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Renewable energy communities virtual islanding: A decentralized service to improve distribution grid security

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ABSTRACT

This article presents a novel service provided by Renewable Energy Communities (RECs) for the distribution network. This service, called Virtual Islanding (VI) and ideally requested to the RECs by the Distribution System Operator (DSO), basically consists in requiring that the net active power exchange between the involved REC and the main grid is zero for a specified time frame. The effectiveness of RECs VI operation is assessed using an Optimal Power Flow (OPF) that considers distribution network operational limits. Simulations, performed in a test case distribution system with massive penetration of RES, highlight the VI benefits both from a technical and sustainability viewpoint.

1. Introduction

In the 2030 scenario, the significant presence of Renewable Energy Sources (RES) in distribution grids prompts the need to define innovative flexibility services to manage dispatchable technologies, prevent RES curtailment and increase hosting capacity. Implementing a centralized control strategy, where the Distribution System Operator (DSO) manages a great number of dispatchable units in both the MV and LV networks, would allow to maximize the exploitation of RES [1]. However, this solution is currently hardly implementable due to the lack of established TSO/DSO coordination systems and of an architecture where the DSO can manage a very large set of flexibility resources belonging to multiple users in the grid [2]. For this reason, DSOs are trying to define, decentralized solutions for grid support services that represents a more feasible and applicable solution in the current grid scenario [3]. On this regard, in [4], five main research gaps for decentralized control of distributed flexible resources have been identified: *(i)* autonomous optimal dispatch without central coordination, *(ii)* financial advantages with respect to market situation, *(iii)* autonomous and decentralized coordination to prevent grid congestion, *(iv)* separation from institutional load monitoring, and *(v)* scalability to large grid systems.

In the literature, there are some examples of decentralized control for congestion management in distribution systems, which partially solve these research gaps. For example, in [5], a method based on the use of gossip algorithms was proposed. This method is intuitive, robust, and allows to clear congestion sharing the control effort among multiple DERs according to an optimal law. However, the method is still based on the knowledge of the exact amount of power to be compensated, which is an information that must be provided centrally by the DSO. In addition, the control is based on the active power exchanged only at the beginning of the feeder. This means that congestions happening intra-feeder cannot be compensated (as it could happen for example if large, lumped loads and RES are located in different portions of the same feeder). An alternative multi-agent system approach proposed in [4] does not require information from a centralized unit, but still relies on the calculations made by a Congestion Management Agent (CMA), which gathers information from all connected users to calculate the cable usage and pass these data onto the next CMA. The limit of this approach is that it relies on the assumption that each CMA, which seems to be located at the secondary substation level, has a perfect observability of what happens below its connection point.

In this context of decentralized and autonomous grid support, Renewable Energy Communities (RECs), which were introduced by the EU Directive 2018/2001/EU and are currently experiencing a rapid and extensive growth [6], can be seem as providers of novel grid services. RECs naturally aggregate distributed energy resources and coordinate their use independently from the DSO to fulfil self-sufficiency and other

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energy efficiency goals. The potential of RECs in offering services to the power system is highlighted in [7], where the authors propose the optimal management of a local distributed energy storage community to improve self-consumption and provide ancillary services. Considering this application, the REC could be configured as a community-based Virtual Power Plant (cVPP), i.e. a collection of Distributed Energy Resources (DERs) that are coordinated by an ICT-based control system and adopted by individuals who collectively play an active role within the energy system [8].

This article proposes an alternative idea for a novel service provided by REC that includes flexibility resources called Virtual Islanding (VI). The idea is partially inspired by the physical islanding operation of MGs and by the possibility of utilizing REC similarly to a cVPP. However, the following differences need to be considered. In a REC, physical islanding is not feasible, since its members can be located in any point of the grid, as long as they are served by the same primary substation. With respect to using REC as cVPP, thus requiring any net active power exchange beside the net zero, one needs to recall the main aim of RECs that is maximizing the sharing of RES production; this is also the element that provides revenue for the REC. VI operation thus represents the REC ideal operation where the RES generation is perfectly balanced by the REC consumption.

The proposed VI service requires RECs to operate in a (quasi) real-time active power balance configuration with the aim of providing a positive impact on voltage profiles, lines loading, and substation congestion and the aim of self-compensating the fluctuations of RES generation and loads. Consequently, the effects of RECs VI control include a reduction in the vulnerability of the electricity system to unpredictable or volatile operational circumstances, and an increase in the share of renewable energy in the distribution system. The idea is that VI is a service that the DSO may require to specific RECs in its power grid when expected grid power flow scenario is critical.

With respect to physical islanding VI can provide some interesting advantages such as involving only active power, leaving reactive power available to additional voltage support purposes, or allowing REC users to remain connected to a robust and reliable grid [9]. This latter aspect implies that even if a null power balance cannot be achieved for some short time interval, e.g. due to a lack of available power from storage or other flexibility resources, users would not experience any risk for their power supply. The same cannot be said if a MG is physically islanded since the shortage of resources may cause partial load/generation disconnection or even a complete MG blackout [10]. For this reason, REC user participation in this novel service is highly likely and more reliable.

Design and implementation of VI are beyond the scope of this work, that rather aims at showing how VI service may provide sensible benefits to the grid and thus represents an interesting novel grid support service. However, it is worth pointing out that the proposed VI service could be easily implemented for REC exploiting the already present aggregation and communication links among REC members, necessary by regulation to measure and quantify the REC shared energy and remunerating the REC and its members. Minor improvement of the REC control resources is thus necessary, related to the need of transmitting additional control signals to the REC users to adjust their behaviour. This can be easily incorporated with standard IoT protocols for home and industrial automation. This aspect allows pointing out the high scalability of the proposed approach, that can be implemented easily by many RECs independently.

Finally, as far as the previously mentioned research gaps about distributed power system management is considered, the proposed VI service fulfils most of the gaps previously listed. The proposed VI approach is decentralized, and it can be implemented autonomously without the involvement of the DSO. None of DSO-owned pieces of equipment are needed, because it all relies on the monitoring and management functions which are developed within the REC. Economic advantage for REC members can be introduced to encourage participation in the control of grid congestions or other security violations. The approach is also naturally scalable.

Test results, developed in a real-world scenario, show the impact of VI applied to a realistically-sized network in the presence of a very large RES penetration.

2. Methodology

The following methodology is proposed to assess the expected impact of implementing VI in a distribution grid with several RECs. The main assumption is that within RECs there are available flexibility resources (e.g. distributed RES, energy storage system (ESS), demand response (DR) and controllable loads, etc.) that can be used to alleviate or solve static security problems such as overloads, congestions, under- or over-voltages in the distribution grid.

The starting point of the following static analysis is given by the results obtained simulating, over a large time window, the performances of a distribution grid characterized by a credible scenario of intense demand and RES capacity increase, namely Base Reference Scenario (BRS). For the BRS, it is assumed to know the active and reactive power of each technology connected to grid (e.g. RES, loads, ESS, etc.) to evaluate security violation for each time step. As previously discussed, it is commonly recognized that DSOs should cope with energy transition through the exploitation of flexibility resources. Ideally, DSOs should gain complete control over distributed energy resources, to be exploited during system operation in a real-time SCADA or Distribution Management System (DMS) framework. This centralized solution, that would provide the best impact on the grid operation, is today hardly feasible from a practical viewpoint since this would imply that the DSO shall have the capability of monitoring and controlling a huge number of flexibility resources property of private and industrial users. Beside the computational complexity of such approach, the practical feasibility is also limited by the necessity of realizing a connection between the DSO and each user participating in the system. On the contrary, demanding the service to the RECs make firstly the solution of the problem much easier and, moreover, allows exploiting the juridical entity of the REC, that to exist, needs to create a management and monitoring architecture to comply with regulatory requirements to operate as a REC [11].

The proposed VI service is based on the possibility of decentralizing the management of flexibility resources considering n_{REC} decoupled optimization problems solved to impose VI condition for each REC. Each problem is formulated considering the availability of flexibility resources within each REC and does not include grid constraints. Clearly, this decentralized approach will find a sub-optimal configuration with respect to the centralized DSO control, however, its applicability is much easier and less impactful from a computation viewpoint.

The decentralized VI control problem for the generic i^{th} REC minimizes an objective function aimed to minimize the control effort. The main idea of this cost function is to achieve the desired goals, while minimizing the deviation of flexibility resources with respect to the BRS values:

$$C_{RECi} = \sum_{j=1}^{n_{RES,i}} \left(\frac{u^0_{RESi,j} - u_{RESi,j}}{u^{\max}_{RESi,j} - u^{\min}_{RESi,j}} \right)^2 + \sum_{j=1}^{n_{ESS,i}} \left(\frac{u^0_{ESSi,j} - u_{ESSi,j}}{u^{\max}_{ESSi,j} - u^{\min}_{ESSi,j}} \right)^2 + \sum_{j=1}^{n_{DR,i}} \left(\frac{u^0_{DRi,j} - u_{DRi,j}}{u^{\max}_{DRi,j} - u^{\min}_{DRi,j}} \right)^2 \quad \forall i^{th}\text{REC} \tag{1}$$

where $n_{RES,i}$, $n_{EES,i}$ and $n_{DR,i}$ are respectively the number of RESs, ESSs and DRs in the i^{th} REC; $u^0_{RESi,j}$ is the initial active power injection from the generic j^{th} RES in the i^{th}REC; $u^0_{ESSi,j}$ is the initial active power injection from the j^{th} ESS in the i^{th}REC and $u^0_{DRi,j}$ is the initial active power absorbed by the generic j^{th} controllable load. in the i^{th}REC. The control variables $u_{RESi,j}$, $u_{ESSi,j}$ and $u_{DRi,j}$ are defined analogously as their respective initial values. Maximum and minimum values of the control

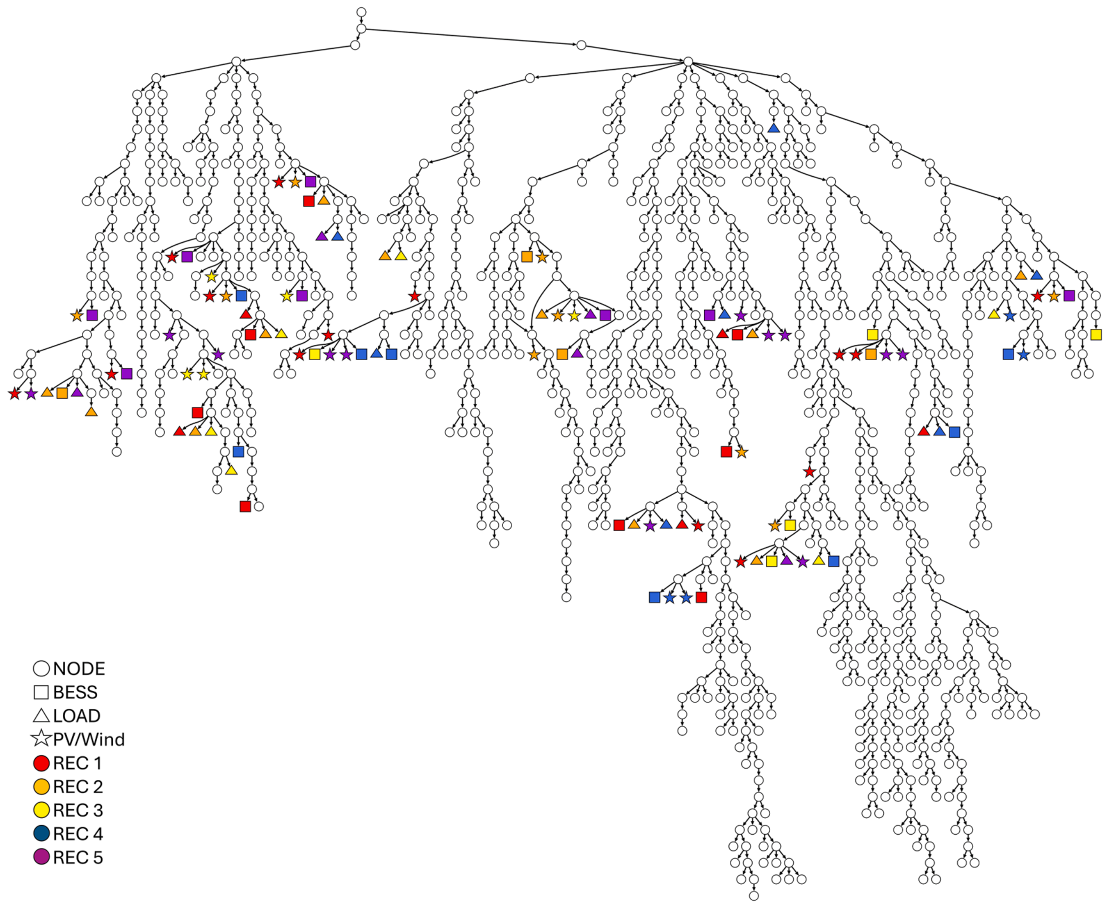

Fig. 1. Distribution grid layout and RECs assignment of Case VI – 5 RECs.

variables are used to normalize the control effort spent on each resource with respect to its capability.

This notation is general enough to model any kind of flexible resource (curtailable generation, dispatchable generation, curtailable and controllable loads, demand response, etc.). For example, in the case of a RES unit operating at MPPT, $u^{\max}_{RESi,j}$ can be assumed equal to $u^{0}_{RESi,j}$. The same assumption can be made also for a curtailable load, where $u_{DRi,j}$ cannot be more than $u^{\max}_{DRi,j}$. In the case of controllable loads or generator the control variables can be assumed to vary in a broader range. In storage systems, $u^{\max}_{ESSi,j}$ and $u^{\min}_{ESSi,j}$ represent the maximum charge and discharge, respectively.

The proposed VI control problem is subject to the following VI equality constraint, defined for each i^{th} REC:

$$\sum \boldsymbol{P}_{G,i} - \sum \boldsymbol{P}_{L,i} + \sum_{j=1}^{n_{RES,i}} \left(u_{RESi,j}\right) - \sum_{j=1}^{n_{ESS,i}} \left(u_{ESSi,j}\right) - \sum_{j=1}^{n_{DR,i}} \left(u_{DRi,j}\right) = 0 \qquad (2)$$

where $\boldsymbol{P}_{G,i}$ and $\boldsymbol{P}_{L,i}$ are respectively the sets of non-dispatchable generation and load. Please note that, in (2), a load convention for storage units was assumed (i.e. $u_{ESSi,j}$ is positive during charge).

In addition, the following limits on flexible resources capacity must be respected:

$$u^{\min}_{RESi,j} \le u_{RESi,j} \le u^{\max}_{RESi,j} \quad \forall \text{RES}(i,j) \qquad (3)$$

$$u^{\min}_{ESSi,j} \le u_{ESSi,j} \le u^{\max}_{ESSi,j} \quad \forall \text{ESS}(i,j) \qquad (4)$$

$$u^{\min}_{DRi,j} \le u_{DRi,j} \le u^{\max}_{DRi,j} \quad \forall \text{DR}(i,j) \qquad (5)$$

Please note that the minimization of (1) subject to (2)-(5) for each REC does not include network constraints and can therefore be decoupled and solved independently by each REC making the problem solution very less cumbersome.

To evaluate the effectiveness of the proposed VI decentralized service comparison is provided with the ideal and theoretical centralized DSO control. Ideal results of the centralized DSO control can be obtained through the Distribution Optimal Power Flow (DOPF) routines presented in [12], which allow easily solving optimization problems in large-sized MV/LV distribution radial networks, in the presence of multiple objectives and operational constraints.

In particular, the centralized DSO control considers a DOPF aimed to minimize the overall use of flexible resources across all RECs. If n_{REC} is the number of RECs participating to VI control, the objective function to be minimized is formulated as:

$$C_0 = \sum_{i=1}^{n_{REC}} \left(\sum_{j=1}^{n_{RES,i}} \left(\frac{u^0_{RESi,j} - u_{RESi,j}}{u^0_{RESi,j} - u^{\min}_{RESi,j}} \right)^2 + \sum_{j=1}^{n_{ESS,i}} \left(\frac{u^0_{ESSi,j} - u_{ESSi,j}}{u^{\max}_{ESSi,j} - u^{\min}_{ESSi,j}} \right)^2 + \right.$$
$$\left. + \sum_{j=1}^{n_{DR,i}} \left(\frac{u^0_{DRi,j} - u_{DRi,j}}{u^{\max}_{DRi,j} - u^{\min}_{DRi,j}} \right)^2 \right) \qquad (6)$$

With the centralized DSO control, the minimization of (6) is subject to load flow equality constraints, expressed implicitly in (7) and security inequality constraints considering voltage limits, line current loading and transformer power limits (8)-(10). The problem can be solved through any DOPF routine. For the interested reader, more information about the DSO centralized control implementation can be found in [13].

$$\boldsymbol{g}(\boldsymbol{V}, \boldsymbol{\theta}, \boldsymbol{u_{RES}}, \boldsymbol{u_{ESS}}, \boldsymbol{u_{DR}}) = 0 \qquad (7)$$

Table 1
Hours with violations.

Scenario	Overall	Lines	UnderV	OverV	Transf.
BRS	1599	1010	93	1498	354
Centralized DSO	0	0	0	0	0
VI Control - 1 REC	230	112	65	157	0
VI Control - 5 RECs	200	94	41	110	0
VI Control - 10 RECs	163	83	32	77	0
VI Control - 15 RECs	143	87	32	56	0

Table 2
Total number of violations for branches and nodes.

Scenario	Lines	UnderV	OverV	Transf.
BRS	32,226	10,008	779,993	354
Centralized DSO Control	0	0	0	0
VI Control - 1 REC	194	13,168	26,752	0
VI Control - 5 RECs	112	5814	18,130	0
VI Control - 10 RECs	107	2567	13,824	0
VI Control - 15 RECs	120	4474	6765	0

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad \forall i^{th}\text{bus} \tag{8}$$

$$I_j \leq I_j^{\max} \quad \forall j^{th}\text{line} \tag{9}$$

$$S_k \leq S_k^{\max} \quad \forall k^{th}\text{transformer} \tag{10}$$

In particular, the routine presented in [12] was adopted because of its simplicity of implementation and good convergence behaviour even in the presence of realistically sized radial distribution networks.

Since RECs in the proposed VI decentralized control dispatch their own resources without an overlook of the network, one could argue that VI control could be scarcely effective, or even counterproductive. For this reason, the solutions obtained by solving all n_{REC} decentralized VI control problems are used to run a power flow calculation, evaluate the violations of constraints (8)-(10) and then compare results with the ones obtained through the ideal centralized DSO control.

An improvement of the VI formulation may include sensitivity signals, provided centrally by the DSO and based on the system operating state, to limit or inhibit the use of certain flexible resources. Sensitivity signals can be used to avoid the use of those flexible resources which might have a counter-effective impact on grid state. For example, in a feeder experiencing an overvoltage, battery power modulation is limited to a charge increase or controllable load variation to a load increase. This is a very simple feature that can be implemented changing maximum and minimum values ($u^{\max}_{RESi,j}$, $u^{\min}_{RESi,j}$, $u^{\max}_{ESSi,j}$, $u^{\min}_{ESSi,j}$, $u^{\max}_{DRi,j}$, $u^{\min}_{DRi,j}$) in (3)-(5).

3. Test results

Test results have been developed in a real-world scenario, considering the full model of the MV distribution grid supplying electricity to a medium-sized Italian city (about 50,000 inhabitants). The network is served by two HV/MV transformers (150/20 kV and rated capacity of 30 and 25 MVA), eleven MV feeders, 903 nodes, 930 lines and 502 loads. In addition, the presence of 111 distributed resources (i.e. 34 interruptible/controllable loads, 33 batteries, 34 photovoltaic and 10 wind power plants) belonging to the RECs has been assumed.

Four VI scenarios have been considered, characterized by increasing number of RECs, respectively 1 REC, 5 RECs, 10 RECs and 15 RECs. The set of flexibility resources is the same for all testcases and allocation in RECs has been done randomly. Applying this very unsystematic criterion means that RECs may have their elements scattered among different feeders. The grid layout is schematically depicted in Fig. 1 showing also one of the four configurations defined above.

The study case was developed starting from actual loading curves, measured every hour for every feeder during six months of operations (January to June). In order to simulate a realistic development scenario of energy transition, according to the 2030 energy transition goals proposed by the Italian Energy Plan (PNIEC), loads were increased by a 20 % and the overall RES generation (photovoltaic and wind) was sized so that 65 % of the load could be theoretically covered by the gross RES production. Following these assumptions, the overall load in the six months of operations is about 96,9 GWh, whereas the potential RES generation is 63,0 GWh. The peak load is about 38.5 MW, whereas the peak RES production is about 82.1°MW.

All RES generation, controllable loads and storage systems were assumed associated to a REC. The flexibility capacity associated to interruptible loads and RES generation is not predefined since it was assumed that, at each hour, these resources can be curtailed from an initial value to zero. In the case of RES production, this initial value is theoretically equal to the maximum RES generation that can be extracted at the MPPT. Overall, in the six-month simulation period, total RES generation varied from 0 to 82.1 MW, while interruptible load consumption ranged from 0 to 3.1 MW. Controllable loads, capable to both increase or decrease consumption, ranged between 0 and 20.0 MW. Finally, each of the 33 storage systems had a maximum charge and discharge rate of 1 MW.

The results of simulations are summarized in Table 1, which shows how, in six months of operation, and without any control of flexibility resources, the network would experience security violations in 1599 hours of operation. The base reference scenario (BRS) is clearly characterized by a huge number of violations, because of the assumed massive capacity of RES (more than 80 MW of RES in a grid with an overall 55 MVA rated capacity), necessary to reach at distribution level the programmed energy transition goals.

In order to give further metrics of the impacts on security, the overall number of security violations on branches and nodes is reported in Table 2, where multiple violations may occur in the same hour. The number of violations is very high also because conservative constraints were adopted (voltages between 0.95 and 1.05, whereas currents and powers below 100 % of the nominal value).

The ideal solution found in the centralized DSO control scenario is clearly the one that permits the maximum reduction of violations and optimizes the overall use of flexible resources. Nevertheless, the application of VI control, which makes no use at all of information about the network, is still able to drastically reduce violations in both number and significance. In a radial distribution system, significant over- or undervoltages, or congestions, affect big pieces of the network with all the elements in it. Therefore, the magnitude of the unsolved violations can be qualitatively inferred by the ratio between the number of components and the number of violation hours.

It is interesting to notice that increasing the number of RECs, at fixed total flexible resources, can also have a positive effect. Cumulatively, the contribution given by VI control on system is impressively significant with up to a 91 % reduction of hours with violations, while solving 99.6 % of branch congestions, 100 % of transformer overloads and 98.6 % of voltage issues. A graphical representation of the results is reported in Fig. 2 for busses and Fig. 3 for lines and transformers. With regard to VI operation, only results for 5 and 15 REC are shown to ensure readability.

Fig. 2 shows in form of a violin plot the distribution of voltages on all buses throughout the entire period of simulation. The violin plot shows also median and quartiles, allowing to have a more comprehensive view on data distribution. It can be noticed how most of overvoltage violations have been solved. In particular, the most extreme violations, with peaks much higher than 1.05 have disappeared in all cases. In the case of VI, few violations of voltage constraints remain. However, it should be argued that these violations are way below typical standard limits of quality of voltage (± 10 % in most standards and norm) and are experienced on very few buses. In addition, it can be noticed that the

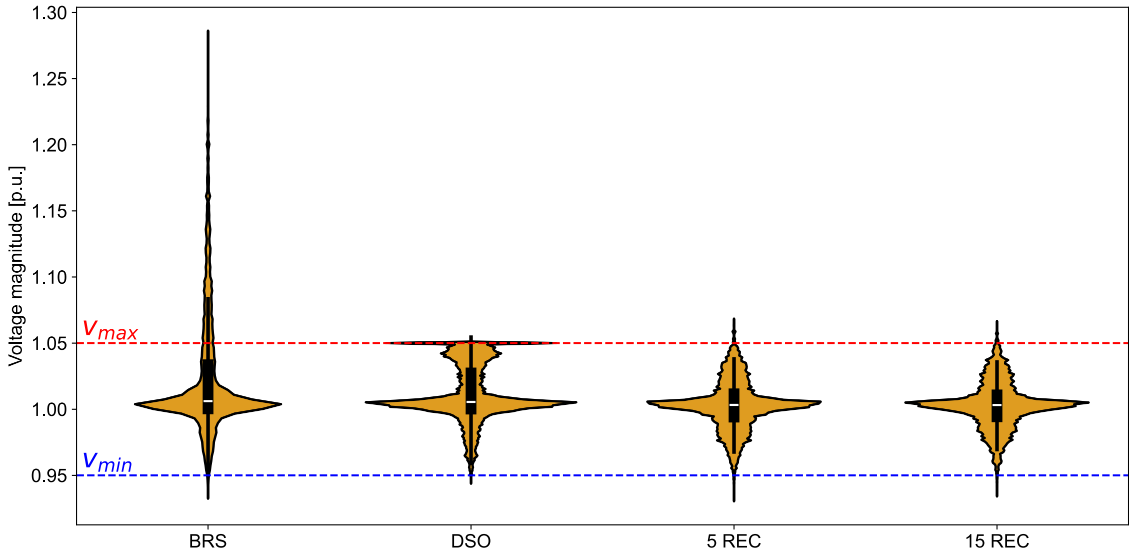

Fig. 2. Violin plot of voltage distribution in the considered configurations.

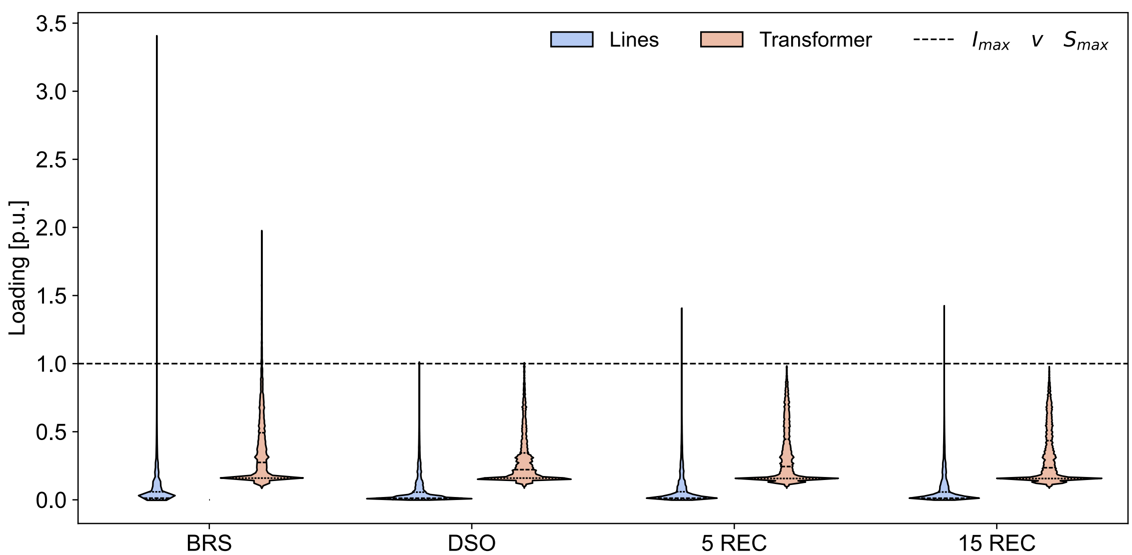

Fig. 3. Distribution plot of lines and transformer loading level for the configurations considered.

distribution of voltages in the centralized DSO approach is characterized by a different shape, with a bimodal distribution and larger variance. Being based on the solution of a constrained OPF, that typically converges to solutions on the frontier of the feasibility domain, the centralized DSO approach leads to solutions where a large number of nodes have voltages very close to the limit (1.05 p.u.). Instead, the VI operation leads to a more compact distribution of voltages, with lower dispersion around the average value (about 1 p.u.). The clearing of large overvoltage violations can determine an overall voltage decrease and, in some cases, lead to small undervoltage violations on few system nodes. This phenomenon was observed particularly in the case of a single VI, where the number of overall undervoltages appeared to have increased. These violations, which are anyway characterized by very small deviations below the threshold limit of 0.95 p.u., were significantly reduced with an increase of the number of RECs which resulted in a more balanced distribution of the control effort within the grid.

Fig. 3 is analogous to Fig. 2 and shows the distribution of loading level on all branches (lines and transformers). It is possible to observe how most severe congestions have been solved. In the case of VI, most unsolved congestions are characterized by overloads below 150 %, experienced only in very few branches. Although difficult to be appreciated in Fig. 3, this is clear from Table 2 where it is possible to notice how congestions were reduced from more than 30,000 to about a hundred.

Table 3
Total use of control resources.

Case	Generation [GWh]	Load [GWh]	Storage [GWh]
Centralized DSO Control	6.68	3.48	7.27
VI Control - 1 REC	10.28	8.54	15.65
VI Control - 5 RECs	15.08	7.11	12.29
VI Control - 10 RECs	16.46	6.67	11.34
VI Control - 15 RECs	15.84	6.42	12.22

Results are highly relevant if one thinks that the two compared approaches, centralized DSO and VI Control, have huge differences in the complexity of the problem solution, and practical feasibility and applicability in a real system; still, VI Control can solve the large majority of grid violations. On the other hand, VI Control consumes more control

Table 4
Hours with violations. (w/Sensitivity).

Scenario	Overall	Branches	UnderV	OverV	Transf.
BRS	1599	1010	93	1498	354
Centralized DSO	0	0	0	0	0
VI Control - 1 REC	229	110	63	156	0
VI Control - 5 RECs	184	77	29	110	0
VI Control - 10 RECs	151	81	8	75	0
VI Control - 15 RECs	119	66	19	51	0

Table 5
Total number of violations for branches and nodes (w/Sensitivity).

Scenario	Branches	UnderV	OverV
BRS	32,226	10,008	779,993
Centralized DSO Control	0	0	0
VI Control - 1 REC	183	11,306	26,743
VI Control - 5 RECs	88	3366	17,855
VI Control - 10 RECs	86	565	13,151
VI Control - 15 RECs	88	2453	6666

Table 6
Total use of control resources (w/Sensitivity).

Case	Generation [GWh]	Load [GWh]	Storage [GWh]
Centralized DSO Control	6.68	3.48	7.27
VI Control - 1 REC	10.31	8.51	14.97
VI Control - 5 RECs	15.03	7.12	11.55
VI Control - 10 RECs	16.31	6.81	10.54
VI Control - 15 RECs	15.72	6.80	11.25

resources with respect to the centralized DSO Control as one can notice in Table 3 showing, for each type of flexible resource, the cumulative control resource effort obtained by summing the absolute deviation of control resources from the BRS to achieve VI in the considered time period. This is because the equality constraint (9) forces RECs to achieve a net-zero energy instant by instant; a condition that may require more effort with respect to the centralized DSO Control.

As a final result, the same scenarios were simulated introducing the sensitivity coefficient described in Section 3 to improve the performance of the VI. Table 4 and Table 5 give an idea of how the performance of the VI control scheme can be generally improved thanks to a sensitivity-based consensus signal.

As one can see from Table 6, this improvement is obtained with a limited additional effort in terms of control resources.

An overall assessment of the impact of the proposed VI operation on the analyzed grid is reported in Fig. 4 where it is possible noticing the improvement trends on the considered violation by increasing the number of REC among which the service has been divided.

4. Conclusions

Results highlighted that REC VI control can provide a strong impact on the distribution power grids, comparable with a centralized optimization done by the DSO. Being based on a decentralized control, VI implementation appears promising because of its simplicity and possibility to well fit with novel aggregation configuration, i.e. RECs. The expected impact of VI goes beyond the results shown in this article; the real-time compensation of active power proposed by VI control can theoretically absorb most of the effects of RES volatility such as voltage fluctuations and reverse power flows from distribution to transmission. Moreover, results proved that VI can bring relief to operating conditions even if distributed resources belong to different feeders of the grid. This may allow extending the proposed idea beyond RECs, but as a novel way of users' aggregation, allowing to extend capacity and perimeter of the service on a wider area, including grid portions served by different primary substations. Further investigation about VI control, in line with the proposed sensitivity coefficient solution, may lead to even more performing results with minimal interaction between the RECs and DSO, keeping the same decentralized architecture. On the other hand, limitation to the flexibility in the REC may limit or compromise VI operation, this may pose the need of introducing criteria to select which REC are suitable for this, for example those that have the higher share and variety of flexibility resources. In the light of the promising results of the proposed analysis, future developments shall involve both the design of the control architecture to be included in the REC to allow the real-time achievement of VI and the definition of possible interaction between REC and DSO to maximize the impact of VI service on the grid operation.

CRediT authorship contribution statement

Bonfiglio Andrea: Writing – review & editing, Supervision, Methodology. **Procopio Renato:** Writing – review & editing, Supervision. **La Scala Massimo:** Writing – review & editing, Supervision. **Velini Angelo:** Writing – original draft, Validation, Methodology, Data

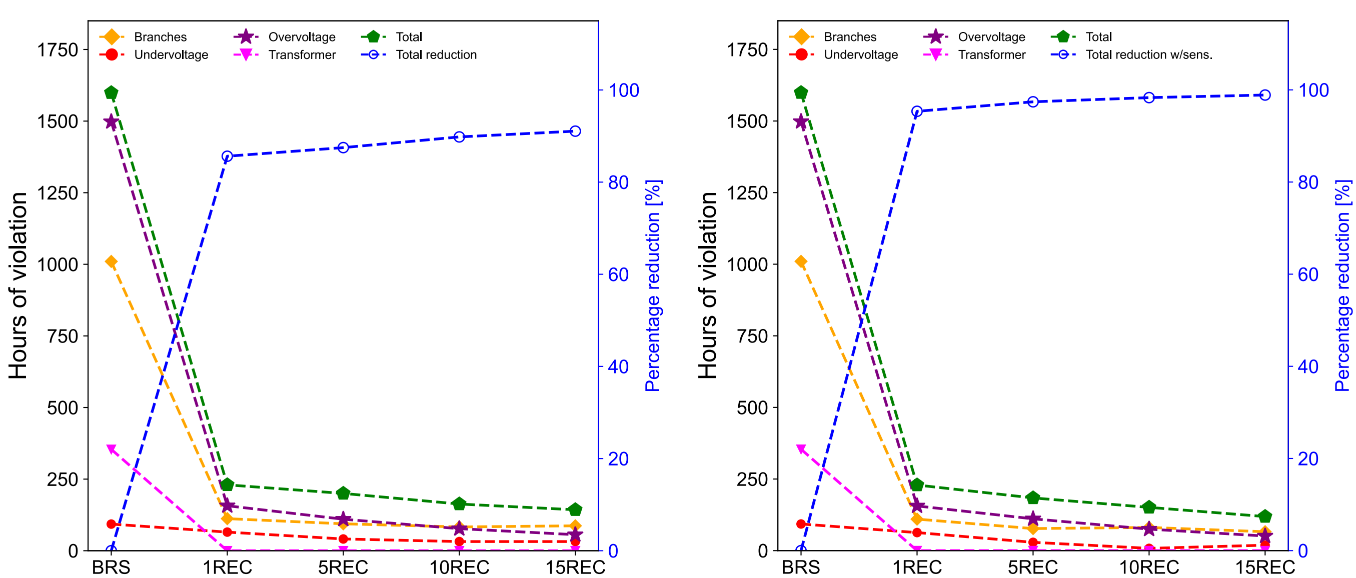

Fig. 4. Analysis of hours with violation as a function of the increasing number of RECs participating in the VI service.

curation. **Minetti Manuela:** Writing – review & editing, Validation, Data curation. **Bruno Sergio:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Data availability

Data will be made available on request.

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