Delft University of Technology

Evaluation of Ramp-Rate Limitation at Distribution Transformer Level via Central and Distributed Storage Systems

Malamaki, Kyriaki-Nefeli D.; Fu, Aihui ; Mauricio, Juan Manuel; Cvetkovic, Milos; Demoulias, Charis S.

DOI
10.1109/PowerTech55446.2023.10202995

Publication date
2023

Document Version
Final published version

Published in
Proceedings of the 2023 IEEE Belgrade PowerTech

Citation (APA)
Malamaki, K.-N. D., Fu, A., Mauricio, J. M., Cvetkovic, M., & Demoulias, C. S. (2023). Evaluation of Ramp-Rate Limitation at Distribution Transformer Level via Central and Distributed Storage Systems. In *Proceedings of the 2023 IEEE Belgrade PowerTech* (pp. 1-6). (2023 IEEE Belgrade PowerTech, PowerTech 2023). IEEE. https://doi.org/10.1109/PowerTech55446.2023.10202995

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Green Open Access added to TU Delft Institutional Repository

'You share, we take care!' - Taverne project

https://www.openaccess.nl/en/you-share-we-take-care

Otherwise as indicated in the copyright section: the publisher is the copyright holder of this work and the author uses the Dutch legislation to make this work public.

Evaluation of Ramp-Rate Limitation at Distribution Transformer Level via Central and Distributed Storage Systems

1st Kyriaki-Nefeli D. Malamaki
Research, Technology & Development Dept.
Independent Power Transmission Operator
Athens, Greece
kyriaki_nefeli@hotmail.com

2nd Aihui Fu
EEMCS Dept.
Delft University of Technology
Delft, Netherlands
a.fu@tudelft.nl

3rd Juan Manuel Mauricio
Dept. of Electrical Engineering
Universidad de Sevilla
Sevilla, Spain
jmmauricio@us.es

4th Miloš Cvetković
EEMCS Dept.
Delft University of Technology
Delft, Netherlands
m.cvetkovic@tudelft.nl

5th Charis S. Demoulias
Dept. of Electrical & Computer Engineering
Aristotle University of Thessaloniki
Thessaloniki, Greece
chdimoul@auth.gr

2023 IEEE Belgrade PowerTech | 978-1-6654-8778-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/POWERTECH55446.2023.10202995

***Abstract*—As the penetration of Converter-Interfaced Distributed Renewable Energy Sources (CI-DRES) increases, several problems are revealed in electric power systems, e.g., power quality issues, reverse power flows and frequency instability. A solution to tackle these issues is the mitigation of high CI-DRES active power ramp-rates (RRs) by utilizing energy storage systems (ESS). In many grid-codes at transmission system (TS) level, it is specified that the CI-DRES limit their RRs, while also the utilization of a central ESS has been proposed to limit the RRs. Nevertheless, this approach involves only large energy market players. Although various RRL methods have been proposed for CI-DRES, a remaining gap is the evaluation of the RR of a Distribution Network (DN) containing CI-DRES and loads together with the influence of distributed ESS in the DN. Towards this direction, in this paper, this evaluation is performed in order to study the RRL capability of a low-voltage (LV) DN considering both central and distributed ESS. The analysis is conducted in the LV CIGRE DN via quasi-steady-state and RMS simulations in PowerFactory considering several techno-economic parameters, e.g., ESS size, type, per unit cost. This evaluation will help towards the integration of the RRL control in the grid codes in DNs so that it can be considered as a new ancillary service to be remunerated in respective markets where also small CI-DRES owners will be able to participate.**

***Index Terms*—Ancillary Service, Active Distribution Networks, Distributed Generation, Energy Storage Systems, Ramp-Rate Limit, Renewable Energy Sources**

I. Introduction

With the continuously increasing penetration of Converter-Interfaced Distributed Renewable Energy Sources (CI-DRES) various issues are brought into surface related to reverse power flows, power quality issues, frequency instability, etc. These problems stem from the CI-DRES dispersion in the electric power systems as well as their stochastic and inertia-less nature. At transmission system (TS) level, the operators (TSOs) are responsible for keeping the frequency in a specific range. Since the CI-DRES intermittent nature which involves high active power Ramp Rates (RRs) might jeopardize the frequency stability, the TSOs often commit large amounts of fuel-driven reserves, [1], [2]. Other solutions recently adopted by TSOs in weak TSs (e.g., Puerto Rico) to mitigate the frequency instability caused by high RRs is the RR Limitation (RRL) of the CI-DRES mainly by active power curtailment, [3], [4] or the placement of central large-scale Energy Storage Systems (ESS), [5]. Each solution comes with specific drawbacks, e.g., loss of income for the CI-DRES owners, or involvement of large energy market players, [1]–[3], [6], [7]. At Distribution Network (DN) level increased CI-DRES penetration with high active power RRs can cause power and voltage quality issues, e.g., flickering and rapid voltage changes, [8]. One promising solution to such issues is the RRL of the CI-DRES active power, [8]–[10], via the combination of the CI-DRES with an ESS in order to avoid active power curtailment. Hence, RRL is an ancillary service (AS) that can be provided either in a central or distributed manner to help towards the mitigation of the aforementioned issues related to the high CI-DRES active power RRs.

Various RRL approaches techniques have been proposed in the literature for Photovoltaics (PV) [11], [12] and Wind Farms [13], [14] considering several ESS types: Battery ESS (BESS), [11], [13], Supercapacitors (SCs) [3], [15], or hybrid ESS, [14]. These methods can be categorized as [4]: (i) moving average methods, [16]; (ii) filter-based approaches, [13], [15]; (iii) direct RRL methods, [3], [7], [17]. Based on the review/comparison studies, [4], [15], [18], [19], [20], [21] the direct RRL methods are preferred due to decreased needed ESS capacity/increased operating life, [3]. Most of the aforementioned studies assume a RRL=10%$/min$ with respect to the CI-DRES primary source, and cannot specify the required RRL for CI-DRES so as to reduce the impact of the reported issues. However, this value is too strict and should be re-assessed, [5].

This work was supported by the European Union, under the H2020 project EASY-RES (GA 764090) and in part financially by the Horizon Europe project ACES (GA 101093126).

Authorized licensed use limited to: TU Delft Library. Downloaded on August 18,2023 at 08:06:57 UTC from IEEE Xplore. Restrictions apply.

Although RRL has been studied widely at CI-DRES level, there are limited studies regarding the RRL performance at DN or TS level considering also techno-economic criteria, e.g., ESS size and cost. In [8] RRL is applied to PV systems with ESS to alleviate voltage fluctuations focusing in the reduction of flickering. In [9], [10] BESS are used for RRL in a LV DN and it is demonstrated via simulations that fast variations of the voltage/power caused by the wind or sun can be maintained within acceptable limits. However, the use of BESS should be avoided for rapid voltage changes due to the BESS slower response, [5], [15]. For this reason, in [3], [15], [18] it is recommended that SCs should be preferred for RRL in DNs. In [2] an investigation via simulations in the IEEE 9-bus TS to evaluate the impact of the RRL action of a CI-DRES - coupled with a SC and directly connected to the TS - on the frequency disturbances considering several parameters: the RRL value, the SC size, the energy provided by the fuel-driven reserves, etc. However, there still exist gaps related to the RRL evaluation at both DN and TS level, [6], considering the fact that load variations are slower than CI-DRES variations. Hence, BESS utilization can be more suitable for RRL at DN substation level and SCs more appropriate at CI-DRES level.

Towards these gaps, this paper proposes the use of SCs at CI-DRES level for RRL control to the CI-DRES power, [3] and the use of BESS located at the MV/LV substation perform RRL to further compensate slower variations caused by the loads, [22]. At CI-DRES level, the RRL control presented in [3], [7] is employed to reduce the significant RRs at specific values considering the SC State-of-Charge (SoC) *a-priori* to allow also the provision of other AS, e.g., virtual inertia, [6] and ensure that even when the SC SoC is close to its limits the RRL is still provided. Conventionally the SCs are sized based of the "worst-case" fluctuation for $\Delta P = 0.9pu$ within 10 minutes, [15] considering a RRL of 10%/min. However, it is not examined if such value is suitable for CI-DRES placed within DNs. In [3], [7] an RRL value of $\Delta P/min \leq 30\%$ of CI-DRES rated power has been proposed while simultaneously not exceeding SC relative additional cost 10% with respect to the total cost of the CI-DRES. In [4], it is shown that both target values are achieved with more than 99% efficiency. At MV/LV substation level, a central BESS performs RRL aiming at RRL=10%/min of the MV/LV transformer rating. The BESS control is presented in [23] and is practically the same as the SC. The goal of this paper is to study whether a decentralized approach for RRL performed by CI-DRES within DNs (engaging smaller CI-DRES owners) can reduce the size of a central BESS while keeping the same RRL target capability compared to the fully centralized approach. This suggestion aims at deferral of investments at DN level, while it simultaneously allows the engagement of both small CI-DRES/ESS owners and large-scale ESS operators.

To evaluate the performance of the central and distributed ESS, in this paper a 2-stage procedure has been followed: (i) 1-day Quasi-steady-state Simulations are conducted on the CIGRE LV DN, [24] for various CI-DRES/load mixtures without engaging the RRL functionalities in order to set the reference case for the DNs, which aims at defining the maximum BESS size when no SCs perform at CI-DRES level. From the reference case the 10-minute interval with the highest RRs in pu/min is isolated. (ii) RMS Simulations are used to validate that by engaging the RRL control using the SCs at CI-DRES level, the BESS size at substation level is reduced compared to the case where only a central BESS exists. It is noted that these two different simulation procedures are established because the two ESS types operate in different time-scales due to their different nature, i.e., BESS are high-energy density ESS while SCs are high-power ESS, [25]. All simulations are conducted in DigSilent PowerFactory. It is shown that the central BESS size is reduced when SCs perform RRL at CI-DRES level. To the authors' best knowledge there exist no studies on this topic.

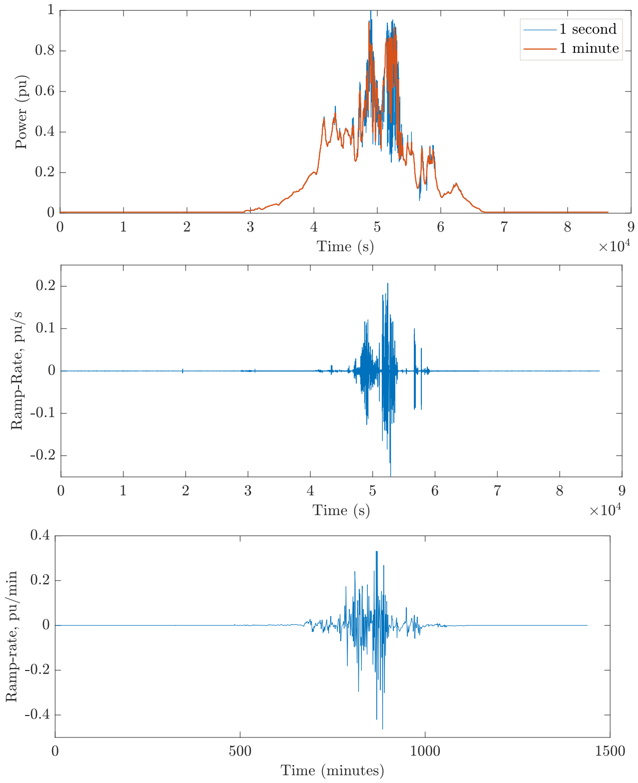

Fig. 1. 1-day PV Profile: (Top) PV Power with 1-s resolution and with 1 minute average; (Middle) RR per 1-s; (Bottom) RR per minute.

The rest of the manuscript is organised as follows: Section II presents the inputs used in the simulations, i.e., benchmark power profiles and the BESS/SC models performance. Section III presents the Quasi-steady-state Simulation procedure to evaluate the Central BESS size and the respective results. Section IV presents the RMS simulations procedure to evaluate the impact of distributed SCs in the reduction of the central BESS size. Finally, Section V summarizes the paper main findings, and proposes new research directions.

II. Input Models

A. Benchmark Power Profiles

In order to perform both types of simulations, it is essential to find data with the highest possible resolution for CI-DRES

Authorized licensed use limited to: TU Delft Library. Downloaded on August 18,2023 at 08:06:57 UTC from IEEE Xplore. Restrictions apply.

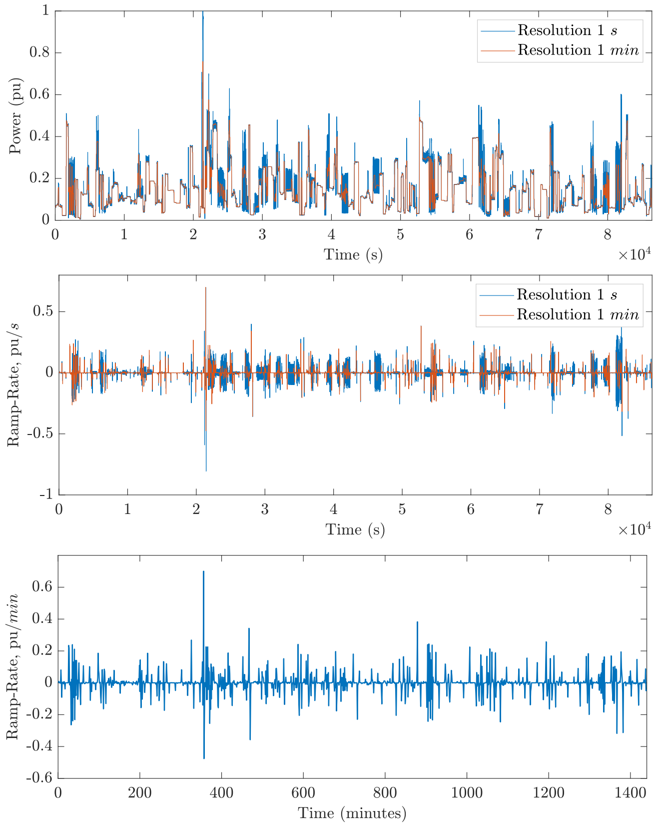

Fig. 2. Residential Load 17/Day 27 from [26]: (Top) pu power profile with two different resolutions, 1 minute (referred to s) and 1-s; (Middle) RR per 1-s; (Bottom) RR per minute.

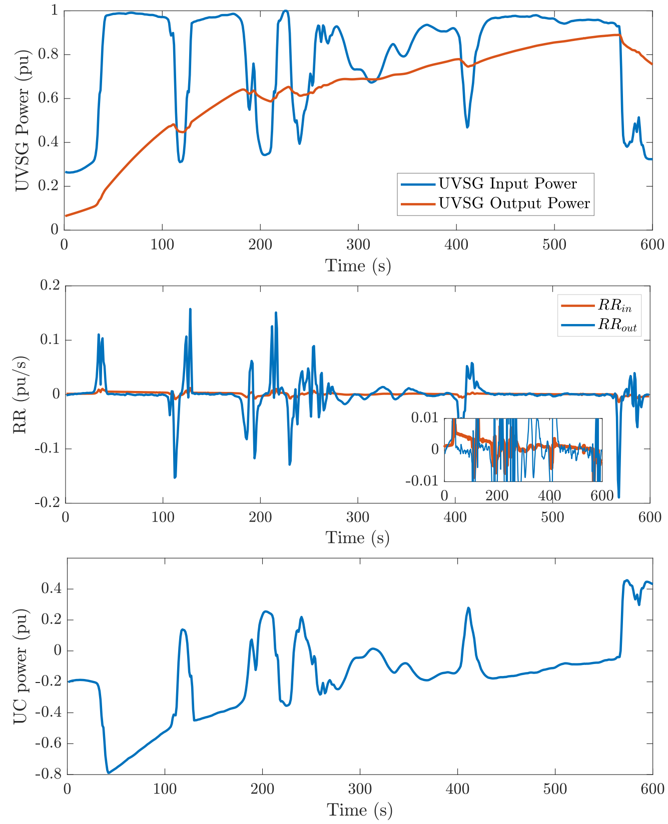

Fig. 3. UVSG Input and Output power: (Top) Input and Output power of UVSG in pu; (Middle) UVSG RR in pu/s; (Bottom) SC power in pu.

and loads. It is noted that the highest possible resolution that appears in smart meters is 1-s, [4]. These high resolution profiles are used in RMS simulations, which have a duration of $600s$. Then, for each type of profile the 1-minute average has been derived and inserted in the quasi-steady-state simulations which concern a whole day (1440 sequential power flows). All profiles have been scaled up in order to match a specific maximum power and derive different CI-DRES/load mixtures. The different CI-DRES/load mixtures have been derived in order to respect thermal/voltage limits within the DN. Details can be found in [25]. Note that in LV DNs PV power plants (PPs) prevail. Therefore, for a PVPP, a cloudy day profile with 1 s resolution data from a 7.32 kW_p PVPP is selected to define a "worst-case" scenario, [3], [4], [7], [25]. The PVPP per unit (pu) profile illustrated in Fig. 1 is derived by dividing with the maximum power 5.384 kW. In addition, residential loads have been considered and more specifically, yearly profiles of [26] for 74 residential loads with resolution 1-s and 1 minute have been carefully studied regarding their RRs. Day 27 of the yearly profile of Load 17 has been chosen (Fig. 2). The pu profile is derived by dividing with the maximum load power (with 1 s resolution) of Day 27, i.e., 10.671 kW. It is noted that in all simulations the reactive power of the PVs and loads are set to 0.

B. BESS/SC Model

In the Horizon 2020 project EASY-RES, the Unified Virtual Synchronous Generator (UVSG) prototype has been built with enhanced functionalities in order to provide several AS, such as RRL, virtual inertia, harmonic mitigation, etc., [6], [25]. The direct RRL algorithm is described and demonstrated in [3], [4], [7], [25] and is preferred because it leads to much smaller SC size compared to other RRL approaches. The respective RRL and SoC control within the UVSG for PowerFactory has been derived in [25]. The UVSG model is based on a 20kVA converter. For modelling a larger CI-DRES, several UVSGs are paralleled. The UVSG performance is depicted in Fig. 3 assuming a target RRL of $0.3pu/min$, i.e., $0.005pu/s$. The SC used energy is 144.44 Wh corresponding to $C = 40F$ for the 20kVA UVSG. The BESS is modelled like an equivalent SC, but its capacity calculation is performed after the quasi-steady state simulations based on the analytical calculations presented in [25]. The BESS is assumed to be placed centrally at MV/LV substation and acts with a target RRL value of $0.1pu/min$, i.e., $0.00167pu/s$.

III. Determination of Central BESS Size

In this section the evaluation procedure and the results regarding the evaluation of the maximum Central BESS size located at MV/LV substation are described. Specifically, in the CIGRE European LV DN [24] the maximum voltage limit has been set to 1.1 pu and the minimum voltage limit has been set equal to 0.9 pu, so as to meet the corresponding Standards, e.g. EN 50160. In the LV Cigre there are two types of underground cables of size 50 (UG3) and 240 (UG1) mm^2. The thermal limits are 158 A and 400 A for UG3 and UG1, respectively.

Authorized licensed use limited to: TU Delft Library. Downloaded on August 18,2023 at 08:06:57 UTC from IEEE Xplore. Restrictions apply.

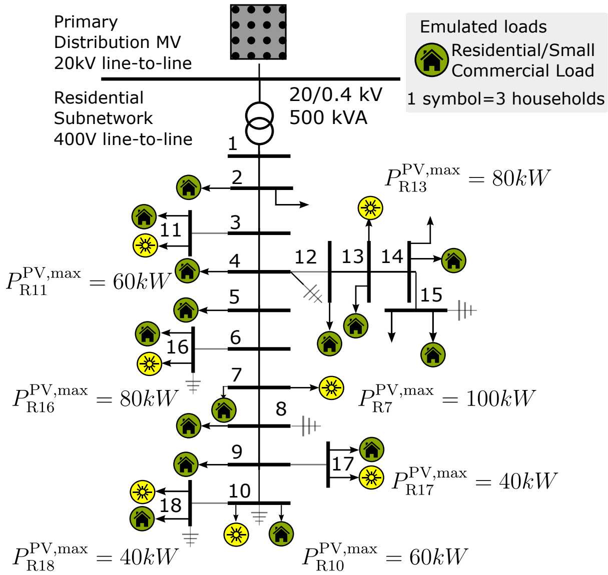

Fig. 4. 100% PV penetration in the CIGRE LV DN.

Procedure 1 aims at the determination of the reference case via sequential power flows where the RRL is not activated. Several different daily Transformer profiles resulting from **Procedure 1** are used as inputs to the RRL control script of [23] for the BESS energy/power calculation so as to limit the RR to 10%/min. The Transformer profile resulting to the largest BESS capacity defines the reference case amongst the five load/PV mixtures. From the reference case a specific time-frame of 10 minutes is isolated for RMS simulations considering the magnitude of RRs per minute, i.e., highest RRs. Detailed steps of **Procedure 1** are listed as follows:

Step 1: In the LV DN set the total Maximum Residential load equal to 95% of the Transformer nominal power (500 kVA), i.e. $P_{load}^{max} = 450kW$.

Step 2: Distribute P_{load}^{max} equally per node (residential loads in Fig. 4).

Step 3: Scale up the residential profile of Fig. 2 with 1-minute resolution (1440 values). The Transformer nominal power is used as pu basis at substation level.

Step 4: **Set PV penetration cases**: In the LV DN set the total maximum PV power at P_{pv}^{max}=x% of P_{load}^{max} (x=20, 50, 80, 100). Distribute P_{pv}^{max} per node in a way that thermal/voltage limits are not violated. The LV DN topology appears in Fig. 4 for P_{pv}^{max}=100% of P_{load}^{max}. It is noted that with respect to P_{load}^{max}: (a) for 20% PV penetration, a UVSG of 20kW rated power is located at node 15 and two PVs of 40 kW are added in nodes 10 and 18; (b) for 50% PV penetration, a UVSG of 20kW is located at node 15 and five UVSGs of 40 kW are added in nodes 10, 11, 16, 17 and 18; (c) for 80% PV penetration, a UVSG of 40kW rated power is located at node 17, a PV of 60kW is located at node 11, two PVs of 80 kW are added in nodes 13 and 16 and a PV of 100kW is located at node 7. The detailed topologies can be found in [25].

Step 5: Scale up the PV profile of Fig. 1 with 1-min resolution.

Step 6: For each penetration level, run 1440 sequential power flows and evaluate the RR at the MV/LV substation.

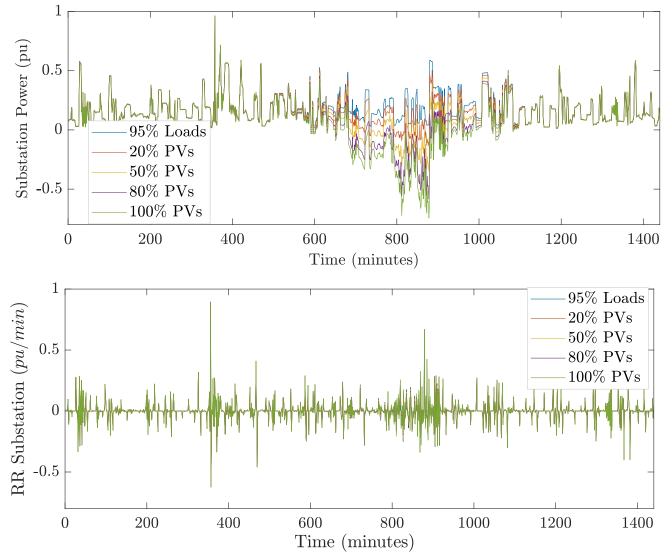

Fig. 5. Quasi-steady-state simulations for different penetration scenarios: (Top) Transformer power in pu; (Bottom) RR in the substation in pu/min

TABLE I
RESULTED LV BESS POWER, ENERGY & COST FOR 1-DAY SIMULATIONS

Scenario	Power, kW	Energy, kWh	Cost,€,	RR_{in}
95% Loads	393.69	161.60	64,638.17	88.74
20% PVs	393.70	160.65	64,258.03	88.74
50% PVs	393.61	163.82	65,528.97	88.72
80% PVs	397.67	174.63	69,851.23	89.53
100% PVs	397.56	183.37	73,346.09	89.51

The daily MV/LV Transformer profiles of **Procedure 1** can be observed in Fig. 5, where it is evident that the most frequent high RRs appear at $t = 800 - 1000min$. The profiles of Fig. 5 have been used as inputs to the script of the Annex of [23], in order to calculate the required BESS capacity and maximum power to achieve RRL 10%/min. The respective results are shown in Table I. In the 5^{th} column the RR_{in} is the maximum RR in %/min that appears within the day at substation level. The total BESS cost is derived assuming a cost equal to 400 €$/kWh$. As it is evident, the BESS converter power is almost equal for all scenarios, since the maximum RR per minute presents slight differences per scenario. However, there is a relative increase in the maximum BESS capacity as the penetration level increases, i.e., between the Scenarios **95% Loads** and **100% PVs** there is 13.5% increase in the capacity and respective cost. Since Scenario **100% PVs** results in the highest BESS capacity, it is used as the reference case in **Procedure 2** described in the following Section.

IV. RELATIVE BESS SIZE REDUCTION WHEN USING DISTRIBUTED SCS TOGETHER WITH THE CENTRAL BESS

Since BESS are high-energy density ESS while SCs are high-power ESS, [18], they involve different dynamics and operate in different time-scales. Therefore, it would be impossible to evaluate simultaneously the two types of ESS. For this reason, two different simulation procedures are established. In this section the procedure for the evaluation of the relative BESS size reduction when using also distributed SCs is described and the respective simulation results are analyzed. In **Procedure 2** RMS simulations are performed while different

Authorized licensed use limited to: TU Delft Library. Downloaded on August 18,2023 at 08:06:57 UTC from IEEE Xplore. Restrictions apply.

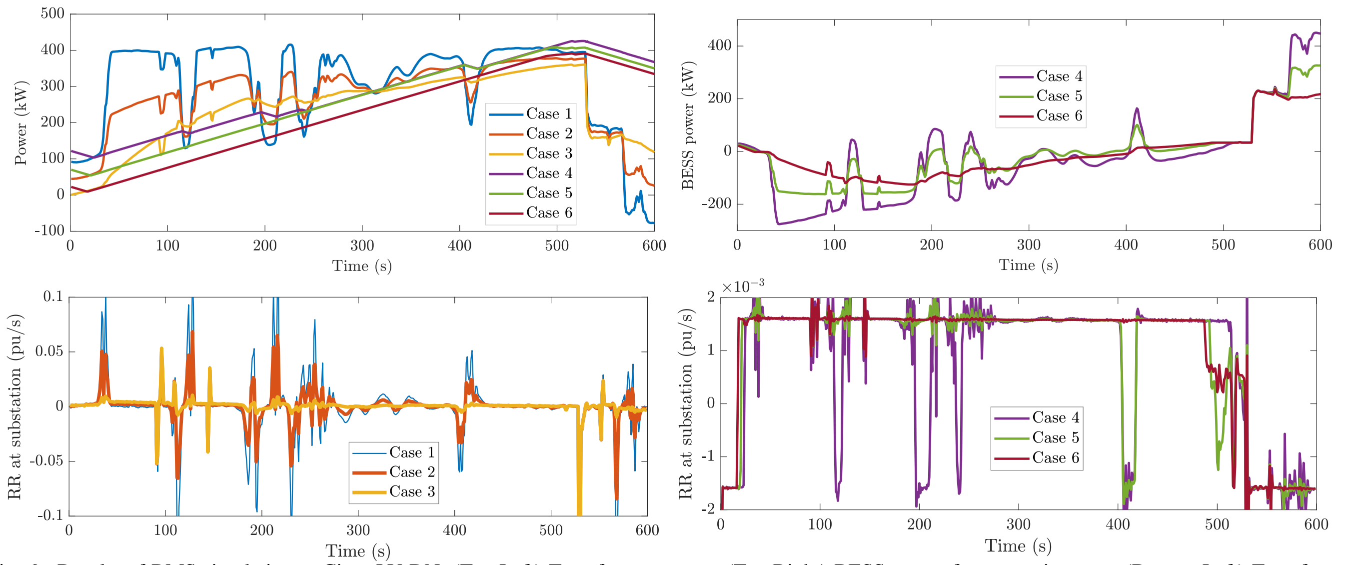

Fig. 6. Results of RMS simulations - Cigre LV DN: (Top Left) Transformer power; (Top Right) BESS power for respective case; (Bottom Left) Transformer RR - Zoom Cases 2-3; (Bottom Right) Transformer RR - Zoom Cases 4-6;

smoothing functionalities are engaged with different mixtures: either by the BESS connected to MV/LV substation with RRL=10%/min or by PVs which employ UVSGs with SCs and perform RRL control at 30%/min or both. Each step of **Procedure 2** corresponds to one case of the LV DN to evaluate the coordinated action of SCs and BESS.

The reference case has already been set in **Procedure 1**. It is assumed that a central BESS size with capacity calculated for the Scenario **100% PVs** is utilized. Based on the highest RR/min that appeared during **Procedure 1** simulations a specific time-frame is selected ("worst fluctuation" 10-minute profile). Based on the specific topology and the results presented in Fig. 5 - (Bottom), the profile within $t = 870 - 880min$ is selected as the "worst-case fluctuation" profile. In **Procedure 2** for this specific time interval and topology the real 1-s data of the PVs and residential loads are isolated and used in the RMS simulations for each node. Each UVSG with SC has an input and/or output profile as depicted in Fig. 3 depending on whether the RRL is activated in the UVSG at specific node or not. The detailed steps are the following:

Step 1-Case 1: Insert the 1-s data per node for these specific 10 minutes/600s selected in **Step 1**. Run 600s RMS simulation with NO ESS (neither central or distributed) to set the base RMS Case.

Step 2-Case 2: Integrate SCs to the 50% of the installed UVSGs at nodes 10, 11, 16 and 17. These UVSGs have total DRES power of $240kW_p$. The SCs should be sized so as to achieve RRL up to RRL $= 0.05pu/s$, i.e., 50% of the total DRES power can be smoothed with this RRL. No central BESS exists. Run 600s RMS simulations. Calculate the energy from the SCs. Evaluate the achieved RR at substation level.

Step 3-Case 3: Integrate SCs to the 100% of the installed UVSGs. These UVSGs have total DRES power of $460kW_p$. The SCs should be sized so as to achieve RRL up to $= 0.05pu/s$, i.e., 100% of the total CI-DRES power can be smoothed with this RRL. No central BESS exists. Run 600s RMS simulations. Calculate the energy from the SCs. Evaluate the achieved RR at substation level.

TABLE II
RESULTED LV SC & BESS ENERGY, kWh FOR THE RMS SIMULATIONS

Case	Case 2	Case 3	Case 4	Case 5	Case 6
UVSG 7	-	3.946	-	-	3.946
UVSG 10	2.368	2.368	-	2.368	2.368
UVSG 11	2.368	2.368	-	2.368	2.368
UVSG 13	-	3.157	-	-	3.157
UVSG 16	3.157	3.157	-	3.157	3.157
UVSG 17	1.578	1.578	-	1.578	1.578
UVSG 18	-	1.578	-	-	1.578
BESS	-	-	19.417	13.892	11.973
Total	9.471	18.152	19.417	23.363	30.125

Step 4-Case 4: Consider that a central BESS exists at substation level with the capacity calculated in **Procedure 1** and RRL $= 0.0167pu/s$. NO SCs are involved. Run 600s RMS simulations. Calculate the energy needed by the BESS. Evaluate the achieved RR at substation level.

Step 5-Case 5: Add the central BESS with RRL $= 0.0167pu/s$ to **Step 2** , i.e., only 50% of the UVSGs employ SCs to perform RRL **together** with the central BESS. Run 600s RMS simulations. Calculate the energy from the BESS and the SCs. Evaluate the achieved RR at substation level.

Step 6-Case 6: Add the central BESS with RRL $= 0.0167pu/s$ to **Step 3** , i.e., all UVSGs employ SCs to perform RRL at $= 0.05pu/s$ **together** with the central BESS. Run 600s RMS simulations. Calculate the energy from the BESS and the SCs. Evaluate the achieved RR at substation level.

The results of the RMS simulations are illustrated in Fig. 6 for Cases 1-6. The energy needed by the UVSGs SCs and the central BESS in Cases 2-6 appear in Table II. The following observations can be made: (i) In Fig. 6 (Bottom Left)- Cases 2-3 it is shown that when involving UVSGs with RRL control, the RR is reduced not only at PV level but also at substation level compared to Case 1; (ii) In Cases 4-6 where the substation BESS is involved, the RR achieves its target value $0.00167pu/s$ - Fig. 6-(Bottom Right); (iii) The same BESS size has been used in Cases 4-6, but it can be observed

Authorized licensed use limited to: TU Delft Library. Downloaded on August 18,2023 at 08:06:57 UTC from IEEE Xplore. Restrictions apply.

in Fig. 6-(Top Right) and in Table II that the energy utilized by the central BESS is much smaller when the RRL is performed at CI-DRES level. Hence, the higher the amount of UVSGs within the DN, the smaller the BESS size: with respect to Case 4, in Case 5 the BESS energy is reduced by 29% while in Case 6 by 38%. In addition, not only the BESS energy is smaller, but the instantaneous power is also reduced: for Case 4 the maximum BESS power is 450kW, for Case 5 326.5kW (reduction 27.5%) and for Case 6 231.4 kW (reduction 48.6%). This means that the BESS converter power is almost half when all UVSGs have activated the RRL control.

V. Conclusions

In this paper, the performance of the RRL functionality has been evaluated via two kinds of simulations so as to achieve a specific RRL at the MV/LV substation. This evaluation considers different values of RRL for the SCs and the BESS, different mixtures of CI-DRES/loads, several mixtures of ESS types and two different time-scales, since the BESS dynamics are much slower than the SC dynamics. Specific results are presented to evaluate the reduction of the power volatility, when RRL control is performed centrally by the BESS or in a decentralized way by the SCs or by combining both approaches. It can be concluded that when the RRL is activated in both ESS types the central BESS size can be 40% smaller with 50% reduction in the BESS converter power. This conclusion is really important, since a solution combining both central and decentralized performance for the RRL AS could mitigate several issues related to voltage stability and quality within DNs. This is turn could lead to deferral of investments by the DN Operators, while it simultaneously allows the engagement of both small DRES/ESS owners together with large-scale ESS operators, contrary to the current situation. Further directions of research include the effect of the decentralized RRL approach to voltage quality and stability improvement within DNs, the implementation at MV DNs and a coordinated control of both ESS types.

References

[1] C. S. Demoulias, K.-N. D. Malamaki, G. C. Kryonidis, E. O. Kontis, S. I. Gkavanoudis, K. O. Oureilidis, and J. M. Mauricio, "Ancillary services provision in terminal distribution systems," in *Encyclopedia of Electrical and Electronic Power Engineering*, J. García, Ed. Oxford: Elsevier, 2023, pp. 411–424.

[2] K.-N. D. Malamaki, D. Gkontoras, and C. S. Demoulias, "Ramp-rate limitation of distributed renewable energy sources via supercapacitors as preventive action towards frequency disturbances," in *2022 2nd Int. Conf. on Energy Transition in the Mediterranean Area (SyNERGY MED)*, 2022, pp. 1–6.

[3] K. - N. D. Malamaki *et al*, "Ramp-rate limitation control of distributed renewable energy sources via supercapacitors," *IEEE Trans. Ind. Appl.*, vol. 58, no. 6, pp. 7581–7594, Nov.-Dec. 2022.

[4] K.-N. D. Malamaki, G. C. Kryonidis, and C. S. Demoulias, "Comparative evaluation of ramp-rate limitation control strategies employing supercapacitors," in *2022 IEEE 21st Mediterranean Electrotechnical Conf. (MELECON)*, 2022, pp. 207–212.

[5] M. B. Vahan Gevorgian and D. Ton, "Interconnection requirements for renewable generation and energy storage in island systems: Puerto rico example," in 4^{th} *Int. Hybrid Power Systems Workshop, Crete, Greece*, May 22–23 2019.

[6] C. S. Demoulias *et al*, "Ancillary services offered by distributed renewable energy sources at the distribution grid level: An attempt at proper definition and quantification," *Appl. Sci.*, vol. 10, no. 20, 2020.

[7] K.-N. D. Malamaki *et al*, "Ramp-rate control of dres employing supercapacitors in distribution systems," in *2021 Int. Conf. on Smart Energy Systems and Technologies (SEST)*, 2021, pp. 1–6.

[8] D. S. Kumar, S. Maharjan, Albert, and D. Srinivasan, "Ramp-rate limiting strategies to alleviate the impact of pv power ramping on voltage fluctuations using energy storage systems," *Solar Energy*, vol. 234, pp. 377–386, 2022.

[9] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "Mitigation of rapid voltage variations caused by passing clouds in distribution networks with solar pv using energy storage," in *8th International Conference on Electrical and Computer Engineering*, 2014, pp. 305–308.

[10] M. J. E. Alam, K. M. Muttaqi and D. Sutanto, "Battery energy storage to mitigate rapid voltage/power fluctuations in power grids due to fast variations of solar/wind outputs," *IEEE Access*, vol. 9, pp. 12 191–12 202, 2021.

[11] H. Liu, J. Peng, Q. Zang, and K. Yang, "Control strategy of energy storage for smoothing photovoltaic power fluctuations," *IFAC-PapersOnLine*, vol. 48, no. 28, pp. 162 – 165, 2015.

[12] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "A novel approach for ramp-rate control of solar pv using energy storage to mitigate output fluctuations caused by cloud passing," *IEEE Trans. Energy Convers.*, vol. 29, no. 2, pp. 507–518, 2014.

[13] A. Addisu, L. George, P. Courbin, and V. Sciandra, "Smoothing of renewable energy generation using gaussian-based method with power constraints," *Energy Procedia*, vol. 134, pp. 171 – 180, Jan. 2017.

[14] Ming Pang, Yikai Shi, W. Wang, and Xiaoqing Yuan, "A method for optimal sizing hybrid energy storage system for smoothing fluctuations of wind power," in *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conf. (APPEEC)*, 2016, pp. 2390–2393.

[15] L. G. González, R. Chacon, B. Delgado, D. Benavides, and J. Espinoza, "Study of energy compensation techniques in photovoltaic solar systems with the use of supercapacitors in low-voltage networks," *Energies*, vol. 13, no. 15, 2020.

[16] J. Martins, S. Spataru, D. Sera, D.-I. Stroe, and A. Lashab, "Comparative study of ramp-rate control algorithms for pv with energy storage systems," *Energies*, vol. 12, no. 7, 2019.

[17] J. Marcos, I. De la Parra, M. García, L. Marroyo, "Control strategies to smooth short-term power fluctuations in large photovoltaic plants using battery storage systems," *Energies*, vol. 7, no. 10, pp. 6593–6619, 2014.

[18] S. Sukumar, M. Marsadek, K. Agileswari, and H. Mokhlis, "Ramp-rate control smoothing methods to control output power fluctuations from solar photovoltaic (pv) sources—a review," *Journal of Energy Storage*, vol. 20, pp. 218 – 229, 2018.

[19] G. C. Kryonidis, A. I. Nousdilis, K. D. Pippi, and T. A. Papadopoulos, "Impact of Power Smoothing Techniques on the Long-Term Performance of Battery Energy Storage Systems," in *2021 56th Int. Universities Power Engineering Conf. (UPEC)*, 2021, pp. 1–6.

[20] S. D. Tragianni, K. O. Oureilidis, C. S. Demoulias, "Supercapacitor sizing based on comparative study of PV power smoothing methods," in *2017 52nd Int. Universities Power Engineering Conf. (UPEC)*, 2017.

[21] J. F. Patarroyo-Montenegro, J. D. Vasquez-Plaza, O. F. Rodriguez-Martinez, Y. V. Garcia, and F. Andrade, "Comparative and Cost Analysis of a Novel Predictive Power Ramp Rate Control Method: A Case Study in a PV Power Plant in Puerto Rico," *Appl. Sci.*, vol. 11, no. 13, 2021.

[22] EASY-RES H2020 Project (GA:764090), www.easyres-project.eu.

[23] K.-N. D. Malamaki *et al*, "D1.7 final report (after feedback form lab tests) presenting: the reactive power control algorithm for converter-interfaced dres/bess, the analytical tool for parametric bess sizing for low-frequency power smoothing and the analytical tool for the evaluation of the converter operational losses due to exchange of reactive power," *H2020 EASY-RES Project Deliverable*, Dec. 2021.

[24] CIGRE, "Modeling and aggregation of loads in flexible power networks," *CIGRE Working Group C4.605*, 2014.

[25] K. - N. Malamaki *et al*, "D6.5 report on the evaluation of project kpis," *H2020 EASY-RES Project Deliv.*, Dec. 2021.

[26] Tjaden, T.; Bergner, J.; Weniger, J.; Quaschning, V., "Representative electrical load profiles of residential buildings in Germany with a temporal resolution of one second, Dataset, HTW Berlin," pvspeicher.htw-berlin.de/veroeffentlichungen/daten, 2015.

Authorized licensed use limited to: TU Delft Library. Downloaded on August 18,2023 at 08:06:57 UTC from IEEE Xplore. Restrictions apply.