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Advanced Load Shedding, Load Restoration and Substation Control Schemes based on IEC 61850 in Distribution Substations

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1 INTRODUCTION

This paper describes the practices, requirements and implementation of a complete Substation Control and Protection System, including advanced Load Shedding and Load Restoration schemes in five of the Israel Electric Corporation (IECo) substations, taking advantage of the modern protection relays with IEC 61850 communication protocol, arriving to a higher level of substation control.

In this paper a modern high-speed and controlled Load Shedding and Load Restoration system is presented, where the information is shared between IEDs in different bays, and a fully controlled Load Restoration is achieved.

Two Load Shedding restoration schemes implemented are presented, the traditional scheme based on a Star topology with a frequency-based initiation of the restoration by priority groups, together with an advanced Ring topology with a fully controlled restoration feeder by feeder. This advanced topology can be achieved using modern IEDs and intra-substation communications based on peer-to-peer communications with IEC 61850 GOOSE messages, and provides a higher level of control on a feeder basis vs. a group of feeders.

The paper also covers the new topic of redundancy of the control developed in this new advanced Load Restoration schemes.

The complete implementation of the Substation Control System based on IEC 61850 achieved is presented, including details and considerations in the implementation of substation logic schemes as Breaker Failure Protection, control of the closure of Capacitor Banks in coupled busbars, or control of the Earthing system (Petersen Coil or Solidly Earthed) connected in the different busbars considering their couplings and blocking or unblocking different protection functions, using only IEC 61850 GOOSE messages.

2 INFORMATION ON THE 161KV SUBSTATIONS

The Substations consist of the following main components:

- High-Voltage station, 161kV. Two versions of HV stations exist. Open Station that consists of two air-insulated single busbars, one coupler, and typically four line feeders and four transformer feeders and GIS Station that consists of gas-isolated double-busbars, one coupler and typically four line and four transformer feeders.
- Medium-Voltage station, there are three versions:
 - Standard GIS (24 or 36kV) that consists of up to four gas-insulated single busbars. Each of the busbars includes one transformer (30MVA or 45MVA) infeed, two

- couplers, one capacitor bank feeder, one earthing transformer (for 45MVA) and up to eight line feeders.
- Expanded (24 or 36kV) GIS Station that consists of up to four gas-insulated single busbars. Each of the busbars includes one transformer (75MVA) infeed, two couplers, two capacitor bank feeders, one earthing transformer (for 75 MVA) and up to twelve lines
- 13.2 kV Air-Insulated Metal-clad station that consists of two single busbars for each transformer (50/25/25MVA). Each busbar includes one infeed, one coupler, one capacitor bank feeder and up to eight line feeders.
- 161/24kV or 161/36kV, 30, 45 or 75MVA Transformers, or 161/13.2/13.2 kV 50/25/25 MVA transformers.



Fig. 1: Communication Architecture in Jerusalem C Substation

3 PROJECT DEVELOPMENT AND IMPLEMENTATION

3.1 Breaker Failure Protection

The Breaker Failure Protection (BFP) for the MV busbars in the substation is based on IEC 61850. This function provides a backup for the MV circuit breakers and control wiring, determining when a Breaker has not tripped under fault conditions. Under these circumstances an IEC 61850 GOOSE message will be sent to all the bays connected to the same busbar and the upstream Breakers to isolate the fault.

Each MV Feeder relay will receive the IEC 61850 GOOSE message and will evaluate if the conditions for tripping the breaker are fulfilled. In case the disconnecter is not open, this means closed or in an undefined status, the relay will trip the bay and also block the Autoreclose function.

The reception of the IEC 61850 GOOSE for the BFP Trip does not directly trip the bay. If the circuit breaker has been tripped or opened before the reception of the IEC 61850 GOOSE message, the status of the MVCPU CB is considered in the logic and no action will be taken.

All the information required to evaluate the need to trip or not a bay will be received in each MVCPU (Medium Voltage Control and protection Unit) through IEC 61850 messages including the status of the Busbar Couplers and the BFP Trip commands sent by the other bays.

3.2 Capacitor Bank

The Capacitor Bank back-to-back inhibition protection function has been designed to reduce the inrush current that is produced when a Capacitor Bank closes. This protection function will control the closing of the Capacitor Bank bays avoiding parallel operation.

There are two possible schemes for the Structure of the Capacitor Banks, detailed in the 0 Fig. 2: Non Modular Capacitor Bank and 0 Fig. 3: Modular Capacitor Bank.

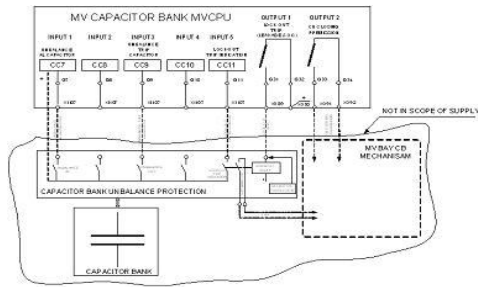


Fig. 2: Non Modular Capacitor Bank

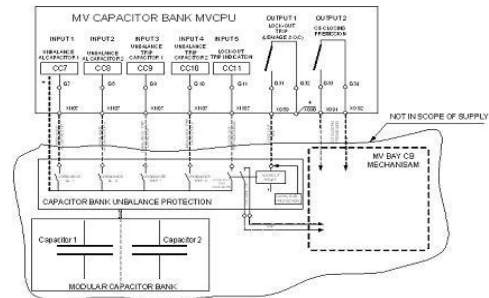


Fig. 3: Modular Capacitor Bank

The F650 relay used in the Capacitor Bank bay controls the Voltage of the bay and will trip and then block the closing, if the Voltage is out of range. The closing is also delayed until the current has been stabilized. To avoid the parallel operation, a logic that controls the number of Capacitor Banks that are connected to the coupled MV busbars has been developed. If a busbar has a Capacitor Bank connected or is coupled to another busbar that has a connected Capacitor Bank connected, the closing of the second Capacitor Bank will not be permitted. In case of having a Modular Capacitor Bank, it will be enough to have one of the Capacitors closed to consider all the Capacitor Bank connected.

This Special Function has been fully based on IEC 61850 GOOSE messages, without any wiring between the different bays. The mentioned logic has been implemented in all the Capacitor Bank F650 IEDs that have previously received the information related to the status of all Capacitor Banks and Couplers.

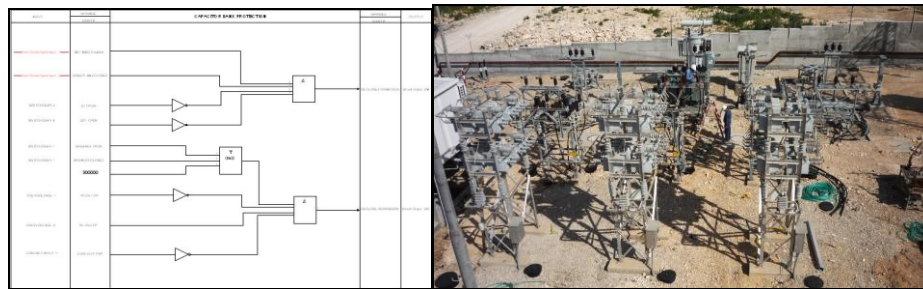


Fig. 4: Example of Capacitor Bank Logic and Capacitor Banks in Cabri 161/24/13.8kV Substation

3.3 Load Shedding and Load Restoration Schemes

A main Underfrequency unit has been defined in each substation dedicated to initiate the Load Shedding and the Restoration process. Connected to the 161kV High Voltage busbars, controls the frequency and the frequency rate of change, and takes the decision to trip and reclose the 24kV and 36kV Medium Voltage feeders sending the corresponding order in a IEC 61850 GOOSE message.

The frequency can be measured from the first or the second 161kV HV busbar VT, and the decision is taken by the operator selecting the corresponding option through the IEC 61850 client HMI.

Three protection stages for Underfrequency and Frequency rate of change have been chosen to define three different priorities: Priority 1 “Low frequency”, Priority 2 “Very low frequency” and Priority 3 “Extremely low frequency”.

The priority is independent for each MV feeder and can be changed by the operator in the SCADA HMI. When the operator selects a new priority for a feeder on the HMI, the system will send a command to the selected relay to set it. The simultaneous activation of several priorities in a line is avoided thanks to the use of interlocks.

When the Underfrequency Relay detects that the frequency has dropped down below one of the defined frequencies or exceeded one of the frequency rate of change levels, it will send a trip IEC 61850 GOOSE message to all the MV line bays. Three different trip messages have been defined, one per priority.

The F650 relays protecting each MV feeder will receive the trip IEC 61850 GOOSE message and compare it with its preconfigured priority. If it matches, the line will be tripped and will set an internal flag to enable the feeder for a later automatic restoration, differentiating the Load Shedding

trip from a Feeder Protection Trip. The Autorecloser function of the relay will be also internally blocked to avoid its operation after a Load Shedding.

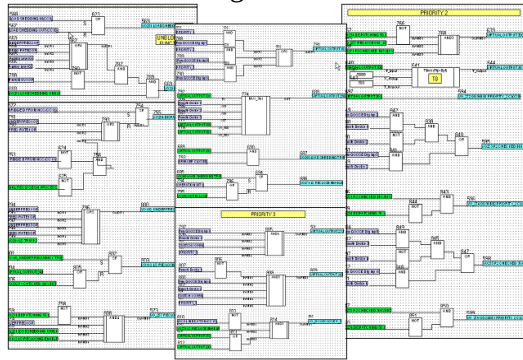


Fig. 5: Load Shedding logic of UF F650 relay and Line F650 Relay

Two different Load Shedding restoration schemes have been implemented, the traditional scheme based on a Star topology with a frequency-based initiation of the restoration by priority groups, together with an advanced Ring topology with a fully controlled restoration feeder by feeder.

3.3.1 Start Topology

This restoration scheme follows the traditional approach of initiating the restoration of feeders by priority groups, but it has been implemented using the IEC 61850 GOOSE messages replacing all the wiring between bays.

When needed, the Star Topology scheme can be forced by the operator or by the Dispatching Centre to replace the fully controlled Ring Topology scheme, just activating a Contact Input of the Underfrequency relay defined as “50.1”

In this forced mode, it has been defined that the Load Restoration process will start once the frequency is recovered above the Underfrequency levels configured. Under these conditions, the HV Underfrequency relay will send the IEC 61850 GOOSE message with the closing command to all the MV Feeder bays, starting with the Priority 3 and finishing with the Priority 1. The F650 Feeder Relays will compare their own priority with the priority of the IEC 61850 GOOSE message received and will send the close command to the circuit breaker when they match, only if the internal flag indicating that the feeder was tripped because of a Load Shedding Trip is active and not by any other Protection function.

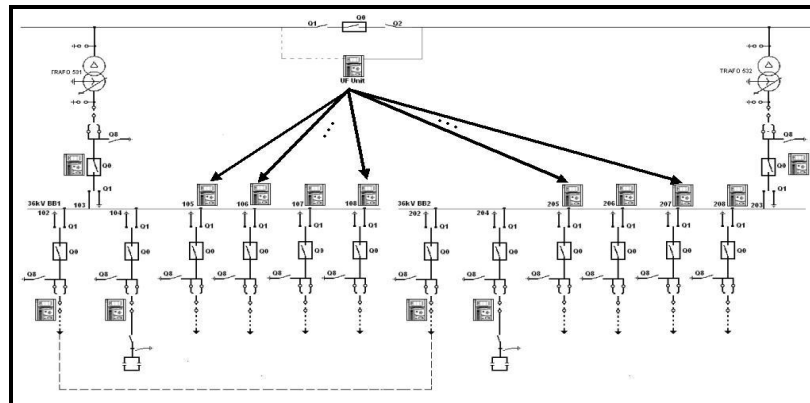


Fig. 6: Example of IEC 61850 GOOSE Transmission in the Load Restoration with Radial Topology

3.3.2 Ring Topology

When the Contact Input “50.1” of the HV Underfrequency F650 Relay (UF) is deenergized, the system is set to follow the advanced Ring topology in the Load Restoration (LR) scheme. In this scheme a fully controlled restoration feeder by feeder is started when the frequency is restored above the predefined Overfrequency level configured. The Underfrequency relay will send the command to start the LR of the feeders with Priority 3 to the two first relays of the first busbar. In the example shown in the figure below of the Jerusalem C Substation, the LR IEC 61850 GOOSE message will be sent from the UF unit to the two first Lines of the 36kV Busbar-1. The IEC 61850 GOOSE message

will then progress along the Busbar-1, until all its Line Bays have been checked. At this point of the scheme, the UF will receive back another IEC 61850 GOOSE message indicating that LR for the Busbar-1 and Priority 3 has been completed, so that the UF can start the process with the next Busbar. This process will continue until all Busbars and Priorities have been checked.

When a Line Bay receives the LR message to close the circuit breaker, the fulfilment of all conditions for the restoration is checked (Priority of the bay and of the LR message match, Line circuit breaker previously tripped by Load Shedding and not a Protection Function, etc). If the conditions are fulfilled the Line Bay will close the circuit breaker and wait until a security time expires before passing the LR IEC 61850 GOOSE message to the next Line Bay of the busbar, otherwise the Line Bay will immediately send the LR IEC 61850 GOOSE message to the next bay without taking any action in the Line.

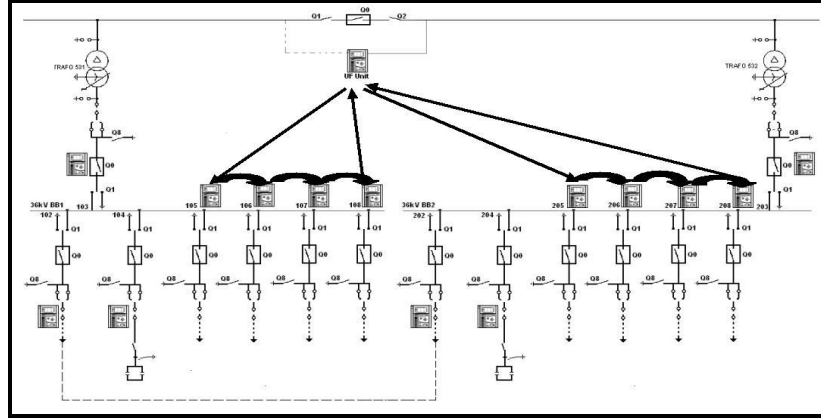


Fig. 7: Example of IEC 61850 GOOSE Transmission in the Load Restoration with Ring Topology

A redundant ring topology has been implemented in the case of the LR with Ring Topology, in order to achieve a higher level of reliability and a system capable of supporting a failure in the LR logic ring. With this purpose two different Load Restoration IEC 61850 GOOSE messages have been implemented in all the bays. The Underfrequency Unit will start the scheme sending the LR message to the first and second relay of the busbar, and so will do each relay sending the LR message to the next two relays. Finally, the last two relays of the busbar will return the LR message back to the Underfrequency relay.

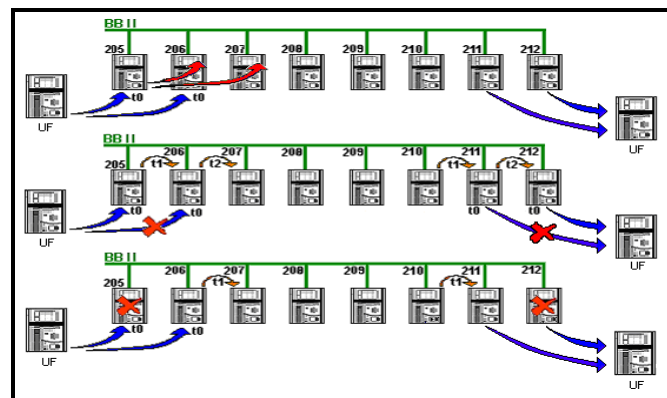


Fig. 8: Redundancy of the Load Restoration IEC 61850 GOOSE in the Ring Topology

3.4 Earthing State

The Medium Voltage busbars are equipped with a Petersen coil and an earthing switch, to provide two different methods of earthing system. There are two possible schemes:

- The busbar is equipped with an earthing transformer with a Petersen coil and an earthing switch for direct earthing, usually in 45MVA transformers.
- The neutral point of the Transformer bay is equipped with a Petersen coil and an Earthing switch for direct earthing, usually in 30MVA transformers.

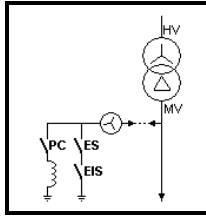


Fig. 9: 45MVA Transformer

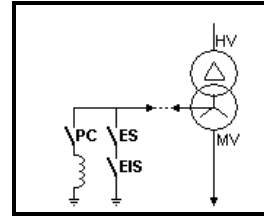


Fig. 10: 30MVA Transformer

Depending on the status of the Petersen Coil, Earthing Switch and Earthing Isolator Switch switchgears, different protection functions will be enabled or inhibited:

- Leakage protection: When the busbar and the busbars that are coupled with it are solidly earthed.

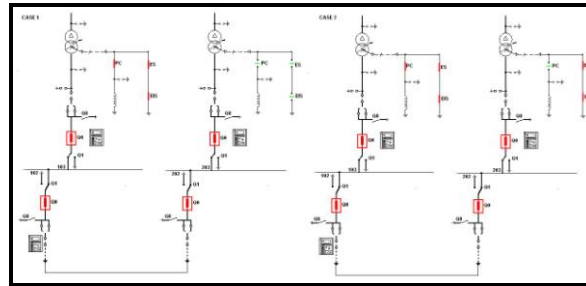


Fig. 11: Examples of Solidly Earthed Busbars

- Watmetric protection: When all the busbars that are coupled are earthed through the Petersen coil and the “Resistor on” input signal of the Petersen coil is activated in the busbar or in one of the busbars coupled to it.

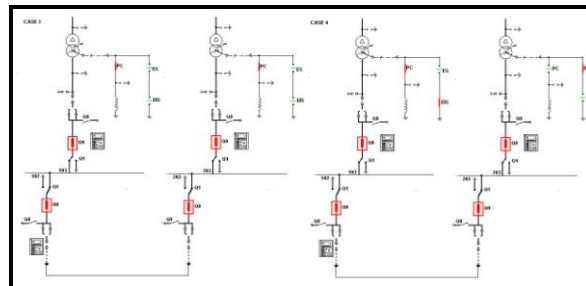


Fig. 12: Examples of Inductively Earthed Busbars

- Unacceptable State of Earthing system: Mixed mode operation of solidly and inductively earthing types in two or more busbars that are coupled should activate the leakage protection and block the wattmetric protection. E.g. BB2 has the direct earthing switch closed (solidly earthed) and it is connected to BB3 that is earthed through Petersen-coil. When the substation is in ‘Unacceptable state of earthing system’ an alarm will be activated in the substation HMI, and is also sent to the Dispatch Centre.

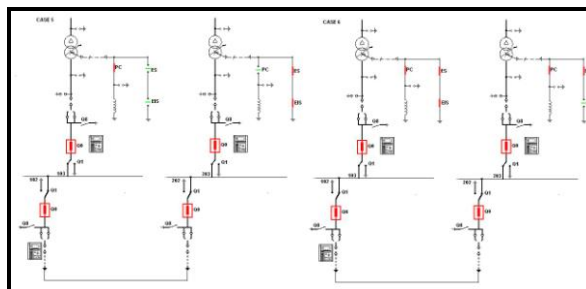


Fig. 13: Examples of Unacceptable State of Earthing system

The relay is configured to enable or block the different protection functions automatically. If the busbar is solidly earthed, the relay will block the 32N protection function and set the 50/51G, and if

the busbar is inductively earthed (Petersen Coil connected and Earthing Switch open) it will activate the 32N and block the 50/51G protection.

- Loss of earthing system: If a loss of system earthing is caused by intent commands, an alarm will be sent to the station HMI, and to the Dispatch Centre. If after 15 minutes the conditions are not corrected, an IEC 61850 GOOSE trip command will be sent to the circuit breakers of the MV Infeeder bay and to the respective HV Transformer bay.

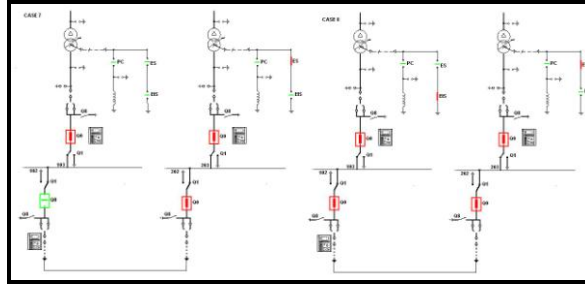


Fig. 14: Examples of Loss of System Earthing

Specific libraries have been designed in the Infeeder IEDs to implement this logic evaluating all the different combinations of Earthing and Coupler Switchgears between all the busbars. The maximum possible configuration defined for the substations has up to four 24kV MV busbars. Using the information from the other Infeeder Bays and Coupler Bays received in IEC 61850 GOOSE messages, every Infeeder IED is able to check the type of earthing of its controlled busbar, of the busbars connected to it, and also the type earthing connected in these other busbars coupled.

3.5 Devices Used

The entire Substation Control and Protection System has been based on the use of the GE F650 relays with IEC 61850 Communication Protocol and PLC capabilities. An independent F650 relay has been introduced per 161kV HV, 24kV and 36kV bays, including Measuring and Coupler bays.

The Substation Control and Protection System have a multi-level decentralised architecture, which consists on the following main components and equipment:

- CCU1000: Central Control Unit located in the Station Control Room, acting as IEC 61850 Client of all the IEDs, and as Server of the GE Power HMI, providing the operator the control of the whole Substation.
- 161kV HV: One F650 Unit with IEC 61850 per Line and Transformer Bay, for monitoring and controlling the HV Switchgear.
- 36kV and 24kV MV: One F650 unit per bay to provide the Protection and Control of each Infeeder, Line, Coupler and Capacitor Bank.
- General Alarm System: Based on several F650 relays controlling traditional Alarm Panels for the Operators.
- ML2400 Ethernet Switches: Several ML2400 units to build the Fibre Optic LAN of the Substation.

4 FACTORY ACCEPTANCE TESTS (FAT)

In order to complete the Factory Acceptance Tests of an advanced Substation Control and Protection System like the one presented in this paper, the complete system has to be installed, energized and configured.

For all the Substation Control and Protection Systems delivered for each substation of this project, all the Cabinets with all the F650 relays installed have been configured and energized, all the Fibre Optic cables installed to build the Substation Ethernet LAN ring and to connect all the IEDs, having the Central Control Unit communicating with all the F650 relays and the HMI available for all the tests.



Fig. 15: Cabri Cabinets during FAT

The entire System, including IEC 61850 Client-Server Communications, IEC 61850 GOOSE Messages and all the Protection Functions could be tested and validated under real conditions.

5 SITE ACCEPTANCE TESTS (SAT)

The Test Procedures carried out during the SAT were the same as during the FAT. The Virtual Switchgears used during the factory tests made it possible to test the complete Substation Control System and all the Logic tables of the different schemes.

During the SAT, the Virtual Switchgears were disabled, and the same Test Procedures were followed using the real signals wired from field.

The Double Secondary Injection Test sets were used for reproducing fault conditions to validate the Protection Functions and the Control Schemes on site, and all the events and alarms related to each function were checked on the GE Power HMI.



Fig. 16: Kfar Saba Substation Commissioning and Cabri Substation general view.

6 CONCLUSIONS

The work presented in this paper reflects the actual development of complete Substation Protection and Control systems, including advanced Load Shedding and Load Restoration schemes in distribution substations, taking advantage of the modern protection relays with IEC 61850 communication protocol.

The deployment of this technology in the design of a complete solution, has shown the following characteristics:

- A higher level of substation control has been achieved based on this technology.
- Standardization of the interfaces between the primary equipment and the secondary systems.
- Reduction of the number of signalling cables installed within the switchyard as well as between the substation protection and control panel, consequently reducing potential installation problems and minimizing the possible points of failure.
- Complete integrated FAT is completed for all substations delivered, having the capability of testing the complete system and logic schemes in factory, with a reduced need of temporary

wiring between panels and IEDs, or having auxiliary relays to simulate circuit breakers or disconnectors.

- System standardisation and optimisation of the commissioning and maintenance, thanks to the capability of testing the complete system and logic schemes during the FAT,
- Easier and faster replacement of protection and control panels and shorter process of wiring and connection of newly installed substations.
- With the application of these new technologies in the substation protection and control systems the professional profile of commissioning, operation and maintenance specialists has been changing according to the technological evolution.
- The quality of the substation works has to be assured with specific training, test methods and procedures, documentation and skilled staff.
- The content of the training courses has to be adapted and periodic updates will be needed.

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