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REGULATING NETWORK VOLTAGES OF UNBALANCED LV GRIDS USING A DISTRIBUTED REACTIVE POWER CONTROL SYSTEM

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Abstract
The demand for renewable energy rather than fossil fuels is on the increase. This paper suggests a novel control technique for voltage regulation in unbalanced LV distribution networks featuring substantial decentralized renewable energy generation shares. The proposed technique relies heavily on the reactive power of distributed renewable energy sources. Additionally, its distinguishing characteristic is the application of a distributed control architecture that gives priority to DRES responses to keep network voltages within safe parameters and to reduce network losses. In this model, decisions are made locally by each DRES using information from the sensitivity theory, local measurements, and measurements acquired by the other network DRESs. By running time-domain and time-series simulations, it was concluded that the proposed model outperforms decentralized solutions and exhibits near-optimal behavior compared to optimization-based methods but with less computation complexity and monitoring requirements.

Keywords: network, voltage, LV, reactive power control

Introduction

Nigeria is the most populous country and largest economy on the African continent. The country has one of the world's fastest-growing populations, which has resulted in a rapidly expanding demand for energy, which will be critical to unlocking further economic progress. This provides a significant opportunity to harness the country's abundant natural renewable energy resources. Renewable energy has the potential to not only assist Nigeria in satisfying its energy requirements but also in fostering long-term economic expansion, generating employment opportunities, and contributing to the realization of global climate and sustainable development goals. Although the country is rich in renewable energy sources, less than 25% of the renewable energy potentials have been utilized (Jelili et al., 2022). The demand for renewable energy rather than fossil fuels is on the increase. However, power output from renewable sources depends on variable natural resources, making these plants more difficult to control and challenging grid operators.

Distributed generation describes electricity generated from sources, often renewable energy sources, near the point of use instead of centralized generation sources from power plants. Distributed Renewable Energy Sources (DRES) are instrumental in modern smart grids (Althobaiti et al., 2020). Due to the energy transition process, distribution systems will feature a high penetration of distributed renewable energy sources (DRESs) (Liu et al., 2023). Consequently, the penetration level of distributed renewable energy resources is increasing (Anaadumba et al., 2021; Ansarin et al., 2022; Bougouffa & Chaghi, 2021; X. Liu & Bie, 2021; Malamaki et al., 2022; Shuaibu Hassan et al., 2020), posing a series of technical challenges related to the secure and reliable operation of distribution grids (Walling et al., 2008). The advent of DRESs has led to technical issues affecting active distribution networks' secure and reliable operation. Indeed, under/overvoltage, current overload, and voltage unbalance are considered the most critical challenges limiting the increase of DRES penetration (Pippi et al., 2022)
Most DRESs are decentralized units usually connected to low-voltage (LV) distribution grids. Voltage irregularities usually limit the PV hosting capacity of an LV grid (Hashemi & Østergaard, 2018). Considering low-voltage (LV) distribution grids, voltage rise is considered the most crucial issue hindering the further increase of DRES penetration (Malamaki et al., 2022). Some techniques, such as active power control (APC) (Aboshady et al., 2023) and reactive power control (RPC) (Almeida et al., 2021) methods, have been proposed to maintain the power quality and voltage levels within the tolerance limit. Active power control includes generation curtailment, demand response, and use of energy storage systems (Kryonidis et al., 2021), while reactive power control involves using the available reactive power of DRESs (Wang et al., 2020).

On the other hand, the APC method can be seen as a strategy for long-term energy management, in which energy consumption can be reduced, moved, and stored. This poses several drawbacks related to loss of green energy (GC), consumer inconvenience, and additional installation and operation costs. The RPC, on the other hand, can successfully overcome these problems. RPC is the first option to regulate voltage even in LV grids, where its efficiency is diminished because of the high R/X ratio of lines. This is the case even if RPC's effectiveness is lowered. This paper proposes a distributed system for the optimal voltage regulation of unbalanced LV grids. The suggested model aims to reduce network losses by evenly distributing reactive power among the DRESs.

Proposed Model

This section introduces a decentralized control technique for balancing voltage on LV grids that are not in phase with one another. It differs from traditional centralized and distributed optimization approaches by employing a rule-based approach to coordinate DRESs, which results in lower computational complexity and less stringent monitoring requirements. DRESs primarily carry out the voltage regulation of LV grids. Kryonidis et al. (2021) have demonstrated that an overvoltage occurs at a specific network node, and the DRES located at the node absorbed reactive power to tackle this problem with the minimum network losses. However, the lines in LV grids have a high R/X ratio. Therefore, the reactive power of the DRES at a given network node generally will not be enough to handle the overvoltage mitigation of that node in the event of an overvoltage. Therefore, the overvoltage at this node will continue, and another DRES in the network will have to absorb the reactive power.

The selection of the DRES that will contribute to the overvoltage mitigation of this node will be made based on the impact it may have on the network losses. According to the analysis presented in (Pippi et al., 2022), the network losses are increased when the selected DRES is located downstream or upstream of the node with the overvoltage. Therefore, network losses alone cannot serve as a sufficient criterion for selection. To solve this problem, the fundamental criterion for selecting the DRES is the network voltage's sensitivity to reactive power changes. To be more precise, a DRES with a high sensitivity will require less reactive power absorption for the exact voltage change at the same node than a DRES with a low sensitivity. It is important to note that network losses are highly correlated with the total reactive power absorbed. Thus, the network losses are kept to a minimum because the proposed selection strategy results in minimal reactive power absorption.

The distributed control architecture is shown in Fig.1. Following this approach, a two-way communication infrastructure is foreseen to exchange information among the DRESs. To be more explicit, it is the responsibility of each DRES to check the positive sequence voltage of all the other DRESs at the POI with the grid (Vpos). In order to accomplish this goal, each DRES transmits the positive-sequence POI voltage consistently, with the amount of time between transmissions ranging from a few milliseconds to several seconds. It should come as no surprise that the rate at which collected measurements are refreshed can affect the response of a distributed control scheme.

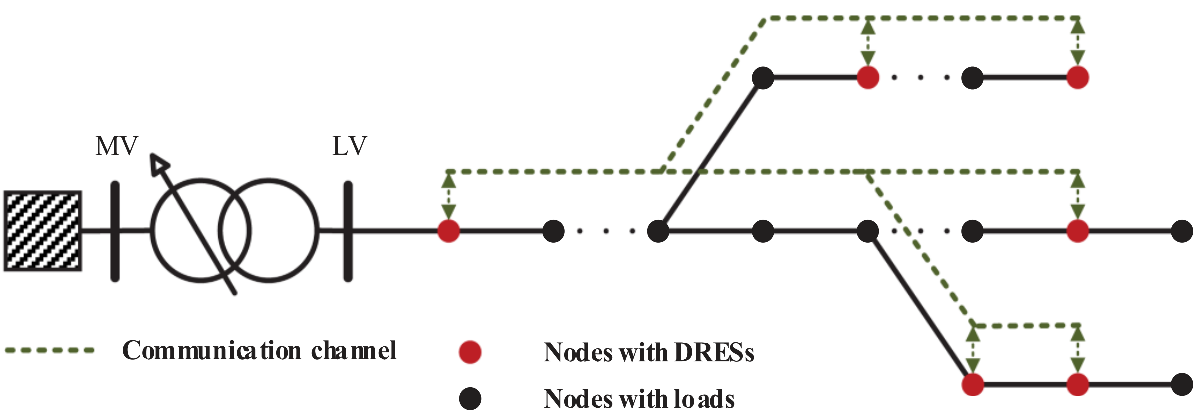

Fig. 2. Distributed architecture of the proposed model

The distributed control scheme is implemented by applying the control notion presented in Fig. 2 to each DRES. This control concept describes the dynamic operation of the DRES connected to node *j*. It consists of two operation modes separated by a small dead band (db), a time region in which no actions occur. This is done to prevent oscillations and repeated activation-deactivation cycles from occurring. The performance of the suggested method is not negatively impacted by the measuring devices' accuracy at the DRES; hence, this is how the dead band is established.

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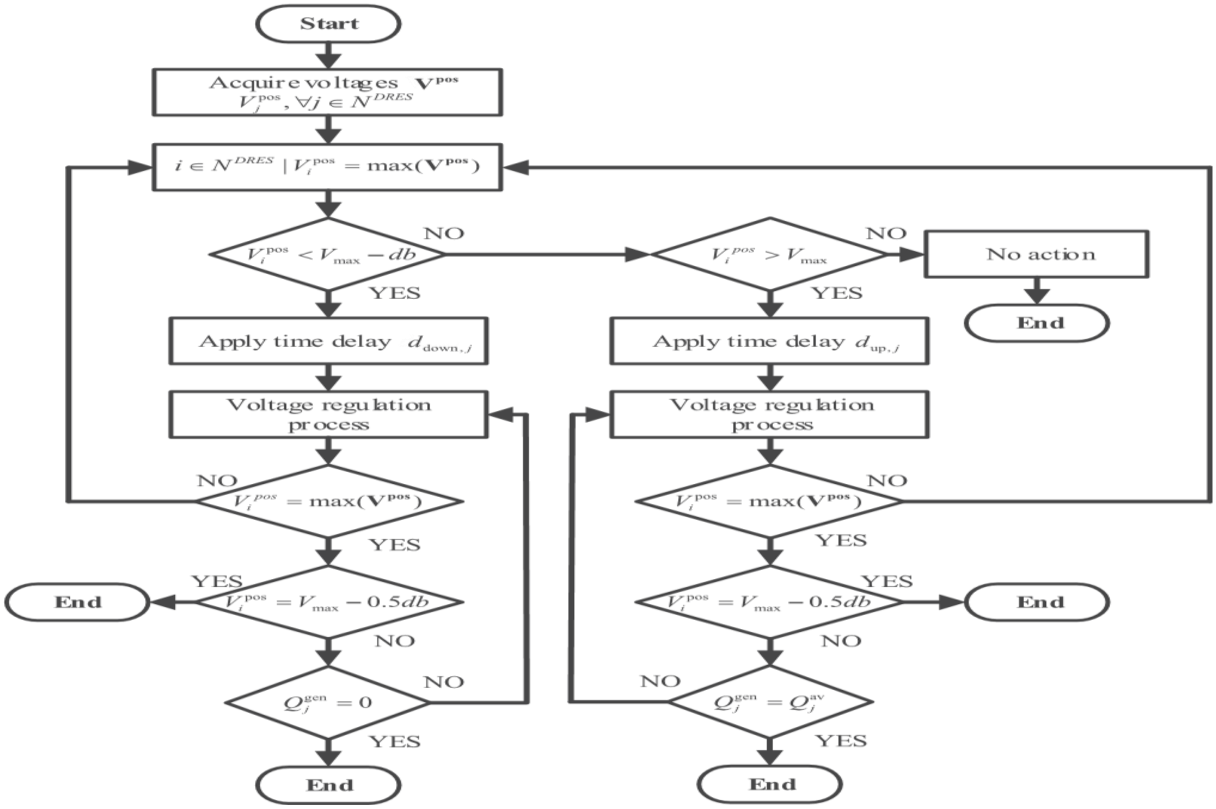


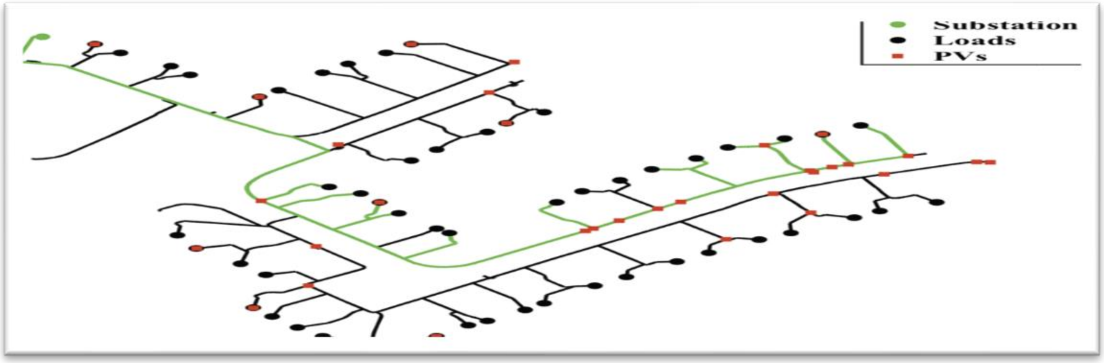
Fig. 2.Reactive power control scheme of the DRES connected to node j

Overvoltage suppression by reactive power absorption is the first mode of operation. This mode is engaged if V^{ipos} is more significant than V_{max}, and it is assumed that TN is located at node *i*. However, unique time delays are included in the response of each DRES to prevent the simultaneous activation of this mechanism ($d_{up,j}$). According to the theoretical control paradigm, the purpose of the time delays is to rank the DRESs' responses during a voltage violation event. The DRES begins absorbing reactive power after a lag time of ($d_{up,j}$), using a proportional-integral controller to remove the difference between the actual voltage (V^{ipos}) and the desired voltage (TV), which is Vmax 0.5db. Unless the voltage is effectively regulated or the TN is shifted to another network node, this process will continue up to the reactive power capability limit of the DRES. The latter requires starting over with a brand-new TN. The second operation mode includes the reverse process of properly reducing the reactive power consumption. This is activated when V_i^{pos} falls below the voltage threshold ($V_{\max} - db$). After a predefined time delay ($d_{\mathrm{down},j}$), the DRES reduces the reactive power to zero unless the voltage is regulated or the TN moves to another network node. In the latter case, the process is repeated for the new TN.

Time Delays Determination

The time delays are locally determined by each DRES combining two types of information, namely the positive-sequence POI voltages of DRESs and the sensitivity matrix. The former is used to define the TN, while the latter is employed to determine the sensitivity factors that quantify the impact of the reactive power variation of DRESs on the TN voltage. Based on this information, each local controller sorts the sensitivities in descending order. In this list, the position of each sensitivity determines the time delay of the corresponding DRES. For example, assuming the first operation mode of Fig. 1, if the DRES at node *j* presents the *n*-th highest sensitivity, then this DRES will react to any voltage violation event following a time delay of $(n - 1)t_d$, where t_d is the time between two successive activations. A similar rationale determines the time delays in the second operation mode.

Traditionally, the sensitivity matrix is calculated by inverting the Jacobian matrix used in the Newton-Raphson approach for the power flow analysis of grids (Christakou et al., 2013)]. Nevertheless, this solution cannot be adopted in distributed architectures since all the necessary information, e.g., the admittance matrix of the network power injections at each node, should be gathered in a single unit. The method proposed by (Brenna et al., 2013) is adopted to calculate the sensitivity matrix and, thus, may help to overcome this issue. In particular, the sensitivity coefficients are determined using limited, time-invariant information, i.e., line impedances. Thus, it can be readily integrated into the proposed distributed method by calculating offline the sensitivity coefficients and forwarding them to the local controller of DRESs. The DSO can undertake this process and be repeated in case of network reconfiguration. Based on the above analysis, the duration of the voltage regulation process (T_{reg}) is equal to Kt_d, where K denotes the number



of activations of the reactive power control scheme among the DRESs.

Fig. 3. *One-line diagram of the European LV test feeder. The part of the grid denoted with green color is used to perform time-domain simulations*.

It should be noted that T_{reg} should be less than the activation time of the built-in overvoltage tripping mechanism of DRESs to avoid possible interference. This can be attained by reducing either t_d or K. The former can be implemented using a communication infrastructure that supports fast data exchange with minimal latency. The latter can be achieved by grouping the activation of the reactive power control among the DRESs. For example, DRESs with similar sensitivities can be grouped to react concurrently toward a voltage violation event. This reduces the number of activations K, leading to a smaller T_{reg}.

Table 1 shows the connection node and rated power of the installed PV

Node	kWp	Node	kWp	Node	kWp	Node	kWp	Node	kWp
70	5	320	10	482	5	619	5	861	5
73	10	388	5	556	5	651	5	869	5
166	5	388	5	556	5	681	10	882	10
219	10	447	5	580	5	785	5	885	5
234	5	453	5	580	5	763	5		
247	5	461	10	588	5	794	10		
248	5	476	10	644	10	845	5		

Table 2 shows nodes of loads and PVs used in the time-domain simulation

PV	**247**	**388**	**447**	**453**	**461**	**476**	**482**
PV	567	580	588	604	619	651	681
Load	19	20	21	22	23	29	31
Load	34	35	36	37			

Numerical outcome

The performance of the proposed voltage regulation method is assessed by performing time-domain and time-series simulations. The one-line diagram of the examined network is depicted in Fig. 3 and consists of a 906-bus LV network with radial configuration, feeding 55 single-phase loads. This allows the investigation of the proposed voltage regulation of LV grids under real-field conditions. In order to overcome the absence of DRESs in the original configuration of the network, 32 three-phase PVs are randomly allocated to the LV network. The connection node and the rated power of the installed PVs are presented in Table I, while the location of each PV is graphically depicted in Fig. 4 using the red square symbol. The rated power factor (PF) of PVs is 0.85.

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Time-Domain Simulations

The performance of the proposed distributed voltage regulation strategy is evaluated by performing time-domain simulations with the PSIM software (Pompodakis et al., 2021). This modification is made to decrease the execution time of the simulation process to a reasonable value. In particular, the part of the grid denoted with green color is considered in the time-domain simulations, consisting of 250 nodes. Only the PV units and loads directly connected to these nodes are included in these simulations. Their connection node is presented in Table 2.

The suggested voltage regulation system is tested in the worst-case scenario, which occurs at 13:53 h and includes maximum generation and minimum consumption. The PV units inject their rated power into the grid at this point, whereas the absorbed power of the loads is determined by the appropriate profiles specified (Kersting, 2011). Furthermore, a balanced network is assumed by examining just the positive sequence components of the lines, although loads and PV units with three-phase designs are evaluated. The voltage deadband (db) is finally equivalent to 0.01 p.u. The voltage on the slack bus is assumed to be 1.0675 p.u. The rated power of all PV units is fed into the LV grid. Maximum network voltage occurs at the PV619 POI located at node 619. This node is one of the network's most remote nodes with PV units. Figure 5 depicts the RMS value of the voltage magnitude detected by the PV619. The reverse power flow induced by the injected power of the PV units results in overvoltage.

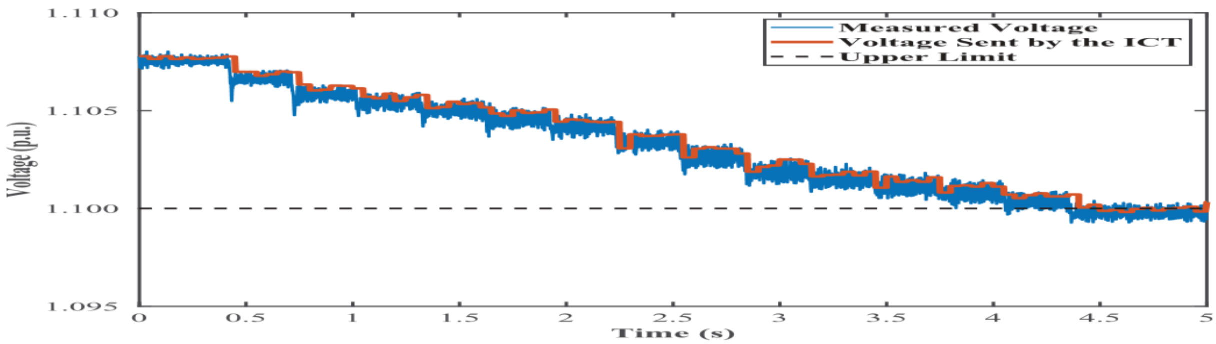

Fig 5. RMS voltage magnitude at the POI of the PV619, where the maximum network voltage occurs

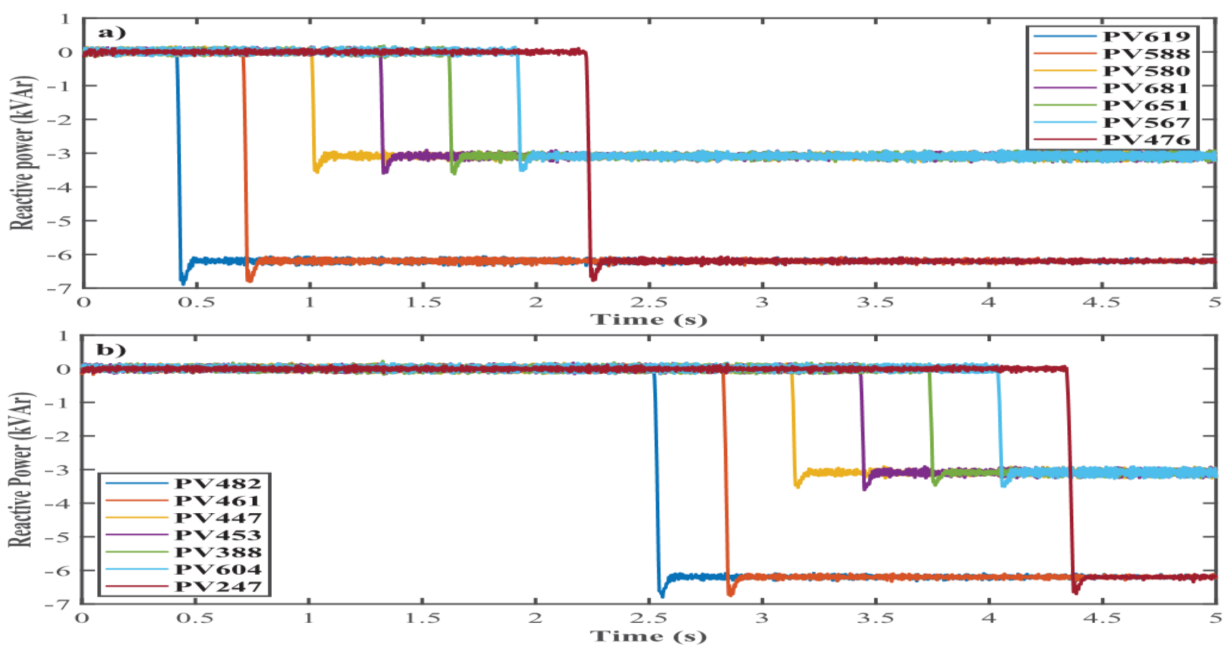

Fig 6. Reactive power of PVs.

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Table 3: shows time delays for the PV units

PV	**247**	**388**	**447**	**453**	**461**	**476**	**482**
d_{up}	3.9	3.3	2.7	3.0	2.4	1.8	2.1
d_{down}	0.0	0.6	1.2	0.9	1.5	2.1	3.0
PV	567	580	588	604	619	651	681
d_{up}	1.5	0.6	0.3	3.6	0.0	1.2	0.9
d_{down}	2.4	3.3	3.6	0.3	3.9	2.7	3.0

At 0.4 s, the reactive power absorption mechanism is activated. According to the analysis described in Section IV-C, each PV unit may decide the delay that will be applied to a voltage violation event by combining the information gained from the sensitivity theory and the remaining PV units of the network. The time lags are detailed in Table 3. For instance, PV619 will respond immediately to overvoltage because it has the highest voltage sensitivity at node 619, the node with the highest network voltage, with regard to variations in reactive power. This allows it to respond immediately to any overvoltage that occur. In addition, PV588 has the second most significant level of sensitivity. As a result, the process of reactive power absorption will become active following a delay of 0.3 seconds. Table 3 provides an overview of the time delays associated with the remaining PV units. When determining the time delays during the reverse process of appropriately reducing the reactive power absorption, PV units use a line of reasoning analogous to the preceding one.

The voltage sent by each PV unit is modeled as a discrete signal with a refreshing period of fifty milliseconds so that the behavior of the ICT system can be mimicked as closely as possible under real-field situations. As an illustration, the voltage that PV619 transmitted is shown in Fig. 5 as the orange line. It is essential to point out that relatively low values have been assigned to the time delay between two consecutive activations of the process that absorbs reactive power and the refresh rate of ICT. This option has been chosen to cut down on the total time needed to complete the time-domain simulation process. These time constants can be increased in real-field conditions without negatively impacting the effectiveness of the suggested voltage regulation approach; however, this is only possible when the conditions are more extreme.

Figure 6 depicts the reactive power output of the PV units participating in the overvoltage mitigation process, whereas Figure 5 depicts the maximum network voltage. As seen in Fig. 6, PV units initially run at a PF of one. The proposed voltage regulation control technique is initiated at 0.4 s. PV619 immediately responds to overvoltage by raising reactive power until the minimum PF of 0.85 is met. The highest network voltage is lowered in Fig. 5, although it is still substantially beyond the maximum allowed limit. Thus, after a 0.3-second delay, the voltage regulation mechanism moves on to the next PV unit in the activation sequence, PV588, which increases the absorbed reactive power until the lowest PF is reached, as shown in Fig. 6. This procedure is repeated until the maximum network voltage is finally adjusted at 4.4 seconds. During this procedure, the activation sequence of the reactive power control among the PV units adheres to the time delays shown in Table 3. As a result, the reactive power is appropriately distributed among the PV units, resulting in near-zero network losses.

Discussion

When used in LV grids that have a high R/X ratio, the RPC's usefulness is significantly diminished. Therefore, it is likely that the available reactive power of DRESs may not be sufficient to maintain the network voltages within the legal limits. This is because DRESs are relatively new technologies. In order to solve this problem, APC should be utilized as an additional technique for voltage regulation. It is essential to point out that the RPC step should come before the APC step in the activation sequence. The effect of the APC's participation in the voltage regulation can thus be reduced to a minimum using this method. This suggestion does not cover further examinations into the combined operation of APC and RPC, which are considered future research efforts. Instead, they are outside the scope of this particular paper. As the standard requires, the voltage regulation technique is compliant with managing only the positive sequence component of the network voltages. Despite this, the zero- and negative-sequence voltages should also be managed if the network has significant levels of imbalance. It is possible to achieve this by utilizing any of the numerous voltage imbalance mitigation (VUM) approaches suggested in the relevant research (Kersting, 2011). In addition, because the proposed approach for voltage control has been implemented in the positive-sequence domain, it is easily combinable with VUM techniques without the two methods interfering with each other. This is one of the many benefits of using the positive-sequence domain.

Conclusion

The study proposes a new distributed control strategy for regulating network voltages of unbalanced LV grids while minimizing network losses. Decisions are made locally by each DRES using information from the sensitivity theory, local measurements, and measurements acquired by the other network DRESs, according to the proposed model. By running time-domain and time-series simulations, it is possible to conclude that the suggested method outperforms decentralized solutions and exhibits near-optimal behavior compared to optimization-based methods but with less computation complexity and monitoring requirements.

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