Benefits of On-Load Tap Changers Coordinated Operation for Voltage Control in Low Voltage Grids with High Photovoltaic Penetration

Alessandro Ciocia, Gianfranco Chicco and Filippo Spertino
Dipartimento Energia "Galileo Ferraris"
Politecnico di Torino
Torino, Italy
{alessandro.ciocia,gianfranco.chicco,filippo.spertino}@polito.it

***Abstract*—The transformers that connect the Medium Voltage (MV) grid with the Low Voltage (LV) system are classically equipped with tap changers with tap positions variable only at no load. The evolution of the technologies and the increasing needs of controlling the voltage profile in the LV networks require better control capabilities. The use of MV/LV transformers with On Load Tap Changers (OLTCs) is increasing, to provide further control capabilities in LV grids with high penetration of distributed generation. In this paper, centralised voltage control is evaluated by simulating the operation of an OLTC installed inside the MV/LV transformer substation. The goal is to stabilise the voltage at the LV bus of the transformer. It is supposed that the OLTC does not communicate with other devices in the grid; thus, it does not know the voltage levels at the other nodes. At the same time, the distributed PV inverters control the voltage in their grid connection points without any information about the other nodes. The expected benefits of exploiting OLTCs in LV grids with high photovoltaic (PV) penetration are determined through indicators that assess the voltage deviations with energy flows, the global overvoltage or undervoltage persistence, and the overvoltage or undervoltage duration. The results show that the use of an OLTC can help the mitigation of voltage fluctuations, especially limiting the undervoltages. The effectiveness strongly depends on the control parameters, especially the maximum number of daily taps.**

I. INTRODUCTION

A. *Motivation and Background*

The evolution of electric distribution systems in the present *smart grid* paradigm requires new solutions for the modernization of the distribution networks, in order to respond to technical needs and improve the distribution system operation. One of the technical needs is voltage control in Medium Voltage (MV) or Low Voltage (LV) distribution networks. With the diffusion of distributed energy resources (DER), that can exploit renewable energy sources (RES), the voltages in these networks have become more variable, sometimes reaching their upper and/or lower limits in different periods of the day.

In the traditional distribution systems (without DER), the active power *always* flows from substations to loads, while the reactive power *typically* (i.e., in most cases) flows from substations to loads, with the possible exception of the possible over-compensation of reactive power from power factor compensation capacitors (in this case the reactive power flows in the reverse way on the line that connects the overcompensated load). In today's distribution systems with DER, a high local production of active (and, in case, reactive) power could revert the power flow in more branches, up to causing reverse power flows at the supply substation at some points in time [1,2].

In general, the presence of DER has extended the ranges of variation of the voltages in the networks, introducing the “new” issue of reaching voltages higher than the limits for normal conditions at some network nodes. This fact calls for the deployment of additional control capabilities to guarantee a reasonable voltage profile. The solutions used consist of centralized and decentralized voltage control. Centralised controls include the use of devices like transformers equipped with tap changers, capacitor banks, Static Var Compensators (SVCs), or D-STATCOM (static synchronous compensator for distribution systems) [3,4]. Decentralised controls are used along the network (e.g., step voltage regulators - SVRs), or at the local side (such as localised capacitor banks and inverters for DER grid connection). Sometimes, when the DER is connected to a large-scale distribution system, it is preferred that the DER remains active in case of a network fault, in order to contribute to the fault ride-through capability [5]. At the point of common coupling (e.g., the network node seen as the supply point of the network user), the control devices may also provide benefits for different waveform quality issues, such as voltage variation, harmonic content, frequency, unbalance, and flicker [6]. In extreme cases, important fluctuations of the parameters that represent the waveform quality can cause the grid interface systems of the plants to disconnect the local generators. A solution to these problems would be the coordination among different technologies for voltage control. However, this coordination could require the deployment of communication systems, with additional costs and the need for synchronisation of the control devices [7,8]. Yet, the control devices are generally owned and managed by different entities, making their coordination difficult. The prescriptions for imposing directions for coordinated control have to be issued by the national legislation, regulatory bodies and authorities.

This paper focuses on MV/LV transformers with On Load Tap Changers (OLTCs). This technical solution is classically used in substation transformers that connect the High Voltage (HV) network to the MV grid. The traditional connection between MV and LV grids consists of using MV/LV transformers with off-load tap changers, in which the tap position has to be chosen a priori in order to guarantee a reasonable voltage profile in the LV network.

B. *Relevant Literature*

With the evolution of the technologies, in recent years some MV/LV transformers have been replaced with new devices equipped with an OLTC, to better integrate RES in the grid [9]. The MV/LV transformer with OLTC is able to provide better voltage control capabilities, due to the tap changes that may occur in time by following the evolution of generation and load patterns. In some cases, retrofitting of existing MV/LV transformers has been considered [10].

The use of OLTCs in MV/LV transformers allows approaching practical problems, such as voltage control or power losses mitigation in the grid with more available control resources. Nevertheless, the OLTC contains movable components, inside which electric arcs occur during operation. These electric arcs cause further degradation of the materials and shorter service life. Accurate diagnostics techniques have been recently proposed to identify different mechanical faults [11,12] or to analyse vibrations and arcing signals at the same time in a condition monitoring system [13].

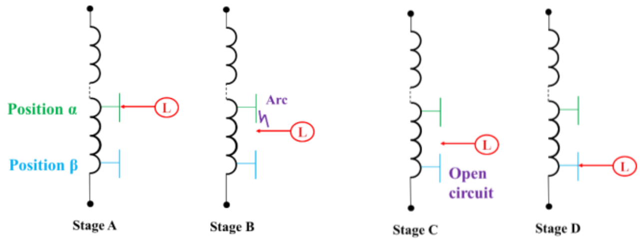

Fig. 1. Operation principle of an On-Load Tap Changer, represented as an auto-transformer.

The computation tools developed have been mainly applied to MV networks. The discrete nature of the OLTCs introduces some computational issues, with the need to use integer variables. The computation methods are continuously refined to include easier ways to deal with these integer variables. Recent developments are described in [14] with a mixed-integer second-order cone programming version of the distribution optimal power flow. OLTCs with discrete tap changes are used in [15] within a hierarchical distributed voltage optimisation method. A two-objective voltage control optimisation is solved in [16] by considering the network energy losses and the frequency of tap changes as conflicting objectives.

Emergent studies are considering OLTC applications in LV networks with DERs. Two control methods for OLTCs are proposed in [17] to mitigate the voltage issues with a low number of tap changes. Hovewer, these methods are less efficient in addressing thermal overloads, especially for high DER penetrations.

C. *Contributions and Organization*

In this paper, centralised voltage control is evaluated by simulating the operation of an OLTC installed inside the MV/LV transformer substation. The goal is to stabilise the voltage at the LV bus of the transformer. It is supposed that the OLTC does not communicate with other devices in the grid; thus, it does not know the voltage levels at the other nodes. At the same time, the distributed PV inverters control the voltage in their connection points to the grid without any kind of information about the other nodes. The main contribution of this paper is a procedure to assess the effectiveness of OLTC operation for MV/LV transformers in grids with high DER diffusion. Losses and voltage issues in the LV network with or without OLTC operation are assessed by using existing and two new indicators.

The next sections of this paper are organized as follows. Section II describes the operation principle of an OLTC, provides information about the tap changing process for a mechanical OLTC, and gives indications about possible control methods. Section III describes the case study, in which the use of an OLTC to control voltage in LV grids is evaluated. Another case assessed includes the use of OLTC for centralised control actions, and PV inverters that contribute to local control independently of the OLTC. The last section contains the conclusions.

II. OLTC OPERATION AND CONTROL

A. *Operation principle of an OLTC*

On load tap changers are installed at the primary side of the transformer to vary the voltage at the transformer output without interrupting the power supply. To understand which technical issues are involved in this operation, the voltage variation process is shown in Fig. 1. For sake of simplicity, the OLTC is drawn as an auto-transformer. The voltage change starts with stage “A”: the loads (letter “L”) are supplied and it is required to increase the voltage level. Without service interruption, the movement of moving parts causes the generation of an electric arc (stage “B”).

In the disconnection from the first position (α), the system elements are subject to strong electrodynamic and thermal stresses. Furthermore, when the arc is extinguished, there is a time interval in which the load is not supplied, as shown in stage “C”. After the tap changing process has been completed, the final position is represented in stage “D”.

It is necessary to use devices able to vary the voltage at the transformer terminals without reducing the useful life of the components. The types of OLTCs that achieve this goal are based on two main types of components, namely, mechanical devices and power electronics devices (outlined at the end of the section). The mechanical OLTC is equipped with resistive auxiliary elements to limit the problems related to the electric arc, which are properly sized to limit the thermal losses. The two main elements of the mechanical OLTC are switches, represented in Fig. 2, where the sequence of the tap changing process is shown. The main contacts of the OLTC are labelled with the letters “a” and “d”, respectively. The auxiliary contacts, indicated with “b” and “c”, are connected to the main contacts by the resistors “R_1” and “R_2”, respectively. The auxiliary contacts are necessary to guarantee the continuity of the supply during the tap change. On the other hand, “a” and “d”, are the main connections of the selectors. By varying the number of windings, these main connectors allow the regulation of the output voltage.

According to Fig. 2, the tap changing process can be described by the following stages:

- Stage α: The current runs through “a” and “r” terminals, while the line connected to the “d” is not involved.
- Stage β: The line connected to the “d” terminal is not involved; it is possible to switch from “s” to “q”.
- Stage γ: the selector starts moving towards the terminal “d”. The auxiliary terminal “b” and the resistance connected to it are involved in the power transfer.
- Stage δ: the current necessary to supply the load flows entirely through the auxiliary terminals, forming a mesh. A current is generated between the auxiliary terminals, whose intensity depends on the resistive elements.
- Stage ε: the contact “b” is opened and the current passes entirely between the terminal “c” and the terminal “q”.
- Stage ζ: The current flows between the terminal “d” and the terminal “q”; thus, the other line of the selector is unpowered and ready to assume another position.

The operations described above have been indicated as a linear movement along the terminals at the right-hand side. However, in practice the movement is rotational. During

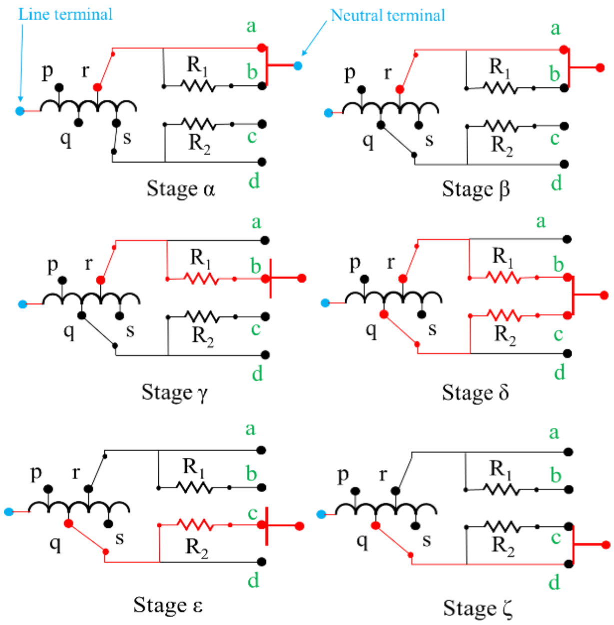

Fig. 2. Sequence of the tap changing process in a mechanical OLTC.

the transition, the voltage amplitude assumes an intermediate value and there is a loss on the auxiliary contacts due to the resistors "R_1" and "R_2" (from stage γ to stage ε).

B. *Limitations for OLTC operation*

Despite the technical measures to reduce arcs in mechanical OLTC, this device has considerable limitations. The following are some issues:

- Arc striking during switching: when the conduction is established or interrupted, the current generates an electric arc at the contacts of the selector. This involves the introduction of impurities into the insulating oil in which the selector is immersed and the wear of the contacts.
- High maintenance costs: insulating oil, contacts and mechanical elements must be periodically tested to verify their functionality. This need is even more stringent due to the wear and tear caused by the arc in the normal operation.
- Modest switching speed: this aspect is closely linked to the use of mechanical components for switching and the time necessary to accumulate enough energy to complete the operation.
- High losses related to switching: since the power passing through these devices is very high, it is necessary to use resistors of modest value so as not to increase the magnitude of losses related to thermal dissipation. From this point of view, electrical contacts are critical: in fact, the local increase in temperature can lead to uncontrolled variation in resistance, which is the main cause of malfunctioning.

In order to overcome the limitations of the mechanical OLTC, semiconductor switches can be used [18,19]. The devices that derive from semiconductor switches can be divided into two categories: Electronically Assisted OLTC (Hybrid OLTC) and Full Electronic OLTC (Solid-State OLTC). This first group includes all those devices in which semiconductor switches are used with the mechanical ones to limit the problems related to the electric arc triggering. In the second group, semiconductor switches replace all the mechanical devices. The total absence of moving parts means reduced maintenance costs and increased operating speeds. Nevertheless, the disadvantages of this technology consist of higher voltage drops with respect to mechanical switches and increased cost of the components.

C. *Control logic of OLTC operation*

The control of an OLTC is based on important physical quantities, briefly described below:

- Voltage variation between two tap positions ΔV_{tap}: this quantity represents the voltage variation (in module) between two adjacent tap positions. For the most widespread components, ΔV_{tap} is generally between 0.8% and 2.5% of the rated voltage of the transformer [20]. The step considered here is 0.0125 p.u. (1.25%).

- Number of selectable voltage levels n: corresponds to the number of available tap positions. The voltage levels implemented are symmetrical with respect to the central position that represents 1 p.u.
- Target voltage V_{trg}: it is the voltage level goal that the control aims to achieve at the node where the voltage is measured. In the present work, it is measured at the node where the transformer is installed, because there is no communication system with other nodes of the grid. In a traditional control, without high penetration of DER, it is typically set to a value above 1 p.u. to compensate for the voltage drops between the power supply node and the network nodes (Line Drop Compensation). In the presence of a significant amount of DER, voltage rises may occur in the network nodes, and setting the target voltage above 1 p.u. is no longer justified.
- Voltage control dead-band (DB): control logics require the comparison between the measured voltage at the observed node and the target voltage V_{trg}. Since the variator can vary the voltage in a discrete way (ΔV_{tap}), a defined dead-band of non-regulation does exist. This value corresponds to half the voltage variation between two tap positions, $DB = \Delta V_{tap}/2$.
- Voltage violation time (t_{viol}): in some control logics, the maximum time for which a voltage violation is considered acceptable is introduced. When this time is exceeded, a specific action is performed, for example, the tap change. In [9], t_{viol} represents the theoretical time for which the maximum overvoltage is accepted. For example, if the maximum overvoltage is 1.1 p.u. and the voltage violation time is $t_{viol} = 10$ min, it is theoretically accepted that the voltage may be at most constant and equal to the maximum acceptable value 1.1 p.u. for ten minutes (or less). In real cases, the voltage does not have to reach this condition for a so long period of time. This value is used as a parameter to setup an integrative controller. More details are presented in the next paragraphs.

Starting from these parameters, different control algorithms can be developed. In the present work, a proportional-integrative controller is used for the OLTC [9,21]. The analysis is carried out with a time step Δt sufficiently long to assume steady-state conditions. In this paper, the time step is one minute. At the beginning of each time step, the deviation between the voltage at the connection point of the transformer V_{tr} and the target voltage V_{trg} is evaluated. The convenience or varying the transformation ratio is evaluated taking into account only the cases with considerable overvoltages or undervoltages. Thus, a counter $A(t + \Delta t) = A(t) + B(t)$ is updated only when the voltage deviation is outside the dead-band DB. If an *overvoltage* occurs with $|V_{tr} - V_{trg}| > DB$ and the counter is activated, the increment $B(t)$ is calculated as:

$$B(t) = \frac{2(|V_{tr} - V_{trg}|)}{t_{\text{viol}} \cdot DB} \cdot \Delta t \qquad (1)$$

where Δt is the time step between two simulations, expressed in seconds.

Likewise, in case of *undervoltages*, if $|V_{tr} - V_{trg}| > DB$ the counter $A(t)$ is decreased as follows:

$$A(t) = -\frac{2(|V_{tr} - V_{trg}|)}{t_{\mathrm{viol}} \cdot DB} \cdot \Delta t \qquad (2)$$

Finally, when $A(t+\Delta t) > 1$ (overvoltage), the tap position is *increased* to reduce voltage. On the contrary, if $A(t+\Delta t) < -1$, the tap position is *decreased* to increase voltage. After the tap change, the counter is reset and the procedure restarts. In addition, if there is an extreme voltage variation, i.e., the voltage exceeds the range 0.9–1.1 p.u., the tap change is immediately activated.

The operation of the proportional-integrative controller is strictly dependent on the value of the parameter t_{viol}. To understand which t_{viol} gives the best compromise between performance in voltage control and OLTC maintenance costs, it is necessary to perform simulations with different values of t_{viol}.

The graph in Fig. 3 shows the evolution of the number of tap changes during a week, as a function of the parameter t_{viol}. This trend is based on simulations performed for the case study presented in the next section. Only the parameter t_{viol} varies, when all the other conditions and parameters do not change. Supposing to keep low the number of tap changes per day and the consequent maintenance of the OLTC, it is considered a limit of 2–3 tap changes per day (about 20 per week). Thus, t_{viol} is considered in the present work equal to 10 minutes.

III. Simulation of the Operation of an OLTC in a LV Grid with High PV Penetration

The main goals of the OLTC, regardless of the technology used, are the continuity of the power supply during the tap changing process, and the reduction of electric arcs. Regarding electric arcs, they cause further degradation of the materials associated with the winding or their insulation, meaning a shorter service life of the tap changing mechanism. For this reason, in addition to the improvement of materials and components to reduce arcs intensity, it is important to reduce the number of arcs, that is, to keep the number of tap changes low [22]. This is an interesting challenge, in particular when the voltage should be frequently controlled, such as in case of LV grids with high DER penetration [23]. In some cases, new logics have been proposed to integrate the operation of centralized systems, as an OLTC, with distributed devices [24,25]. In fact, the information about the state of the grid could permit a performance increase; nevertheless, it would require a wide communication system. Obviously, it is a not practical solution to monitor all the loads in LV grids, because it would require too high investments. Thus, this option is not considered in this paper.

A. *Description of the case study*

In order to simulate the operation of an OLTC in a LV grid with high PV penetration, it is selected a case study, consisting of an IEEE LV grid [26]. The network consists of 22 nodes, in which 3 PV generators (starting from the beginning of the line, the sizes are 70, 35, and 75 kW, respectively) are installed as shown in Fig. 4. It represents a case of residential area with small commercial activities (e.g., a small supermarket, a farm, a shop). The system has grounded neutral and all the lines are three-pole underground cables. In this case, the lines between the worst connection point (node #19, corresponding to the connection point of the farthest PV system from the transformer) and the LV bus of the transformer have total resistance 156 mΩ, reactance 27 mΩ, and susceptance $2.9\cdot10^{-5}$ S. Regarding the transformer, originally it was not equipped with devices for voltage control: the voltage was seasonally changed by acting on the off-load tap changer. There is a three-phase transformer 20kV/400V with rated power $S_{\text{rated,tr}} = 250$ kVA and rated current $I_n = 361$ A. The short-circuit impedance is $Z_{sc} \approx 38$ mΩ, and the short circuit power at 75°C is $P_{SC\_75°C} = 3.4$ kW. For the sake of simplicity, the classical pi-model is used to represent the transformer as a double bipole for power flow calculations, in which the iron losses are neglected [27]. The series impedance is calculated starting from the transformer datasheets. The value of the OLTC tap is included in the longitudinal and shunt parameters of the pi-model. Each time the tap is changed, the transformer parameters are changed, and the new pi-model is incorporated in the representation of the electrical distribution system used for power flow calculations.

Simulations are performed with the assumption of the new installation of an OLTC, with the consequent replacement of the transformer with a new one with the same electrical characteristic.

The tap changer has a voltage step equal to 1.25% of the nominal value and seven tap positions (-3,…,0,…,+3): the lowest position (-3) corresponds to the output voltage 0.9625 p.u. when the transformer is supplied at its rated primary voltage. The consumption and generation profiles are taken from accurate measurement of real aggregation of loads and generation systems. The data acquisition system used to obtain the PVprofiles is described in [26].

B. *Power Flow Solution*

The power flow calculation determines all the voltage values, in magnitude and phase, in the nodes of the analysed grid. The radial grid under analysis has a symmetrical and balanced configuration[1]. The loads in the simulation correspond to the aggregation of different apartments and/or offices, i.e., the loads are the connection points of entire apartment and office buildings. Thus, the simulation is performed considering an equivalent single-phase model and is limited to the use of the positive sequence. Therefore, the Backward Forward Sweep technique (BFS) is used. BFS is an iterative procedure, stopped when the voltage variation at any node in two successive iterations is lower than a threshold ε defined a priori. In this case, the voltages converge to the final values.

[1] In general, the unbalance can be particularly high in the terminal parts of the LV feeders, while at the point in which the OLTC is installed the unbalance could be mitigated by the diversity of the loads and generations in the downstream network.

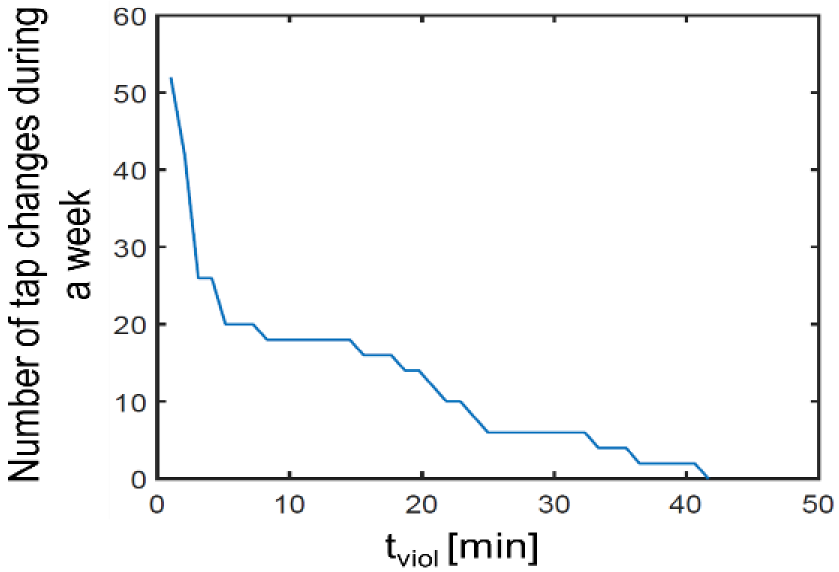

Fig. 3. Number of tap changes in a week.

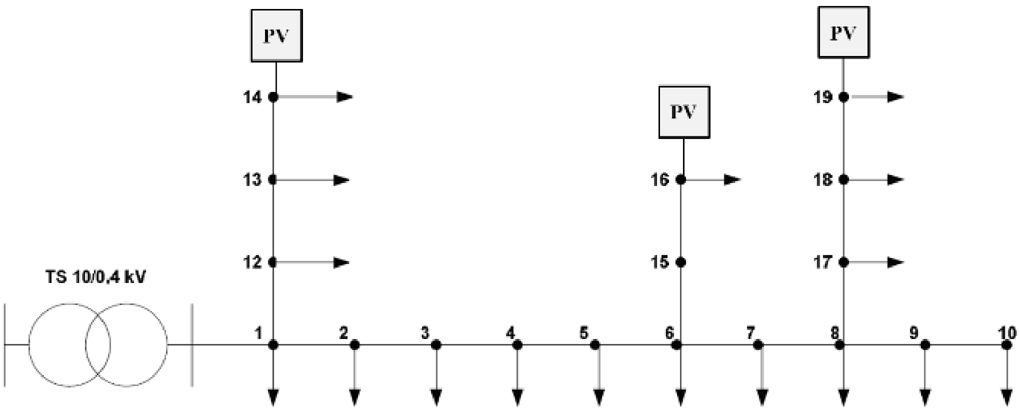

Fig. 4. LV grid under study.

C. *Voltage indicators*

Voltage indicators are used to compare different solution for voltage control. They are based on the voltage data calculated in each node *k* of the network at each time step *t*. The following indicators are considered [9]:

- Voltage Deviations with Energy Flows (*VDEF*): it is calculated as the sum of the squares of voltage deviations (with respect to the reference value). The *energy weight* $E_{k,t}$ is introduced to give more importance to the nodes and time steps with higher energy. This sum is divided by the total energy E_{total} consumed in all the nodes during the whole simulated time horizon.

$$VDEF = \frac{\sum_{t=1}^{M}\sum_{k=1}^{N_{nodes}}\left(V_{k,t}-V_{ref}\right)^{2}\cdot E_{k,t}}{E_{total}} \quad (3)$$

- Global OverVoltage Persistence (*GOVP*): it calculates the number of nodes in which the voltage (at each time step) is higher than the defined threshold V_{lim}. Then, this value is divided by the total number of time steps *M* and the number of nodes in grid N_{nodes}. In the same way, the Global Undervoltage Persistence (*GUVP*) counts the nodes in every time steps in which voltage is lower than the defined threshold V_{lim}.

$$GOVP = \frac{\sum_{t=1}^{M}\sum_{k=1}^{N_{nodes}} u_{k,t}^{(V>V_{lim})}}{N_{nodes}\cdot M} \quad (4)$$

$$GUVP = \frac{\sum_{t=1}^{M}\sum_{k=1}^{N_{nodes}} u_{k,t}^{(V<V_{lim})}}{N_{nodes}\cdot M} \quad (5)$$

  where $u_{k,t}$ is a binary variable, equal to unity if there is a voltage constraint violation at node *k* in the time step *t* under consideration, and zero otherwise.

- Overvoltage Duration (*OD*): it is conceptually similar to *GOVP*. The difference is that, in case of overvoltages in multiple nodes at the same time step, the indicator is considered only one time. Likewise, the Undervoltage Duration (*UD*) counts the time steps with voltage (at least at one node) lower than the threshold V_{lim}:

$$OD = \frac{\sum_{t=1}^{M} w_{t}^{(V>V_{lim})}}{N_{nodes}\cdot M} \quad (6)$$

$$UD = \frac{\sum_{t=1}^{M} w_{t}^{(V<V_{lim})}}{N_{nodes}\cdot M} \quad (7)$$

  where w_t is a binary variable, equal to unity if there is at least one voltage constraint violation at any node in the time step *t* under consideration, and zero otherwise.

D. *Simulation results*

The simulations are performed for one week, with a time step of 1 min. The OLTC is installed in the MV/LV substation. The voltage variations during the week are mainly due to the high PV production during light hours. In addition, there are considerable loads mainly concentrated during early morning and evening, when people are home. The results are shown in Table I, where the second column (with no voltage control) is used as the reference. In the third column, the OLTC is not present (no centralized voltage control). Only PV converters are involved in voltage control, by stabilizing voltage in the respective connection points, according to the logics described in [9]. Converters cannot work at night (with no production), according to the prescriptions [28]. The results in the last column refer to non-coordinated operation of OLTC and PV converters.

The losses increase is due to the reactive power injection from the PV converters: the Joule losses increase from 159 kWh/week to 194 kWh/week (about 20% rise). By introducing the OLTC, the losses remain high due to the effect of the PV converters, with negligible variation.

Regarding the voltage parameters, the installation of the OLTC permits an additional improvement of voltage profile, with respect to the only use of PV converters. In fact, *VDEF* decreases from $2.84 \cdot 10^{-4}$ to $2.24 \cdot 10^{-4}$, corresponding to ≈21% improvement. The reasons are different. Unlike PV converters, the OLTC can work during all day: it means that also during the evening, when loads are high and PV generation is zero, undervoltage is mitigated by the OLTC. In fact, in case of absence of OLTC, *GOVP* is always higher than *GUVP*; that is, overvoltage is the dominant problem, occurring during light hours due to PV generators. On the contrary, in case of OLTC and PV converters, the results are inverted: *GOVP* is lower than *GUVP*, as the voltage deviations are now higher during the night due to high loads. However, in this paper the OLTC is set up with limited tap changes, to reduce maintenance costs. Thus, it cannot mitigate too much evening and night loads. A higher number of tap changes per day (with lower t_{viol}) could further reduce the voltage deviations.

The indicators *OD* and *UD* confirm the considerations resulting by analysing *GOVP* and *GUVP*. In addition, the ratio between *GOVP* and *OD* gives information about the time and nodal distribution of the voltage violations. In fact, a high ratio means that many violations occur at the same time step, but in different nodes of the grid. This is the case of no voltage control: the ratio *GOVP*/*OD* is about 12, while in the other two cases is about 1.3. Thus, for overvoltages, PV converters and/or OLTC permit to reduce the number of violated nodes, more than the moments at which there are violations. On the contrary, in case of low voltages, the ratio *GUVP*/*UD* is 7.86 in case of no control, 7.02 for PV converters, and 6.33 in the last case with OLTC. The similar values indicate that the variation of low voltage violations in time and nodes is less significant.

IV. CONCLUSIONS

The results show that the use of an OLTC with appropriate control is helpful for the mitigation of voltage fluctuations in a LV grid with high penetration of RES. The effectiveness of the use of this device strongly depends on the control logic. A setup of the OLTC that permits frequent tap changes stabilises the voltage in the grid, but affects the costs in terms of maintenance of the mechanical/electronic switches inside the device. On the other hand, the reduction of the number of tap changes keeps the maintenance low, but also reduces the voltage control ability. The centralised voltage control improves the situation for undervoltages, while overvoltages due to the PV generators should be addressed locally.

TABLE I. RESULT OF SIMULATIONS WITH VOLTAGE CONTROL PERFORMED BY AN OLTC IN THE MV/LV SUBSTATION AND BY DISTRIBUTED PV CONVERTERS.

	No voltage control	**PV converters**	**OLTC and PV converters**
V_{trg} [p.u.]	-	-	1
t_{viol} [min]	-	-	20
losses [kWh]	159	194	193
VDEF	$3.96 \cdot 10^{-4}$	$2.84 \cdot 10^{-4}$	$2.24 \cdot 10^{-4}$
GOVP	$2.25 \cdot 10^{-2}$	$1.64 \cdot 10^{-3}$	$1.74 \cdot 10^{-3}$
GUVP	$6.54 \cdot 10^{-3}$	$1.39 \cdot 10^{-3}$	$3.14 \cdot 10^{-4}$
OD	$1.85 \cdot 10^{-3}$	$1.30 \cdot 10^{-3}$	$1.30 \cdot 10^{-3}$
UD	$8.32 \cdot 10^{-4}$	$1.98 \cdot 10^{-4}$	$4.96 \cdot 10^{-5}$

The optimal solution should be the selection of setup parameters for the OLTC performed as a function of the characteristics of the grid (in terms of impedance, configurations, loads and generators) and as a result of the comparison between maintenance cost of the OLTC and the cost linked to voltage deviations. Better results could be obtained by coordinating centralised and decentralised voltage control devices, at the expense of adding communications among the controllers, by using a suitable objective function for voltage control.

Future works will analyse in detail the effect of different control logics of the OLTC and different selections of the control parameters.

V. References

[1] L.M. Cipcigan and P.C. Taylor, "Investigation of the Reverse Power Flow Requirements of High Penetrations of Small-Scale Embedded Generation," *IET Renew. Pow. Gener.*, vol. 1, pp. 160–166, 2007.

[2] A. Mazza, E. Carpaneto, G. Chicco, and A. Ciocia, "Creation of Network Case Studies With High Penetration of Distributed Energy Resources," *Proc. 53rd UPEC*, Glasgow, UK, 4–7 Sept. 2018.

[3] C. Long and L.F. Ochoa, "Voltage Control of PV-Rich LV Networks: OLTC-Fitted Transformer and Capacitor Banks," *IEEE Trans. Pow. Syst.*, vol. 31, pp. 4016–4025, 2016.

[4] H. Pezeshki, A. Arefi, G. Ledwich, and P. Wolfs, "Probabilistic Voltage Management Using OLTC and dSTATCOM in Distribution Networks," *IEEE Trans. Pow. Deliv.*, vol. 33, pp. 570–580, 2018.

[5] IEEE Recommended Practice for Utility Interface of Photovoltaic Systems, IEEE Standard 929, 2000.

[6] A. El-Naggar and I. Erlich, "Control Approach of Three-phase Grid Connected PV Inverters for Voltage Unbalance Mitigation in Low-Voltage Distribution Grids," *IET Renew. Pow. Gener.*, vol. 10, pp. 1577–1586, 2016.

[7] A.T. Procopiou and L.F. Ochoa, "Voltage Control in PV-Rich LV Networks Without Remote Monitoring", *IEEE Trans. Pow. Syst.*, vol. 32, pp. 1224–1236, 2017.

[8] T.T. Ku, C.H. Lin, C.S. Chen, and Cheng-Ting Hsu, "Coordination of Transformer On-Load Tap Changer and PV Smart Inverters for Voltage Control of Distribution Feeders," *IEEE Trans. Ind. Appl.*, vol. 55, pp. 256–264, 2019.

[9] A. Ciocia, V.A. Boicea, G. Chicco, P. Di Leo, A. Mazza, E. Pons, F. Spertino, and N. Hadj-Said, "Voltage Control in Low-Voltage Grids Using Distributed Photovoltaic Converters and Centralized Devices," *IEEE Trans. Ind. Appl.*, vol. 55, pp. 225–237, 2019.

[10] T. Aziz and N. Ketjoy, "Enhancing PV Penetration in LV Networks Using Reactive Power Control and On Load Tap Changer With Existing Transformers," *IEEE Access*, vol. 6, pp. 2683–2691, 2018.

[11] Y. Xu, C. Zhou, J. Geng, S. Gao, and P. Wang, "A Method for Diagnosing Mechanical Faults of on-Load Tap Changer Based on Ensemble Empirical Mode Decomposition, Volterra Model and Decision Acyclic Graph Support Vector Machine," *IEEE Access*, vol. 7, art 84803–84816, 2019.

[12] R. Yang, D. Zhang, Z. Li, K. Yang, S. Mo, and L. Li, "Mechanical Fault

Diagnostics of Power Transformer On-Load Tap Changers Using Dynamic Time Warping," *IEEE Trans. on Instrument. and Measurement*, vol. 68, pp. 3119–3127, 2019.
[13] J. Seo, H. Ma, and T. Kumar Saha, "On Savitzky–Golay Filtering for Online Condition Monitoring of Transformer On-Load Tap Changer," *IEEE Trans. Pow. Deliv.*, vol. 33, 1689–1698, 2018.
[14] S.R. Shukla, S. Paudyal, and M.R. Almassalkhi, "Efficient Distribution System Optimal Power Flow with Discrete Control of Load Tap Changers,“ *IEEE Trans. Pow. Syst.*, vol. 34, pp. 2970–2979, 2019.
[15] Y. Chai, L. Guo, C. Wang, Y. Liu, and Z. Zhao, "Hierarchical Distributed Voltage Optimization Method for HV and MV Distribution Networks," *IEEE Trans. on Smart Grid*, vol. 11, pp. 968–980, 2020.
[16] G.C. Kryonidis, C.S. Demoulias, and G.K. Papagiannis, "A Two-Stage Solution to the Bi-Objective Optimal Voltage Regulation Problem," *IEEE Trans. Sust. Energy*, vol. 11, pp. 928–937, 2020.
[17] J.F. Franco, et *al*. "Advanced Control of OLTC-enabled LV Networks with PV Systems and EVs," *IET Gen. Transm. Distrib*., vol. 13, pp. 2967–2975, 2019.
[18] G.R. Chandra Mouli, *et al*., "Design of a Power-Electronic-Assisted OLTC for Grid Voltage Regulation," *IEEE Trans. Pow. Deliv.*, vol. 30, pp. 1086–1095, 2015.
[19] S. Monteso Fernández, S. Martínez García, C. Cagigal Olay, J.C. Campo Rodríguez, R. Vela García, and J. Vaquero López, "Electronic Tap Changer for Very High-Power Medium-Voltage Lines With No Series–Parallel Thyristors," *IEEE Trans. Ind. Electr.*, vol. 65, pp. 5237–5249, 2018.
[20] M. Coppo, R. Turri, M. Marinelli and X. Han, "Voltage management in unbalanced low voltage networks using a decoupled phase-tap-changer transformer," *49th UPEC*, Cluj-Napoca, Romania, 2014.
[21] H. Xu, Q. Xu, Y. Gao, and H. Liu, "Coordinate Control Strategy for Current Stabilization in an Aluminium Smelter Including On Load Tap Changer," *Energy and Power Engineering*, vol. 5, 2013.
[22] A. Ciocia, G. Chicco, P. Di Leo, M. Gai, A. Mazza, F. Spertino, and N. Hadj-Said, "Voltage control in low voltage grids: A Comparison Between the Use of Distributed Photovoltaic Converters or Centralized Devices," in *Proc. 2017 IEEE EEEIC / I&CPS Europe*.
[23] T. T. Ku, *et al*. "Coordination of PV Inverters to Mitigate Voltage Violation for Load Transfer Between Distribution Feeders With High Penetration of PV Installation," *IEEE Trans. Ind. Appl.*, vol. 52, pp. 1167–1174, 2016.
[24] S.N. Salih and P. Chen, "On Coordinated Control of OLTC and Reactive Power Compensation for Voltage Regulation in Distribution Systems With Wind Power," *IEEE Trans. Pow. Syst.*, vol. 31, pp. 4026–4035, 2016.
[25] K. Knezović and S. Krajcar, "Modelling and Simulating the Impact of a Small Solar Plant to the Low-Voltage Network," in *Proc. Eurocon* 2013, pp. 1270–1277.
[26] F. Spertino, A. Ciocia, P. Di Leo, R. Tommasini, I. Berardone, M. Corrado, A. Infuso, and M. Paggi, "A Power and Energy Procedure in Operating Photovoltaic

Systems to Quantify the Losses According to the Causes," *Solar Energy*, vol. 118, pp. 313–326, 2015.
[27] J.M. Cano, M. Rejwanur R. Mojumdar, J.G. Norniella, and G.A. Orcajo, "Phase shifting transformer model for direct approach power flow studies,", *Int J. Elect. Pow. En. Syst.*, vol. 91, pp. 71–79, 2017.
[28] CEI 0-21, *Reference technical rules for the connection of active and passive users to the LV electrical Utilities*, 2016 CEI, Online: http://ceiweb.it/doc/norme/14829.pdf (in Italian).