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Adaptation of DER Control Schemes and Functions During MV Network Back-up Connection

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***Abstract*—In the future, active network management (ANM) and adaptive distributed energy resources (DER) control schemes will be increasingly required to fulfill growing power system resiliency and renewable generation integration needs. As part of future ANM schemes more frequent electricity distribution network topology changes could be utilized to improve the electricity supply reliability. However, these topology changes may require DER control methods and functions adaptation accordingly in order to maintain feasible power quality, voltage level and supply reliability in the distribution network. This paper presents a real-life case study from the needed adaptation of DER control schemes and functions after MV distribution network topology change from normal to back-up connection. The focus in the studied case is on MV network connected wind turbine (WT) control scheme adaptation after the topology change based on real measured data from the WT. In addition, the paper presents also simulations from potential future scenarios with centralized and distributed battery energy storage systems (BESSs) which could be also simultaneously utilized for the provision of local and system-wide services.**

Keywords— Distributed Energy Resources, Flexibility Services, Active Network Management, Voltage Control, Frequency Control

NOMENCLATURE

ANM	Active Network Management
BESS	Battery Energy Storage System
DG	Distributed Generation
DER	Distributed Energy Resources
DSO	Distribution System Operator
ES	Energy Storage
EV	Electric Vehicle
HV	High Voltage
J06, J07, J08	MV feeders in the study case
LV	Low Voltage
MV	Medium Voltage
NC	Normally Closed (circuit-breaker)
NO	Normally Open (circuit-breaker)
OLTC	On-Load Tap Changer
PSCAD	Power System Simulation Software
PV	Photovoltaic
RES	Renewable Energy Resources
RfG	Requirements for Generators
RPW	Reactive Power Window
SSG	Sundom Smart Grid
TSO	Transmission System Operator
Volt-VAr	Voltage - Reactive Power
WT	Wind Turbine
$\cos\varphi$	Power factor
$\cos\varphi(P)$	Active Power dependent power factor
f	Frequency
P	Active Power
Pf or P(f)	Active Power - Frequency
PU or P(U)	Active Power - Voltage
Q	Reactive Power
$Q(P)$	Reactive Power - Active Power
QU or Q(U)	Reactive Power - Voltage
QPU	Reactive Power - Active Power - Voltage
t	Time
U	Voltage

I. INTRODUCTION

Main challenges in the future power systems are related to management of uncertainties and improvement of electricity supply reliability and resiliency. The uncertainties are related, for example, to increased amount of weather dependent renewable generation and integration of electric vehicles (EV) as well as variable inertia and fault levels due to changing power system dynamics and increased number of inverter-based DER. Due to these growing challenges, utilization of ANM and adaptive DER control methods will be of importance in future distribution networks.

Different DER units include, for example, distributed generation (DG), energy storages (ESs), demand response (DR) and electric vehicles. These DERs connected in low-voltage (LV) and medium-voltage (MV) electricity distribution networks can provide different local technical flexibility services for the distribution system operator (DSO) and also system-wide services for the transmission system operator (TSO). Active power (*P*) and reactive power (*Q*) control related flexibility services from DER can enable more dynamic management of future DSO and TSO networks. Flexibility services from DER can, for instance, support the whole power system frequency (*f*) or local voltage (*U*) control at corresponding voltage level. The flexibility services from different DERs can also enable larger scale integration of renewable energy sources (RES) and EVs as well as minimize the system and societal costs. In the future, also more frequent distribution network topology changes, for example, between grid-connected and islanded operation are possible if services from controllable DER units can be utilized for the improvement of electricity supply reliability. However, these topology changes may also require DER control methods and functions adaptation accordingly in order to maintain high power quality, voltage level and supply reliability in the distribution network. Therefore, new operation planning principles considering simultaneously possibilities of ANM, adaptation of DER control settings and functions as well as coordination of TSO-DSO needs are increasingly needed for the DSOs. [1]-[5]

In this paper a real-life case study from Sundom Smart Grid (SSG) in Vaasa, Finland is presented regarding to the needed adaptation of DER control schemes and functions after MV distribution network topology change from normal to back-up connection. The focus in the case study is on MV network connected WT control scheme adaptation after the topology change based on real measured data from the WT. This paper presents also simulations from potential future scenarios with centralized and distributed BESSs which could be also simultaneously utilized for the provision of local (DSO) and system-wide (TSO) services.

II. DER Control Functionalities

Active and reactive power related flexibility services of DER units can be realized by different local DER unit inverter control functions like constant power factor (cosφ), fixed *Q*, *Q*(*P*), cosφ(*P*), *Q*(*U*) / *QU* / Volt-VAr, *P*(*U*) / *PU* and *P*(*f*) / *Pf*. *QU*-droop control mode is quite often used DER unit voltage control method in DSO network [3]-[5].

Typically DER control functions are used with fixed settings without coordinated management or communication between different DER units. However, even low level of communication between DER units could enable achievement of better control settings and improved performance. In addition, more accurate state estimation and operation coordination are also of key importance to realize more optimal operation and increase DER and EV hosting capacity in the DSO networks as well as enable improved provision of local (DSO) and system-wide (TSO) flexibility services [6]. Also various other voltage and reactive power control methods have been proposed for the DER units in the literature [7]-[13].

Among different DER units, BESSs will have major role in the future power systems due to their rapid and controllable dynamics as well as high capability for multiple flexibility services provision for the DSOs and TSOs (i.e. multi-purpose use). Regarding the use of BESSs for local voltage control, schemes based on control of both *P* and *Q* have been found to be more effective [14]. Due to their fast response and dynamics, BESSs are also capable of providing frequency control related services for the TSOs. These services can be realized by an individual large-scale BESS or by aggregating multiple small-scale BESSs [15]. The multi-purpose use of BESS for DSO and TSO services provision should be done in optimal and coordinated way by considering also the location (connection point) of BESS in the distribution network.

III. Simulation Study Cases

The focus in the case study of this paper is on adaptation of DER control schemes and functions after MV network topology change from normal connection to back-up connection. The studies are done for a real-life local smart grid pilot SSG. Currently, during normal connection there is a 3.6 MW full-power-converter based wind turbine connected to MV network with own MV feeder J08 (Fig. 1a) and it is typically controlled with constant power factor i.e. *cos(φ)*=1 (case 1). However, during Sundom HV/MV substation maintenance back-up connection will be used (case 2, Fig. 1b). During this back-up connection (Fig. 1b) the physical and electrical distance of WT from Kuutamolahti substation is larger. Therefore, the fluctuations in WT active power output will also have larger effect on MV network voltages if *cos(φ)*=1 based control is still used on WT during back-up connection. Today, in order to avoid these potential voltage fluctuations during back-up connection, the WT is disconnected from the MV network. However, this is not feasible from the WT owner perspective. Therefore, the potential of alternative WT reactive power or voltage control methods during MV network back-up connection should be considered. This paper studies first the effectivity of different WT *Q*-control methods (*QU*-, *QPU*- and *U*-control) and settings during the back-up connection (Fig. 1b).

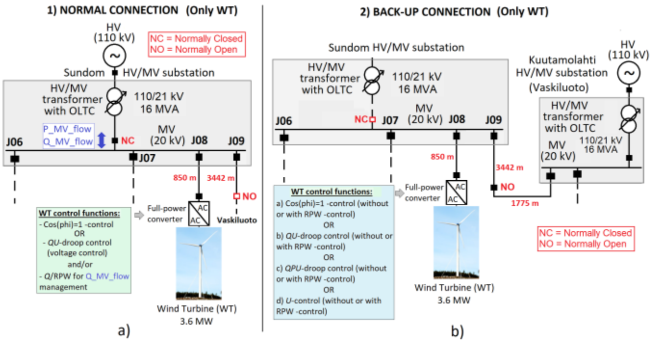

Fig. 1. One-line diagram of the studied SSG during a) normal (case 1) and b) back-up (case 2) connection.

In addition, simulation studies from potential future scenarios (Fig. 2) with centralized (case 3) and distributed (case 4) BESSs with different control schemes are presented in the paper. In all study cases of this paper the HV/MV substation on-load tap changer (OLTC) set value was 20.7 kV (1.035 pu). The total load (including also *P* losses and *Q* produced/consumed by cables & overhead lines) in the simulations during low load and normal connection (case 1, Fig. 1a) was 1031 kW and -696 kVAr. Respectively during high load and normal connection (case 1, Fig. 1a) the total load was 6750 kW and 294 kVAr. Details about the control scheme of WT and BESSs can be found from references [2]-[4].

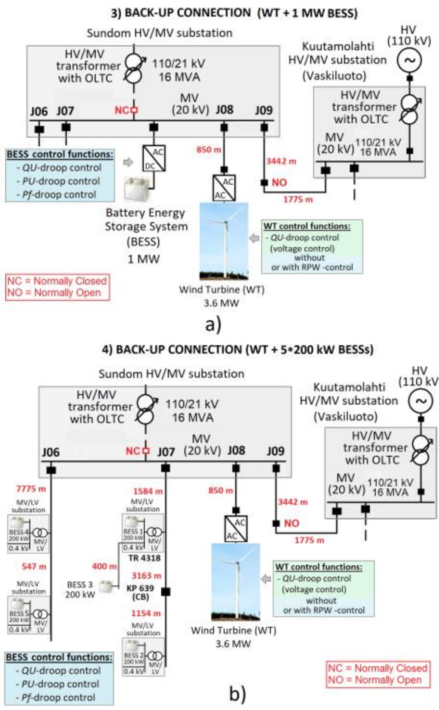

Fig. 2. One-line diagram of the studied SSG during a) back-up connection with centralized BESS (case 3) and b) back-up (case 4) connection with distributed BESSs.

In the PSCAD simulations of this paper (during t = 10–250 s), real measured SSG data (Fig. 3) was used. Measured 30 min (Fig. 3) frequency and WT active power data was converted to 250 s data for the simulations in order to reduce the needed simulation time.

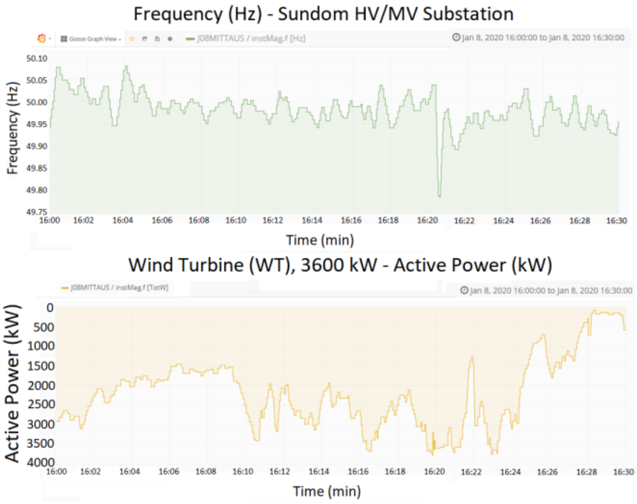

Fig. 3. Measured 30 min frequency and WT active power data from SSG which was used in the PSCAD simulations.

Table I shows the simulated sub-cases related to the study cases 1 and 2 (Fig. 1) and Fig. 4 presents the used WT *QU*-droops in the study case 2 (Table I). Then, in Fig. 5 WT *QPU*-droop settings (case 2c, Table I) are shown. Table II presents the simulated sub-cases related to the study cases 3 and 4 (Fig. 2). Fig. 6a shows the WT *QU*-droop in the study case 3e (Table II). In addition, Fig. 6b presents 1 MW BESS's (Fig. 2a, case 3) and Fig. 6c 200 kW BESSs' (Fig. 2b, case 4) *QU*-droops. All studies in this paper are done by utilizing Fingrid's (Finnish TSO) Reactive Power Window (RPW) -limits [2].

TABLE I. SIMULATION STUDY CASES 1 AND 2 (FIG. 1, 4 AND 5)

Case	Connection	Load level	WT *Q*-control method	WT *RPW*$^{***)}$ -control
1	Normal	Low	cos(φ)=1	Yes/No
2a	Back-up	Low	cos(φ)=1	Yes/No
		High	cos(φ)=1	Yes/No
2b1	Back-up	Low	*QU*-droop 1	No
2b2	Back-up	Low	*QU*-droop 2	Yes/No
		High	*QU*-droop 2	Yes/No
2c	Back-up	Low	*QPU*-droop$^{*)}$	Yes/No
		High	*QPU*-droop$^{*)}$	Yes/No
2d	Back-up	Low	$U^{**)}$	Yes/No
		High	$U^{**)}$	Yes/No

*) $U_{local\_target\_min}$ is 1.034 pu (20.68 kV) and $U_{local\_target\_max}$ is 1.036 pu (20.72 kV) (see Fig.4),
) Voltage U control set value 1.035 pu (20.7 kV), *) RPW with Fingrid's limits, see [2]

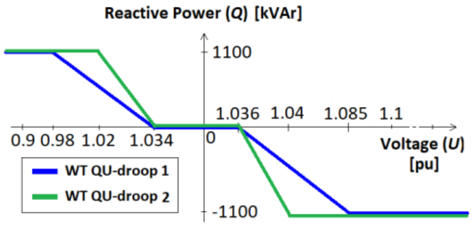

Fig. 4. WT *QU*-droops used in the study cases 2b-4 (Fig. 1 and Table I-II).

Fig. 7a presents 1 MW BESS's (Fig. 2a, case 3) *PU*-droops used in cases 3c-3e (Table II) and Fig. 7b *Pf*-droop 1 of 1 MW and 200 kW BESS.

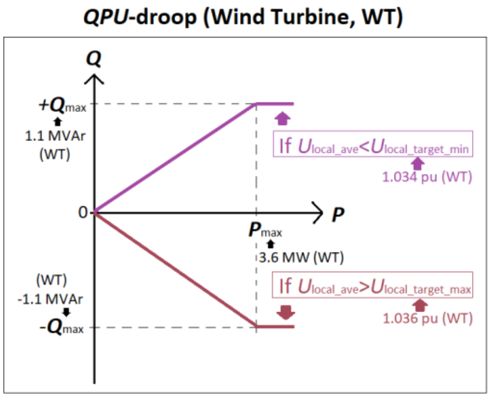

Fig. 5. WT *QPU*-droops used in the study cases 2c (Fig. 1 and Table I).

TABLE II. SIMULATION STUDY CASES 3 AND 4 (FIG. 2, 4, 6 AND 7)

Case	Load level	*QU*-droop (WT$^{**)}$)	*QU*-droop (BESS)	*PU*-droop (BESS)	*Pf*-droop (BESS)
3a	Low	2	1	-	1
	High	2	1	-	1
3b	Low	2	2	-	1
3c	Low	2	1	1	-
	High	2	1	1	-
3d	Low	2	3	2	-
3e$^{*)}$	Low	3	3	3	1
4a	Low	2	4	-	1
	High	2	4	-	1
4b	Low	2	5	-	1

*) With PU-blocking on BESS control scheme, **) WT with RPW-control in all cases

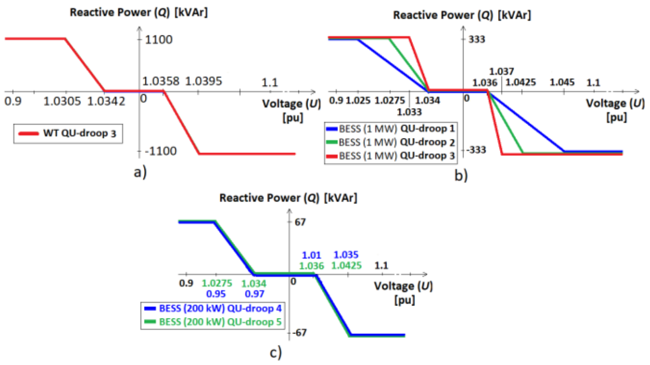

Fig. 6. a) WT *QU*-droop 3 used in case 3e, b) 1 MW BESS *QU*-droops 1-3 used in cases 3a-3e and c) 200 kW BESS *QU*-droops 4 and 5 (Fig. 2 and Table II).

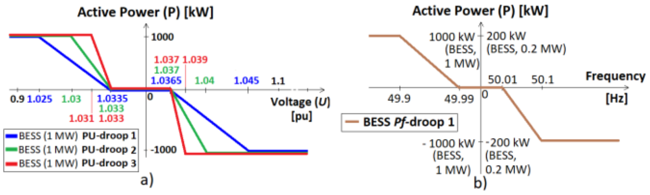

Fig. 7. a) 1 MW BESS *PU*-droops 1-3 used in cases 3c-3e and b) 200 kW and 1 MW BESS *Pf*-droop 1 (Fig. 2 and Table II).

IV. Simulation Results

In the following, the main simulation results from different study cases (see Table I and II) are presented. Section IV.A shows results from cases 1 and 2 during normal and back-up connection and Section IV.B presents the results from case 3 sub-cases during back-up connection. Finally, results from case 4 sub-cases during back-up connection are shown in Section IV.C.

A. Normal and Back-up Connection with WT - Case 1 & 2

The simulation results from cases 1 (normal connection, only WT) and 2a-2d (back-up connection, only WT) are presented in Figure 8-10. Fig. 8 shows the simulation results from the study cases 1 and 2a-2b with low load and without simultaneous WT RPW -control [2]. From Fig. 8a) it can be seen how WT active power changes (Fig. 3) related voltage fluctuations in MV network increase when changing from normal connection (case 1) to back-up connection when *cos(φ)*=1 control is used (case 2a). When WT reactive power control mode is changed to *QU*-droop control with *QU*-droop 1 (Fig. 4) in case 2b1 the voltage changes at Sundom HV/MV substation MV bus are still quite large (Fig. 8a). However, utilization of more sensitive *QU*-droop 2 (Fig. 4) in case 2b2 stabilizes the MV bus voltage variations (Fig. 8a) substantially. Fig. 8b) also shows how much WT reactive power *Q* is controlled in different case 2b sub-cases with different *QU*-droop settings (Fig. 4).

Simulation results related to voltage behavior at Sundom HV/MV substation MV bus (Fig. 9a) and WT reactive power feeding (Fig. 9b) in study cases 2a-2d with high load and without simultaneous WT RPW -control are presented in Fig. 9. It can be seen from Fig. 9a, that when WT reactive power control is *QU*-droop-based with *QU*-droop 2 (Fig. 4) in case 2b2 or *QPU*-droop-based (Fig. 5) in case 2c, variations in the MV bus voltage at Sundom HV/MV substation are smaller than in case 2a with *cos(φ)*=1 control. However, with *QPU*-droop-based control, WT reactive power decreases in case 2c substantially (Fig. 9b) simultaneously when WT active power (Fig. 3) decreases. This can be also seen on MV bus voltage behavior (case 2c, Fig. 9a). Therefore, utilization of *QU*-droop-based control at WT (case 2b2, Fig. 9) seems to be better option. Naturally, use of closed-loop voltage control (*U*-control, case 2d) is good option when WT reactive power control has only one target (i.e. no RPW-control target). However, when WT RPW-control is added as another target then the situation changes a bit as can be seen from Fig. 10 simulation results.

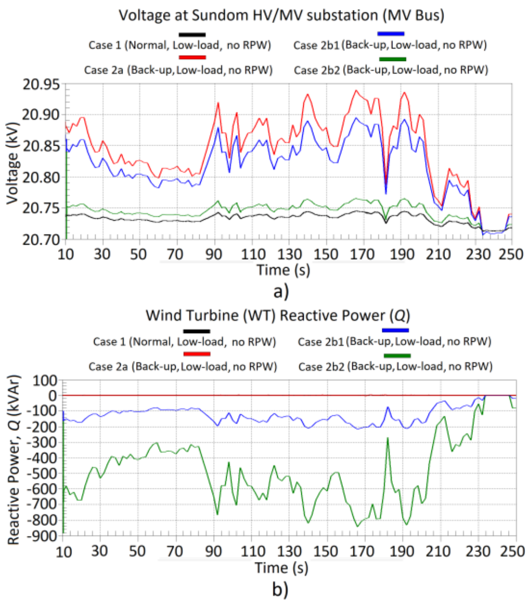

Fig. 8. a) Voltage behavior at Sundom HV/MV substation MV bus and b) WT reactive power feeding in study cases 1 and 2a-2b with low load and when WT is not participating in RPW-control (Fig. 1 and Table I).

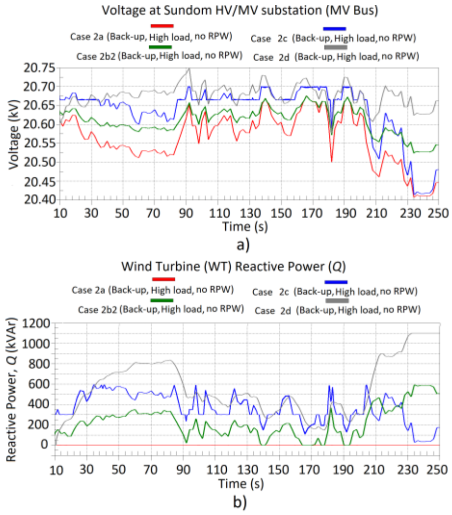

Fig. 9. a) Voltage behavior at Sundom HV/MV substation MV bus and b) WT reactive power feeding in study cases 2a-2d with high load and when WT is not participating in RPW-control (Fig. 1 and Table I).

In general, based on the simulation results presented in Fig. 8-10, it can be stated that WT with sensitive *QU*-droop settings (*QU*-droop 2 in Fig. 4 or *QU*-droop 3 in Fig. 6a) is very feasible way to manage voltage fluctuations during MV network back-up connection. On the other hand, WT *QPU*-droop (Fig. 5) could be also improved and adapted so that it considers simultaneously i) RPW target and ii) local voltage deviation from the target value during low WT active power output (less than $0.3*P_{max}$) as presented in Fig. 11. In this way MV network voltage fluctuations and local voltage level could be managed better also during low DER *P* output situations.

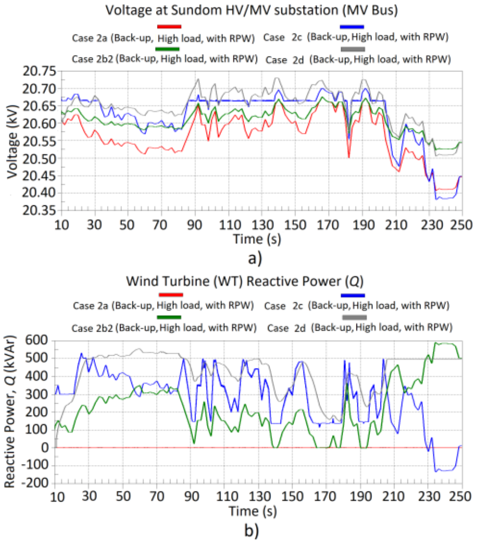

Fig. 10. a) Voltage behavior at Sundom HV/MV substation MV bus and b) WT reactive power feeding in study cases 2a-2d with high load and when WT is participating in RPW-control (Fig. 1 and Table I).

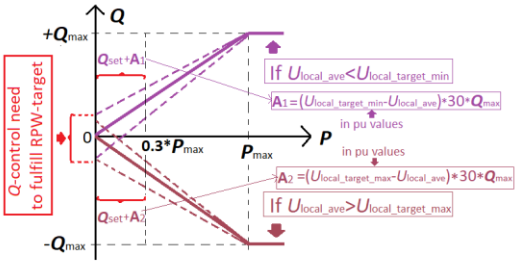

Fig. 11. Proposed advanced adaptive MV network connected DER (e.g. WT) *QPU*-droops.

B. Back-up Connection with BESS (1 MW)- Case 3

In the following, chosen simulation results from cases 3a-3e (with WT and centralized 1 MW BESS, Fig. 2a and Table II) are presented in Fig. 12.

Fig. 12 shows the simulation results about MV bus voltage changes at Sundom HV/MV substation MV bus (Fig. 12a), WT reactive power (Fig. 12b), BESS reactive power (Fig. 12c) and BESS active power (Fig. 12d) in cases 3a-3e during low load and with simultaneous WT RPW -control. WT reactive power control is based on *QU*-droop control (Table II) in all cases, but the BESS control functions (*QU*-, *PU*- and *Pf*-droop) and settings are varied in different cases 3a-3e (Table II). It can be seen from Fig. 12, that by utilizing suitable *QU*- and *PU*-droop (with BESS) settings on WT and BESS, the MV bus voltage fluctuations (Fig. 12a) can be small and acceptable also when BESS is participating on frequency control services provision (case 3e with *PU*-control blocking during *Pf*-control, Fig. 12 and Table II).

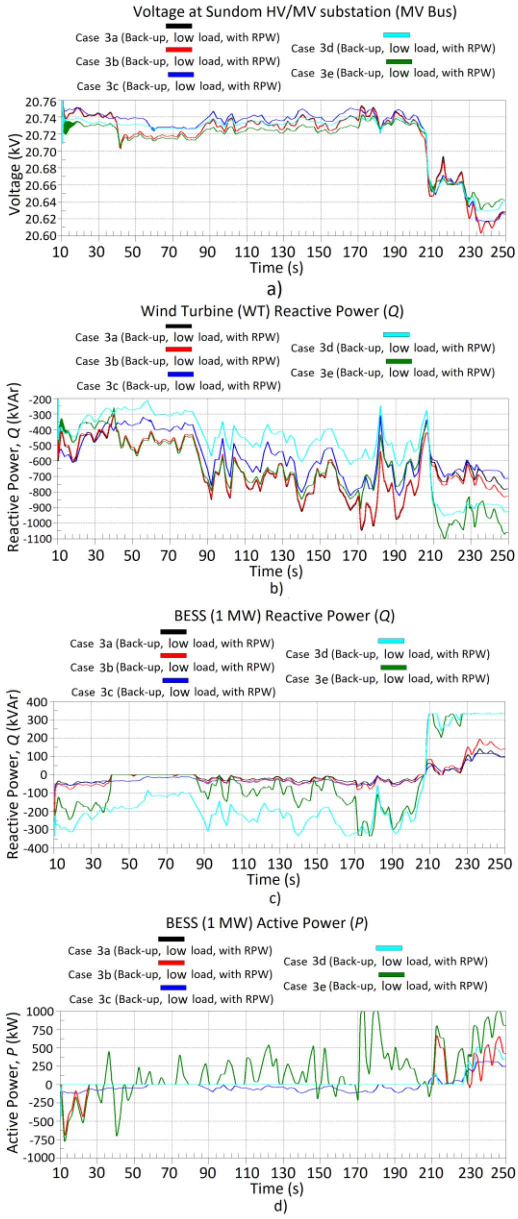

Fig. 12. a) Voltage behavior at Sundom HV/MV substation MV bus, b) WT reactive power, c) BESS (1 MW) reactive power and d) BESS (1 MW) active power in study cases 3a-3e with low load and when WT is participating in RPW-control (Fig. 2 and Table II).

*C. Back-up Connection with BESSs (5*200 kW) - Case 4*

In this Section, simulation results from cases 4a-4b (with WT and distributed 200 kW BESSs, Fig. 2b and Table II) are shown in Fig. 13 and 14.

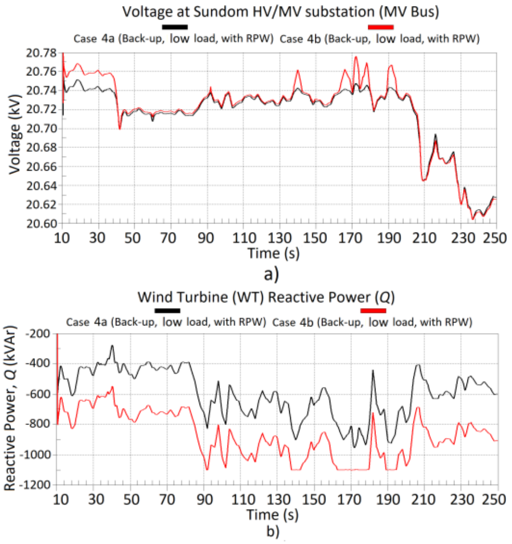

Fig. 13. a) Voltage behavior at Sundom HV/MV substation MV bus and b) WT reactive power in study cases 4a-4b with low load and when WT is participating in RPW-control (Fig. 2 and Table II).

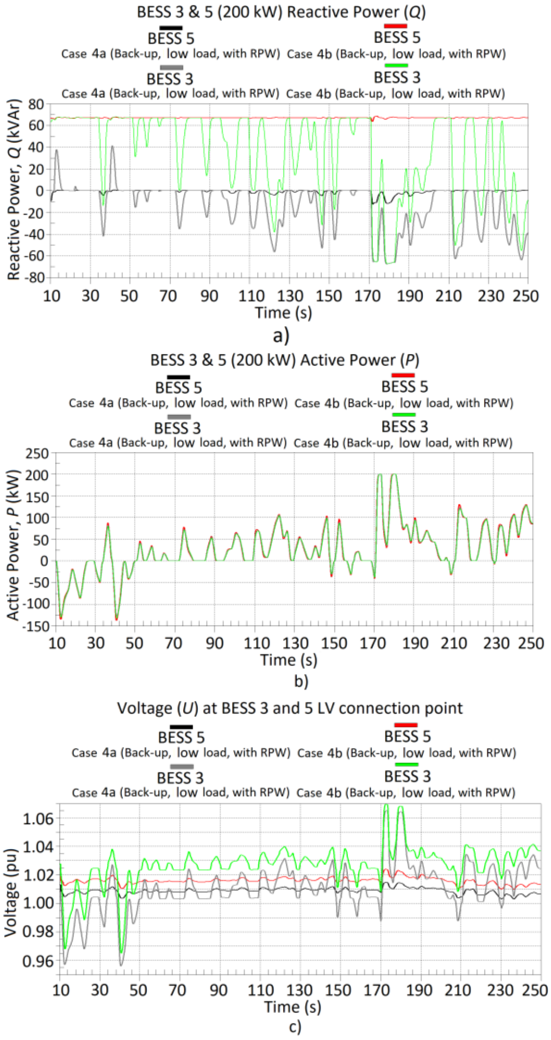

Fig. 14. a) BESS 3 and 5 (200 kW) reactive power, b) BESS 3 and 5 (200 kW) active power and c) BESS 3 and 5 LV connection point voltages in study cases 4a-4b with low load and when WT is participating in RPW-control (Fig. 2 & 12 and Table II).

The only difference between case 4a and 4b was the *QU*-droop setting (Table II, Fig. 6) of the distributed BESSs. All distributed BESSs in case 4a and 4b (Fig. 2b) were also participating on frequency control based on their *Pf*-droop settings (Table II, Fig. 7 and 14b). It can be seen from Fig. 13a that MV bus voltage variations were a bit smaller in case 4a than in case 4b. Fig. 14a also shows how different *QU*-droop settings (Table II, Fig. 6) affect on BESS 3 and 5 reactive power output. Differences between BESS 3 and 5 reactive power outputs (Fig. 14a) and their LV network connection point variations (Fig. 14c) are related to their different locations in LV network (Fig. 2b). Voltage variations due to BESS *Pf*-control and frequency control participation are much higher in BESS 3 connection point which is weaker and further in the LV network (i.e. at the end of LV line, see Fig. 2b, which has larger resistance/reactance-ratio than MV lines).

V. CONCLUSIONS

This paper presented real-life case study related to the adaptation of DER control schemes and functions after MV distribution network topology change from normal to back-up connection. The focus was on MV network connected WT control scheme adaptation after the topology change based on real measured data from the WT active power. In addition, simulations from potential future scenarios with centralized and distributed BESSs, which could be also simultaneously utilized for the provision of local (DSO) and system-wide (TSO) services, were presented.

Based on the simulations of this paper (and previous studies [2]-[5]) it can be recommended to:

I) Utilize sensitive *QU*-droop settings with MV network connected DER (like WT in this case) during back-up connection to better manage renewables rapid active power output variations related voltage fluctuations or alternatively also adaptive *QPU*-droop could be used,

II) Utilize MV network connected DER units (like WT in this case) for

a) *Only RPW -control* if the DER unit is located *less than 1.5 km from the HV/MV substation*

- RPW -control which can also enable correct operation of islanding detection on MV and LV network connected DER units during MV islanding (additionally if intended MV islanding is utilized also e.g. HV/MV substation connected BESS units *P* & *Q* -control can be utilized to enable stable transition to MV island operation)

b) *RPW-control with some local Q-control method* (with weather dependent DER unit like WT or large-scale PV plant) when the DER unit is located *1.5 km - 8 km from the HV/MV substation*

- For more detailed specification of the *Q*-control see I)
- Very small voltage related dead-zone with *QU*- and *QPU*-control methods on MV grid connected DER units
- Adaptation of *QU*-, *QPU*-, and *U*-control settings can be done based on e.g. changes on OLTC setting value at HV/MV substation transformer

c) *Only some local Q-control method* (with weather dependent DER unit like WT or large-scale PV plant) when the DER unit is located *over 8 km from the HV/MV substation* (no RPW-control, but otherwise same as b)

III) On MV/LV substation LV-side directly connected DER (like BESS) units as well as further in LV network connected units should have *QU*-droop control by default

- Larger voltage related *QU*-droop dead-zone than in MV network connected DER units
- Seasonal and adaptive *QU*-droop settings needed on LV network connected DER units (e.g. BESSs) which can be also adapted based on active changes on HV/MV substation transformer OLTC setting value
- BESS units connected at MV/LV substation can also be used for managing the reactive and active power flows between MV and LV networks (enabling intentional islanding and or passive islanding detection of LV network connected DER in case of LV islanding)

In the future, it could be further studied how, for example, local voltage variations in MV and LV network could be further minimized by real-time adaptation of each DER unit droop settings (e.g. *QU*-droop) based on learning from local measurements.

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