ISLANDING DETECTION WITH UNIVERSAL GRID-FORMING INVERTER-BASED GENERATION

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ABSTRACT

One major concern of commonly proposed grid-forming (GFM) inverter-based resources (IBRs) has been the unintentional islanding, because the variables that are typically used for islanding detection of GFMs are different than those traditionally used with grid-following (GFL) IBRs. Therefore, this paper studies the effect of recently proposed new universal frequency-locked-loop (U-FLL) -based GFM synchronization method on islanding detection with different passive methods like voltage vector shift, positive sequence voltage angle difference, voltage unbalance and voltage total harmonic distortion. The PSCAD simulations are done with 100 % IBR-based system as well as with hybrid power system including IBR-based distributed energy resources (DER) and synchronous generation (SG). Based on the simulations it can be concluded that the recently proposed universal U-FLL GFM method does not risk the operation of the traditional passive islanding detection schemes unlike some other commonly proposed GFM control methods.

INTRODUCTION

In the future power systems, the share of GFM IBRs must be increased in order to guarantee stability of the power system during rapid changes in generation, consumption and network topologies. Therefore, it is important that the behavior and response of GFM IBRs is also stable during different type of operation modes, events and faults. In addition, the fault behavior and response of the inverters must be compatible with the network protection and islanding detection scheme. The main control schemes of IBRs can be divided into GFM and GFL schemes which can behave differently during disturbances and rapid changes e.g. in network topology. In the future power systems, the amount of GFM IBRs must be increased to guarantee stability of the power system during rapid changes in generation mix as well as during topology changes and transitions between normal grid-connected and intended islanded (microgrid) operation. [1], [2]
Synchronization of GFM and GFL IBRs is one main difference between them and has an effect also on their disturbance behavior and stability. Conventionally, a GFL IBR uses voltage-based synchronization [3] i.e. it is synchronized to measured or estimated grid voltage angle e.g. by phase-locked-loop (PLL) or frequency-locked-loop (FLL) component. While most of the GFM IBR control schemes don't have a PLL or FLL. Instead, their synchronization can be based e.g. on power synchronization [3], [4] which tries to emulate the SGs'power synchronization principles [5]. [2]
In [6], it was stated that GFMs suffer greater impacts from faults in strong grids and GFLs suffer larger impacts from faults in weak grids. [5] notified also that the GFM IBRs can have challenges related to, angle stability, fault-ride-through (FRT) capability, and transition from islanded to grid-connected mode. In addition, it has been stated that the unintentional islanding of commonly proposed GFM IBRs is a risk to the reliability of future IBR-based power systems, because the variables that are used for islanding detection of GFMs are different than with GFL IBRs [7]. [2] In [7] it was stated that

- With GFL IBRs frequency deviation after islanding is ruled by reactive power mismatch ($\Delta Q \rightarrow \Delta f$) and
- With commonly proposed GFM IBRs frequency deviation after islanding is ruled by active power mismatch ($\Delta P \rightarrow \Delta f$).

In this paper the effect of recently proposed new U-FLL -based GFM synchronization method, which can directly replace the PLL-component of GFL inverters [2], on islanding detection with passive methods like voltage vector shift, positive sequence voltage angle difference, voltage unbalance and voltage total harmonic distortion is examined. The PSCAD simulations are done in two main study cases:

1) 100 % IBR-based system with full power converter wind turbine, WT (in MV network) and battery energy storage, BESS (in LV network) and
2) Hybrid power system with IBR and SG including WT with full power converter (in MV network) and SG (in MV network).

In the simulation studies the effect of IBR control and synchronization method (PLL or U-FLL) is compared. In addition, the effect of WT reactive power-frequency (*Qf*)-droop [8] control on islanding detection is studied.

Universal grid-forming IBR grid synchronization method

Currently there does not exist any universal GFM control and synchronization method. Therefore, a new universal grid-forming/-supporting U-FLL-based synchronization (Fig. 1) for IBRs was proposed in [2].

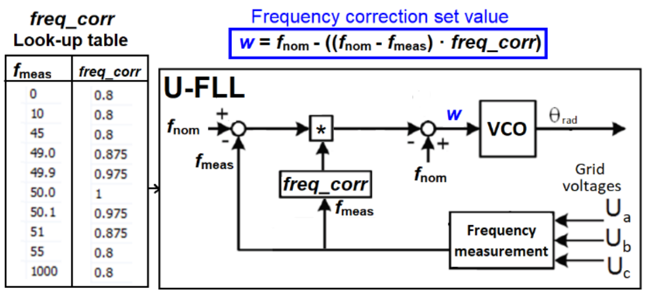

Figure 1. Universal grid-forming and supporting U-FLL synchronization method [2].

More information about the general targets and related issues as well as details of U-FLL can be found from [2].

Studied passive islanding detection schemes

In this paper the focus is on previously proposed passive islanding detection parameters such as

i. voltage vector shift (VVS) [9],
ii. positive sequence voltage angle difference ($U_{1\_\Delta angle}$) [10],
iii. voltage unbalance (VU) [11]-[14] and
iv. voltage total harmonic distortion (U_{THD}) [11]-[14].

These parameters can be used alone or as part of multi-criteria or combined islanding detection algorithms. [11]-[18]

SIMULATION STUDY CASES

The main study cases of this paper are summarized in Table 1.

Table 1. Main study cases.

Case	Voltage level	Type and number of generating units	Synchroniza-tion of IBRs
CASE_1_MV_IBR / CASE_1_LV_IBR	MV and LV	WT (1, full power converter), BESS (1)	PLL or U-FLL
CASE_2_MV_HYBRID	MV	WT (1, full power conv.), SG (1)	PLL or U-FLL

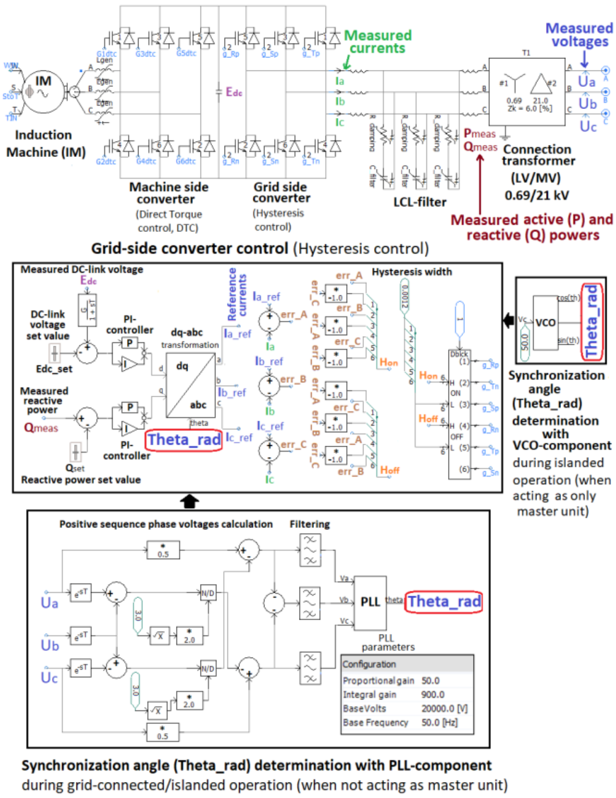

Figure 2. Detailed PSCAD model of wind turbine, WT, with full power converter control scheme without utilization of new U-FLL (Fig. 1) in *CASE_2_MV_HYBRID* (Fig. 6) and *CASE_1_MV_IBR* (Fig. 5).

The main simulation cases (Table 1) included:

a) Different type of DER units with traditional PLL-component for grid synchronization (PLL was replaced by the new U-FLL -component, Fig. 1)
   - Wind turbine (WT) with full power converter, detailed model including power electronic switches, connected in MV network (Fig. 2)
   - Battery energy storage system, BESS with AC/DC-inverter, detailed model including power electronic switches, connected in LV network, operation in discharge mode (generation) (Fig. 3 and 4)

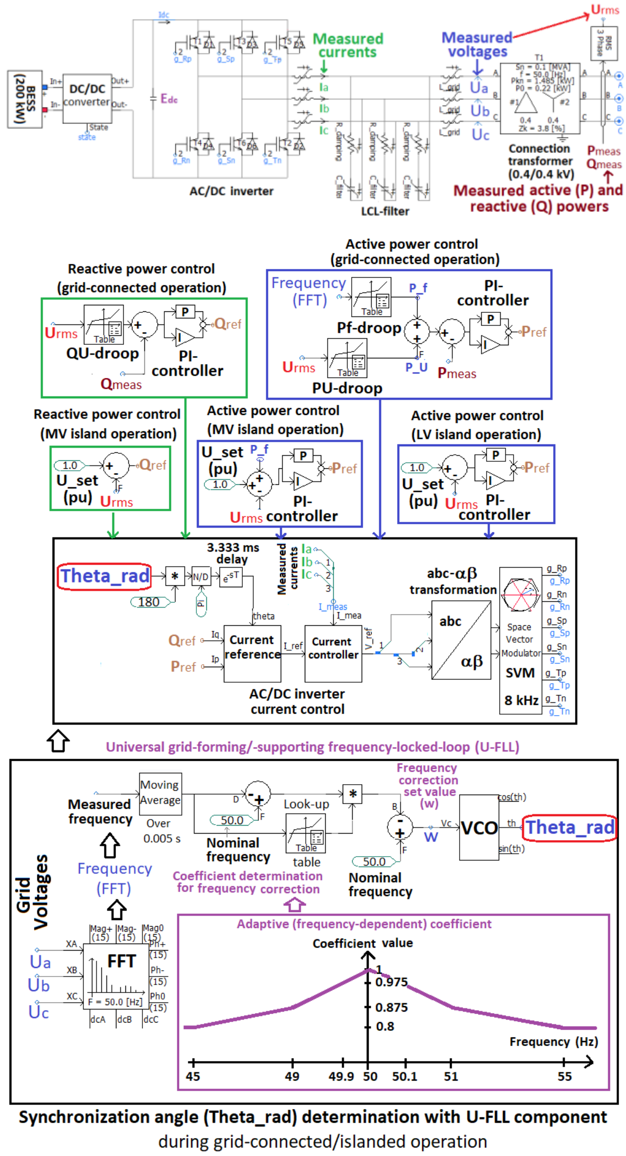

Figure 3. Detailed PSCAD model of battery energy storage system, BESS with AC/DC-inverter control scheme including U-FLL (Fig. 1).

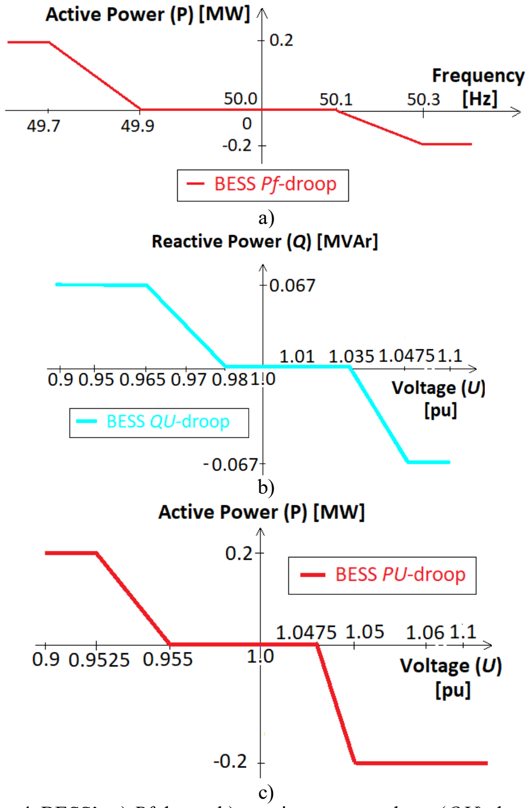

Figure 4. BESS's a) *Pf*-droop, b) reactive power-voltage (*QU*)-droop and c) *PU*-droop settings (Fig. 3).

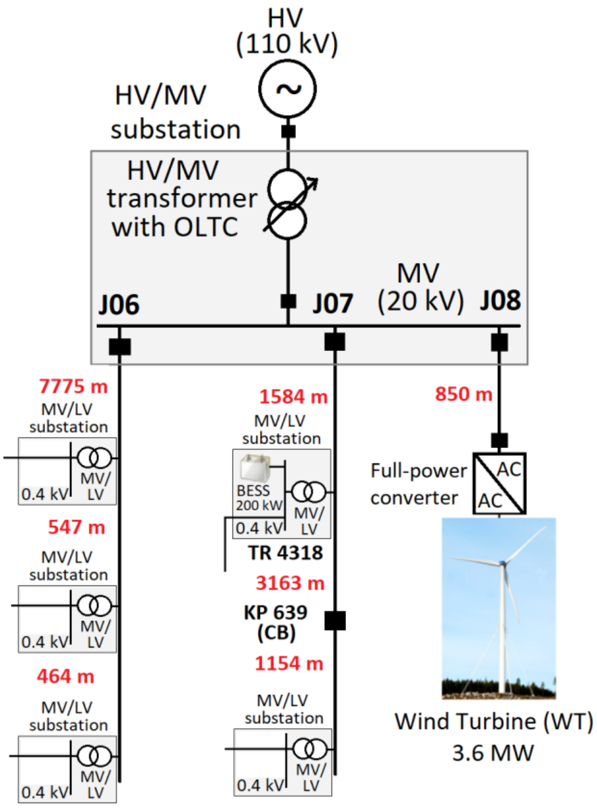

Figure 5. One-line diagram of the 100 % IBR-based MV and LV network with WT (MV network, Fig. 2) and BESS (LV network, Fig. 3) in *CASE_1_MV_IBR* and *CASE_1_LV_IBR*.

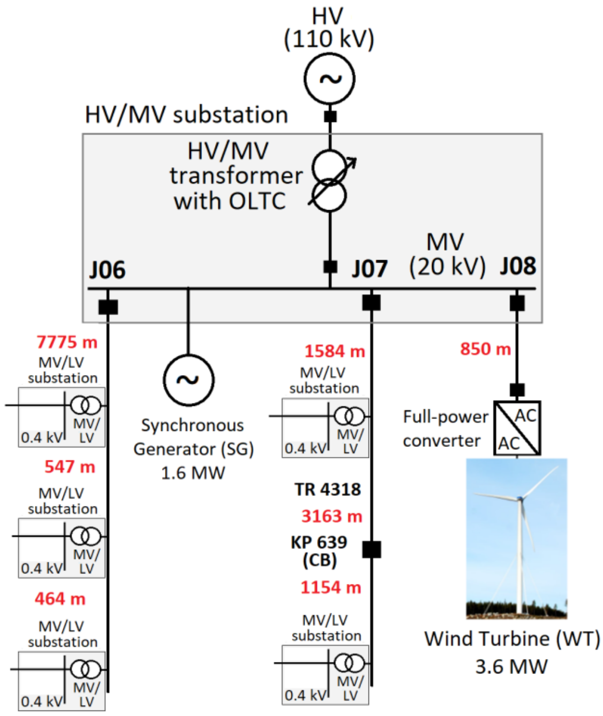

Figure 6. One-line diagram of the MV hybrid network with IBR (Fig. 2) and SG (*CASE_2_MV_HYBRID*).

SIMULATION RESULTS

In the following, the main simulation results from the different study cases (Table 1) are presented. First, simulation results with 100 % IBR-based generation in MV and LV network (*CASE_1_MV_IBR* and *CASE_1_LV_IBR*, Fig. 5 and Table 1) are shown. After that, the results from cases with hybrid MV network (*CASE_2_MV_HYBRID*, Fig. 6 and Table 1) are presented.

100 % IBR-based distribution network

The total simulation time was t=4.0 s, transition to MV islanded operation with WT (Fig. 2) and BESS (Fig. 3 and 4) happened at t=1.9 s and transition to LV islanded operation with BESS happened at t=2.7 s. In addition, BESS *Pf*-blocking after MV islanding took place at t=2.0 s (see Fig. 3, active power control (MV island operation) i.e. P_f = 0 after t=2.0 s). In the following, the PSCAD simulation results with 100 % IBR-based generation in *CASE_1_MV_IBR* and *CASE_1_LV_IBR* (Fig. 5 and Table 1) subcases (Table 2) during MV and LV islanding are shown in Fig. 7-12. The differences between the studied subcases are presented in Table 2.

It can be seen from the simulation results (Fig. 7-12) that, the proposed universal U-FLL GFM method [2] does not risk the operation of the studied passive islanding detection schemes in 100 % IBR-based distribution network (Fig. 5). Actually it enables better islanding detection (Fig. 7-11) than the synchronization with PLL / Fixed master with VCO (control mode change after islanding with small time delay) (Fig. 2, Table 2).

Table 2. Differences between the studied subcases of *CASE_1_MV/LV_IBR* (Fig. 5, Table 1).

Subcase	**Synchronization of WT** (before/after MV islanding)	**Synchroniza-tion of BESS** (before/after LV islanding)	**Events before MV islanding**
CASE_1_MV/ LV_IBR_1A (PLL/Fixed master)	PLL / Fixed master with VCO	PLL / Fixed master with VCO	50.25 Hz over-frequency event at *t*= 1.35-1.6 s
CASE_1_MV/ LV_IBR_1A (U-FLL)	U-FLL	U-FLL	50.25 Hz over-frequency event at *t*= 1.35-1.6 s
CASE_1_MV/ LV_IBR_1B (U-FLL)	U-FLL	U-FLL	-

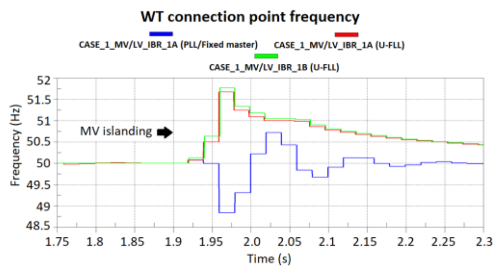

Figure 7. WT connection point frequency (Fig. 5, Table 1 and 2).

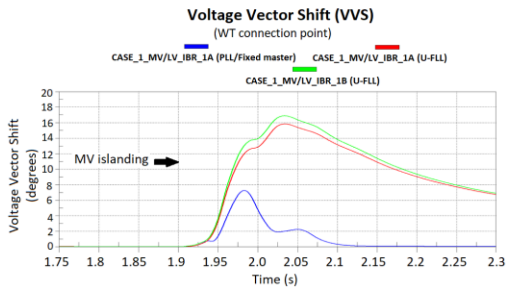

Figure 8. VVS at the WT connection point (Fig. 5, Table 1 and 2).

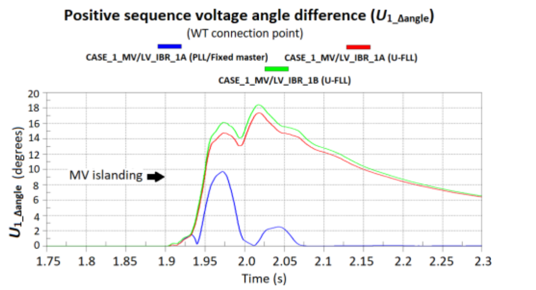

Figure 9. $U_{1\_\Delta\text{angle}}$ at the WT connection point (Fig. 5, Table 1 and 2).

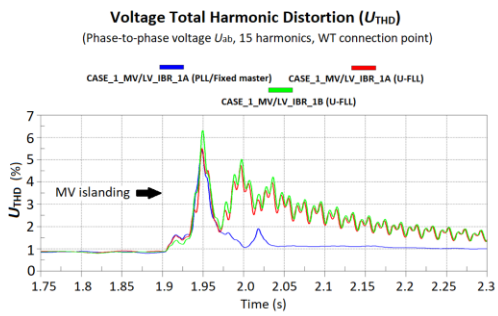

Figure 10. U_{THD} at the WT connection point (Fig. 5, Table 1 and 2).

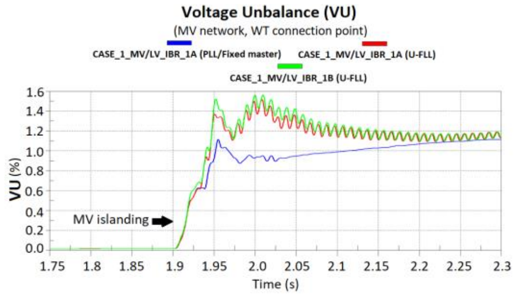

Figure 11. VU at the WT connection point (Fig. 5, Table 1 and 2).

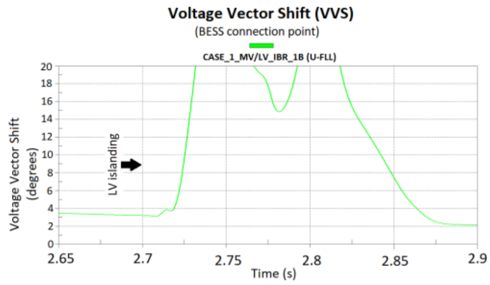

Figure 12. VVS at the BESS connection point in *CASE_1_MV/LV_IBR_1B (U-FLL)* (Fig. 5, Table 1 and 2).

Hybrid DER-based distribution network

The total simulation time was *t*=30.0 s, transition to MV islanded operation with WT (Fig. 2) and SG (Fig. 6) happened at *t*=13.6 s. In the following, the PSCAD simulation results from MV hybrid network with WT and SG (*CASE_2_MV_HYBRID*) (Fig. 6 and Table 1) subcases during MV islanding are shown in Fig. 14-17. The differences between the studied subcases are presented in Table 3. In all subcases (Table 3) SG control mode is changed after islanding so that instead of *PQ*-control it is acting as grid-forming unit with PI-control to minimize the steady-state frequency deviation during islanding.

Table 3. Differences between the studied subcases of *CASE_2_MV_HYBRID* (Fig. 6, Table 1).

Subcase	**Synchronization of WT** (before/after MV islanding)	**Synchroniza-tion of BESS** (before/after LV islanding)	**WT reactive power control**
CASE_2_MV_ HYBRID_1A (PLL)	PLL	PLL / Fixed master with VCO	Fixed *Q*-control (set target value)
CASE_2_MV_ HYBRID_1A (U-FLL)	U-FLL	U-FLL	Fixed *Q*-control (set target value)
CASE_2_MV_ HYBRID_1B (U-FLL)	U-FLL	U-FLL	Fixed *Q*-control (set target value) + *Qf*-droop control (Fig. 13)

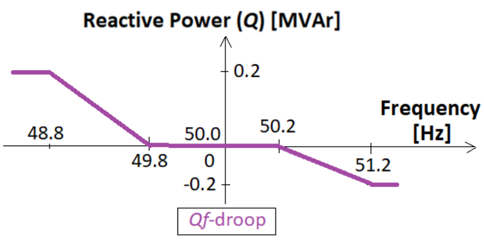

Figure 13. WT's reactive power-frequency (*Qf*)-droop (Fig. 2).

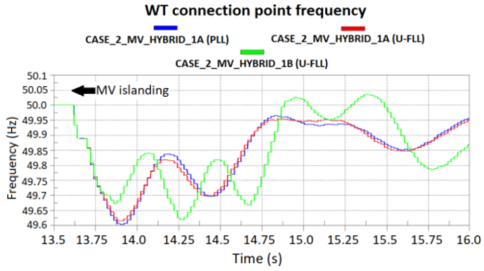

Figure 14. WT connection point frequency (Fig. 6, Table 1 and 3).

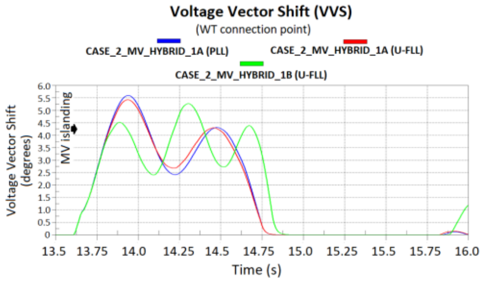

Figure 15. VVS at the WT connection point (Fig. 6, Table 1 and 3).

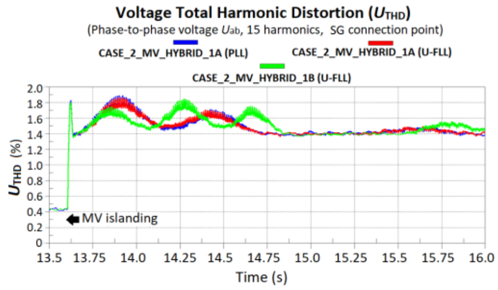

Figure 16. U_{THD} at the SG connection point (Fig. 6, Table 1 and 3).

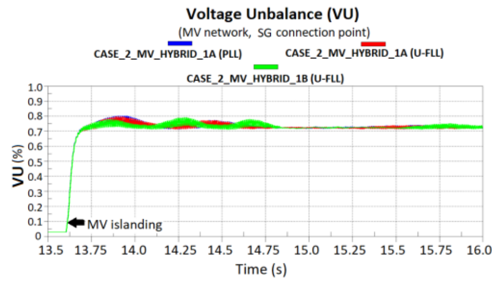

Figure 17. VU at the SG connection point (Fig. 6, Table 1 and 3).

Also in case with MV hybrid network (Fig. 6), the simulation results (Fig. 14-17) confirm that the U-FLL synchronization method [2] does not risk the operation of the studied passive islanding detection schemes. The effect of WT (Fig. 2) *Qf*-control (Fig. 13) was also studied. It can be seen from Fig. 14 that it changed the MV microgrid frequency dynamics after islanding and this mostly affected negatively to VVS-based islanding detection (Fig. 15).

CONCLUSIONS

This paper studied the effect of recently proposed new U-FLL -based GFM synchronization method on islanding detection with chosen passive methods i.e. VVS, $U_{1\_\Delta angle}$, VU and U_{THD}. In the PSCAD simulation studies, 100 % IBR-based and hybrid (IBR+SG) distribution network islanding were examined to find out the effect of IBR control and synchronization method (PLL or U-FLL) on the studied passive islanding detection methods. In general, it can be concluded that the proposed U-FLL GFM method does not risk the operation of the chosen passive islanding detection methods unlike some other commonly proposed GFM control methods. In case with 100 % IBR-based distribution network, it can enable even better islanding detection with the examined parameters.

REFERENCES

[1] A. Tuohy, P. Dattaray, E. Farantatos, A. Kelly, E. Lannoye, 2019, *Implications of Reduced Inertia Levels on the Electricity System: Technical Report on the Challenges and Solutions for System Operations with Very High Penetrations of Non-Synchronous Resources*, EPRI, Palo Alto, CA.

[2] H. Laaksonen, 2022, "Universal Grid-forming Method for Future Power Systems," *IEEE Access*, vol. 10.

[3] X. Wang, M. G. Taul, H. Wu, Y. Liao, F. Blaabjerg, L. Harnefors, 2020, "Grid-Synchronization Stability of Converter-Based Resources - An Overview," *IEEE Open Journal of Industry Applications*, vol. 1, 115-134.

[4] L. Zhang, L. Harnefors, H. Nee, 2010, "Power-synchronization control of grid-connected voltage-source converters," *IEEE Trans. Power Syst.*, vol. 25, 809-820.

[5] R. Rosso, X. Wang, M. Liserre, X. Lu, S. Engelken, 2021, "Grid-Forming Converters: Control Approaches, Grid-Synchronization, and Future Trends—A Review," *IEEE Open Journal of Industry Applications*, vol. 2, 93-109.

[6] A. Hadjileonidas, Y. Li, T. C. Green, 2022, "Comparative Analysis of Transient Stability of Grid-Forming and Grid-Following Inverters," *IEEE PEAC-conference*.

[7] T. Liu, X. Wang, F. Liu, K. Xin, Y. Liu, 2022, "Islanding Detection of Grid-Forming Inverters: Mechanism, methods, and challenges," *IEEE Electrification Magazine*, vol. 10.

[8] H. Laaksonen, 2014, "Securing Passive Islanding Detection and Enabling Stable Islanding with Q/f -droop Control of DG Unit," International Review of Electrical Engineering, vol. 9.

[9] M. Kandakatla, H. Laaksonen, S. Bonela, 2015, "Advanced Vector Shift Algorithm for Islanding Detection," *CIRED 2015*, Lyon, France, June 15-18, 2015.

[10] H. Laaksonen, 2013, "New Passive Islanding Detection Method based on Cumulative Sum of Change in Voltage Positive Sequence Phase Angle," *International Review on Modelling and Simulations (IREMOS)*, vol. 6.

[11] H. Laaksonen, 2012, "New Multi-criteria-based Algorithm for Islanding Detection in Smart Grids," *IEEE PES ISGT Europe 2012*, Berlin, Germany, October 14-17, 2012.

[12] H. Laaksonen, 2013, "Advanced Islanding Detection Functionality for Future Electricity Distribution Networks," *IEEE Transactions on Power Delivery*, vol. 28.

[13] H. Laaksonen, 2014, "Enhanced Multi-Criteria-Based Passive Islanding Detection Scheme," *International Review of Electrical Engineering (IREE)*, vol. 9.

[14] H. Laaksonen, P. Hovila, 2018, "Islanding Detection During Intended Island Operation of Nested Microgrid," *ISGT Europe 2018*, Sarajevo, Bosnia and Herzegovina, October 21-25, 2018.

[15] H. Laaksonen, 2016, "Grid code compatible islanding detection schemes using traditional passive methods" *The IET 13th International Conference on Developments in Power System Protection*, Edinburgh, Scotland, UK, March 7 - 10, 2016.

[16] H. Laaksonen, 2016, "Need for New Islanding Detection Schemes and Prioritization with Generator Grid Code Requirements," Int. Review of Electrical Engineering, vol. 11.

[17] H. Laaksonen, P. Hovila, 2017, "Future-proof Islanding Detection Schemes in Sundom Smart Grid," *CIRED 2017*, Glasgow, Scotland, 12-15 June, 2017.

[18] H. Laaksonen, P. Hovila, K. Kauhaniemi, 2018, "Combined Islanding Detection Scheme Utilizing Active Network Management for Future Resilient Distribution Networks," *The Journal of Engineering*.