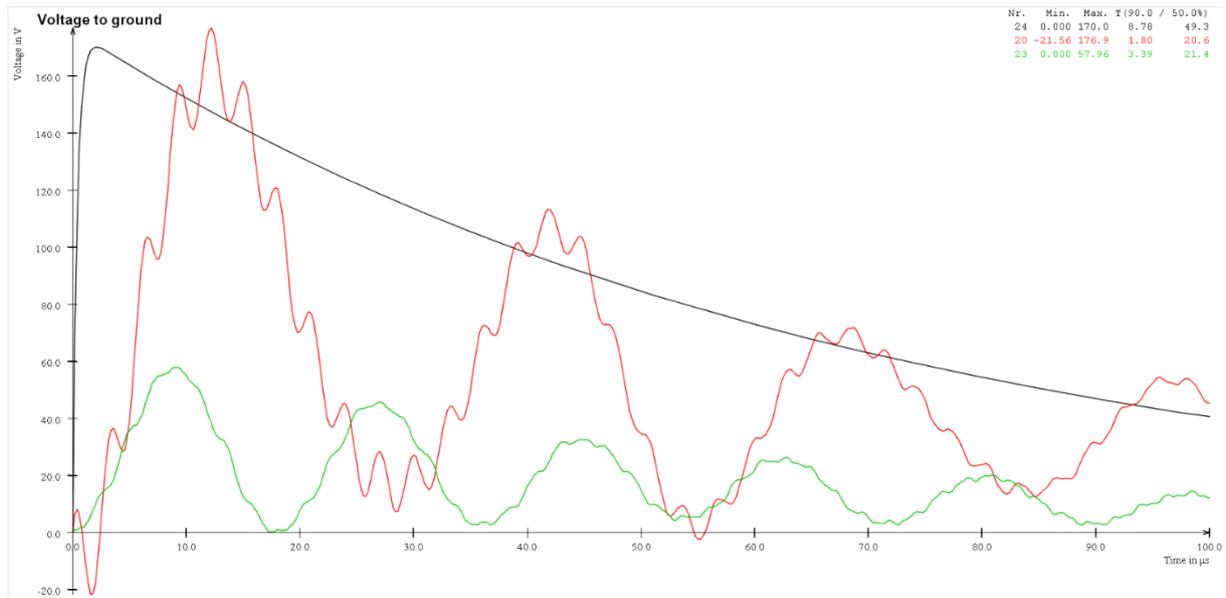


Fig. 3. Response of selected nodes in LV winding to FWLI on terminal X1 at 170 kV

All the critical aspects of the insulation structure were analyzed using the electrostatic field program, utilizing a boundary element method. The stresses were modeled under the applied and induced voltage test conditions (see Fig.4.). In order to check the distribution of electric stresses, the transient voltages were converted to the equivalent ac voltages using Design Insulation Factors (see [3] for more details).

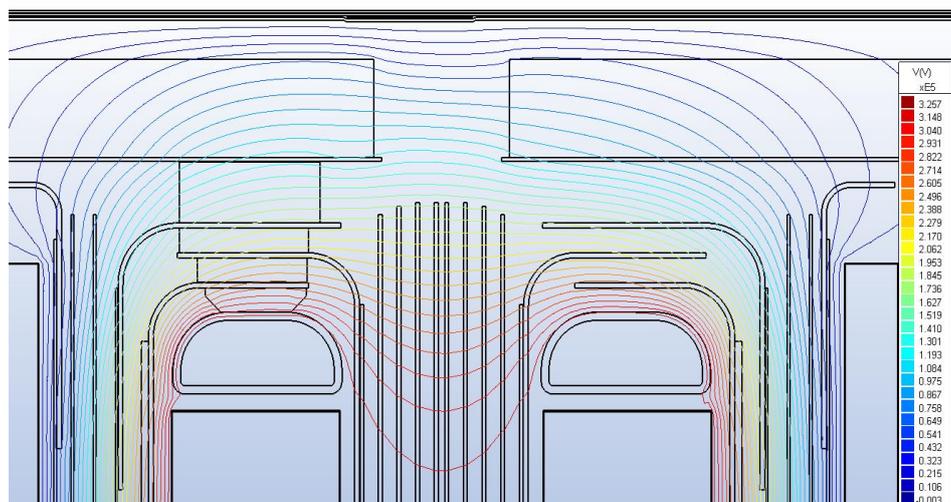
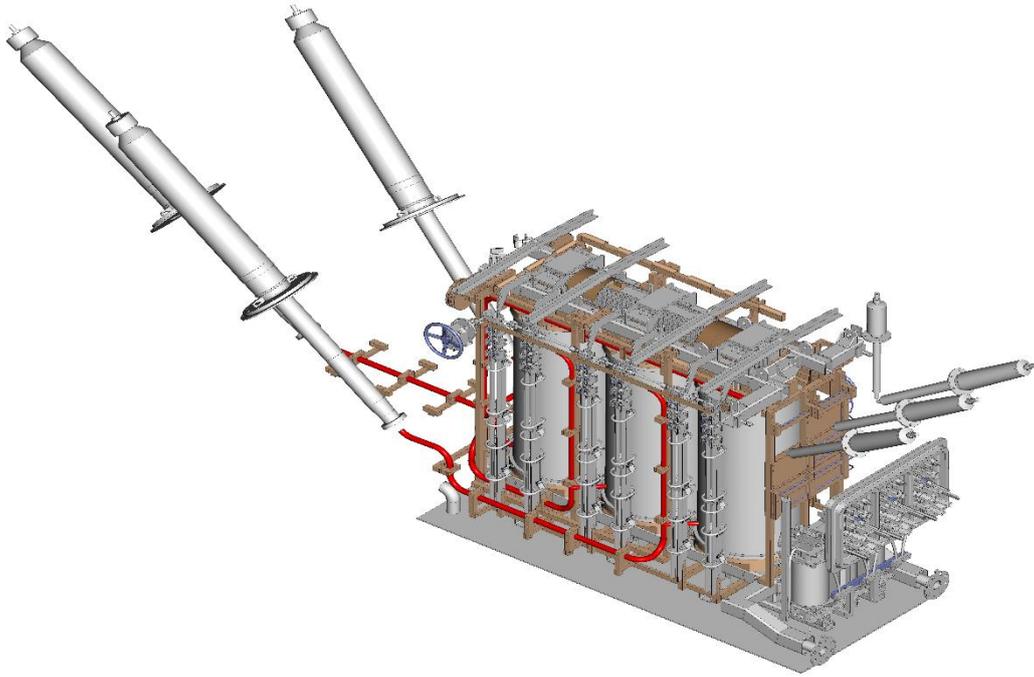


Fig.4. The equipotential lines between two phases of the transformer under the applied voltage test at 325kVac

Both HV and LV series parallel switches involved special considerations. The contacts required special shielding and pressboard barrier arrangements. Specially designed and formed moulded parts were used for external insulation of the HV series-parallel switch. All parts in the vicinity of the HV leads and switch were shielded to optimize the clearances by reducing maximum point stresses. The HV series-parallel switch had become the limiting factor for dielectric test levels of these units.

Due to size and weight limitation of mobile transformer, the internal assembly design is a challenging part of design process. This particular mobile transformer was built with the HV series parallel switch, LV series-parallel switch, LV LTC and a preventive auto transformer (i.e. LTC reactor). See details of the assembly below:



*Fig.5. HV side of the internal unit assembly: HV series parallel switch, HV leads, HV bushings; in front: LTC head, LTC reactor, LV bushings*

Mechanical integrity of the core-coil assembly was achieved with a robust tie-rod and box clamp structure. The box clamp was also used to direct the flow of oil into the windings. Hydro One recognized robust construction of the clamping structure and allocated maximum points in a bid evaluation score card.

The mechanical design of mobile substation transformer is very critical and needs special expertise due to dimensional and weight limitations. The mobile unit has to meet Department of Transport requirements with regard to dimension and weight. The HV bushings have to be positioned at tank bottom to limit the height during movement of the trailer. A specially designed rectangular conservator was used for oil preservation to meet axial height limits as shown in the figure below:



*Fig.6. The transformer on a trailer with cooler and surge arrestors (photo taken in the plant on a mobile substation assembly line)*

The sub station lay-out was reviewed with the customer to evolve an optimum solution. The transformer external and substation details were designed using CREO parametric 3D modelling software.

### Test results

The mobile units successfully passed the factory tests. The test results were well within the guaranteed values. Summary of test results are as shown in the table below.

**Table II Test results and guaranteed values**

| Test Parameter  | Design 1                |           | Design 2                 |           |
|---|-------------------------|-----------|--------------------------|-----------|
|   | Test                    | Guarantee | Test                     | Guarantee |
| No-load loss(kW)  | 17.2                    | 21.4      | 19.1                     | 22.4      |
| Load loss(kW)   | 318.6                   | 328.5     | 279.8                    | 302.6     |
| Impedance (%)   | 13.46                   | 13.5      | 13.67                    | 13.5      |
| Top oil temperature rise(°C)                                  | 43.5                    | 70        | 41.1                     | 70        |
| Average winding temperature rise(°C)                          | 57                      | 95        | 50.4                     | 95        |
| Hotspot temperature rise(°C)                                  | 94.2                    | 115       | 86                       | 115       |
| Sound pressure level (dBA)                                    | 68.7                    | 80        | 68.4                     | 80        |
| Partial discharge level during induced voltage test at 150% V | 7 (230kV)<br>96 (115kV) | 300       | 32 (230kV)<br>89 (115kV) | 300       |

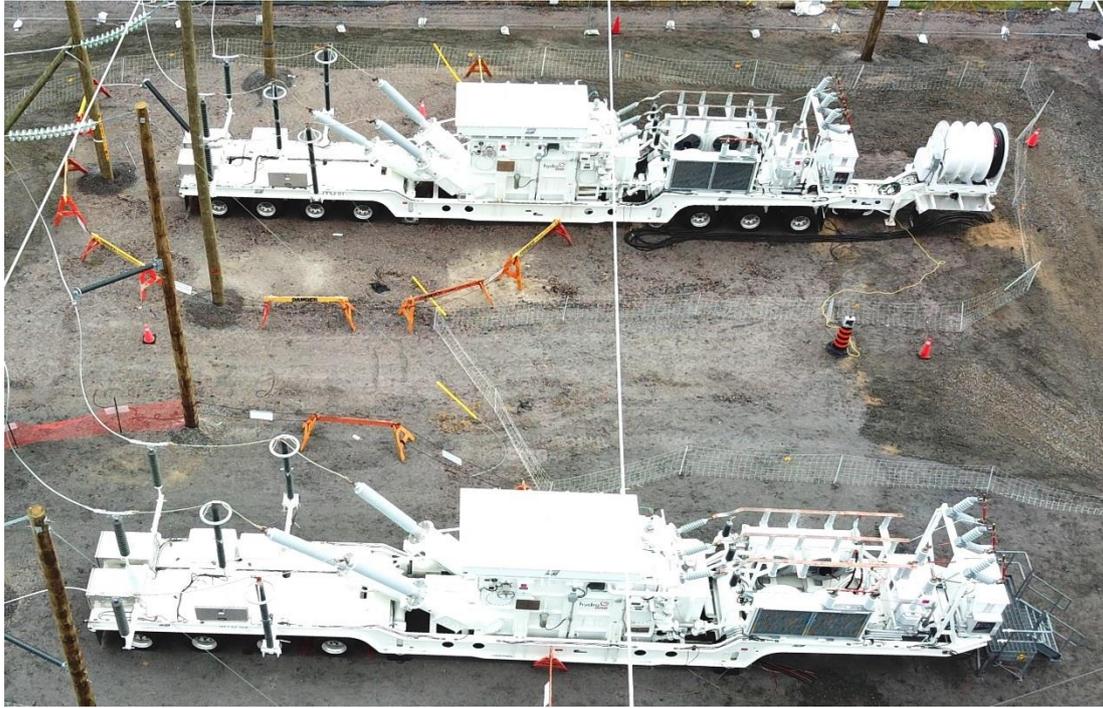
The tank wall during the temperature rise test were also monitored with IR camera for highest temperatures – see Fig.7.



*Fig.7. Thermal scan of a transformer during the temperature rise test*

### Conclusions and future work

- The four 30 MVA mobile transformers of 230 kV class with reconnection capability on HV side were successfully developed, tested and delivered.
- Immediately after delivery these units were placed in service [4], see Fig.8.
- In future development a higher power rating of transformers will be a next critical goal.
- As there is still a need to bring more equipment to site in emergency situation, Hydro One considers multi-trailer mobile substation as the next step in providing quickest possible post contingency response.
- To improve speed and safety of installation, the safe-to-touch terminations, as well as other dead-front equipment will be considered in the future mobile substation design.



*Fig.8. Two 30 MVA 230kV mobile transformers deployed in emergency situation at HONI substation*

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