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Planning and operation of an intelligent power electronics series voltage regulator for PV-Rich distribution feeders

Emilio Ghiani, *Senior Member, IEEE*, Rocco Di Gregorio, and, Stefan Hoppert

***Abstract*-- The connection of photovoltaic systems on weak electrical distribution networks can lead to the occurrence of excessive overvoltages or undervoltages that lead toward unsatisfactory operating conditions for renewable energy producers. In such critical situations, where electrical parameters are outside standard regulatory levels, the untimely tripping of electrical protections can lead to losses of renewable energy production and thus to the reduction of producers' economic revenues. In this context, this article describes aspects related to the planning and operation of an intelligent voltage regulator capable of solving voltage regulation problems in PV-rich low-voltage networks. The results achieved with the application of the power electronics device in electric distribution networks are shown with a real case study in a network with a high penetration of photovoltaic-type renewable energy installations. The results show the effectiveness of the application of the device considering both technical and economic aspects; these results are also compared with traditional distribution network planning strategies, highlighting the advantages for the distributor and the owners of photovoltaic systems.**

***Index Terms*-- Photovoltaic installations, voltage profile, radial distribution networks, measurement on power systems, expansion of distribution systems.**

I. Introduction

THE increasing spread of distributed generation from renewable sources, and thus of decentralized and stochastic generators, is causing additional power fluctuations at the medium voltage (MV) and low voltage (LV) levels. A good indicator for the study of electrical voltage quality is the value of the deviation of the grid voltage from the nominal value. In general, the grid voltage increases at points where active energy is fed in and decreases at points where active energy is obtained. The longer and weaker the lines are, the more pronounced this effect is. In particular, with the increasing shares of renewable energy sources being integrated into the power distribution system, power quality issues related to voltage regulation and stability problems are becoming relevant for distribution system operators DSOs [1]. If generation from photovoltaic (PV) systems is taken into account, the variations in solar radiation throughout the day may cause relevant power fluctuations that may reflect as negative impacts on the grid, such as reverse power flow, variation in voltage levels [2], voltage flicker and harmonic distortions [3].

To accommodate more distributed energy resources (DERs) without incurring this kind of problems, the so-called "hosting capacity" of the network must be increased with network investments or with the "no-network" solutions, where operation issues can be fixed with innovative optimal network management approaches (i.e. smart grid operation) [4].

The modern planning methodologies include "network" and "non-network" solutions as valid planning alternatives intrinsically capable of a favorite the integration of renewable generation [5], [6].

TABLE I. shows the most common distribution planning issues arising from the current need to integrate larger quantities of renewable generation.

TABLE I. Network and Non-Network Solutions in Modern Distribution Planning with High Shares of RES Installed.

Challenge	Current solution	Future alternatives
Voltage rise	Reinforcement Operational p.f. 0.95 lagging Generation tripping	Volt/VAR control Storage Generation Curtailment On-line reconfiguration
Voltage drop	Reinforcement Fixed capacitor banks	Volt/VAR control Storage Demand Side Response On-line reconfiguration
Network Capacity	Reinforcement	Storage Generation Curtailment Demand Side Response On-line reconfiguration
Network Power Factor	Limits/bands for demand and generation	Storage Unity power factor generation
Sources of Reactive Power	Transmission network Fixed capacitor banks	Storage SVC Volt/VAR control
Network asset loss of life	Strict network designs specifications based on technical and economic analyses	Dynamic protection settings Asset condition monitoring

It is interesting to observe that each planning issue can be faced with traditional network solutions (e.g. upgrade a transformer to meet growing demand) and with innovative no-network solutions (e.g. reduce network demand to avoid or defer the network investment [7]). The potential benefits of non-network solutions in term of lower cost and greater

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flexibility are becoming more well understood, but the two approaches tend to be very different [7] as summarized in TABLE II. , and, for that reason, non-network approaches have difficulty being employed and establishing themselves, and some of the most innovative non-network solutions require that the not regulated players (e.g., the DER owners) cooperate with the distribution operator to manage the system.

TABLE II. NETWORK AND NON-NETWORK SOLUTIONS APPROACHES COMPARISON.

Network solution	Non-Network solution
Well known and understood	Limited experience & capability
Firm (reliable result)	Greater uncertainty in result
Long life asset	Shorter term solution
Controlled by network system operator	Customer may have control
Limited customer engagement	May need high customer engagement
CAPEX solution/ regulated asset based	May be CAPEX+OPEX solution

All planning network or non-network solutions do not necessarily have the above characteristics, some could be called hybrid solutions, particularly when they deviate from conventional solutions proposed by the distributor and achieve economic savings through the use of innovative approaches.

Among the various distribution planning aspects, this paper concerns the management of voltage profiles in the electrical network. It proposes an hybrid non-network alternative and cheaper solution to the physical reinforcement of the distribution network to ensure that high shares of renewable source plants can be integrated into existing networks.

This paper illustrates the operation of a longitudinal voltage controller that belongs to the family of Flexible AC Transmission Systems (FACTS) devices [8]-[17] and demonstrates its effectiveness in LV networks with high amounts of renewable production systems. In particular, the study proposes a planning approach to solve a voltage regulation problem in PV-rich low voltage power distribution network by applying to this network an intelligent voltage regulator (named by the manufacturer as LVRSys™ [10]).

In the current situation, before using the voltage regulator, these PV sources make the voltage exceed the permissible upper limit of the voltage (1.1 Vn). The main aim of the research is to validate the application of the device [10] demonstrating that it will be able to maintain the voltage within the permissible standard range (0.9–1.1Vn), thus allowing the correct functioning of the PV systems connected to the grids and permitting that all the energy can be produced and injected through the existing lines.

The paper has six additional sections. In Section II, the basic concepts of voltage regulation problems in radial distribution networks are recalled. In Section III, the adverse effects on power generation of PV systems due to large voltage deviations resulting in disconnection of the systems from the grid are illustrated. Section IV describes the operating principle of the longitudinal (series) voltage regulator, and the specific characteristics of the voltage regulator used in this study are underlined Section V. A detailed scenario in which a voltage regulator can effectively impact the voltage profiles along a distribution line for improving PV systems energy production is presented in Section VI. Finally, the concluding remarks are reported in Section VII.

II. VOLTAGE REGULATION PROBLEMS IN RADIAL DISTRIBUTION SYSTEMS

The paper deals with solving voltage quality issues related to the impact of distributed generation (DG) on radial distribution networks [11].

The DG effects on weak distribution networks are well known, particularly the limitation to integrating additional DG caused by voltage rise, particularly in networks with long distances to be covered and high R/X ratios in network impedance.

The theoretical effects on voltage rise can be described by Fig. 1, where a distributed generator and a load are connected at the end of the line, and the voltage regulation problem is described considering a generator and a load connected at the end of the line.

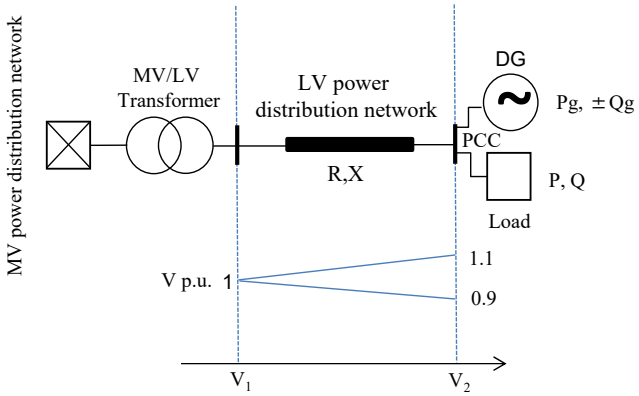

Fig. 1. Voltage rise effects in radial weak distribution networks

The voltage variation in the feeder can be expressed by (1).

$$\Delta V = V_1 - V_2 = \frac{R(P - P_g) + X(Q \pm Q_g)}{V} \quad (1)$$

where:

- V_1 =Voltage at the beginning of the feeder;
- V_2 = Voltage at the end of the feeder (or at the point of connection coupling of the distributed generator);
- R = resistance of the feeder;
- X = reactance of the feeder;
- P = active power absorbed by the load at the end of the feeder;
- Q = reactive power absorbed by the load at the end of the feeder;
- Pg = active power generated by DG at the end of the feeder;
- $\pm Qg$ = reactive power absorbed/generated by DG at the end of the feeder.

In case of no-load condition (P=Q=0), (1) can be rewritten as in (2) that shows the relationship between the injected power and the voltage V_2 at the point of common coupling (PCC).

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$$V_2 = V_1 + \frac{R \cdot (P_g) + X \cdot (\pm Q_g)}{V} \quad (2)$$

According to (2), DG can provide voltage support to raise the low voltage V_2 at the end of the feeder, but, in case of minimum/no load and high values of R, the magnitude of V_2 can result in an overvoltage, limiting the capacity which can be installed, or, in general, the active power that can be injected at the end of the line.

As in this presented study, the PV power generation could offset the load and cause reverse power flow through the distribution system, causing operational issues, including overvoltage and loss of voltage regulation. The voltage rise can be considerable in weak radial distribution networks with long distances to be covered and high R/X ratios.

Managing the active and reactive power generated by the PV system in an intelligently coordinated way can mitigate the adverse impact on the voltage at the end of the line, limiting overvoltage and improving voltage regulation.

III. Detriment of Renewable Energy Production Due to Overvoltage Problems and Protection Tripping

This paragraph describes the working limits of the electrical protections used in electricity networks in Italy, which, in the presence of weak grids with high penetration of renewable sources, can cause untimely tripping during voltage fluctuations that may occur during the operation of renewable energy plants. The Italian standards regulating the connection to the public distribution networks are the CEI 0-21 [12] for LV connections and the CEI 0-16 [13] for MV and HV connections.

The operation of a production plant in parallel with the distribution network must respect the following conditions defined by the standards:

- must not cause disturbances to the service on the distribution network;
- must stop immediately and automatically in the absence of power supply or if the mains voltage and frequency values are not within the values specified by the Distributor;
- the parallel device must not allow the parallel with the network in case of power failure or voltage and frequency values outside the values specified by the Distributor.

To ensure the separation of the production plant from the distribution network in case of a power failure, an Interface Device (DDI) must be installed. The DDI is controlled by interface protection relay (SPI) with overvoltage protection (59), Undervoltage protection (27), over frequency protection (81>), under frequency protection (81<), protection codes are defined by ANSI /IEEE Standard C37.2 [14].

The mentioned protections are necessary to rapidly detect malfunctioning of the power distribution network and disconnect the DG plant of the customer by Italian standards CEI 0-16 and CEI 0-21. CEI 0-16 and CEI 0-21 settings must be consistent with EN50160 standard [15], related to voltage characteristics of electricity supplied by public distribution networks, which defines, describes, and specifies voltage quality criteria at the customers PCC in public LV, MV, and HV alternating current networks under normal operating conditions. TABLE III. gives an overview of steady-state voltage criterion and permissible frequency deviations defined by EN 50160.

TABLE III. EN 50160 Frequency/Voltage Supply Characteristics

Parameter	Limit
Frequency variations	• 49.5–50.5 Hz during 99.5% of a year • 47.0–52.0 Hz during 100% of the time
Supply voltage variations	• at least 99% of the 10-min mean RMS values of the supply voltage shall be between _10% of the systems nominal voltage • none of the 10-min mean RMS values of the supply voltage shall be outside the limits _15% of the declared voltage

The thresholds are reported in TABLE IV. are the protection interface (DDI) overvoltage and undervoltage setting values defined by CEI 0-21 standard for PV systems, in low voltage networks with nominal voltage 400/230V. Similar settings are also defined by the CEI 0-16 for HV and MV networks.

TABLE IV. CEI 0-21 Over/Under Voltage Protection Settings

Protection threshold	Threshold values	Time of intervention
59.s1	253.0 V (1.10 Vn)	≤3.0s
59.s2	264.5 V (1.15 Vn)	<0.2 s
27.s1	195.5 V (0.85 Vn)	<0.4 s
27.s2	92.0 V (0.4 Vn)	<0.2 s

According to CEI 0-21 requirements, the PV plant has to be disconnected from the distribution network when:

1. network voltage measured as an average on 10 minute period is over 253 V (U>10) with a time of intervention ≤ 3s;
2. network voltage is over 264 V with a time of intervention <0.2 s;
3. network voltage is below 195.5 V with a time of intervention <0.4 s;
4. network voltage is below 92 V with a time of intervention <0.2 s;

By applying these settings during the operation of PV systems in weak networks, a typical disconnection situation due to voltage fluctuations is shown in Fig. 2, which presents a cycling behavior of disconnection, automatic reclosing and further reclosing disconnection of the inverter to the intervention of the overvoltage protection. The Fig. 2 has a qualitative purpose, in the case of photovoltaic disconnection there would undoubtedly be an effect on the voltage which is not shown, see reference [1] for more details.

Voltage fluctuations may result in frequent unintentional disconnections of the PV system, causing accelerated detriment of the apparatus and reduction of energy production with the related economic loss for the PV owner.

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In the meantime that the innovative grid concepts will be compulsorily applied to the existing networks in rural weak distribution networks, the power quality issues related to voltage regulation are becoming significant problems for power distribution companies and PV owners.

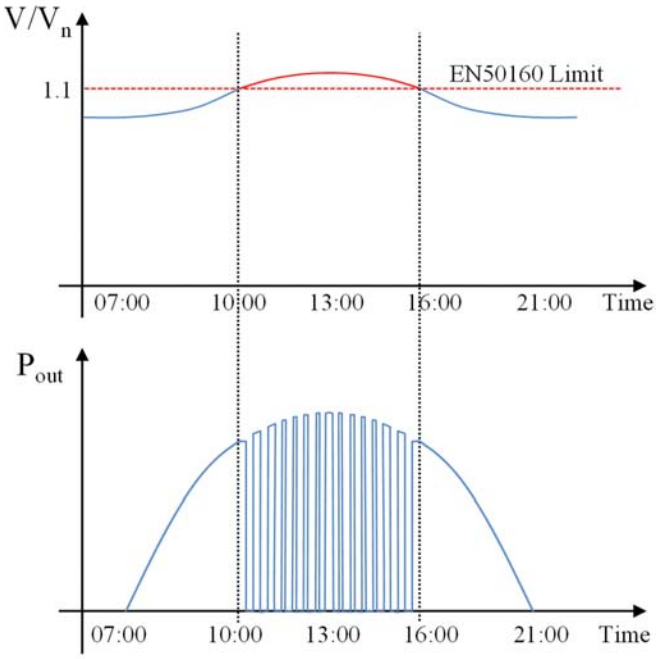

Fig. 2. Repeated PV network disconnections due to overvoltage in weak distribution networks

Traditional upgrading (e.g. feeder reinforcement) of the networks to meet the PV owners right to have a voltage with sufficient quality may result in quite expensive investments for the distributor system operator. On the contrary, the PCC voltage fluctuations may result in frequent unintentional disconnections of the PV system, causing accelerated detriment of the apparatus and reduction of energy production with the related economic loss for the PV owner. Trade-off solutions need to be found and applied.

IV. Voltage Stabilization with Longitudinal Regulator

With the advent of power electronics in the 1990s, new elements in power transmission became possible, with which it is possible to influence active and reactive power flows and voltages in the electrical system. These elements were designated by the abbreviation FACTS (Flexible AC Transmission Systems) and are increasingly widely used today. Initially, with the introduction of electricity market liberalization, the initial focus was on controlling power flows at the level of high-voltage transmission networks, with the aim of making the best use of line transmission capacity [16]. Through the use of FACTS devices, it is possible, for example, to relieve congestion on transmission lines that reach their limits due to fluctuations in power exchange volumes, to regulate voltage levels at specific points in the power grid [17] and perform voltage transformation [18][8]. In the course of the development of the FACTS, the so-called unified power flow controller (UPFC) has proven to be a universal circuit for influencing active and reactive power flows as well as the mains voltages. From a technical point of view, a UPFC can be realized, for example, with two converters [19]. As shown in Fig. 3, this contains two inverters coupled via a DC link.

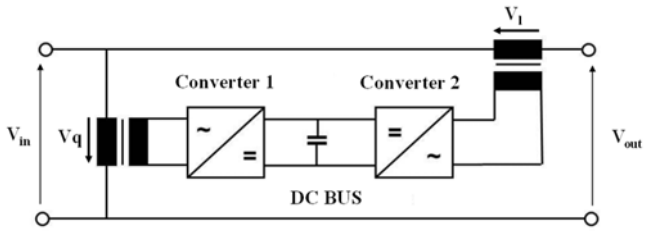

Fig. 3. UPFC voltage regulator (single fase connection)

The voltages longitudinal V_l and quadrature V_q can be adjusted independently of each other in amplitude, frequency and phase. Thus, the UPFC can also be used as a longitudinal control as that refers to the principle of operation of the voltage regulator described in [10] which the first development was presented in [20]. The working operation principle is similar to a transformer with on-load tap control in which the voltage regulation is obtained by power electronics control. One of the possible models of the UPFC is shown in and consists of two coupled voltage sources and two impedances. It is referred to in the literature by the term Voltage Source Based or Voltage Source Model.

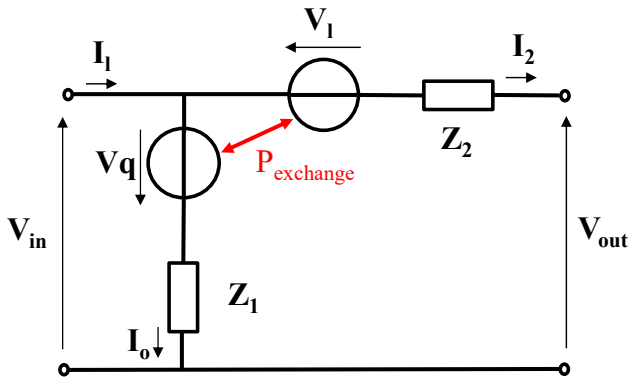

Fig. 4. Single-phase equivalent circuit of a UPFC based on voltage sources

The central element is the longitudinal voltage V_l which is connected in series to the power line. In the general case, with simultaneous influence of active/reactive power and mains voltages, the amount and phase can be specified independently of each other. If only the voltage regulator function is realized, the following adjustments to the model of Fig. 5. The low voltage regulator [10] analysed in this paper considered here generates the longitudinal voltage V_l with the transformer principle.

With the help of electronic switches, the longitudinal voltage V_l is composed of individual V_q partial voltage transformed from the voltage. If one neglects the voltage drops over the electronic switches, the equation $V_l = \nu \cdot V_q$ results.

The circuit of Fig. 6 has different partial voltages. Each partial voltage is either 0 or a constant value, which can be

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switched on positively or negatively depending on the polarity of the voltage. In total, this allows nine different values for ν:

$$v = [-0.1, -0.075, -0.05, -0.025, 0, 0.025, 0.05, 0.075, 0.1]$$

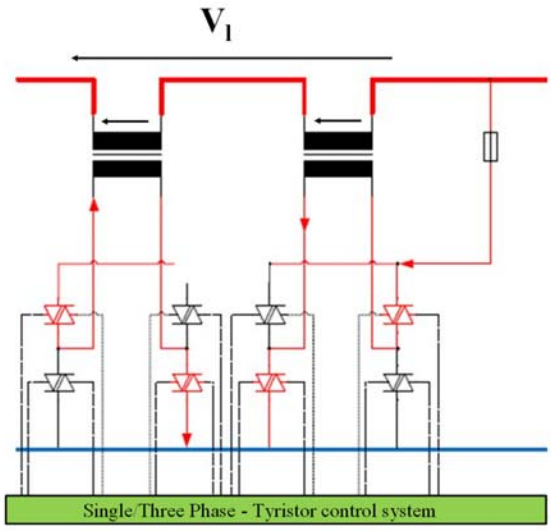

Fig. 5. LVRSys™ tyristor control system

V. LVRSys™ Longitudinal Voltage Regulator

Compliance with voltage limits is mandatory for connected devices of the electricity network users to function properly and not themselves suffer damage or cause other damage. Distribution network operators today have several options for keeping voltage within certain limits. One of these is the use of a longitudinal controller like the one presented in this paper. The basis for the application of this device is the need to maintain the required voltage level of the distribution network and improve the power quality parameters, also in the presence of spreadly connected distributed generation resources in the network under study. The main regulated variable is the voltage (for each phase) at the secondary side of the regulator [10].

The device specifies the voltage values that should be maintained at the regulator output, considering the setpoint and the admitted dead band. If the values of the measured voltages at the device's output exceed the permissible limit, the operation of the regulator/controller will provide the necessary regulation. The device responds after a certain time delay, defined by selecting the appropriate characteristics. The voltage regulator can adjust the voltage on each phase independently every 100 ms for the standard version or about 30 ms for the advanced version. The delay time of the regulator is not relevant for the effects on the voltage regulation process of the electricity grids, whose time constant is of the order of seconds, therefore, the regulator's regulation time, of the order of 35ms, is completely negligible for the operation of the distribution network.

The user can set the reaction behaviour of the controller, since different low voltage grids also require different reaction times. A standard setting of the time behaviour of 1V/s means that if the voltage exceeds or falls below the tolerance bands by 1V, the controller adjust the voltage in one second.

In the advanced version, there is also the option for solving various issues related to voltage dips and fast power quality events.

Moreover, after activating the function 'Grid impedance', new control values can be activated by measuring the currents and parameterisation of the network impedance, which enables precise calculation of the voltage in a given node (even far from the output terminals of the device). This allows the regulation to be also optimised without using network communication devices.

The presented regulator provides independent voltage regulation in each phase by connecting two series transformers with thyristors. The transformers are controlled by thyristors, whose switching settings determine the stages of transformer operation (Fig. 6).

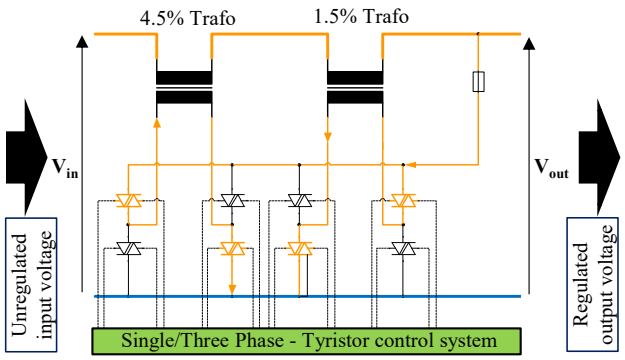

Fig. 6. LVRSys™ Intelligent voltage regulator (single fase connection)

The three-phase low-voltage control system regulates the output voltage by introducing and controlling additional transformers for each of the three-phase systems [20].

The system is completely phase independent, and acts as three single phase voltage regulator.

The voltages are regulated according to a two-stage process. In the first step, the control of the voltages exclusively depending on the tolerance bands and the setpoint of the respective phase.

The regulation would be equivalent to three independent voltage regulators, each per phase. In the second step, the controller evaluates whether the three individual phase voltages are in a symmetrical optimum. If this is not the case, the voltages are balanced towards the setpoint.

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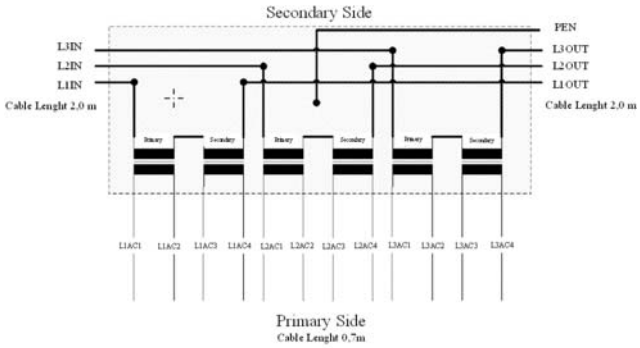

Fig. 7. LVRSys^{TM} Three Phase Connection

The integrated transformer regulator switches the transformers to keep the voltage in the tolerance range, and internal algorithms provide the adjustment command if the voltage setpoint is outside the tolerance band. For example, if the control range is rising above the tolerance band, in this case set + 3% (See Fig. 8), the device regulates the voltage within the limit, checking the value of the voltage every second. If the upper tolerance limit or the lower tolerance limit are overcome, the control will return the voltage value within the set tolerance band.

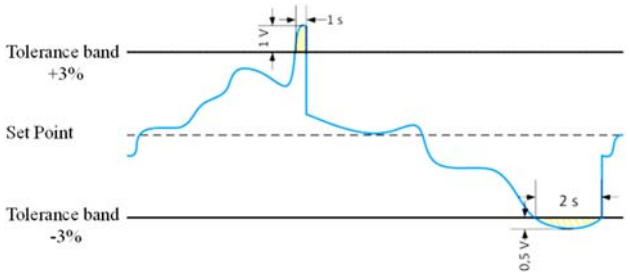

Fig. 8. Tolerance regulation band

The standard adjustment range for increasing or decreasing the voltage is ±6% for the standard version (TABLE V.). It is possible to adjust the voltage regulation range up to ±24% with the advanced versions.
The default setpoint is 230V phase-neutral, but this value can be changed in case of need. As soon as a different/new value is set, the regulator will immediately start regulating according to the new setpoint.

TABLE V. LVRSys^{TM} Regulation Settings Version ±6%

Regulation Step		Trafo 1.5%	Trafo 4.5%
#1	+6 %	+1.5 %	+4.5 %
#2	+4.5 %	0 %	+4.5 %
#3	+3 %	-1.5 %	+4.5 %
#4	+1.5 %	+1.5 %	0 %
#5	0 %	0 %	0 %
#6	-1.5 %	-1.5 %	0 %
#7	-3 %	+1.5 %	-4.5 %
#8	-4.5 %	0 %	-4.5 %
#9	-6 %	-1.5 %	-4.5 %

The regulator's control system is not linked to the current flow in the grid, so this does not change the way the voltage is controlled, as is the case with conventional on-load voltage regulators.

Due to the linear controller principle, the threshold value of the controller is only 0.3%. In the case of distribution network transformers, the threshold values are between 4% and 6%. At maximum load on the controller, the system only drops 0.3% voltage, which does not have to be corrected. In the case of distribution network transformers, this effect cannot be neglected.

The driver stage generates the signals for the power electronics and the semiconductors galvanically isolated. This system does not cause unwanted flickers and harmonics because no relays or capacitors are used for voltage regulation.

The low voltage regulator is equipped with an internal class A network analyser to check the power quality according to CEI EN50160. Furthermore, it is possible to connect this network analyser via RJ45 to use the different protocols available such as Modbus RTU, IEC61850 and IEC60870-104.

The voltage regulator is robust and can withstand overvoltages up to 5kV, short-circuit currents up to 50kA and direct discharges up to 100kA thanks to high-quality components. In the event of a fault, the electronic protection system can activate an automatic bypass to feed the user's load for all the lasting of the temporary critical event. The semiconductor elements are characterised by high durability, ease of use, and low short-circuit resistance.

Finally, the voltage regulator under consideration is suitable for low-voltage distribution networks, which are feed from the MV/LV transformers of the public distributor's secondary substations, which are equipped with voltage regulators with a fixed ratio and therefore do not undergo real-time regulation during distribution network operation. Only in certain cases, some distributors, use on load tap changer equipped by a line drop compensator in MV/LV substations, but even in these situations the regulator does not affect the operation of the electricity network, as it can operate with up- or down-regulation, depending on the voltage level measured at the input of the regulator.

VI. Case Study

A real-life case study is presented and discussed to show the effectiveness of the dynamic variation obtained with the intelligent regulator [10].

Four PV plants are located in an extra-urban area and connected by a low voltage network (230/400 V) feed by a 50 Hz pole transformer rating 100 kVA, voltage ratio 20kV/(400/230)V. Several low voltage customers are positioned along the line, and in particular, 4 PV producers of 18, 10, 27 e 9 kWp at a relative distance from the MV/LV pole transformer of 115 m, 285 m, 590 m and 880 m as illustrated in Fig. 9. Along the LV network path, several additional passive

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customers are connected between the DSO substation and the customer.

A. *Initial situation*

With the absence of PV production, the voltage in the network was correct; the average RMS voltage from 10 min measurements did not fall below the lower limit value of 0.9 Vn when feeding the load of the distribution system, even though to have the correct value at the end of the line, a voltage of 410 V need to be set at the begin of the network (MV/LV pole transformer).

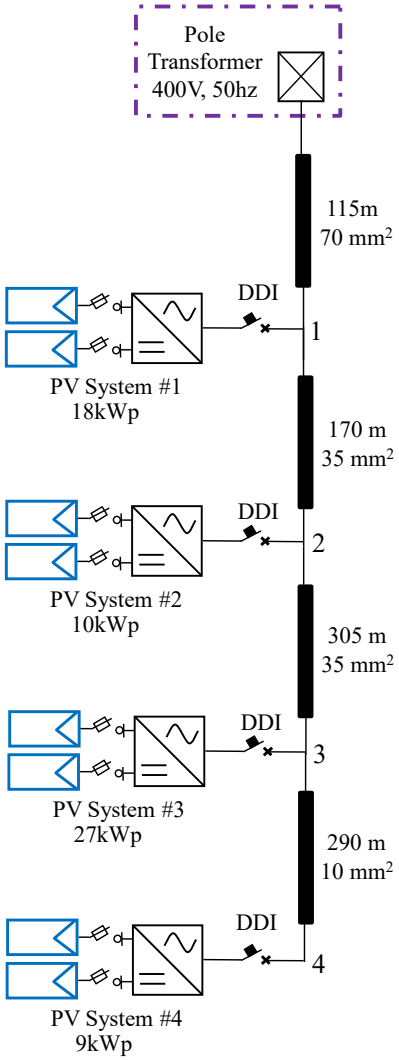

Fig. 9. Case study network

In the case of PV sources generating, the voltage values, especially on sunny days, increase beyond the permissible upper limit of 1.1 Vn for the low-voltage network (i.e., 440 V).

In particular, Fig. 10 shows the voltage profile of the radial feeder; it is noted how the overvoltage limit of 100% is reached at a distance of about 500 m from the installation point of the MV/LV pole transformer, while all the downstream issues register a higher voltage, which reaches the value of 469.3 V at the end of the line.

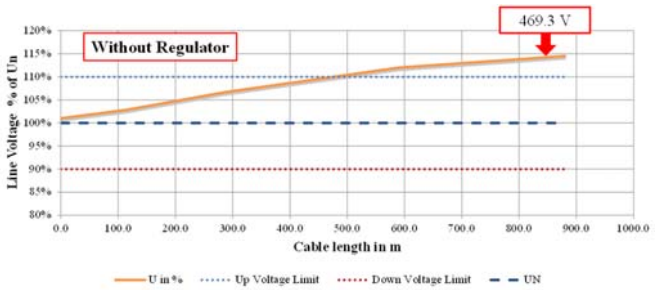

Fig. 10. Voltage boost without any regulation system in the network with PV production.

This condition represents the worst case and is obtained considering only the production, thus excluding the loads present, whose effect will be in favour of an improvement (reduction) of the voltage profile, but it is not sufficient to bring the values within the EN 50160 limits; the presence of such high voltage values cause the intervention of the interface protections of the PV systems installed along with the distribution network with related undesired voltage fluctuations due to connection/disconnection of the PV plants.

B. *Situation after installation of intelligent LV regulator*

To solve the mentioned problems, an LVRSys™ of 44kVA with -10% voltage step regulation has been installed in an optimal position at node two and the network to maintain the voltage at node 2 of the network within the limit e consequently also the downstream voltage profile (Fig. 11).

Using the voltage regulation device control system with a control range of ±10%, the permissible voltage drop has maintained in the range from 97%% to 107% along with all the feeders as depicted in Fig. 12, permitting the operation of PV systems without disconnections due to overvoltages.

C. *Trend of voltages upstream and downstream of the regulator*

The case study that is presented in the article is a condition in which large voltage regulation problems are evident with frequent voltage variations beyond tolerable limits and which would lead to the malfunction of the power generation facilities if solutions are not adopted.

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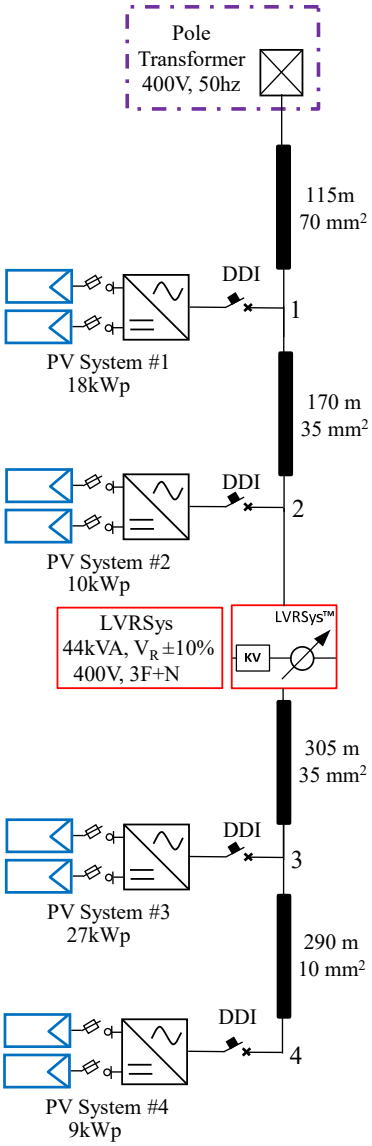

Fig. 11. Case study network with the addition of an intelligent regulator.

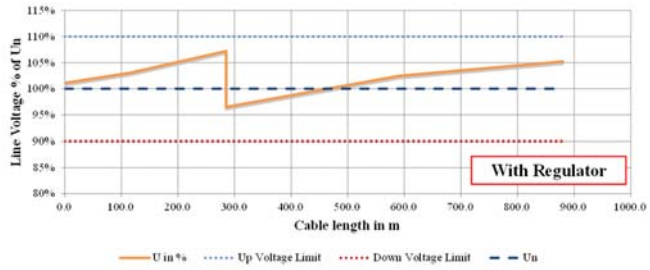

Fig. 12. Line Voltage with LVRSys optimally located in the network.

Voltage trend upstream and downstream of the voltage regulator for phase L1 are shown in Fig. 13 indisputably shows the classic bell-shaped behaviour corresponding to the output of grid-connected PV systems, relative to the dates of April 10 and 11, 2022 to which the measurement record refers. Very high voltages are detected that also exceed 255V value beyond the permissible limit for interface devices of photovoltaic systems, resulting in the disconnection of the systems from the grid.

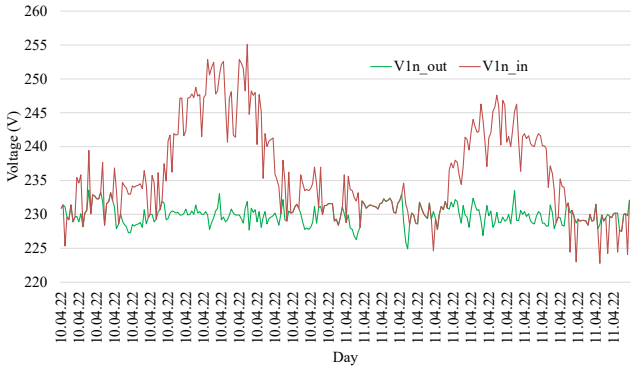

Fig. 13. Voltage trend upstream and downstream of the voltage regulator

The analysis was carried out from November 2021 to July 2022, to analyse in more detail the behaviour of the regulator by considering upstream and downstream voltages, and representing them with probability distribution to see the most frequent values and also be able to investigate in detail the effectiveness of voltage regulation.

The Fig. 14 shows the probability distribution of the input voltage to the regulator, and it can be seen from TABLE VI that this takes an average of 234,62 V value with standard deviation of 5.43V, and maximum value of 256V.

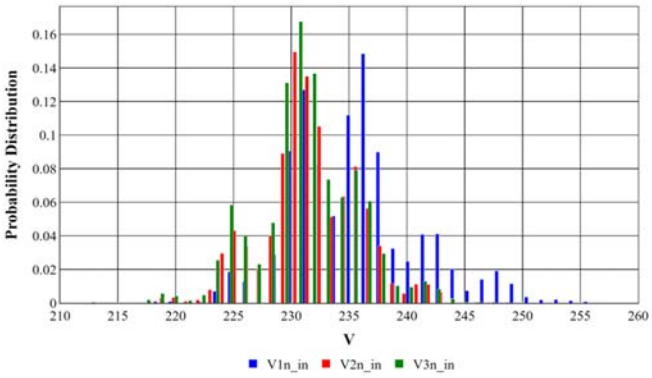

Fig. 14. Probability histogram of the voltage upstream the regulator.

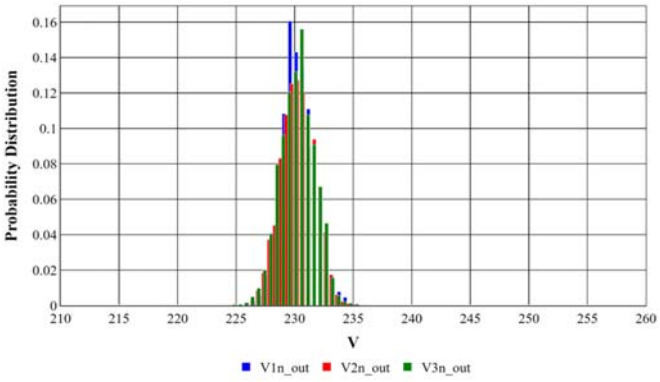

Fig. 15. Probability histogram of the voltage downtream the regulator.

Thanks to the use of the regulator as shown in the Fig. 15,

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the average voltage value stabilizes around the nominal value of 230V for all phases, and the standard deviation is greatly reduced (1.40V), thus a significant beneficial effect on voltage stabilization in the distribution network is shown.

TABLE VI. STATISTICAL ANALYSIS OF UPSTREAM AND DOWNSTREAM VOLTAGES

Voltage line	Statistical Parameters			
	Vmin [V]	Vmax [V]	V mean [V]	Standard Deviation [V]
V_{1_in}	211.83	256.74	234.62	5.43
V_{2_in}	212.47	249.19	231.18	4.18
V_{3_in}	206.91	248.75	230.95	4.35
V_{1_out}	218.10	236.40	230.02	1.40
V_{2_out}	219.60	236.50	230.01	1.47
V_{3_out}	218.00	236.40	230.02	1.46

In conclusion, the application of the voltage regulator can significantly improve voltage levels in the power distribution network and allow them to be kept within the standard range [21].

D. Cost comparison analysis for the installation of intelligent LV regulator and network reinforcement

In this last part of the case study, the analysis examines if the scenario considered the voltage regulation device pays off compared with conventional distribution network reinforcement.

Fig. 16 shows the new voltage profile of the line if the rewiring of the line is carried out by replacing all the existing conductors at 35 mm^2 and 10 mm^2 with a new cable of 70 mm^2.

The voltage profile in Fig. 16 shows that it would be possible to stay within the high limit of 110%; therefore, the reinforcement of the network would be a valid option to solve the voltage rise problem due to PV systems.

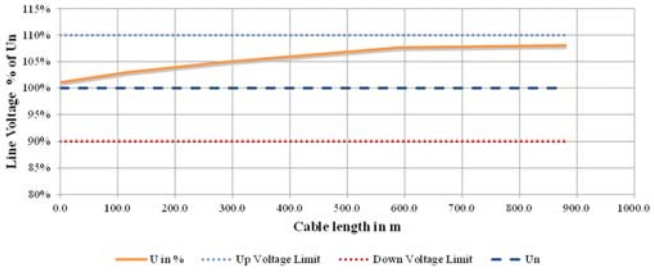

Fig. 16. Voltage profile with line reinforcement @70mm^2.

From an economic point of view, the replacement of the overhead conductors, considering a cable replacement cost of 45 k€/km for the conductor of 70 mm^2, corresponds to an investment cost of approximately 34.5 k€ (765 m cable replacement). In contrast, the price of the regulator is roughly equal to 20 k€, so it is possible to conclude that it represents a cheaper alternative to line expansion. The costs indicated at the time of writing this article could change in the near future due to the international geopolitical situation (e.g. the continuation of the war in Ukraine) and the scarcity of material supplies in the post-pandemic situation COVID-19.

In addition, from the technical point of view, always if compared to line expansion, the following further benefits must be taken into consideration:

- Flexible use: assembly/disassembly/change location if required;
- EN 50160 monitoring/data recording;
- Increase in the transmission power of the lines used by around 20%; and,
- Reduction of network losses.

VII. CONCLUSIONS

Voltage regulation problems can occur in low-voltage distribution grids when high PV penetration exists. Smart features of modern power electronics longitudinal (series) voltage regulators can be implemented to improve the voltage profile of the power grid and the overall performance of PV systems connected to the distribution grid at a reasonable investment cost when compared to traditional grid reinforcement.

In this context, the article provides a comprehensive view of a planning method to solve voltage regulation problems in low-voltage grids, which may represent the best compromise for the distributor who needs to ensure good quality electrical service and the producers who are entitled to have a grid that allows them to maximize their investments without interruptions in power generation due to technical limitations of the electrical distribution system.

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IX. BIOGRAPHIES

Emilio Ghiani (M'03, SM'15) graduated in electrical engineering from the University of Cagliari in 1999 and received his Ph.D. in electrical and computer engineering in 2005.
He is currently an associate professor of power systems in the Department of Electrical and Electronic Engineering, where he teaches power generation, control and electrical markets for undergraduate courses in electrical and energy engineering.
His research focuses mainly on the development of methodologies and tools for decision making processes in planning and operation of power distribution networks with large penetration of distributed energy resources. His research interests includes all aspects related to network integration and control of renewable generation with smart grid operation.
He is the author of more than 100 papers published in international journals or presented at various national and international conferences, and 8 book chapters dealing with smart grids, network planning for integration of renewable sources and distributed energy resources, energy communities and microgrids, receiving 1800+ citations with and h-index 22 (Scopus data January 2023).

Rocco Di Gregorio graduated from high school as an electrical technician in 2009.
In 2019 he started at VOLTA S.p.a. in the power quality department as a sales and project manager, in 2020 he became national business development manager for smart grid systems and application.
During ICHQP 2022 conference he was the recipient of "Constantin Budeanu" best paper award 2022.

Stefan Hoppert graduated in electrical engineering from the University of Applied Science of Würzburg-Schweinfurt in 2010. From 2019 to 2021 he studied business management at the Friedrich Alexander University in Nuremberg and graduated with an MBA.
In 2010 he started at A. Eberle GmbH & Co. KG in the power quality department as a support engineer, in 2012 he became product manager for smart grid systems and in 2019 he became head of the operative business.
He is currently a Managing Director at A. Eberle.

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