OPERATIONAL TESTING OF VIRTUAL AND PHYSICAL IEDs USING GOOSE FOR PROTECTION APPLICATION

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Abstract:

The integration of Operation Technology such as Intelligent Electronic Devices (IEDs) brings added challenges for testing and operation of complex interconnected protection systems. The hardware limitations of IEDs, such as integration in existing infrastructure and reduced run time control, limits engineers and researchers to test complex protection and automation scenarios. Virtualization of these technologies, allows seamless integration of software units into existing systems, which can be scaled up for large scale system testing. In this paper, the operation of virtual IEDs has been validated with that of physical IEDs. Two separate test platforms are used; one for the physical IED infrastructure and the other for virtual IED (vIED) infrastructure. A use case for overcurrent feeder protection using GOOSE communication has been demonstrated. The performance of circuit breaker tripping and GOOSE communication has been demonstrated and compared for both the test platforms. The vIED operational ability is validated and key insights for future work are given.

1 Introduction

Integration of IEDs is becoming an important part of future power systems. Modern substations are employing improved and more reliable control devices known as Intelligent Electronic Devices. These new digital technologies automate the process of substation protection and control, allowing for faster and more reliable protection and control schemes [1]. For this purpose, IEC 61850 standard defines all the processes and the communications behind the phenomena of substation automation. The advantages of faster communication between IEDs, less cabling in substations and more control for the operators are some of the reasons these technologies are being integrated with existing infrastructure [2, 3].

The modern complexities of these devices bring added cyber and physical challenges for substation control and monitoring. The Ukraine cyber-attack demonstrated how a packet payload modification can cause disconnection of a transmission substation [4]. Also hardware infrastructure (IEDs) has some limitations, such as integration in existing infrastructure and reduced run time control. Due to this restricted control, operators or engineers cannot fully test the operational and security performance of the IEDs. Virtualization of IEDs helps to test advanced and complex protection schemes in a real time environment before field deployment. With a virtual platform comprising of IEDs and protection schemes, the communication infrastructure and the power system operation can be tested without the risk of malfunction of devices or the system. Through virtualization, the device functionality can be mimicked and can be developed as software programs that run on Virtual Machines (VMs). It also allows to scale up the simulation for more complex scenarios as the software programs can be easily deployed on the VMs and can increase the flexibility for real time testing [5]. The system can be dynamically configured during run time that reduces hardware dependency and costs of integration. The virtual components are flexible due to separation of functions and resources such as CPU or memory. Hence by increasing the resources, a virtual device can operate better and can be instantiated several times [6, 7].

Virtual IEC 61850 platforms are still relatively new. The need for virtualization arises when large scale simulations with remote measurements and attack scenarios need to be investigated. Authors in [5] develop virtual IEDs on a virtual server and investigate the performance parameters of tripping time and GOOSE data rate in a virtual platform. Security mechanisms for IEC 61850 are also new and have been carried out by authors [*8*] and [*9*]. Recent works show the integration of GOOSE communication with protection applications. Authors in [*10*] investigate how GOOSE messaging between IEDs can change the relay characteristics. This investigation is useful for overcurrent feeder protection as the Logical Node PTOC changes the relay operation is case of a fault. The authors in [*11*] demonstrate how GOOSE messaging can trip a breaker connected to a transformer to clear a fault at the distribution feeder. Islanding and non-islanded modes have been also been investigated by [*12*]. They show how IED LNs change their data attributes and send GOOSE messaging to make the system stable during transitioning from grid-connected to islanding mode. References [*13*] and [*14*] show

how distance relays can be configured with IEC 61850 specifications to carry out distance protection. Another application that has been tested is load shedding using GOOSE communication by authors in [*15, 16, and 17*]. All these research works show the importance and the need for enhanced testing of IEC 61850 for future scenarios. Existing literature work has tested the performance of virtual IED testbeds. However, a complete analysis of operation, communication, and control of virtual IEDs with protection systems is needed. Furthermore the communication data rate and delays encountered by Generic Object Oriented Substation Events (GOOSE) using virtual IEDs for real time operation needs to be tested. The expected research from this work is in synergy with this research gap. In this paper, the performance of both real and virtual IEDs in two different research infrastructures is tested for reverse blocking schemes with GOOSE communication that conforms to the IEC 61850-8-1 standard [18]. The novel contribution is the validation and analysis of the GOOSE communication under substation events for both the platforms and validating the operational behaviour of the virtual IEDs with the physical IEDs. Important comparisons are given between testing approaches and the results for virtual and physical infrastructures.

2. Research background

2.1 GOOSE and IEC 61850

The IEC 61850 in recent years has been widely used by research laboratories and modern substations. According to IEC 61850, the physical device is the IED which measures current and voltage inputs, enables time synchronization to the measurements and issues command to other IEDs or the Human Machine Interface (HMI) for control measures. These devices in the substation use effective communication protocols such as GOOSE [15]. GOOSE is a method for fast transmission of real time data to IEDs. The GOOSE methodology is based on the subscriber/publisher model. Both the subscriber and publisher exchange data through a local buffer. GOOSE messages are sent sporadically with high frequency. Different data in the IED is grouped or configured into a data set. The GOOSE message can contain one or several data sets. Any change in this data set trigger GOOSE messages, and this increases the frequency of GOOSE messages. In the GOOSE transmission model, there are four interval times: T0, T1, T2 and T3. T0 is the normal retransmission time when no event change occurs. This is the heartbeat of the GOOSE message. When an event occurs, T1 is the minimum retransmission time. For substation events, T1 should not be more than 4ms. After the new event occurs, retransmission time is increased gradually from T2, T3 back to T0. The substation events can be analyzed according to this retransmission model and the time intervals can be investigated for these events [19].

2.2 Protection Applications for IEDs

There are different protection applications which are used in distribution substations. Protection applications in substations comprise of feeder protection, line protection, distance protection or generator protection. Overcurrent in the system can lead to failures or disconnections of the feeders or other critical points of the grid. Hence modern substations and micro grids require high speeds for circuit breaker and relay control for protection purposes. IEDs have the operational ability to configure, communicate and react to fast changing scenarios such as overcurrent or under-voltage conditions. The concepts of interlocking or reverse blocking can be realized by IEDs using fast trip or block messages to protect the system. Applications such as loss of Mains (LOM) and Fault-ride-through are important when dealing with large scale complex scenarios and require relay coordination and fast messaging between the IEDs [20, 21].

3 Test Infrastructure

3.1 VTT

The MultiPower laboratory in VTT Espoo was used to execute the experiments for the physical relays. Figure 1 shows the VTT hardware infrastructure interconnection. The feeder load of 15kW is connected to an ABB REF615 relay that sends GOOSE messages to the REF615 receiver that is connected to the 20kV distribution grid connection. The use case of feeder overcurrent with GOOSE communication is tested. In this test the feeder load is increased to its maximum capacity so test an overcurrent scenario at the feeder. This enables fast GOOSE communication from the REF615 sender that is connected to the feeder load to the receiver IED that is connected to the grid connection. The sender sends a block message and prevents the circuit breaker at the receiver from tripping. GOOSE communication allows the upstream breakers to be blocked and critical points of the grid do not lose operation.

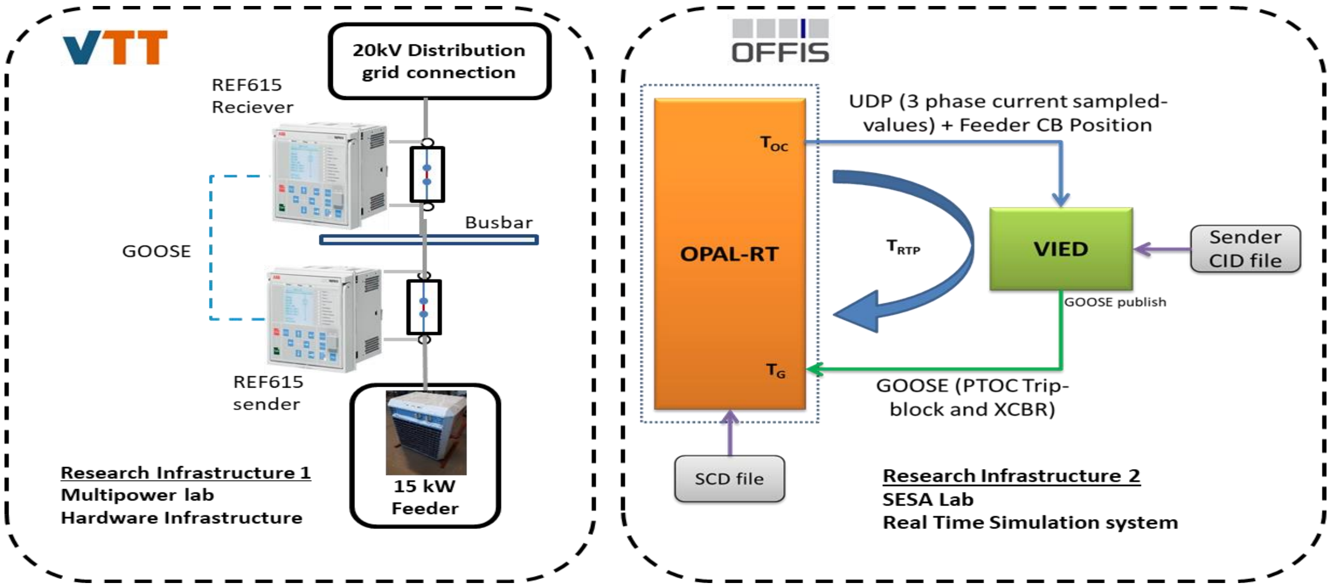

Figure 1 Test Infrastructure at VTT and OFFIS

3.2 OFFIS

At OFFIS, the research infrastructure is used to simulate the use case performed at VTT Finland. It consists of OPAL-RT real-time simulator, a Virtual IED and IEC-61850 engineering files required for substation configuration. The overcurrent scenario for VTT is simulated. The current measurements from the feeder load are sampled and sent via the UDP protocol to the vIED. The vIED then performs its logic for overcurrent by converting the UDP measurements into GOOSE control blocks. It then publishes the GOOSE messages back to the OPAL-RT where it subscribes to the GOOSE. The modelling and development of the test platform is done in three phases. First, the VTT network model is modelled in RT-LAB, the IEC 61850 engineering for SCL files is done in HELINKS STS and the virtual IED is developed in OFFIS. These three parts are discussed in detail below.

3.2.1 VTT Network Model

The model of the electrical network was made in the MATLAB Simulink environment and was simulated in OPAL-RT real time simulator. The network model of VTT is mimicked with the same grid topology. In the network model, the circuit breakers and relays interconnections are modelled with three phase circuit breakers and overcurrent relays using logic operators and SR flip-flops. The OPAL model has several key components of the electrical network with active components e.g. circuit breakers, measurement units, dynamic 3-phase load, and programmable switches for load control. Three two features of the control and communication of the model are listed below.

- UDP three phase current values sender.
- GOOSE subscriber block for PTOC and XCBR values.

3.2.2 IEC 61850 Engineering

The IEC 61850 engineering files in SCL were created using the HELINKS STS software. The required logical functions were mapped with the logical nodes of 2 virtual-IEDs, one of which acts as a GOOSE publisher and the other as a subscriber. After configuring the GOOSE Control Block (GCB), the CID files of both the IEDs were extracted along with the SCD file of the entire substation-model. The SCD file was used to configure the IO-module of the OPAL-RT model for real-time communication with the vIED. The GOOSE-publisher vIED was configured using the CID file of the sender IED.

3.2.3 vIED

The vIED is a console application written in C that implements its IEC61850 functionality using the open source library libiec61850 version 1.4. It consists of three integrated units: The data input, the logic and the IED server as shown in Figure 4. The data input supports the reception of data via the communication protocols UDP, MMS, Sampled Values and GOOSE and decodes the data under consideration of special properties (e.g. a transmitter-specific header with metadata). Inside the logic, the data is processed according to the desired functionality and then passed on to the IED server. The IED server loads the data model and the dynamically configures the communication parameters from the CID file. For the generation and validation of the configuration file a model generator tool provided by the libiec61850 library can be used. The data passed by the logic is assigned to the corresponding data attribute objects of the model and the server is updated. This data can be published via Sampled Values, GOOSE or MMS. In this test case, the vIED takes in the sampled UDP values and wraps them in to GOOSE control blocks. The communication parameters are dynamically set from the CID file from HELINKS and then it publishes the GOOSE messages.

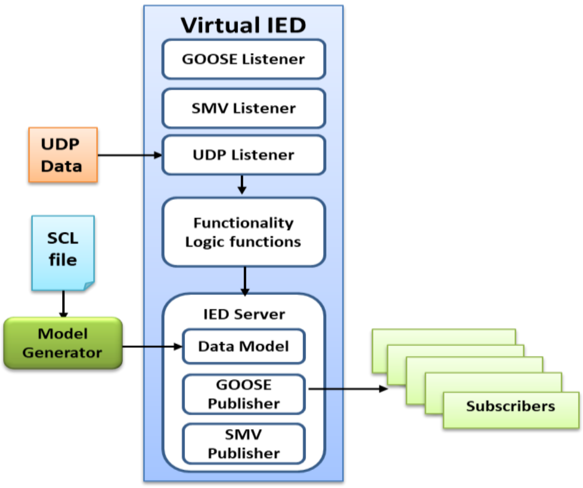

Figure 2: vIED concept and structure

4 Results and Discussions

4.1 VTT

The main point of investigation was the tripping time of the feeder circuit breaker and the GOOSE time for blocking the grid circuit breaker. Figure 1 shows the scenario of how the feeder and grid IEDs operate once the overcurrent scenario starts. The figure shows the stNum of the GOOSE and how it changes when there is a change in the substation event. Figure 3 shows the circuit breaker operation of the grid circuit breaker. Once the feeder load is increased at 120ms, the PTOC for the feeder IED starts and it takes 25ms for PTOC to change from start to operate. In this 25ms it is critical that the IED sends GOOSE messages to block the operation of other upstream IEDs (in this case the grid connection IED). The GOOSE messages are sent before this 25ms and hence the receiver IED operation is blocked. The stNum of the feeder IED changes to stNum2 when the PTOC Boolean is true. This is the most important GOOSE event change as it changes the PTOC block from false to true. After that the PTOC operates and the circuit breaker opens. The stNum is increased respectively. Afterwards, once the current in the system reaches zero, the PTOC resets and stNum increases again. The GOOSE retransmission time when the PTOC starts is shown in Figure 4. The figure shows how the GOOSE packets are transmitted very fast when the PTOC is started and stNum changes to 2. Four packets are retransmitted and the average retransmission time when PTOC starts is calculated. The times for the tripping of the feeder circuit breaker and the average GOOSE blocking time is shown in Table 1.

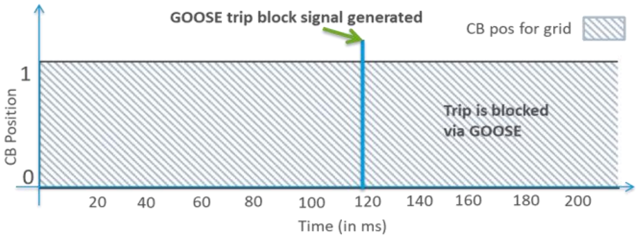

Figure 3 Grid circuit breaker status with blocking operation

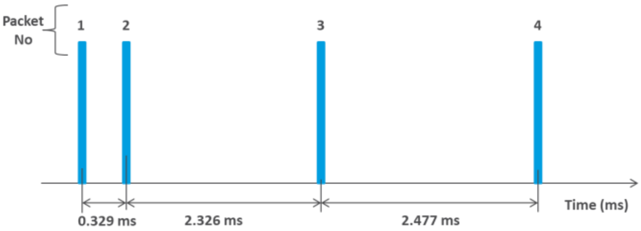

Figure 4 GOOSE packet retransmission intervals

Table 1 Results from VTT testing

Event	Time(ms)
GOOSE retransmission	1.71
Feeder trip	46

Table 2 Results from vIED testing

Event	Annotation	Time(ms)
GOOSE round trip	T_{RTP}	0.6
Maximum clearing	T_{MC}	67.8

4.2 OFFIS

Using the test setup at OFFIS the network at VTT system was simulated in real time and the performance of an IEC-61850 compliant virtual IED based setup was assessed. The key parameters measured and recorded over the simulation period of 9s were the circuit current, the CB positions and the GOOSE value and status (stNum and sqNum). In the model, at a pre-defined time an over-current situation was initiated and the time when the over-current threshold was reached was defined as the over-current time (T_{OC}). The GOOSE subscription time (T_G) is the time when the first GOOSE message after the substation event was received. The zero-current time (T_Z) is when the feeder circuit breaker is fully open, and the line currents are zero. From these times (T_{OC}, T_G and T_Z) the GOOSE round-trip time (T_{RTP}) and maximum clearing time (T_{MC}) were calculated. Table 2 shows the times measurements for the round-trip time and the max clearing time. They are calculated from the equations (1) and (2).

$$T_{RTP} = T_G - T_{OC} \qquad (1)$$

$$T_{MC} = T_Z - T_{OC} \qquad (2)$$

For the real time simulations after 3 seconds the feeder load is turned on. Until 8 seconds the system is under stable condition i.e. the current is below the threshold limit for PTOC which is 14.5A. At 8 seconds the overload takes place and the overcurrent threshold is met. At this overloading, the UDP messages are translated to GOOSE and wrapped in the vIED and sent back to the OPAL-RT simulator. The OPAL-RT subscribes to this message and the GOOSE stNum and the sqNum is observed. Figure 6 (a) shows the current characteristics of the feeder load. It can be seen from the figure that when the threshold is met, the current goes to zero after T_{MC}. The tripping time for feeder is set to 45ms and for the grid circuit breaker to 50ms, once the overcurrent is met. The relays in the model are configured in such a way that within a 5ms interval both the feeder CB and grid CB will trip. This modelling is done to emulate a real scenario for relay protection and control. If there is no GOOSE in the system, both the circuit breakers would trip, and no blocking operation would take place. However, since due to the vIED and GOOSE communication, the vIED sends a PTOC blocking message to the OPAL-RT grid circuit breaker that prevents it from tripping. This is shown Figure 6 (b) and (c). At 8002ms a substation event (overcurrent) occurred and a GOOSE message was published by the vIED. This published message is again received by the subscriber in OPAL-RT model at 8002.6ms (Figure 7).

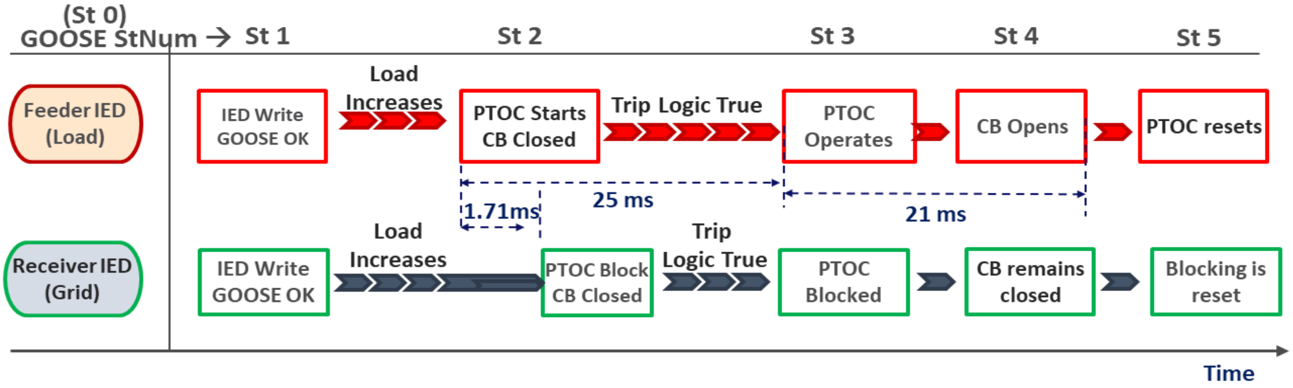

Figure 5 Relation of stNum with GSE for sender and receiver IEDs

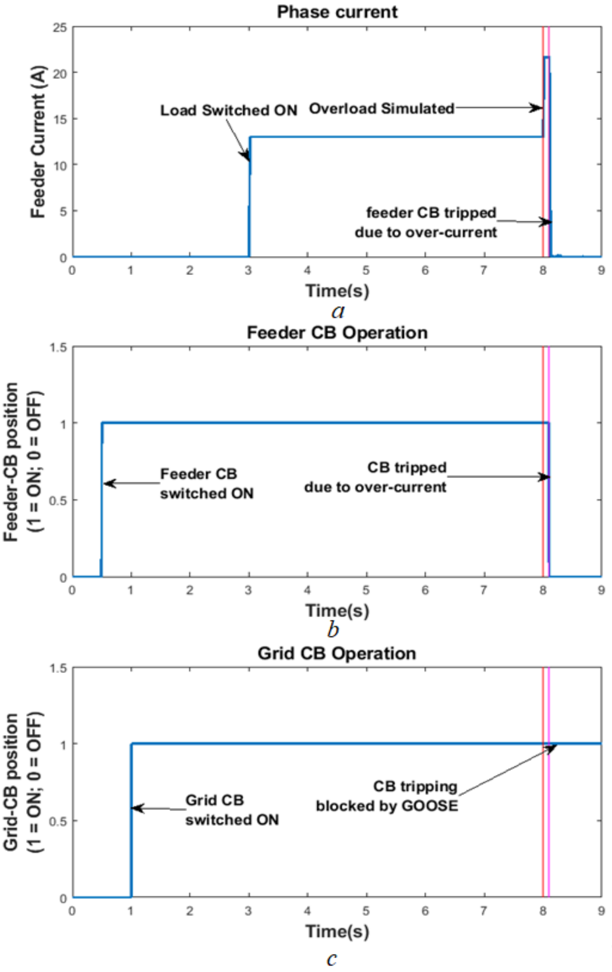

Figure 6 Feeder current **(b)** Feeder CB position (c) Grid CB position

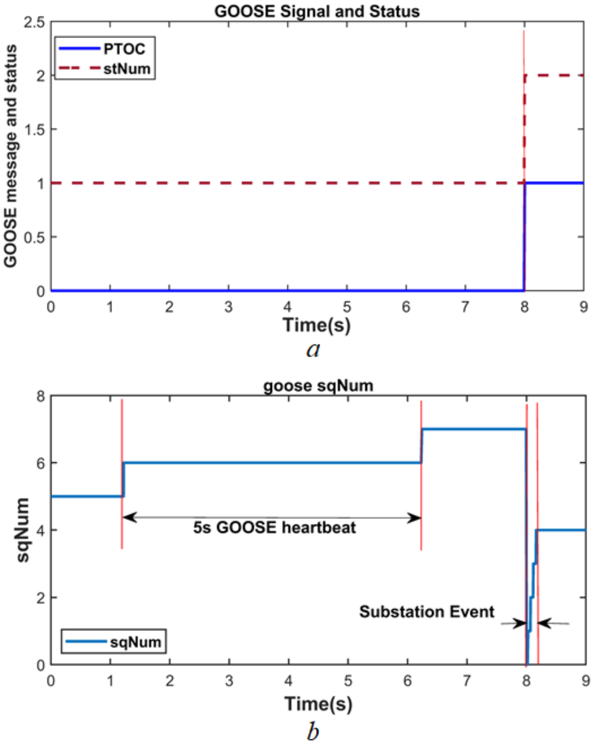

Figure 7 (a) GOOSE signal and stNum (b) sqNum

5 Conclusion and future work

In this research work, the results for both hardware IED and real time simulation systems with vIED, are compared and analysed. The measurements for the current values, the

GOOSE stNum, GOOSE sqNum and the timings of the tripping and the blocking are measured. The results for the GOOSE show that in the real time simulation, once the substation event of overcurrent occurs, the GOOSE message is faster than the ABB REF615 relays. For the hardware infrastructure, the operational time of the relays and the processing time of physical inputs of the current measurements could account for the higher GOOSE delay. In the virtual environment, the vIED runs on a VM and hence the hardware operating delays and the processing time of the relays is minimised.

The research work validates the performance of the real time simulation environment with the hardware infrastructure. The performance of the virtual environment can be further improved by having a time synchronisation PTP server for future work. Also, more complex protection scenarios can be modelled and simulated using the virtual platform and vIED can be further developed to deal with complex protection functions. The communication for Sampled Values is also incorporated in the vIED software and will be a useful feature to test current and voltage measurements for sampled value scenarios. Ongoing work is also underway to develop cybersecurity attacks for the vIED which can disrupt or attack the operating system of the vIED and can cause undesirable delays for the IEC 61850 communication. These cyber security feature will help to test the security vulnerabilities for IEDs and IEC 61850

6 Acknowledgement

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