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Innovative 5G transmission for anti-islanding protection in MV distribution networks

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ABSTRACT

This paper proposes an innovative communication infrastructure for anti-islanding protection enabling large-scale integration of renewable energy producers on the medium voltage (MV) grid. Based on 5G communication network, a demonstration was carried out in EDF R&D laboratory with a photovoltaic (PV) farm connected to a MV grid, while the underlying communication infrastructure was based on a 5G standalone network (5G SA).

INTRODUCTION

When an outage occurs on the MV grid, renewable productions (mostly PV and wind farm) may operate independently from the main grid, as in the case of isolated microgrids. For security reasons and grid stability, the French grid code requires that renewable production must be disconnected from the grid once a power outage occurs. The requirement for this specific grid code is stringent to insure network protection and grid reliability. The maximum end-to-end response time between the disconnect order transmission and its reception by the remote relay must be below 50 ms, making this requirement challenging, if not impossible, with previous generations of cellular network. For instance, this could hardly be achieved with 4G, since 4G network performance is highly dependent on network load which can lead to significant delays when network is saturated.

As of today, communications for the anti-islanding protection are carried out by copper cable, for which wiring is deployed in each individual producer premises, leading to additional cost and an entry barrier to renewable energy integration. To simplify the deployment at large scale of renewable production, EDF R&D (French energy utility), Enedis (French Distribution System Operator - DSO), Nokia (5G communication infrastructure supplier), and Orange (Telecom Operator) developed an innovative demonstrator based on a private 5G SA communication network to reach the requirement of the French grid code for anti-islanding protection. The main challenge was to set up a 5G SA network and to interface the protection relays transmitting continuous analog signals over a TCP/IP connection on the 5G network.

TAC ANTI-ISLANDING PROTECTION

Enedis deploys systems called "teleaction" (or TAC) to secure the connection to the electrical network of "large" renewable energy producers, connected by an MV line (20kV) with an operating power superior to 5MVA.

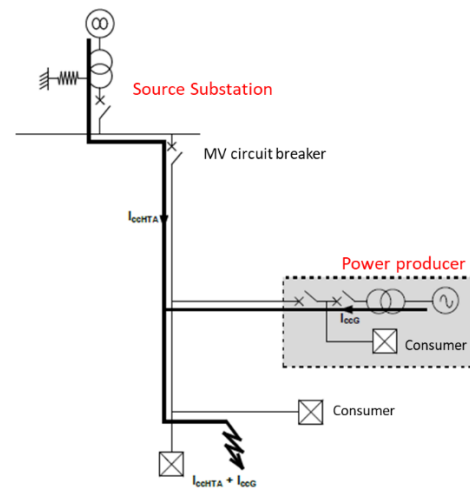


Figure 1 – typical tele-action configuration

The TAC system consists of two remote circuit breakers: one on the producer's side and the other at the electrical substation to which the producer is connected by an MV line. The control system ensures that, in the case of a fault detected by the network, the generator is automatically disconnected as soon as the circuit breaker on the electrical substation side is open. This prevents a situation known as "islanding" where a portion of the MV electrical grid is still powered (the local Power production balancing the electric demand locally) while Enedis shut it down, usually for incident or maintenance work.

DSO requirement

This control system must act in a time frame of 50ms calculated between the opening of the circuit breaker on the Enedis substation side of the MV feeder and the opening of the circuit breaker on the Producer side. If the TAC device does not work or if the 50ms delay is not respected, a local protection mechanism is activated, but this one being much more sensitive generates higher decoupling induced on the Producer side, reducing the quantity of electricity injected by the Generator.

OBJECTIVES

An experiment was previously conducted in Nokia'Lab as part of the H2020 5G-EVE (5G European Validation platform for Extensive trials) project by EDF R&D and Nokia to measure the latency of an electrical protection device in a test bed environment [1].

The goal of the present experimentation is to demonstrate the ability of 5G to meet the requirements of an anti-islanding protection system (named TAC) in a real-life environment and before field test. The objectives set for this experiment are:

- Validate correct operation of TAC over 5G connectivity
- Measure 5G latency and the stability of this performance
- Compare 5G and 4G performances and stability

EXPERIMENTAL ENVIRONNEMENT

The EDF R&D campus named “Les Renardières” was chosen because it hosts the EDF Concept Grid playground and Enedis Smart Substation Lab which enables to drive test being as close as possible to field environments where Enedis is willing to deploy such solution.

Concept Grid is a real «smart» distribution network. It integrates innovative testing resources implemented specifically to prepare for future developments in electrical networks. The Concept Grid distribution network includes 3 km of medium voltage network (20 kV) supplying 9 km of low voltage network. Additional electrical hardware, such as lithium battery, domestic loads in a real neighborhood, PV production or a power amplifier can be used to demonstrate complex use-cases.



Figure 2 – Concept Grid overview

For the demonstration a standard 20 kV distribution network was used involving overhead lines and underground cables with and a real PV field of 120 kVA peak supplied from the main station. The experimental validation was carried out on the EDF site, based on a full 5G communication infrastructure (including 5G NR and 5G SA core network). Using a fault-generating contactor, more than a dozen of short circuit events was created to assess if the decoupling order transmission delay met the required performances.

MATERIAL AND TOPOLOGY

Communication infrastructure

Although France started 5G rollout at the end of 2020, there is yet no commercial deployment of standalone 5G (5G SA) that is required to enable constant and guaranteed low latency. Thus, Enedis relied on Nokia and Orange to setup a dedicated private 5G SA network infrastructure on the demo site Concept Grid.

Private Standalone 5G network vs 4G public network

The 5G SA infrastructure provided by Nokia is based on the following components: a 5G Core (5GC), a Base Band Unit (BBU) and a micro RRH AWHQF antenna (in R21B version). The 5G radio cell is configured with 20Mhz of spectrum temporarily allocated by Orange in the 3710 - 3800 MHz segment (N78 band). Tests in 4G configuration are performed over Orange commercial public 4G network. The closest Orange 4G site is approximately at 900 meters.

TAC devices and cellular routers

The TACs used are TPU-1 devices from the manufacturer ZIV in software version 3.5.2. The enclosure includes a motherboard (MWTU), an analog I/O card (IPTU) to command the circuit breakers and an IP transmission card (IPIT) to connect the 2 TPU units using an IP network (here the 5G or 4G network).

The 5G/4G routers connecting TAC systems are Cradlepoint R1900. It enables to operate in 4G, 5G NSA and 5G SA mode and support N78 band spectrum. They are equipped with a Panorama LGMM4-6-60 omnidirectional MIMO 4x4 antenna.

Implementation of the network

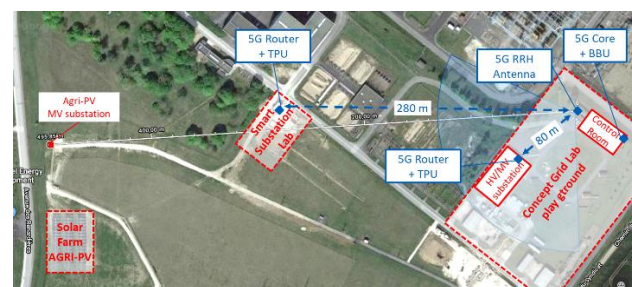


Figure 3 – 5G test environment on EDF R&D site

The first of the two TAC units is installed in the HV/MV station and the second in the MV/LV substation where the PV farm is connected at respectively 80- and 280-meters distance from the 5G cell antenna.

TAC units on both ends are connected with 5G/4G routers. Thus the data connection between the two TAC units includes two 5G/4G hops. HV/MV are more likely to be connected with existing fiber infrastructures than

decentralized production. But, having both ends connected with 5G simplifies TAC deployment and will enable to leverage 5G edge User Plane Function (UPF) connecting 5G users, instead of transiting through a gateway (PDN-GW) between cellular network and fixed network.

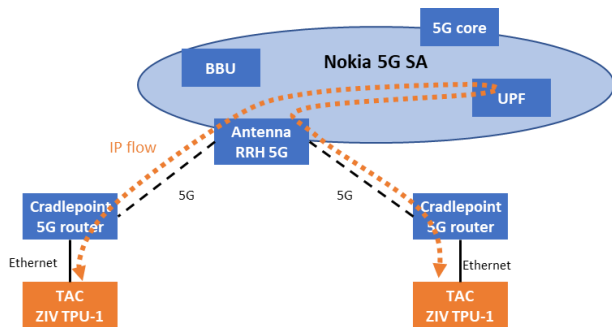


Figure 4 – Cellular connectivity setup

A Generic Routing Encapsulation (GRE) tunnel is setup between the two cellular routers to create a virtual private network (VPN) agnostic of underlying 5G or 4G IP configurations. Cyber security protections such as IPsec VPN or private APN (Access Point Name) will be tested on a later stage.

MEASUREMENT INSTRUMENTATION AND METHODOLOGY

End-to-end measurement on grid system

Measurement instrumentation

To measure the latency between transmission and reception signals, Yokogawa SL1000 acquisition systems were installed in the HV/MV station and the MV/LV substation, both synchronized with Network Time Protocol.

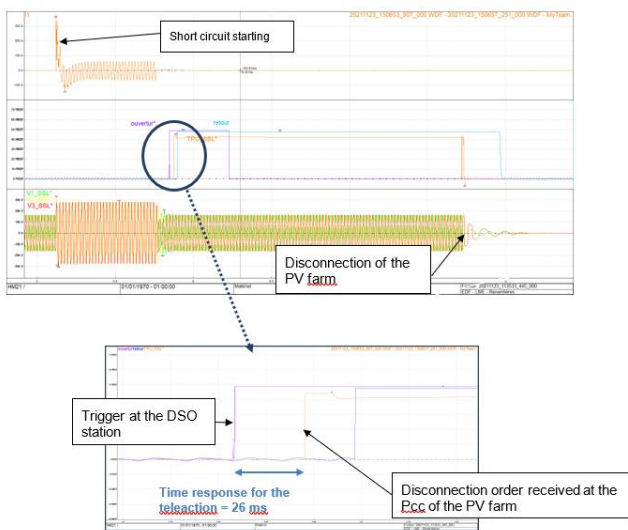


Figure 5 – Results analysis

Measurement analysis

On figure 5, the second graph is the visualisation of the opening of the circuit breaker in purple and the order sent by the 5G network to the PV substation. The order of decoupling is in orange. The requirement from the DSO on the overall latency is then the time delay between the opening of the circuit breaker in purple and the order of decoupling transmitted to the PV station in orange. On the figure, the delay was measured at 26 ms.

Additional measures on communication systems

As TAC devices send and acknowledge IP packets continuously, they provide a permanent monitoring of the performance indicators: latency, jitter (latency variation) and packet-loss on the IP network. Threshold overrun alerts are configured and logged. But the maximum configurable thresholds are 15ms for latency and 1ms for jitter. Such thresholds are not consistent with the use-case requirements. An evolution of the ZIV TPU-1 software should be requested to enable logging of consistent threshold overruns.

Cellular routers were not performing continuous latency measurements. To confirm the end-to-end measurements, occasional measurements and captures were achieved:

- Measurement of the round-trip latency (ping) between the 2 routers and to a reference point on the 5G core
- Speed tests to ensure cellular connectivity provides sufficient bandwidth to support the TAC IP flow.
- IP captures to analyze packet exchanges between TAC units and confirm measurements and correct configuration of TAC devices.

EXPERIMENT RESULTS

Parameter's involved in the demo

During the demonstration, several parameters have been changed to analyse the performances of the teleaction. Both electrical and communication parameters were involved in the sequence.

Electrical parameter

As expected, electrical parameters did not impact the performance of the transmission. Different kinds of fault were performed (phase to ground, phase to phase with different network topologies) without significant deviation on the delay of transmission.

Analog/digital interface settings

TAC devices are constantly replicating the binary signal (+48 or 48V) acquired on the input analog interface of the first unit to the output analog interface of the remote end unit. To achieve a reliable and low latency transmission of this binary command over an IP network, the TAC devices exchange short IP packets with the binary value as

payload, at a high frequency: every K millisecond. K is a configurable setting ranging from 1 to 15 ms.

To avoid unexpected trigger of TAC protection due to error or packet-loss that may occur over IP networks, the remote-end TAC device performs a simple error correction technique on the received bit stream. It analyzes the last N received bits (N is called “window size”) and triggers the output command if and only if P or more bits are equal to 1 (P is called “threshold”). The window size (N) and threshold (P) are configurable settings on TAC units. Recommended settings are a threshold P=3 for a window size of N=5. But the 3 parameters (K, N and P) will be tuned during the experiments as it may impact the latency of the command signal transmission.

Results

Measurement campaigns

Several measurements campaigns were conducted to fulfil the different objectives: validate correct operations for various electrical faults, measure impact of TAC settings on performances and compare 5G and 4G performances.

Dates	Tests performed and key facts
23/11/2021 24/11/2021	15 tests performed in 5G with various types of electrical faults.
25/11/2021	15 tests performed in 5G with various TPU settings, to observe the impact on latency.
26/11/2021	8 tests performed in 4G, but measurements were altered with significant packet loss. The root cause was identified: 4G subscription reached the “fair-use” quota and speed was then limited to 128kbps.
17/02/2022	New test campaign in 4G with no packet loss. 19 tests performed with various TPU settings.

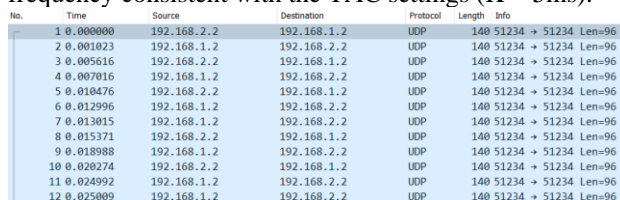
Table 1 – Synthesis of measurement campaigns

Invariance according to the nature of electrical faults

The tests were performed during campaign #1 (on 23 and 24th November 2021) with different types of generated electrical faults. The results show a constant behaviour of the TAC protection and stable performance in terms of latency (one-way). Consequently, to simplify the next test campaigns, only one type of fault will be tested.

Large volume of data

The packet captured on 5G/4G routers (Figure 6) shows the exchange of 140 bytes packets in both directions at a frequency consistent with the TAC settings (K = 5ms).



No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000	192.168.2.2	192.168.1.2	UDP	140	51234 → 51234 Len=96
2	0.001023	192.168.1.2	192.168.2.2	UDP	140	51234 → 51234 Len=96
3	0.005616	192.168.2.2	192.168.1.2	UDP	140	51234 → 51234 Len=96
4	0.007816	192.168.1.2	192.168.2.2	UDP	140	51234 → 51234 Len=96
5	0.018476	192.168.2.2	192.168.1.2	UDP	140	51234 → 51234 Len=96
6	0.012996	192.168.1.2	192.168.2.2	UDP	140	51234 → 51234 Len=96
7	0.013815	192.168.1.2	192.168.2.2	UDP	140	51234 → 51234 Len=96
8	0.015371	192.168.2.2	192.168.1.2	UDP	140	51234 → 51234 Len=96
9	0.018988	192.168.1.2	192.168.2.2	UDP	140	51234 → 51234 Len=96
10	0.028274	192.168.2.2	192.168.1.2	UDP	140	51234 → 51234 Len=96
11	0.024992	192.168.1.2	192.168.2.2	UDP	140	51234 → 51234 Len=96
12	0.025009	192.168.1.2	192.168.2.2	UDP	140	51234 → 51234 Len=96

Figure 6 – Capture of packets between TAC devices

Even with small 140 bytes packets (+24 bytes related to the GRE tunnel), TAC generates a 262 Kbps constant traffic for K=5ms (1.3 Mbit/s for K=1ms). This leads to a volume of data exchanged of 2.8 GB per day, or 85 GB per month. The high frequency exchanges, required to guarantee a reliable and low latency transmission, generate a large volume of data.

It shall be anticipated in the sizing of 5G subscription plans for TAC usage, as it is much larger than usual traffic expected for machine-to-machine type of communications (M2M).

Impact of TAC settings on latency

Several tests were performed during the campaigns in 5G and 4G with various TAC settings. Such settings are noted K (N / P) with K being the frequency of packet emissions in milliseconds, and N & P being respectively the window and threshold of the error code algorithm.

Date	Time	4G or 5G	TPU settings	Latency (ms)
25/11/2021	11h19	5G	5 (3 / 1)	24,7
25/11/2021	11h21	5G	5 (3 / 1)	17,6
25/11/2021	12h24	5G	5 (3 / 1)	27,6
25/11/2021	12h28	5G	5 (3 / 1)	21,6
25/11/2021	12h35	5G	5 (3 / 1)	22,5
25/11/2021	15h12	5G	5 (15 / 9)	39,6
25/11/2021	15h15	5G	5 (15 / 9)	38,7
25/11/2021	15h17	5G	5 (15 / 9)	31,9
25/11/2021	15h21	5G	5 (15 / 9)	35,6
25/11/2021	15h24	5G	5 (15 / 9)	30,5
25/11/2021	15h26	5G	5 (15 / 9)	29,6
25/11/2021	16h09	5G	2 (5 / 3)	28,7
25/11/2021	16h12	5G	2 (5 / 3)	27,6
25/11/2021	16h16	5G	2 (5 / 3)	24,8
17/02/2022	13h33	4G	5 (5 / 3)	46,7
17/02/2022	13h52	4G	5 (5 / 3)	40,7
17/02/2022	14h05	4G	5 (5 / 3)	48,6
17/02/2022	14h15	4G	5 (5 / 3)	46,0
17/02/2022	14h25	4G	5 (5 / 3)	42,4
17/02/2022	14h58	4G	5 (15 / 9)	39,4
17/02/2022	15h06	4G	5 (15 / 9)	42,4
17/02/2022	15h11	4G	5 (15 / 9)	48,0
17/02/2022	15h17	4G	5 (15 / 9)	46,5
17/02/2022	15h23	4G	5 (15 / 9)	51,7
17/02/2022	15h50	4G	15 (5 / 3)	49,6
17/02/2022	15h57	4G	15 (5 / 3)	37,7
17/02/2022	16h06	4G	15 (5 / 3)	39,8
17/02/2022	16h12	4G	15 (5 / 3)	58,1
17/02/2022	16h18	4G	15 (5 / 3)	58,9
17/02/2022	16h43	4G	2 (5 / 3)	35,6
17/02/2022	16h48	4G	2 (5 / 3)	45,2
17/02/2022	16h51	4G	2 (5 / 3)	41,2
17/02/2022	16h55	4G	2 (5 / 3)	40,2

Table 2 – Measurements of campaign 2 (5G) and 3 (4G)

The tests confirmed that K setting (frequency) directly impacts the measured latency (Figure 7). K=5ms is a good compromise as the gain in latency becomes marginal under 5ms, whereas the throughput and exchanged volumes grow exponentially as K is reduced (2.8 GB per day for K=5ms and 7 GB per day for K=2ms).

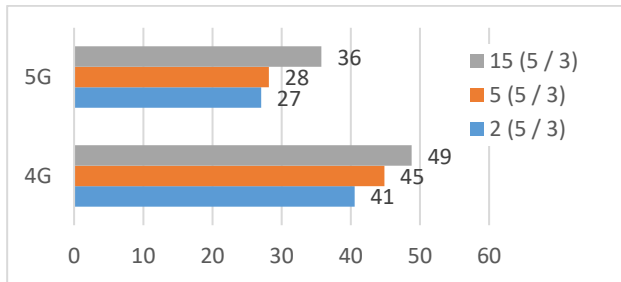


Figure 7 – Average measured latency (ms) for different K settings (frequency)

The tests also confirmed that the recommended settings (N/P) = (5/3) are optimal. A larger window size will increase the latency. A smaller window size led to marginal latency gain and increasing risks to trigger the protection due to an error on IP network transmission.

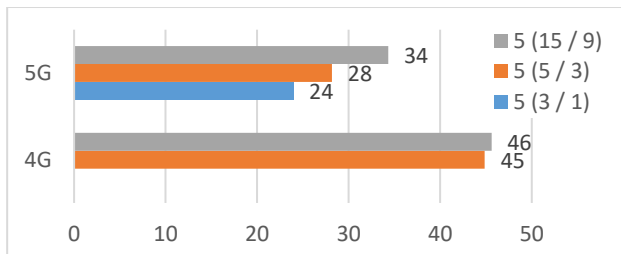


Figure 8 – Average measured latency (ms) for different N / P settings (window and threshold)

Comparison between 4G and 5G performances

With the reference TPU settings $K = 5\text{ms}$ and $(N/P) = 5/3$, the measured latency is on average **28.2 ms with 5G**. This performance is significantly below the 50ms requirements. It is reminded that this one-way delay includes two 5G cellular radio transmission hops. This value is consistent with the latency measured at 14ms between the 5G routers and the 5G core (including only one hop). Moreover, the standard deviation of the latency in 5G is 2.7 ms (confirmed with jitter measurements). That is a good stability of performances.

In comparison, measurements performed on the Orange commercial 4G network, for the same reference TPU setting, show an average transit time of **45ms**, which is 60% higher than 5G, and really close to the 50ms requirements. The jitter measured on 4G was not stable with an average of 10ms. It means that the latency could be above requirements more than 5% of time.

CONCLUSION

The average end-to-end latency measured with 5G is 28ms and allows a comfortable margin compared to the 50ms required for the use-case. It should be noted that the private 5G network infrastructure benefits from convenient radio conditions (proximity of the 5G cell antenna, no other

users on the cell) and on-site 5G core infrastructure.

Nevertheless, the comfortable margin compared to the 50ms requirements, should allow to accommodate with additional delay on a less favorable public 5G network (concurrent access to spectrum, more centralized 5G core infrastructures).

In addition, other evolutions, or optimizations for 5G have not yet been implemented and could help limit the impacts mentioned above, such as prioritization at the radio level, network slicing and decentralized UPF on network edge.

The experiment also confirmed that 4G performances (latency and jitter) are not suitable to meet the 50ms requirements in a constant and reliable way.

PERSPECTIVES

These results are promising and allow Enedis to go a step further before massive roll-out. Enedis wants to confirm the results with tests on a real renewable production site and a public 5G network in 2023. This new validation step should allow to:

- Accumulate results continuously and over a long period of time in a production environment
- Validate these results under "normal" network conditions (commercial 5G network) and radio reception conditions (distance, presence of other subscribers nearby, etc.)

In line with the deployment projects of Orange, this step will be achieved in two stages:

1. Field test on a renewable production site with commercial non-standalone 5G network (5G NSA)
2. Field test with first 5G standalone network (5G SA) pilots enabling the capabilities offered by e.g., network slicing mechanisms.

REFERENCES

- [1] EVE Project, 2021, "Final pilot test and validation", H2020-ICT-17-2018 deliverable 2.5, 83-90