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Decentralized system controlling the phase connection of a single-phase installation

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Abstract. In this paper, a phase switching system working in a fully decentralized and autonomous way is proposed. Thanks to this device, named the Automatic Phase Switching (APS) system, the phase connection of a single-phase installation will change automatically during normal operation in order to reduce adverse effects of single-phase loads and Decentralized Generators (DGs) in a low-voltage distribution network, such as voltage unbalance, neutral current, voltage deviation, and network losses. The paper presents the APS system architecture with the inside algorithm and the required decentralized measurements. A self-learning tool to estimate the network local sensitivity, which is essential in the connection phase calculation algorithm, is proposed too. Then, simulation results are presented, where the impact of the APS system is evaluated in many scenarios (DG insertion rate, customer load curve, number of APS systems, etc.). In the last part, a prototype of this connection phase control system is associated with a real single phase installation and evaluated through a Power Hardware in The Loop (PHIL) real-time simulation.

Keywords: Decentralized control, DG control, distribution network, network sensitivity estimation, PHIL simulation, real time simulation, single phase installation control, Smart Grid.

1. Introduction

In the last fifteen years, renewable energy penetration rate in distribution networks has increased significantly, most of it being low-voltage and single-phase connected distributed generation (DG). Single-phase connections coupled with the random behavior of renewable energy production have led to more and more

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difficulties with respect to network constraints, like the voltage magnitude [1]–[3], voltage unbalance [4], [5], current magnitude [6], and neutral current. In order to increase network capability to receive DG without deteriorating the voltage quality or involving expensive network reinforcements, many control solutions have been considered. Those controls can be focused on building up a decentralized active power flexibility reserve [7], regulating the DG active and reactive power [8], optimizing tap changer utilization [9], and so on. Two different types of approaches can be distinguished: centralized and decentralized solutions. With a centralized solution, controls will be based on measurements of dispersed equipment installed in the distribution network (including smart meters [10]), whereas with a decentralized solution, control works only with local measurements. The Automatic Phase Switching (APS) control system developed in this paper is a decentralized solution that focuses on reducing voltage unbalance and magnitude problems through real-time phase connection optimization of single-phase installation.

In Europe, the low-voltage distribution network is mostly a three-phase four-wire system (the neutral wire is distributed). Most LV customers and DGs are single-phase connected. With the four-wire distribution, the three-phase conductors are present in the electric distribution box of the installation. In this context, the APS control system can be placed between the network and the single-phase installation. If a rural distribution network is considered, an APS system will mainly be useful on magnitude voltage deviation issue. Indeed, in a rural network, the feeder length can be high, which may cause voltage problems, especially with a high renewable-energy penetration rate [11], [12]. By connecting, in real time, the single-phase DG to the most loaded phase, the local voltage deviation will be improved. In an urban context, with short feeders, voltage magnitude is not an ongoing issue; however, voltage unbalance and high neutral current are common problems [13], [14]. The APS system will ensure better phase balancing and reduce neutral current. In both cases, the APS system will improve network losses by reducing energy flows.

In the scientific literature, only a few solutions are proposed to solve the unbalance issue, and the most frequent one is to use a three-phase inverter instead of a single-phase one [15], [16]. With this solution, local voltage unbalance problems can be solved by using suitable control of the inverter, but the investment in a three-phase inverter is much more important, considering that it must be oversized. Indeed, each branch of the three-phase inverter must be sized for the full PV power (instead of one third).

In order to develop a system that can be easily inserted between the network and the single-phase installation, the measurements needed to calculate the real-time best phase connection have to be exclusively available locally. In that way, the system is not intrusive from the point of view of the Distribution System Operator (DSO). Thus, it is not necessary to place any sensors on the grid. In [17]–[19], a phase-switching solution is presented using the measurements of the three-phase currents of the feeder. With this information, the best phase connection can be calculated in function of the local grid current unbalance, but sensors are installed on the main grid. With the APS system, currents in the main line are not needed.

In this paper, the APS control system is presented with a PhotoVoltaic (PV) installation as an example, but it can be used with other production systems, storage, electrical-vehicle (EV) charging stations, and loads with no or little effort.

2. Presentation of System

In the following section, the main parts of the APS system will be presented: the architecture with the hardware switching; the two algorithms, one to calculate the best phase connection in real time and the second one to learn and memorize the grid behavior with switching situations; and the required switching conditions.

A. System Architecture

The APS system hardware part is mainly composed of three controllable switches, one per phase, and protection circuits, to prohibit simultaneous closing of two switches.

In Figure 1, the APS system architecture and its location are presented. Phase connection is achieved by static switches. In parallel with each switch, an RC snubber is used to limit voltage transients. The input measurements needed by the algorithm, like the three-phase voltages, may come from a local smart meter (i.e. Figure 1) or can be included in the APS system itself.

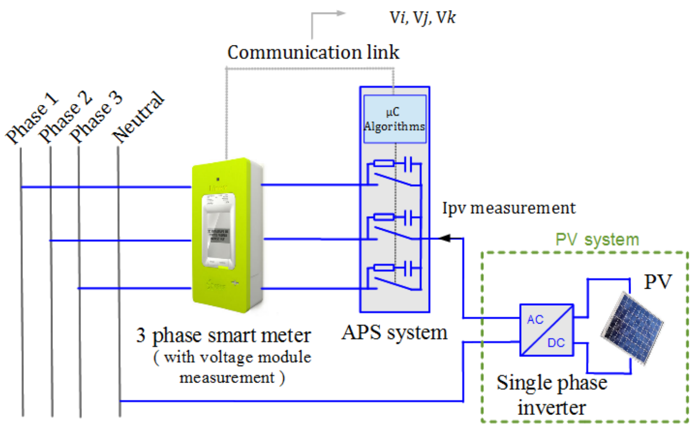

Fig. 1. Location of an APS system associated with a single-phase DG solar installation as an example.

The manufacture of the APS system must be simple and cheap. Indeed, the single-phase inverter and APS system together must be cheaper than an oversized three-phase inverter. Otherwise, a three-phase inverter with the adapted control algorithm for the voltage balance may lead to a better result. The APS system prototype designed and presented in Section IV also demonstrates the low-cost design of the system.

B. Algorithm Architecture

The best real-time phase to connect the single-phase installation is determined by the APS system's internal algorithm. It can be divided into two parts: the phase-switching algorithm and the sensitivity self-learning algorithm. The first one checks whether the switching conditions are true to authorize the connection on a new phase. The second one estimates the network sensitivity after each switching to evaluate the impact of the new connection on the network and to adjust the switching conditions better in the future. In Figure 2, the sequential steps of both algorithms are presented.

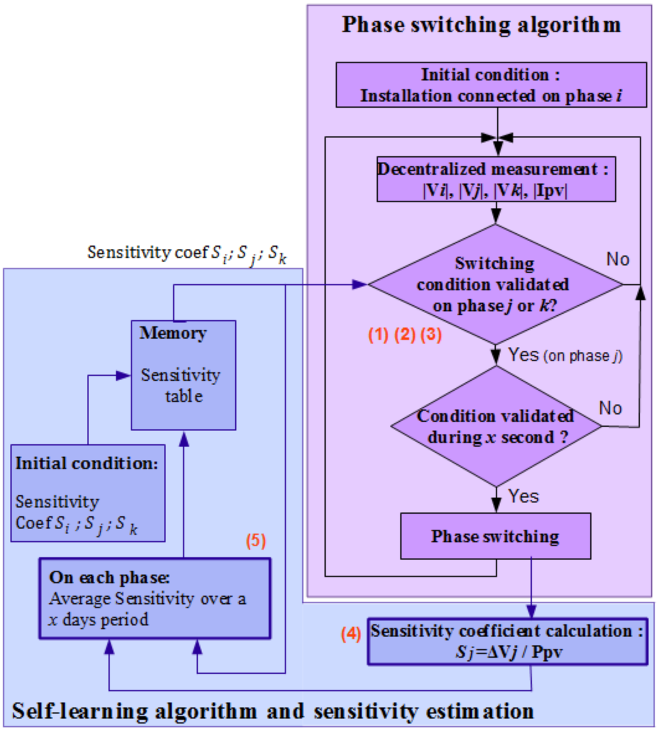

Fig. 2. Phase switching and self-learning algorithms.

C. Validation of Switching Conditions

Switching conditions are true if the three following inequalities are validated (example: switching from phase *i* to phase *j*):

$$\left(V_j + S_{j(V/W)} \cdot P_{pv}\right) \cdot 0.95 < V_i \tag{1}$$

$$V_j < V_k \tag{2}$$

$$P_{pv} > 10\% P_{\max} \tag{3}$$

with:

i, j and k: Three network phases;

V_i: Voltage module on phase i;

S_j: Voltage sensitivity of the j phase to a step of active power;

P_{pv}: PV single-phase installation active power production;

$P_{\max}$: Maximal active power produced by the PV installation.

With inequality (1), the phase j voltage, V_j, is estimated by considering the effect of the single-phase installation if it were to be connected to this phase. Indeed, the sensitivity S_j multiplied by the real time power P_{pv} is the estimate of the phase voltage deviation induced by the installation. A 5% hysteresis is added through the 0.95 constant to avoid repeated and unnecessary switching.

Among the two phases where the installation is not connected, inequality (2) checks whether the evaluated phase (in this case j) has a lower voltage than the last one. If not, it could be more interesting to consider switching to the third phase (in this case k).

The last inequality, (3), avoids useless switching. If the power produced by the installation is lower than 10% of the rated power, switching impacts would be negligible.

D. Sensitivity Estimation

Knowledge of the local network voltage sensitivity is essential in inequality (1). This value is estimated for each phase after each switching with the following equation:

$$S_j = \frac{V_j(t_2) - V_j(t_1)}{P_{pv}} \qquad \left(\frac{Volts}{Watts}\right) \tag{4}$$

with:

$V_j(t_1)$: Voltage magnitude of phase j before connection of the installation to this phase;

$V_j(t_2)$: Voltage magnitude of phase j after connection of the installation to this phase.

Obviously, this calculated sensitivity is an estimation. The real value of the sensitivity changes in function of the network operating point, but this variation is small. Indeed, by simulating load variations in the power system, the maximal "real" sensitivity variation measured (calculated from the Jacobian matrix of a load flow program) is less than 2% for a network load variation from 0 to 100% of the rated power of the feeder.

Another approximation from this measurement concerns the amount of time between t_1 and t_2. With the use of the APS system with solar production, due to the inverter reconnection time needed after a phase modification, the delay before returning to normal condition after switching can take some tens of seconds to a few minutes. During this period, other network loads and productions can change and thus distort the estimation. In this case, the voltage deviation calculated in (4) is not only the result of the switching.

A sliding average value of the past estimates is then used to smooth the impact of these two approximations in the sensitivity calculation:

$$Sensitivity_{coej}\,j = \frac{S_{j_t} + \sum_{n=1}^{Nb_{s_j \in [t-x_{day};t]}} S_{j_n}}{Nb_{s_j \in [t-x_{day};t]} + 1} \tag{5}$$

with:

$Sensitivity_{coej}\,j$: Average value of the past sensitivity estimates for phase *j* during the last x_{day};

S_{j_t} : New sensitivity estimate calculated at *t*;

S_{j_n} : Past sensitivity estimate subscript *n*, calculated between $[t-x_{day};t]$, with x_{day} the chosen sliding average;

$Nb_{s_j \in [t-x_{day};t]}$: Number of sensitivity estimates for phase *j* during the last x_{day}.

The use of a sliding window is guided by the fact that many parameters can evolve over a long period of time, such as the network topology, consumer habits, number of DGs, and so on. Thus, there is no need to consider estimates that are too old.

Before the first sensitivity estimation, a typical value of $-4.5 \cdot 10^{-4}$ V/W is used for each phase. This value comes from the average sensitivity calculation at different nodes of many feeders with the Jacobian matrix. Of course this initialization value can be far from the real value, but after some commutations, new values will be used.

3. Non-Real-Time Simulation

Thanks to the flexibility of simulations, the APS system is tested in many cases in order to evaluate its benefits in a low-voltage network. The results are focused on voltage variation, line and neutral currents, voltage unbalance and losses regarding the network, and number of switching operations per day with respect to the APS system.

A. Study case

The APS system has been evaluated on the following low-voltage feeder extracted from a real French network.

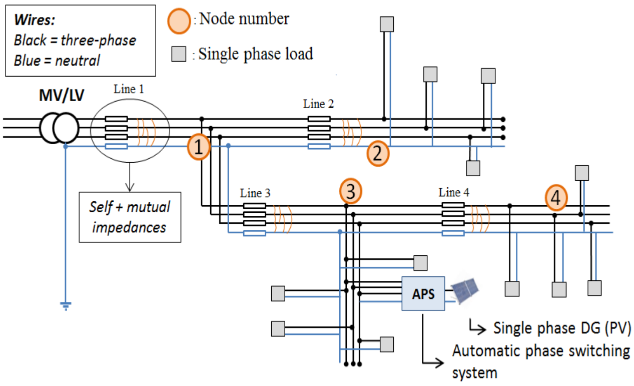

Fig. 3. Low voltage feeder model for APS system evaluation. At node 3 is an example of an APS system associated with a PV installation.

The considered feeder is a three-phase network with distributed neutral. It is an urban network in a residential area, with a total length of 1.3 km, supplying 12 single-phase consumers. All the conductors are underground and the mutual inductances of the cables have been taken into account in the model. Cable data are presented in Table 1.

Table 1. Feeder information

Line number	**1**	**2**	**3**	**4**
Length (m)	49	573	237	463
Phase/Neutral section (mm²)	150/70	70/50	70/50	70/50
Material	Aluminium	Aluminium	Aluminium	Aluminium
Phase/Neutral impedance (Ω/km)	0.206 + j*0.76 0.443 + j*0.78	0.443 + j*0.78 0.641 + j*0.8	0.443 + j*0.78 0.641 + j*0.8	0.443 + j*0.78 0.641 + j*0.8
Maximal permissible current (A)	324 / 150	195 / 100	195 / 100	195 / 100

From a database of real active and reactive residential consumption curves, a random draw is performed to associate a curve to each consumer of the modeled network. At the same time, three PV installations are randomly placed at the buses of the feeder with one PV system per bus. The PV production curve is obtained from real measurements and the same curve is used for the three installations. Then, the simulation is run twice, the first time with a classic connection of PV installations and the second time using the APS system (example result given in Section B below). This is done 125 times in order to obtain realistic results from the statistical point of view (Section C). The considered PV systems have a maximal power of 6 kWp

B. Results on the Advantage of the APS system in a 24-hour Simulation

Before the presentation of statistical results, an example of the impact of the APS system on the local voltage and voltage unbalance is presented.

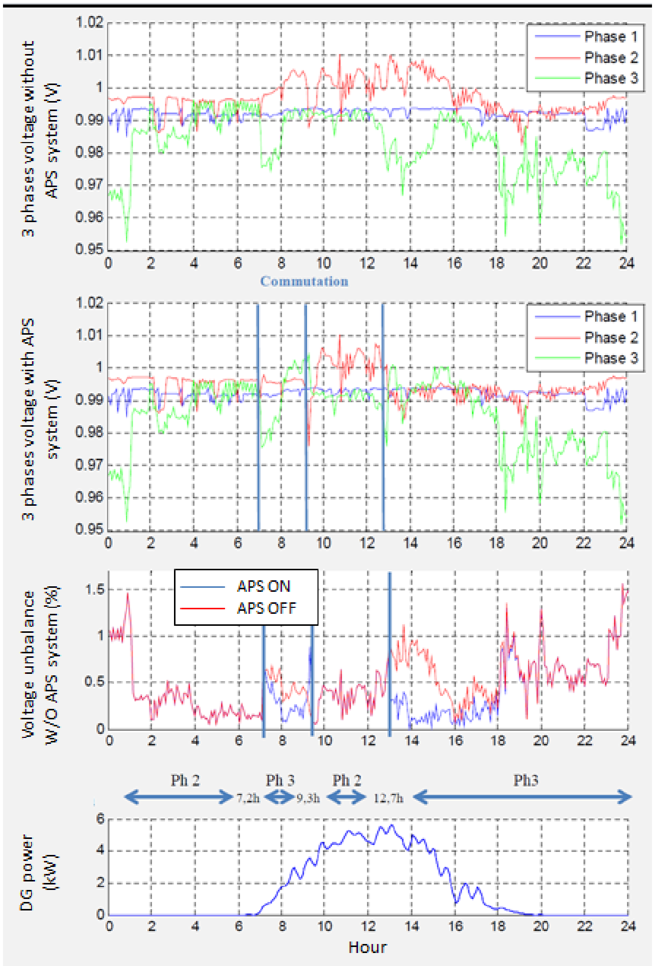

Fig. 4. Example of impact of APS system on local variables.

Figure 4 is divided into four parts. In the first one, the evolution of the three-phase voltage magnitude (in p.u.) at the PV connection point during a full day is shown. In this case, there is no APS system and the PV is connected to phase 2. In the second graph, the APS system is added to the PV system. In this example, three switching operations have been done during the day. During the PV production time (i.e. between 7 am and 6 pm), thanks to the APS system, the magnitude of voltage variations is reduced.

The third part of Figure 4 presents the daily evolution of the voltage unbalance with and without the APS system. The voltage unbalance is defined with a Fortescue

transformation [20] by the ratio of negative and positive sequences of voltage magnitude at the considered three-phase point of the grid. According to European standards, this ratio has to be kept under 2%. By connecting the PV installation to the most loaded phase over time, the unbalance voltage can be improved. Obviously, when an APS system is associated to a solar panel installation without storage, problems during evening consumption peaks cannot be solved.
The last graph presents the PV power injected during the full day.

C. Statistical Results

Results from the 125 simulations computed with the presented network are presented. First, special attention is paid to the number of switchings per day. Indeed, the hysteresis parameter in inequality (1), which is fixed at 0.95, strongly influences the number of switchings. Empirical experience has shown that a high number of switchings (more than 6 or 8) does not improve the impact of the APS system (90% of simulations with more than six commutations are among the least profitable 50% in terms of reduction of losses). However, each switching involves production losses, due to the inverter reconnection time. So, the number of switching operations has to be controlled. The switching number repartition in the 125 simulations is presented in Figure 5. For three PV installations running on the feeder (nodes 2, 3, and 4), the average number of switchings per day is 4.2. The number of switchings of an installation is also strongly influenced by its distance from the transformer. With an installation close to the transformer, the number of switchings is small (because voltage variations are smaller). This number reaches 0.3 on average for the closest bus and increases to 9 for the farthest one. With the three PV installations on the feeder, statistically, one PV is connected to each phase 49% of the time, two PVs are connected to the same phase 48% of the time, and the three PVs are connected to the same phase only 3% of the time. That means that even if consumers have been correctly distributed to the phases, which is the case in these simulations, a phase balancing connection of PV installations is the optimal solution only 50% of the time.
In the second part of Figure 5, the distribution of the gain of active losses is presented. For 94.4% of the simulation, the APS systems generate a loss reduction, with an average gain of 13.6%. The results are dispersed and strongly dependent on customers' load curves. Indeed, with a very constant consumption by customers, the usefulness of the APS system is low.

Regarding the unbalance, the APS system is more effective at the farthest nodes. On the full feeder, 48% of the unbalanced points which were higher than 2% during the simulation with the APS system off have been solved. The voltage unbalance moves from 0.61 to 0.56%.

Thanks to this statistical study, the APS system has been evaluated in many scenarios. In order to validate these results, a real-time simulation has been carried out in the following section: a real solar inverter is connected to an APS prototype and the results of real-time and non-real-time (NRT) simulations have been compared.

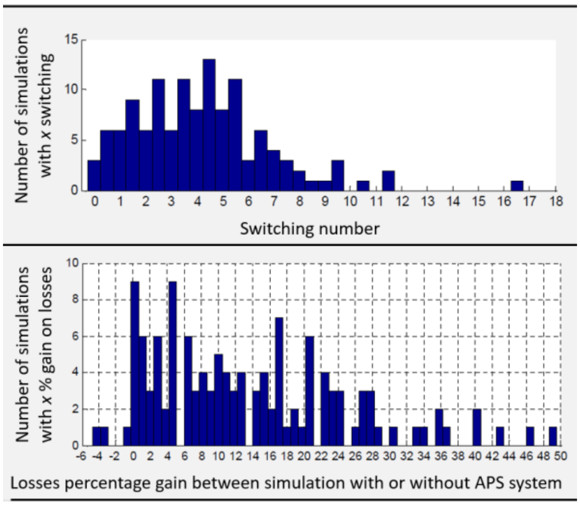

Fig. 5. Switching repartition of 125 random simulations

4. Real-Time Simulation Results

In this last part, a PHIL real-time simulation is presented. First, the platform architecture needed to evaluate the APS system is detailed, then the APS prototype is presented, and finally, the real-time simulation results are discussed.

A. PHIL Simulation Architecture and Operation

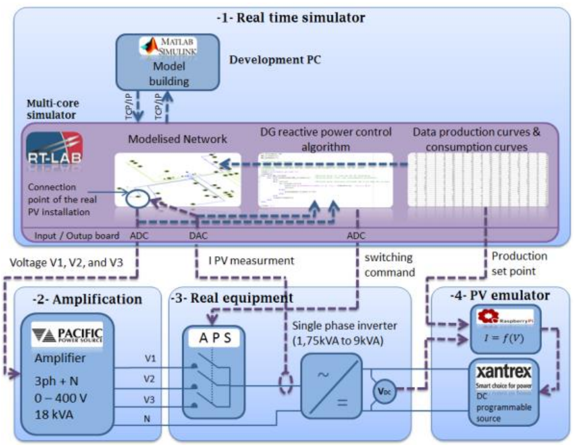

Fig. 6. Architecture PHIL simulation.

In Figure 6, the architecture of the PHIL simulation is presented and can be divided into four parts: (1) The real-time digital multi-core simulator: This is the main component of the simulation. The LV network is modelled inside. A specified point of the network is selected to connect the real PV installation. The voltage values of the three phases at this point are converted into an analog signal and are sent by the output card. (2) Amplification: The amplifier creates a three-phase system according to the magnitudes and phases communicated by the simulator. (3) Real equipment: A real solar inverter and the APS prototype (presented in the next part) are connected to the amplifier output. (4) PV emulator: A DC programmable source is used to produce DC current in function of the input PV curve i = f(V), which is stored on a nano-computer.

B. APS Prototype

In order to validate the APS system in the PHIL simulation, a prototype has been built. Three static switches are used to connect and disconnect the installation to a phase. To prohibit short circuits in the case of simultaneous operation of two switches (abnormal situation), protections have been added. Figure 7 presents the main components of the prototype.

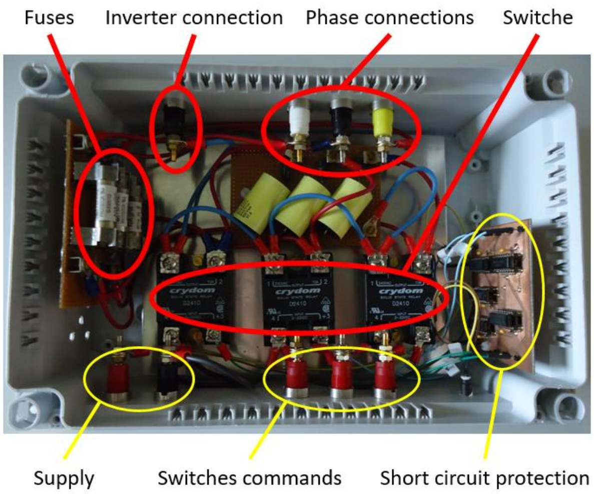

Fig. 7. The APS prototype.

C. PHIL Simulation Result

The purpose of the PHIL simulation is multiple: to observe the inverter performance with real-time phase switching, to measure the inverter reconnection time after a switching operation, and to validate the results of the NRT simulations with the prototype.

1) Inverter Response and Reconnection time

To evaluate the impact of phase switching on the inverters' production, the APS prototype will be successively associated to three different inverters of different brands: inverter *a*: 9 kVA; inverter *b*: 1.8 kVA; and inverter *c:* 1.75 kVA.

At the moment of switching, all three inverters respond in the same way: phase switching is considered as a network fault and the inverters stop their production. When the connection to a new phase is done by the APS prototype, a time delay is needed to enable the inverters to produce again. During this period, the inverters check the network compliance. The reconnection time is presented in Table 2.

Table 2. Inverter reconnection time after phase switching

Inverter	Power = 1 kW	Power = 2.5 kW
a: 9 kVA	3–3 .5 minutes	1–8 minutes
b: 1.8 kVA	1–1.5 minutes	
c: 1.75 kVA	Around 30 secondes	

As can be seen in Table 2, the reconnection times vary considerably from one inverter to another. During this period, no PV production is possible. For this reason, it is better to associate the APS system with a fast inverter, if possible, and to limit the number of switchings per day.

2) Comparison of PHIL and NRT Simulations

To achieve this comparison, the same input data for customers' load curves and the PV production curve are used in both simulations and the results are compared. In the PHIL simulation, the inverter *a* is used. The evolution of the voltage unbalance during the 12 hours of PV production and the switching operations are presented in Figure 8.

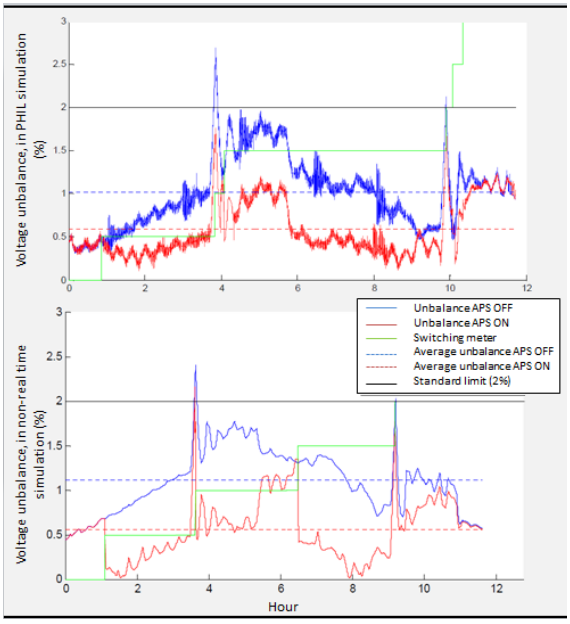

Fig. 8. Evolution of voltage unbalance with APS system OFF and ON in NRT and PHIL simulations.

As can be seen in Figure 8, in both cases, the APS system reduces the average voltage unbalance by a similar amount (–0.4% in the PHIL simulation and –0.5%

in the NRT simulation). Switching times are slightly different because of the measurement noise and the reconnection time present in the PHIL simulation. But in both cases, the switching generates an interesting reduction in the voltage unbalance.

5. Conclusion

A fully decentralized phase-control solution has been proposed and investigated experimentally with a single-phase PV installation on a low voltage feeder. This experimentation has been performed first with the NRT simulation in order to assess the performance of the APS system in many scenarios. Second, a PHIL simulation has been carried out with the connection of the APS system to an emulation of PV panels through a real inverter.

The results presented show that the APS system helps reduce local voltage unbalance, variation of the voltage magnitude, and network losses. This increases the network's capacity to integrate new DGs without involving expensive investments for the DSO. The APS system is not intrusive as it works with local measurements only and does not need a communication system, except with the local smart meter if its measurements are used.

The main difficulty, highlighted by the real-time simulation, concerns the inverter reconnection time after a switching operation. For this reason, the primary perspective for further works is to develop an upgraded solution where the APS communicates with the inverter in order to restart the production faster after switching.

Another solution is to work on a hardware solution in order to be able to change the phase connection without switching off the power. This opens the way for load switching phase. If the switching operation does not involve a temporary power interruption, the APS system can easily be associated with EV charging stations and buildings.

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