



Vaasan yliopisto
UNIVERSITY OF VAASA

OSUVA Open
Science

This is a self-archived – parallel published version of this article in the publication archive of the University of Vaasa. It might differ from the original.

Novel DER and OLTC management during islanded operation of MV microgrid

Author(s): Laaksonen, Hannu; Hatziargyriou, Nikos

Title: Novel DER and OLTC management during islanded operation of MV microgrid

Year: 2025

Version: Accepted manuscript

Copyright © 2025 The Institution of Engineering and Technology.

Please cite the original version:

Laaksonen, H., & Hatziargyriou, N. (2025). Novel DER and OLTC management during islanded operation of MV microgrid. In *28th Conference and Exhibition on Electricity Distribution, CIGRE 2025*, paper 0333. IET conference proceedings 2025(14), 893-897.
<https://doi.org/10.1049/icp.2025.1731>

NOVEL DER AND OLTC MANAGEMENT DURING ISLANDED OPERATION OF MV MICROGRID

Hannu Laaksonen^{1*} and Nikos Hatziargyriou²

¹School of Technology and Innovations, University of Vaasa, Vaasa, Finland

²School of Electrical and Computer Engineering, National Technical University of Athens, Athens, Greece

*hannu.laaksonen@uwasa.fi

Abstract

Importance of electricity distribution networks' resiliency and supply reliability has been constantly increasing and due to that also interest towards momentary island operation and microgrids has grown. This paper proposes novel distributed energy resources' (DERs') and on-load tap-changers' (OLTCs') management concept in order to enable longer duration island operation of MV microgrid. Main focus of the studies is on medium-voltage (MV) network-connected battery energy storage system's (BESS's) voltage level control as well as on its interconnection transformer's OLTC management during the island operation. The PSCAD simulation studies show how the proposed MV BESS's interconnection transformer OLTC control logic during MV microgrid's island operation together with chosen minimum voltage control set value reduces the needed amount of current from the MV BESS and therefore the duration of the island operation can be increased. Based on the simulations, for example, with MV BESS voltage control set value 1.0 pu, the utilization of MV BESS OLTC can reduce 11 % the needed current from the MV BESS and when lowering voltage control set value to 0.96 pu, the BESS current can be even further reduced by 8 %. In addition, paper presents simulation results to indicate how MV microgrid reconnection can be successfully done also with the proposed novel MV BESS and OLTC control concept when having universal frequency-locked-loops (U-FLLs) on the inverter-based DERs. Based on the studies stable reconnection was possible even with $\pm 145\text{-}160^\circ$ angle difference.

1 Introduction

In the future, improvement of electricity distribution networks' resiliency and supply reliability will be increasingly of importance. Therefore, distribution system operators' (DSOs') interest towards island operation and microgrids with BESSs has increased. During normal grid-connected operation microgrid with BESS(s) and other flexible energy resources could provide active and reactive power (P and Q) control related flexibility services for the local DSO and transmission system operator (TSO). In case of some major disturbance, for example, due to storm or cyber-attack, microgrid could transfer to intentional island operation to continue electricity and possibly heat and gas supply to the loads in the microgrid. In this paper, the main focus is on novel DERs' and OLTCs' control concept (see Fig. 1 for further details) in order to enable longer duration islanded operation of 100 % inverter-based MV microgrid with BESSs, PVs and controllable loads in MV and low-voltage (LV) network. It is assumed that the MV network-connected DER units (BESS, PV and electrolyzer) have MV/LV interconnection transformers equipped with OLTCs. In [1], novel interconnection transformer OLTC control scheme for MV DER units' was proposed during the normal grid-connected operation. However, the focus on this paper is on the island operation. During MV microgrid islanded operation the MV and LV BESSs change operation to active power-voltage (PU) -droop mode and active power-frequency (Pf) -droop control is simultaneously disabled. In addition, synchronization of all the DER units is based on grid-forming U-FLLs [2].

Fig. 1 shows the proposed BESS and OLTC management concept consisting of parts I-III) (focus is on I) and II) for the island operation of MV microgrid. The PSCAD simulations are done to see if the proposed MV BESS's interconnection transformer OLTC's control logic during islanding together with chosen minimum voltage control set value reduces the needed amount of current from the BESS to enable longer duration island operation. In addition, PSCAD simulations are

done to study MV microgrid's reconnection [3] with using the proposed MV DER and OLTC management concept.

Novel DER and OLTC Management During Island Operation of MV Microgrid for Improved Resiliency and Electricity Supply Reliability & Continuity

I) & II) Active power and OLTC control of MW-scale BESS during MV microgrid island operation

Basic idea is during microgrid island operation to maximize the operation duration/capacity utilization of BESS by

- I) Controlling BESS LV side voltage with interconnection transformer OLTC to maximum value e.g. 1.075 pu (reduces current from BESS) and
- II) Controlling voltage-level of microgrid by BESS active power-voltage (PU) -control (used in this case during microgrid island operation) to voltage U minimum setting value (e.g. 0.96 pu or dependent on SOC value i.e. if SOC 50-100 % U -setting value is 0.96 pu and if SOC 0-50 % U -setting value is 0.935 pu) (further reduces current from BESS)

- Idea is similar to conservation voltage reduction (CVR) during grid-connected operation meaning that lowering voltage reduces power consumption of load (depending on the load type)

- By I) and II) also more active power could be drawn/discharged during islanding from aged or second-life BESSs

III) Local under-voltage level-dependent /measurement-based disconnection/re-connection logic

- III) If possible, local under-voltage level-dependent /measurement-based disconnection/re-connection logic with main household loads (electric heating, water electric heating, air-conditioners, heat-pumps and EV charging, sauna stove/heater) to support electricity supply continuity / duration with I) and II)

- For example, so that if $U < 0.92$ pu loads on/off for 10-15 min and if $U < 0.9$ pu loads off for 20-25 min (setting values need to be coordinated with I) and II))

- With EV charging some charging load adaptation could be done already when local voltage level goes below 0.935 pu (moving average over 5 min)

Fig. 1. Proposed BESS and OLTC management concept consisting of parts I-III) (focus on I & II) for the island operation of MV microgrid to improve resiliency and electricity supply reliability and continuity.

As described in Fig. 1, the main idea is to maximize the operation duration/capacity utilization of MV BESS by I) controlling BESS's LV side voltage with interconnection transformer OLTC to maximum value e.g. 0.43 kV / 1.075 pu (reduces current from BESS) and II) controlling voltage-level of microgrid by BESS PU -control (used in this paper during microgrid island operation) to voltage U minimum setting value (e.g. 0.96 pu). The principle of II) (Fig. 1) is similar to conservation voltage reduction (CVR) during grid-connected operation which means that lowering voltage reduces power consumption of load (depending on the load type) [1]–[7]. By I) and II) (Fig. 1) also more active power P could be drawn/discharged during islanding from aged or second-life BESSs.

In III) (Fig. 1), additional local under-voltage level-dependent disconnection/reconnection logic with main household controllable loads (electric heating, water electric heating, air-conditioners, heat-pumps, EV charging and sauna stove/heater) to support electricity supply continuity / duration with I) and II) is presented. It could be realized, for example, so that when $U < 0.92$ pu (moving average (MA) over 5 min) loads are on/off for 10–15 min and if $U < 0.9$ pu loads are on/off for 20–25 min (setting values need to be coordinated with I) and II), Fig. 1). Regarding EV charging in III) some charging load adaptation could be done already when local voltage level goes below 0.935 pu (MA over 5 min). In CC/CV (Constant Current/Constant Voltage) charging CC is typically used during 0–90 % state-of-charge (SOC), meaning that if under-voltage limit is exceeded then CC-level would be reduced if SOC between 0–90 %. This kind of under-voltage dependent loads' switching logic described in III) (Fig. 1) could also support distribution network's voltage-based hosting capacity management during normal grid-connected operation [1], [7]–[11].

2 Study System

The simulation studies are done with simplified HV/MV/LV network PSCAD model, like e.g. in [3], including three active DER units in the MV network (1 MW PV, 2 MW BESS, 1 MW hydrogen electrolyzer) and in the LV network (0.45 MW PV, 0.2 MW BESS) as well as OLTCs at HV/MV and MV/LV substations as shown in Fig. 2. In addition, all the MV network-connected DER units (BESS, PV and hydrogen electrolyzer in Fig. 2) have OLTCs on their MV/LV (0.4/20 kV) interconnection transformers. MV BESS's OLTC, for example, is controlled in the simulations as described in Fig. 1. MV BESS's average PSCAD model with controlled voltage sources and related control scheme with U-FLL-based synchronization has been presented in [3] and it has been used also in the other previous studies like [1], [2], [8] and [12]–[14]. The studied MV microgrid of this paper is 100 % U-FLL and inverter-based (Fig. 2) i.e. it does not have any synchronous generators (SGs) and therefore the Pf -control of the DER units' is disabled and the 2 MW MV & 0.2 MW LV BESSs are operated in the PU -control mode during the island operation. In addition, MV and LV DER units have fixed Q -setting value for reactive power provision (see [2] or [3] for more details about

control of DERs). 2 MW MV BESS is acting as a ' Q slack bus'. After the correct islanding detection [15] transition to PU -control [2], [3] takes place instantly.

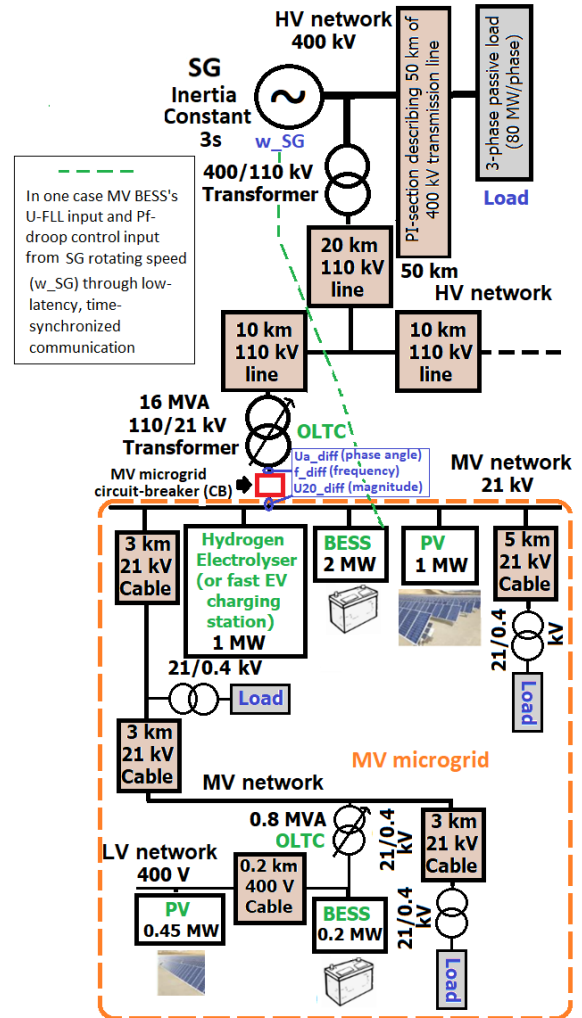


Fig. 2. Study system with MV microgrid. [3]

3 Simulations

In this section, the studied main simulation cases and simulation results from these study cases are presented. In the following, subsection 3.1 is focused on studying the effect of novel DER and OLTC management during MV microgrid island operation and subsection 3.2 on MV microgrid reconnection with OLTCs on MV DER interconnection transformers.

3.1 Effect of novel DER and OLTC management during island operation

Basic information about the study cases of this subsection is shown in Table 1. After that, Table 2 presents more information about the main study cases 1 and 2 including, for example, the PU -control voltage U setting values for MV and LV BESSs and MV/LV OLTCs' setting values for each subcase. In Table 3, the simulation sequence for all the study cases 1-2 (i.e. CASES 1A-2C_PV in Table 2) is shown.

Table 1. Basic information of the study cases (see Figs. 1 and 2 & Tables 2 and 3 for more information).

Case	Microgrid Voltage Level control during Island Operation	U-FLL input Frequency of DER	Reactive Power Q -control of DER Units
All Cases	PU -control of MV and LV BESSs	FFT (see [3] for U-FLL details ^{***})	MV and LV DER units with fixed Q -setting value ^{o)}
Case	MV/LV OLTC ^{**} control / Time delay	MV DER OLTC ^{**} setting value / Time delay	
CASE_2A-2C_PV ^{o)}	Fixed setting value / 10 s	0.43 kV / 3 s	

^{o)} MV BESS is acting as a 'Q slack bus, ^{**} Tolerance 2 % and Tap Step Size 2.5 %, ^{***} In Case 4 (Table 5) with MV BESS input from SG rotating speed, ^{o)} See Table 2 for more information

Table 2. Main study cases 1 and 2 (see also Table 1).

Case	PU -control's U -target/set value (pu) of MV and LV BESS	MV/LV OLTC's setting value	MV DERs with OLTC	Other
CASE 1A	1.0	No OLTC at MV/LV transformer	No	
CASE 1B	1.05			
CASE 1C	0.96			
CASE 2A	1.0	0.4	Yes	
CASE 2B	1.05	0.41		
CASE 2C	0.96	0.38		
CASE_2C_PV	0.96	0.38		With more rapid PV P output variation than in CASE_2C (Fig. 3c)

Table 3. Simulation sequence.

Time (t)	Event
19.9	HV network load increase
20.0	MV network microgrid islanding (Fig. 2)
50.0	HV and MV network (during MV islanding) load increase
50-100 ^{o)}	MV network microgrid reconnection (Fig. 2)

^{o)} Reconnection at $t=100$ s in all CASES 1A-2C_PV (Table 2)

The PSCAD simulation results from Table 2 study cases 1-2 are shown in Figs. 3 and 4. In Fig. 3a), MV network voltages at the HV/MV substation and in Fig. 3b) LV network voltages at the end of LV feeder with PV and BESS (Fig. 2) during MV island operation in different cases (Table 2) are presented. In addition, Fig. 3c) shows the active power P behaviour of MV BESS and MV PV in cases 2C and 2C_PV (Table 2) to highlight the differences in PV P output variations and its effect to PU -controlled MV BESS's P output. It can be seen also from Fig. 3b) how MV/LV transformer's OLTC increases the LV network voltage level in cases 2A-2C (Table 2) during MV microgrid island operation when compared to cases 1A-1C without OLTC on MV/LV transformer (Table 2). Fig. 4a) shows the voltage at the LV side of MV BESS's MV/LV (20/0.4 kV) interconnection transformer with OLTC, Fig. 4b) MV BESS's active power P and Fig. 4c) MV BESS's phase A current rms value at the LV side of MV/LV

interconnection transformer during MV microgrid island operation in different cases (Table 2).

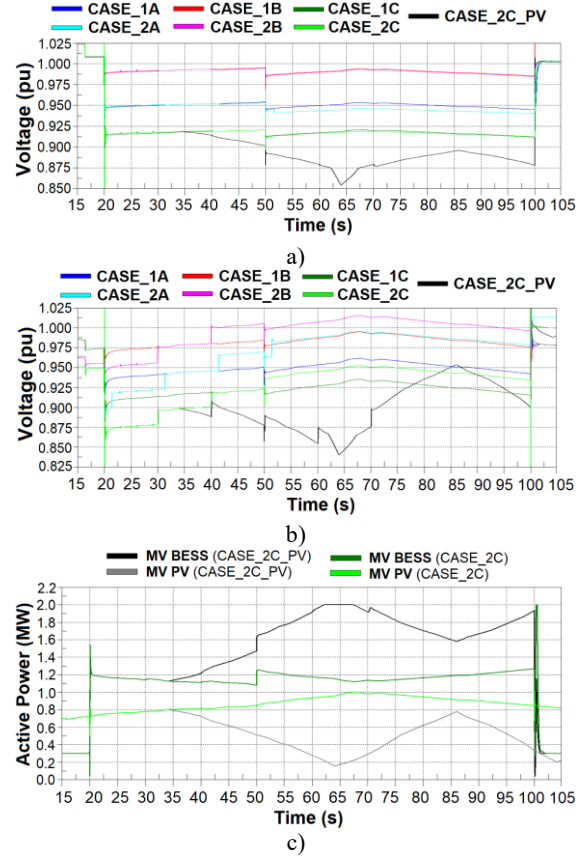
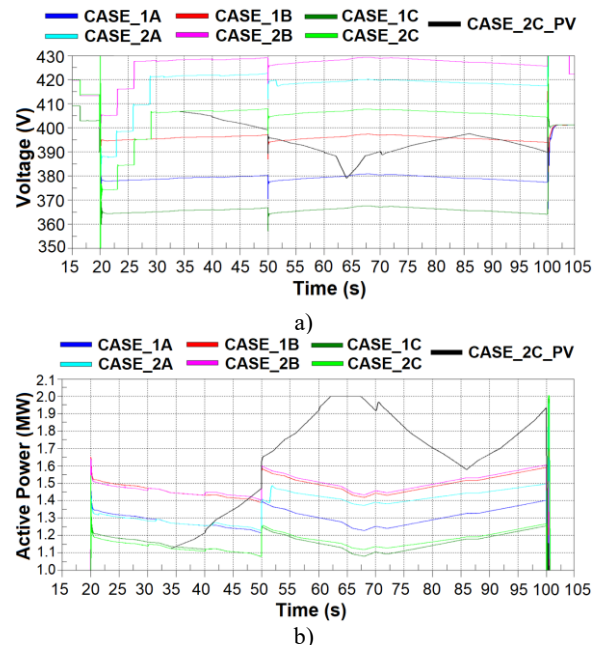


Fig. 3. a) MV network voltage at the HV/MV substation and b) LV network voltage at the end of LV feeder with PV and BESS during MV microgrid island operation between $t=20$ -100 s in different cases as well as c) active power of MV BESS and MV PV in cases 2C and 2C_PV (see Fig. 2 and Tables 1-3).



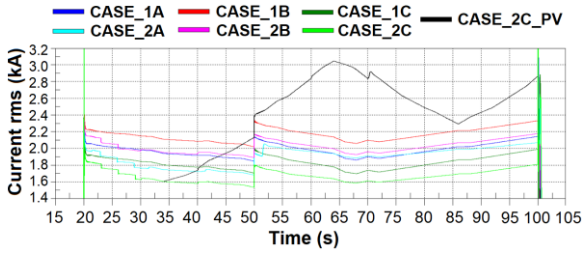


Fig. 4. a) Voltage at the LV side of MV BESS’s MV/LV (20/0.4 kV) interconnection transformer with OLTC, b) MV BESS’s active power P and c) MV BESS’s phase A current rms value at the LV side of MV/LV interconnection transformer during MV microgrid island operation between $t=20-100$ s in different cases (see Fig. 2 and Tables 1-3).

In Table 4, MV BESS’s active power P (Fig. 4b) and phase A current rms values (Fig. 4c) at $t=30.0$ s during the island operation of MV microgrid in the study cases 1-2 (Table 2) are presented. From Table 4 it can be seen, for example, that with MV BESS’s PU -control set value 1.0 pu in cases 1A and 2A, the MV DER OLTC in CASE_2A can reduce 11 % the needed current from the MV BESS when compared to CASE_1A. In addition, when lowering voltage control set value to 0.96 pu in CASE_2C, the MV BESS current can be even further reduced by 8 % when compared to CASE_2A (Table 4).

Table 4. MV BESS’s active power P (Fig. 4b) and phase A current rms value (Fig. 4c) at $t=30$ s during the island operation of MV microgrid (Fig. 2 and Tables 1-3) in study cases 1-2 (Table 2).

	CASE_1A / CASE_2A	CASE_1B / CASE_2B	CASE_1C / CASE_2C
P_{MV_BESS} (MW)	1.298 / 1.285 (-12 % from CASE_2B)	1.472 / 1.458	1.162 / 1.140 (-11 % from CASE_2A)
$I_{A_RMS_MV_BESS}$ (kA)	1.983 (-8 % from CASE_1B) / 1.764 (-10 % from CASE_2B & -11 % from CASE_1A)	2.150 / 1.968	1.845 (-7 % from CASE_1A) / 1.627 (-8 % from CASE_2A & -12 % from CASE_1C)
Time t (s)	30.0		

3.2 MV microgrid reconnection with OLTCs on MV DER interconnection transformers

Table 5 presents the main study cases 3 and 4 of this subsection. The simulation sequence for all the Table 5 study cases 3-4 is presented in Table 3. Table 6 shows the phase A voltage phase angle difference Ua_diff (maximum value in other cases than CASE_4) for stable MV microgrid reconnection (Fig. 2) and simultaneous values for frequency difference f_diff and voltage magnitude difference $U20_diff$ (across MV microgrid circuit-breaker at the moment of microgrid reconnection, see Fig. 2) in study cases 3-4 (Table 5).

Based on the Table 6 simulation results, like also seen in [3], the U-FLL based DERs have very good voltage phase angle difference (Ua_diff , Fig. 2) or phase jump ride through /

withstand capability i.e. depending on the case $\pm 145-160^\circ$ also when the proposed novel MV BESS and OLTC control concept (Fig. 1) is used. This is much more than required, for example, by IEEE 1547-2018 [16] which requires that the voltage phase angle jump withstand / ride-through requirement for multi-phase DERs should be $\leq 20^\circ$. On the other hand, IEEE Standard 2800–2022 [17] defines that any inverter-based resource should be able to ride through a voltage phase angle change of $\pm 25^\circ$. Regarding to the stability after MV microgrid reconnection, it can be seen from Table 6 that in CASE_3C with PU -control voltage U target/setting value 0.96 pu the voltage magnitude difference $U20_diff$ is much larger than in cases 3A and 3B. Therefore, also the Ua_diff maximum value is a bit smaller in CASE_3C than in cases 3A and 3B.

Table 5. Main study cases 3-4 (see also Tables 1-3).

Case	PU -control’s U -target/set value (pu) of MV and LV BESS	MV/LV OLTC’s setting value	MV DERs with OLTC	Other
CASE_3A	1.0	0.4		-
CASE_3B	1.05	0.41		
CASE_3C	0.96	0.38		
CASE_4 ^{*)}	1.0	0.4	Yes	MV BESS’s U-FLL and Pf -droop control ^{*)} input frequency from SG rotating speed (Fig. 2)

^{*)} Pf -control activated after MV microgrid reconnection, ^{**)} See also [3]

Table 6. Phase A voltage phase angle difference Ua_diff (maximum value in other cases than CASE_4) for stable MV microgrid reconnection (Fig. 2 and Tables 1, 3 & 5) and simultaneous values of frequency difference f_diff and voltage magnitude difference $U20_diff$ (across MV microgrid circuit-breaker at the moment of microgrid reconnection) in study cases 3-4 (Table 5).

	CASE_3A	CASE_3B	CASE_3C	CASE_4 ^{*)}
Ua_diff (degrees)	-161°	151°	145°	18°
f_diff (Hz)	0.1	0.288	0.013	0.001
$U20_diff$ (pu)	0.055	0.0142	0.091	0.06
MG reconnection time t (s)	58.3	52.53	94.23	61.59

^{*)} Reconnection always successful with 100 % IBR-based microgrid with U-FLLs when utility grid SG’s rotating speed (Fig. 2) is used as input to U-FLL (not possible if there is SG inside microgrid during the island operation and in these cases only local freq. meas. should be used), see also [3]

In Fig. 5, MV microgrid’s and utility grid’s frequency at the moment of MV microgrid reconnection are presented in CASE_3A (Fig. 5a, see Table 5) with maximum allowed Ua_diff for stable MV microgrid reconnection (Table 6) as well as in CASE_4 (Fig. 5b, Table 5). It can be seen from the simulation results of CASE_4, (Fig. 5b) that perfectly synchronized reconnection could be always achieved by only having U-FLL input of one MV DER (e.g. MV BESS, Fig.2) from utility grid SG’s rotating speed (ω_{SG} Fig. 2) through time synchronized, low-latency communication.

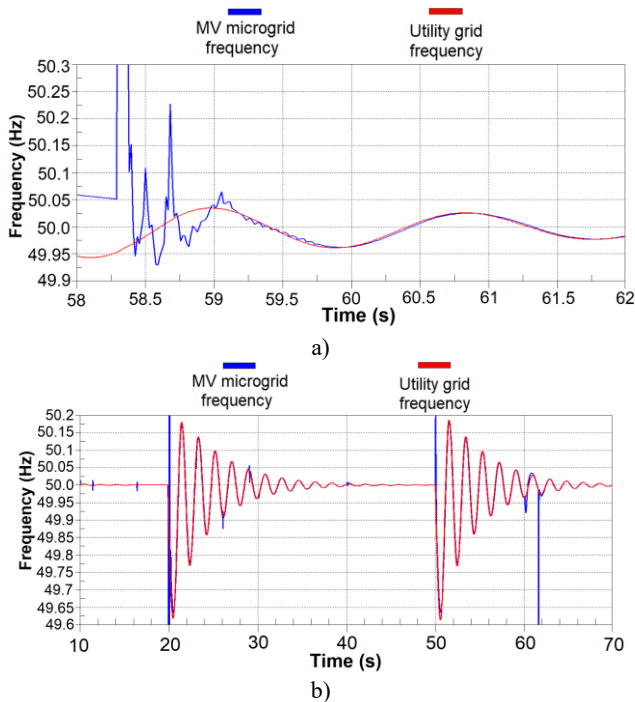


Fig. 5. MV microgrid’s and utility grid’s frequency at the moment of MV microgrid reconnection in a) CASE 3A at $t=58.3$ s and b) CASE 4 at $t=61.59$ s (see also Fig. 2, Tables 1, 5 and 6 and simulation seq. in Table 3).

4 Conclusions

This paper proposed novel MV DERs’ and OLTCs’ management concept (Fig. 1) in order to enable longer duration island operation of MV microgrid by reducing the needed amount of current from MV BESS. The PSCAD simulation studies showed how the proposed MV BESS’s interconnection transformer OLTC’s control logic during MV microgrid’s island operation together with chosen BESS *PU*-based voltage control set value (0.96 pu, 1.0 pu or 1.05 pu) affects to the needed amount of current from the BESS. Based on the simulations, for example, with BESSs’ *PU*-control set value 1.0 pu, the MV DER OLTC could reduce 11 % the needed current from the MV BESS and when lowering voltage control set value to 0.96 pu, the BESS current could be even further reduced by 8 %. Simulations also showed that the U-FLL-based DERs used in this paper (modelled with average voltage sources) have also very good voltage phase angle difference ride through capability when proposed novel MV BESS and OLTC control concept is used. Stable MV microgrid reconnection was possible even with ± 145 - 160° angle difference before the reconnection.

5 Acknowledgements

This work has been done as a part of “Smart Grid 2.0” -project funded by Business Finland with grant No. 1386/31/2022.

6 References

[1] Laaksonen, H., Khajeh, H., Hatziargyriou, N.: 'Advanced Distributed Energy Resources and On-Load Tap-Changer

Control Principles for Enhanced Flexibility Services Provision', IEEE Access, 2024
 [2] Laaksonen, H.: 'Universal Grid-forming Method for Future Power Systems', IEEE Access, 2022
 [3] Laaksonen, H., Hatziargyriou, N.: 'Reconnection of MV Microgrid with Universal Grid-forming Inverter-based Resources', Proc. MedPower 2024, Athens, Greece, 2024
 [4] Schneider, K. P., Tuffner, F. K., Fuller, J. C., Singh, R.: 'Evaluation of Conservation Voltage Reduction (CVR) on a National Level', Pacific Northwest National Laboratory, United States, 2010
 [5] Sen, P. K., Lee, K. H.: 'Conservation Voltage Reduction Technique: An Application Guideline for Smarter Grid', IEEE Transactions on Industry Applications, 2016
 [6] Lim, I.-H., Lee, M.-H., Shin, Y.-H.: 'Application of Conservation Voltage Reduction using Automatic Voltage Regulator of Linear Voltage Control in Campus Microgrid with Power Consumption Reduction', The Transactions of the Korean Institute of Electrical Engineers, 2017
 [7] Laaksonen, H., Parthasarathy, C., Khajeh, H., Shafie-khah, M., Hatziargyriou, N.: 'Flexibility Services Provision by Frequency-Dependent Control of On-Load Tap-Changer and Distributed Energy Resources', IEEE Access, 2021
 [8] Laaksonen, H., Khajeh, H., Hatziargyriou, N.: 'Coordinated Control Schemes for Improved DER Hosting Capacity and Flexibility Provision', CIREAD 2024 Workshop, Vienna, Austria, 2024
 [9] CIREAD Working Group - WG 2021-2: Network Planning and System Design with Flexibility, Final Report, ISSN 2684-1088, <http://www.cired.net/files/download/341>, 2024
 [10] Laaksonen, H., Khajeh, H., Parthasarathy, C., Shafie-khah, M., Hatziargyriou, N.: 'Towards Flexible Distribution Systems: Future Adaptive Management Schemes', Applied Sciences, 2021
 [11] Laaksonen, H., Hatziargyriou, N.: 'Frequency-dependent Control of DERs and OLTCs in the Future Distribution Networks', CIREAD 2025, Geneva, Switzerland, 2025
 [12] Laaksonen, H.: 'Improvement of Power System Frequency Stability with Universal Grid-forming Battery Energy Storages', IEEE Access, 2023
 [13] Laaksonen, H.: 'Solutions to Improve Transient Stability of Universal Grid-forming Inverter-based Resources', Int. Review of Electrical Engineering (IREE), 2023, 18, 3
 [14] Laaksonen, H.: 'Stability of Future Low-Inertia Power Systems with Different Grid-Forming Control Schemes', Proc. CIREAD 2024 Workshop, Vienna, Austria, 2024
 [15] Laaksonen, H.: 'Islanding Detection with Universal Grid-forming Inverter-based Generation', Proc. CIREAD 2023, Rome, Italy, 2023
 [16] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces, Standard IEEE 1547-2018, IEEE Standards Association, IEEE Standards Coordinating Committee 21, 2018
 [17] IEEE standard for interconnection and interoperability of inverter-based resources (IBRs) interconnecting with associated transmission electric power systems, IEEE Std 2800-2022, 2022