Black start and island operation of distribution grids with significant penetration of renewable resources

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***Abstract*—Power system restoration is the process to re-energise the grid after a blackout. The bottom-up strategy consists of a restoration process of several areas of the grid through black start units in order to form island grids and achieve their subsequent synchronisation. Nowadays, distributed generation units based on renewable resources, such as PV systems, have already achieved in Germany and some countries a significant penetration level. Therefore, it is important to investigate the impact and potential of renewable generation for the power system restoration process. This paper analyses a bottom-up process of a rural distribution grid in Germany with significant power feed-in from distributed PV systems. A mobile diesel emergency supply unit is used as black start unit and a biogas plant takes over the frequency control of the grid in island operation. The proposed analysis is performed in DIgSILENT *PowerFactory* by RMS simulation and is based on real grid data of a German distribution system operator. Low voltage loads and distributed generation units are represented by a distribution system equivalent. The load model includes cold load pick-up as well as voltage and frequency dependency. The distributed generation includes over- and under-frequency protections, P-f control and power ramp-up behaviour after reconnection. Loads and generation are modelled according to the German low voltage grid code.**

Keywords – Power system restoration, bottom-up strategy, low voltage loads, biogas plants, distributed generation, diesel units, black start, frequency control, PV systems.

I. Introduction

Power system restoration process aims to re-energise the electrical power system after a blackout. Depending on the system's structure and characteristics and the outage scenarios, system restoration may perform different tasks and have different objectives [1]. The restoration process is an extremely complicated procedure involving different steps: system status determination, plants preparation, restoration of generation, transmission path re-energisation, supply of loads and system synchronisation [2].

The standard procedure used by system operators for this restoration process is the top-down strategy, which requires the assistance of other transmission systems operators (TSOs) to re-energise (part of) the system of a TSO [3]; all the lower voltage levels are energised from the transmission network and the entire system is maintained synchronised [4]. However, in this paper a black start and island operation of a distribution grid with significant penetration of renewable generation, as part of a bottom-up process, is proposed and analysed. The bottom-up strategy consists of starting from black start units to form island grids; these small electrical islands are started and operated in parallel and should be synchronised in order to restore the entire system. The island grids are expanded by picking-up loads and also connecting renewable resources. The novelty of this approach is the integration of distributed renewable generation units such as PV systems and a biogas power plant (BGP).

The proposed analysis is performed in DIgSILENT *PowerFactory* using RMS simulations. The focus of this approach is on frequency control during grid re-energising and island operation. A mobile diesel emergency supply unit (ESU) is used as black start unit and works in isochronous and droop frequency control modes. Low voltage (LV) loads and distributed generators (DGs), such as PV systems, are represented by a distribution system equivalent. The load model includes cold load pick-up as well as voltage and frequency dependency. The distributed generation includes over- and under-frequency protections, P-f control and a power ramp-up behaviour after reconnection. The reconnection of DGs is modelled according to the latest German LV grid code from 2011. The test system for this investigation is based on real grid data from a German distribution system operator (DSO). After sufficient loads are supplied, the mobile diesel system is disconnected and the BGP takes over the isochronous frequency control, thus the mobile ESU can be used for the restoration of further distribution grids. This approach does not consider the incorporation of grid protections and aims to evaluate the feasibility of a bottom-up restoration process without power support of external grids and by using local energy resources only.

II. Black start and island operation

In case of a power outage with entire absence of external grid voltage, so-called black start (BS) units are needed to re-start the electrical system into operation. This BS capability is the capability of generation units to start-up by themselves without an external power supply, reach the nominal voltage and supply an island grid [1], [2]. The start-up process, the connection to the grid and the pick-up of loads can be controlled locally or remotely. BS units are a fundamental prerequisite for the bottom-up restoration strategy [5]. For small or local grids, diesel ESUs can be used as BS units to re-power the grid. Since the power capacity of ESU is strongly limited, no significant grid equipment and resources can be supplied, therefore ESU systems are capable of provisionally supplying limited grid areas. As BS units themselves can only supply a small fraction of the system load, these units should be used to assist the starting process of larger units by supplying their auxiliary power loads (self-consumption of power plants) [5]. In order to achieve a bottom-up restoration by utilising local renewable supply resources, a diesel ESU should supply non-BS plants nearby (short electrical distance), such as biogas or biomass plants, to reconnect them to the grid. However, the task of the system operators for the black start procedure is the successive reconnection of transformers, lines, loads and DGs in order to restore the grid to a stable operation condition. The central aim is to maintain voltage and frequency values to prevent protection tripping and damage.

In case of blackout, it is not feasible to restore the entire system at once. The de-energised grid must be segmented in sub-grids or island grids, which will be reconnected to the grid after stabilisation. A sub-grid works in island operation if it operates autarkic and independently of the interconnected power system [6]. Hence, each island grid needs at least one voltage source as grid-forming unit. The basic structure of an island grid is the operation with only one generation unit and the corresponding loads to be supplied. Moreover, diesel systems are typically used as grid-forming units in conventional island grids [7]. One major challenge for island operation is a possible power imbalance between generation and consumption, especially if we consider the presence of DG. If the magnitude of the power imbalance within the island grid exceeds the power plants' controllability, additional measures such as load shedding and grid disconnection are needed [8]. In the past, the amount of DGs in distribution grids was insignificant and therefore, DSOs were capable of estimating the implications of their measures to reconnect consumers. With a high DG penetration in distribution networks, uncontrolled reconnection of DG units during the restoration process can compromise its success [9]. This means that thermal generation units need to be loaded with sufficient consumption in order to reach their minimum load and thereby contribute for a stable restoration process.

Fig. 1 shows the active power control concept for normal and island operation according to [10]. The green characteristic line corresponds to the P(f) characteristic for up-to-date distributed generation systems. P_M represents the present active power injection of a DG when the frequency exceeds the 50,2 Hz threshold and sets the reference for the power reduction characteristic considering a 40% P_M/Hz gradient.

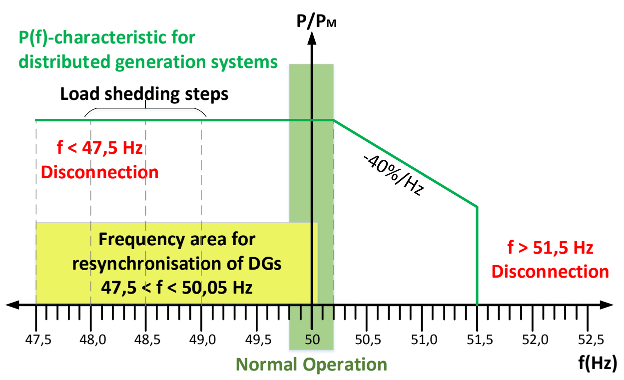

Figure 1 Active power control concept according to German LV grid code [11]

III. Modelling

A. Test system

The test system considered for this approach is based on real grid data of a German DSO and corresponds to a section of a 20 kV grid, which supplies two rural areas at the LV level, as shown in Fig. 2. These LV grids are represented by a dynamic distribution system equivalent with consumption and DGs at the LV side. The dynamic of this equivalent system represents the loads and DG behaviour during normal operation and after reconnection considering a time scale from several seconds up to a couple of minutes. The generation in the test system consists of a diesel ESU, a BGP and distributed PV systems. Electrical cables are used as distribution lines.

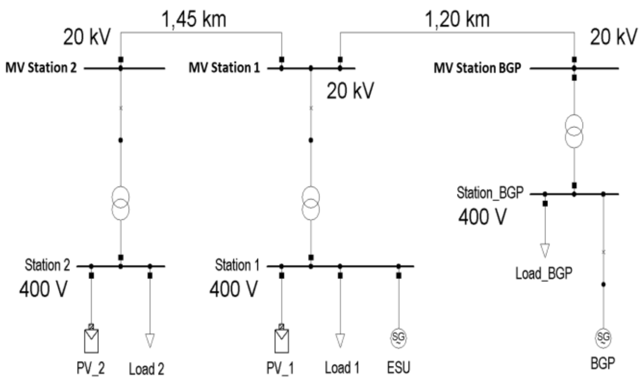

Figure 2 Topology of the test system

B. Low voltage loads

The consumption of each LV grid is represented by an aggregated load and is modelled as an exponential load according to [12] and considers frequency and voltage dependency:

$$P = P_0 \left(\frac{V}{V_0}\right)^{\alpha} \cdot \left(1 + k_{pf} \cdot \Delta f\right) \quad (1)$$

$$Q = Q_0 \left(\frac{V}{V_0}\right)^{\beta} \cdot \left(1 + k_{qf} \cdot \Delta f\right) \quad (2)$$

where P and Q represent the active and reactive power consumed by the aggregated load at the LV level. P_0 and Q_0 are the active and reactive power under the reference voltage V_0 referring to the nominal operating condition. The exponents α and β represent the voltage dependency and incorporate the dynamics of induction motors [13], and depend on the type of load. The parameters k_{pf} and k_{qf} characterise the load's frequency dependency. The self-regulating effect of the load is considered with k_{pf} = k_{qf} = 1%/Hz which corresponds to 1%/Hz of the nominal active and reactive power. For cold load pick-up, the exponential load model is based on [14]:

$$P_{Load}(t) = P\left(1 + a \cdot \exp\left(-\frac{t - t_0}{\tau}\right)\right) \quad (3)$$

$$Q_{Load}(t) = Q\left(1 + a \cdot \exp\left(-\frac{t - t_0}{\tau}\right)\right) \quad (4)$$

where P_{Load} and Q_{Load} represent the active and reactive power consumption of the aggregated load during the cold load pick-up event. P and Q are the steady-state values for the active and reactive power. The factor a represents the peak value due to cold load pick-up. The parameter τ is the time constant of the cold load pick-up event. The mentioned parameters are presented in Table I.

TABLE I. PARAMETERS OF LOAD MODEL

Parameter	Description	Value	Unit
α	Active power voltage dependency	0,62	[-]
β	Reactive power voltage dependency	0,96	[-]
PF	Power factor	0,95	[-]
k_{pf}	Active power frequency dependency	1	[%/Hz]
k_{qf}	Reactive power frequency dependency	1	[%/Hz]
a	Base load	1	p.u.
τ	Cold load pick-up time constant	1000	[s]

C. Distributed generation

Distributed generation units, such as PV systems, are represented by an aggregated generation model based on the WECC PVD1 model according to [15]. Two operation modes are available: normal operation and reconnection. The DG model includes over- and under-frequency protections, a ramp-up behaviour after reconnection and active power reduction at over-frequency (P(f) characteristic), according to the German LV grid code [10].

D. Diesel emergency supply unit

For this case study, a 250 kVA diesel ESU has been modelled based on a standard diesel system [16] using a combustion engine as prime mover. The governor system allows isochronous and droop frequency control and is shown in Fig. 3. The AVR IEEE Type II model from the *PowerFactory* library is used for the excitation system and the synchronous generator is implemented according to commercial generator data [17].

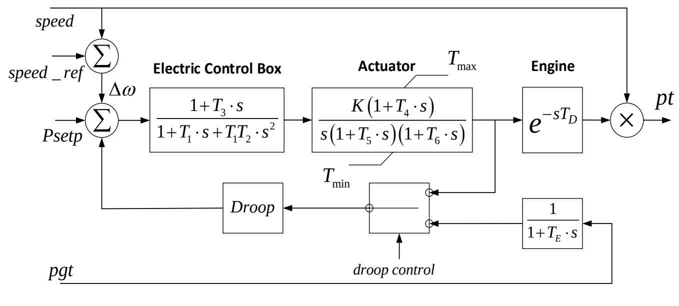

Figure 3 Block diagram of governor model

The parameters $T_j \; \forall \; j \in \{1,..,6\}$ are the time constants of the electric control box and actuator blocks. T_D corresponds to the time constant of the engine block and T_E to the power feedback time constant, K is the actuator gain and T_{min} and T_{max} represent the lower and the upper torque limit, respectively. Droop is the factor for droop control. The actuator block reflects the mechanical process and describes fuel injection of the diesel machine. The engine block through its dead time behaviour corresponds to the motor inertia and represents the needed time from start-up of the combustion motor to achievement of the steady-state mechanical torque. The acceleration time constant of the synchronous generator is 1,2 seconds. The parameter values used for the diesel ESU governor model are shown in Table II.

E. Biogas power plant

The BGP has been modelled as a gas combustion engine according to [18] in a similar form as for the diesel ESU model, using the same governor structure, as shown in Fig. 3, and the same generator. The excitation system is given by the AVR IEEE Type II. The parameter values used for the BGP model are shown in Table II.

TABLE II. PARAMETER VALUES FOR ESU AND BGP

Parameter	Unit	ESU	BGP
T_1	s	0,022	0,01
T_2	s	0,02	0,02
T_3	s	0,1	0,2
T_4	s	0,25	0,25
T_5	s	0,039	0,009
T_6	s	0,009	0,0
T_D	s	0,05	0,024
T_E	s	0,1	0,1
T_{max}	p.u.	1,1	1,1
T_{min}	p.u.	0	0
K	p.u.	18	10
Droop	p.u.	0,04	0,04

IV. CASE STUDIES

A 20 kV test system has been implemented in DIgSILENT *PowerFactory* based on real grid data of a German DSO, as shown in Fig. 2. Stations 1 and 2 correspond to two LV rural villages which are represented by aggregated loads and DGs. There is a BGP station which corresponds to the connection point with the medium voltage (MV) grid. Each aggregated load has a peak consumption of 160 kVA with a power factor 0,95. The diesel ESU as well as BGP have an installed capacity of 250 kVA with a nominal power factor of 0,8. The self-consumption of BGP (station service load) has a value of 10 kVA. The aggregated DG model for each LV grid has a nominal power of 33,33 kVA. It is assumed that PV units work with unity power factor and maximal power injection. Transformers and electrical cables are implemented according to real grid data and the *PowerFactory* library. The starting situation for this analysis is an entire power outage.

A. Black start

A mobile diesel ESU performs a black start and supplies the LV grid located at Station 1. A higher frequency set-point is set to avoid PV injections during the start-up process, if DGs are directly connected to the LV side of the distribution substation. At $t = 0$, the ESU is started. As soon as the ESU has reached nominal speed, the excitation system of the ESU is activated ($t = 10\ s$) and the LV side of the distribution substation (Station 1) is re-energised. At $t = 30\ s$, 50% of the nominal load at Station 1 is reconnected. A new frequency set-point is set to achieve nominal grid frequency (50 Hz). The ESU works in isochronous speed control mode. Cold load pick-up is considered after reconnection and maximal PV injection has been simulated. DGs are configured according to the German LV grid code [10] and their active power injection is limited by a gradient of 10% of the nominal installed power per minute. Fig. 4 shows the output frequency of the ESU and the voltage at Station 1 during the black start and re-energising procedure. The frequency oscillates and needs approximately 3,5 s to reach normal values for DG reconnection.

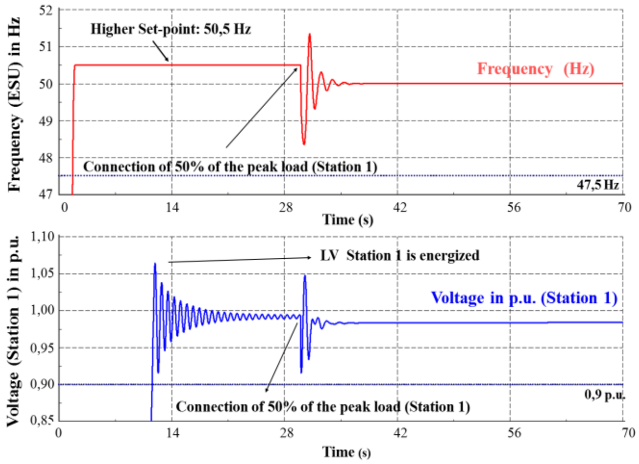

Figure 4 Black start and load reconnection at Station 1

The diesel ESU is started-up and after reaching the nominal speed, the LV side of the distribution substation (Station 1) is re-energised. After several seconds and as soon as the voltage reaches an acceptable value, some feeders are reconnected. It is assumed that the reconnected feeders represent the re-supply of 50% of the aggregated peak load causing voltage and frequency oscillations, which are rapidly diminished. Thereafter, voltage and frequency return to nominal values. The output frequency stays within the frequency tolerance range after reconnecting 50% of the peak aggregated consumption at Station 1. During load reconnection, cold load pick-up is considered with a peak of 200% of the aggregated load at Station 1. Cold load pick-up parameters are presented in Table I.

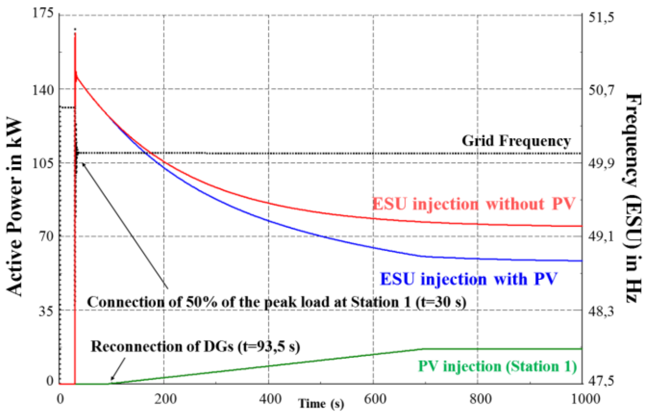

Figure 5 Active power injection of ESU with and without PV participation as well as grid frequency at Station 1

Fig. 5 shows the active power injection of the ESU with and without PV injection from DGs. According to [10], DGs must reconnect when the frequency stays between 47,5 and 50,05 Hz for more than 60 seconds and the reconnection occurs with an active power ramp limitation of 10% of the nominal power per minute for a period of ten minutes. The DGs are reconnected after 93,5 s considering that the frequency needs approximately 3,5 s to stabilise for DG reconnection.

B. *Expansion of the island at the MV level and integration of BGP*

The LV island grid at Station 1 is expanded to the MV level by connecting a section of the 20 kV grid to supply the station service load of the BGP. This action aims to incorporate the BGP into the new MV island grid in order to take over the isochronous speed control of the system. ESU changes to droop speed control. This situation is presented in Fig. 6.

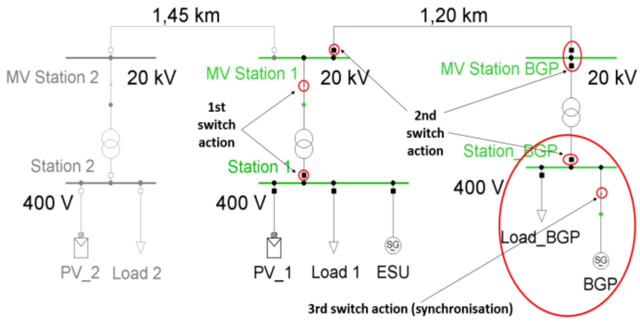

Figure 6 Expansion of the island grid and BGP integration

The first switch action incorporates the distribution transformer at Station 1 to reach the MV level. After the second switch action, the MV line to the BGP and the corresponding distribution transformer are switched simultaneously to counteract the capacitive charging current of the line (electrical cable) and to supply the auxiliary power load (self-consumption) of the BGP as well. These two switch actions produce insignificant and negligible frequency and voltage oscillations. The BGP is synchronised with the island working in isochronous speed control mode, whereas the ESU does the voltage control until its disconnection. Since the ESU works in droop control mode, its power reference is changed to reduce the diesel consumption, as shown in Fig. 7. The BGP compensates the active power need of the island grid.

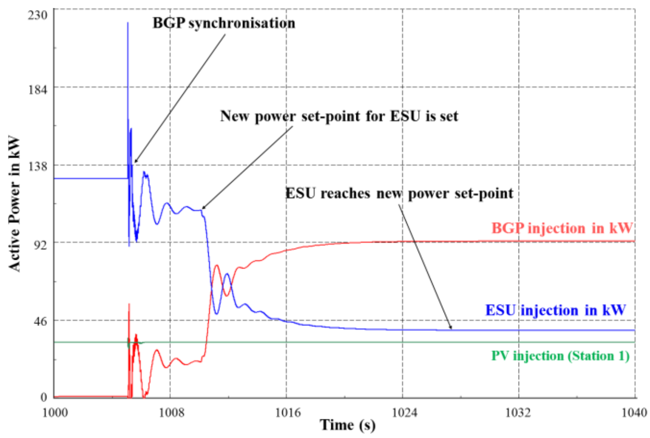

Figure 7 Active power injection after BGP synchronisation

C. *Further expansion and pick-up of loads of the MV island grid*

The MV island grid is further expanded by integrating the LV grid at Station 2 and the associated MV lines and distribution transformer, as shown in Fig. 6. First, the consumption at Station 1 increases by 10%. Thereafter, the MV line between Station 1 and 2 and the distribution transformer at Station 2 are re-energised. Afterwards, 50% of the peak load at Station 2 is reconnected. Fig. 8 presents the frequency response during the described load events and switch actions. The speed governor of the BGP can keep the frequency in a normal range and bring it back to its nominal value. Fig. 9 shows the active power feed-in of ESU, BGP and PV systems. The BGP governor can control the reconnection as well as the increment of loads. The power set-point of the ESU is changed to compensate the active power consumption and the MV island stays stable.

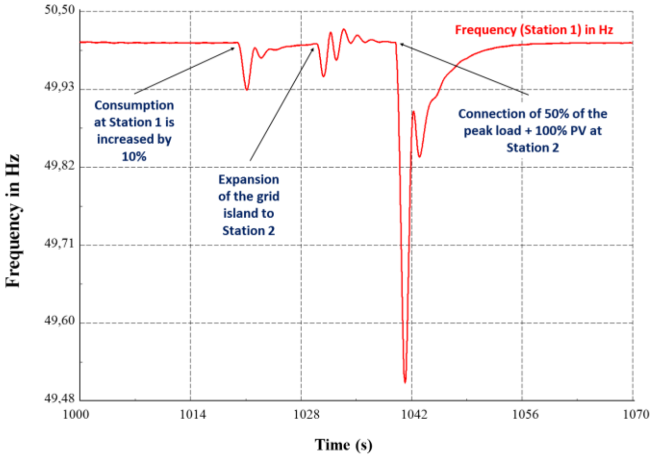

Figure 8 Frequency response during further reconnection of MV grid sections and LV loads

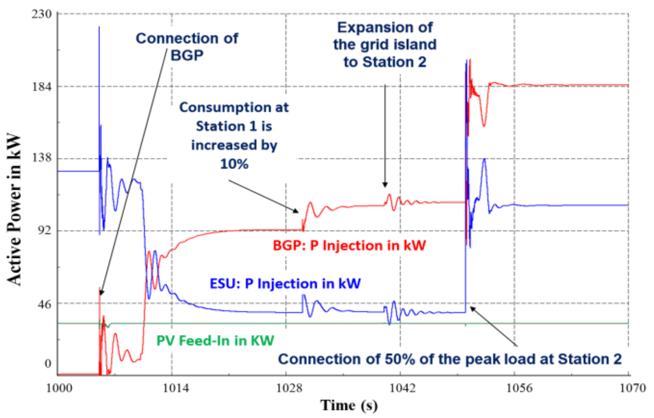

Figure 9 Active power injection of ESU, BGP and PV systems

D. Disconnection of the ESU

As soon as the MV island reaches a stable operation after grid expansion as well as load increment and reconnection of

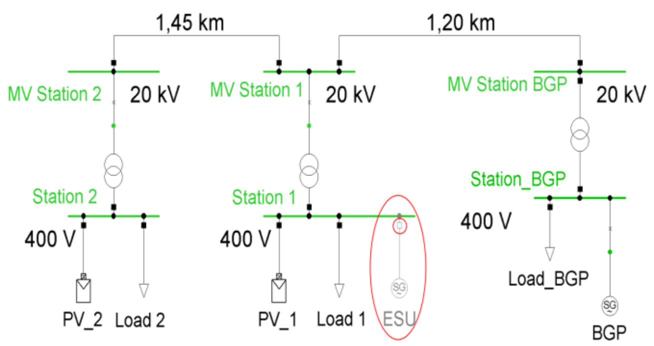

Figure 10 Final state of the island grid

further loads, the mobile diesel system is switched-off in order to achieve a reduction in the diesel consumption. Moreover, the mobile diesel ESU can be used to re-energise further LV grids. The BGP takes over the voltage control of the island grid when the ESU is set for disconnection. Fig. 10 shows the final state of the island with the disconnected ESU and the BGP works as grid-forming unit. Fig. 11 presents the generator speed of the ESU and the BGP during the ESU disconnection. BGP achieves a stable island operation of the grid after ESU disconnection.

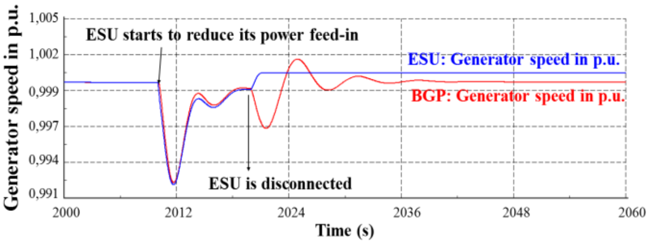

Figure 11 Generator speed of ESU and BGP during ESU disconnection

The power feed-in from the ESU is reduced in order to disconnect the diesel unit. The active power reduction of the ESU produces a small frequency drop, which is rapidly compensated and the grid frequency returns to its nominal value.

V. Conclusions

This paper presents a simulation analysis of a black start and island operation of a distribution network with participation of renewable energy generation units. This work has shown the feasibility of black start and island operation of a distribution grid within the framework of a bottom-up restoration process. The diesel ESU model is based on commercial data and technical literature. It operates as a grid-forming unit during black start of a LV grid and is capable of re-energising the MV level. Aggregated PV systems represent the presence of DGs at the LV level and are modelled according to the German LV grid code. In order to avoid the participation of PV during the black start procedure, a higher frequency set-point is set.

After black start and the first stage of re-energising of the MV level, the station service load of the BGP is supplied. The diesel ESU can deliver the charging current for MV lines (electrical cables). Electrical lines and transformers are reconnected at the same time to compensate the charging current of electrical cables. The ESU changes its governor mode from isochronous to droop control mode and the BGP takes over the frequency control of the grid. If the ESU works in droop mode, it is possible to set a new power set-point in order to save fuel costs and at the same time ensure that the ESU minimal load is covered. A further expansion of the island is done by increasing the supplied consumption and picking-up new loads as well as incorporating additional PV feed-in. It is feasible to operate an island grid with a BGP, if it is capable of operating as a grid-forming unit.

This approach has shown in general terms that it is technical feasible to re-energise LV grids and synchronise them at the MV level by using mobile diesel ESU and utilising the power injection from distributed PV systems as well as from further renewable generation systems, such as BGPs. This technical feasibility is subjected to grid code requirements, e.g. PV feed-in regarding grid frequency behaviour during normal operation or after reconnection. Local PV systems can support the re-energising process and the island operation of distribution networks. PV feed-in can reduce the generator loading of mobile diesel ESUs and the associated diesel consumption. Moreover, the operation of mobile diesel ESUs is limited due to the fuel availability and therefore, local energy storage systems could be attractive in the future to support the restoration or island operation of distribution grids. It should be taken into account that PV systems with old LV grid code requirements (i.e. before 2011) have difference dynamic behaviour during the reconnection process, which could deteriorate the restoration of the grid [19]. Further work is planned to investigate the influence of higher levels of PV penetration as well as the impact of abrupt fluctuations of the solar radiation in island grids, such as PV-diesel island grids, or in distribution networks with microgrid functionality during power outages.

Distributed renewable generation units can improve power system restoration, if island operation is allowed and BS capability is available. If we consider that distributed generation is increasing, DSOs in collaboration with TSOs could define reconnection steps of generation units at the distribution level to enhance the overall restoration process.

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