

Reconnection of Photovoltaic Systems in Low-Voltage Diesel-Powered Microgrids

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Abstract—Low-voltage grids can be supplied by diesel generator units for example in case of maintenance of the distribution substation transformer or in case of a power outage at the medium voltage level. Usually, photovoltaic (PV) systems are deliberately disconnected from the system in order to avoid unexpected behavior of the PV systems. This is done by operating the diesel generator at over-nominal frequency. Diesel-PV systems are already in place in remote areas without a transmission system. In these cases, usually a few large PV systems are in place and the operation strategy relies on communication. This paper investigates the reconnection of PV systems in a typical German low-voltage network with a significant amount of small-scale PV systems and without additional communication. A separate analysis is done for PV systems that behave according to the present German low-voltage grid code and for PV systems that adhere to older versions of that code. Moreover, the reconnection of a mix of old and new PV systems is investigated

Index Terms—Photovoltaic generation, PV, distributed generation, RMS simulation, island grid, microgrid, renewable energy.

I. INTRODUCTION

Low-voltage (LV) grids are supplied by a diesel generator unit in different circumstances. During maintenance of the medium-voltage (MV) to low-voltage transformer, mobile emergency diesel generators can be used to ensure the power supply to the LV grid. Furthermore, emergency diesel generators are used to supply LV networks during system outages at the MV level, which is especially important for LV grids with critical infrastructure, e.g. retirement homes [1].

Moreover, the power supply of LV grids in remote areas, that are not connected to a transmission system, is often done by diesel generators. For example, in India there will exist a high number of island grids that are powered by diesel generators. In these networks, photovoltaic (PV) systems can be used to save fuel [2]. The installed capacity of PV systems that these networks can handle needs to be addressed. Furthermore, it needs to be determined which behavior for these PV systems is optimal to guarantee system stability and allow for optimal economic grid operation. One choice would be to use the same behavior as for grid connected systems. The other choice would be to define grid codes specific tailored to the need of PV-diesel island systems.

Applications for industrial LV microgrids based on diesel generators and PV systems have already been implemented

by various companies and institutions [3] [4]. In these settings, the PV systems are usually of substantial size, exceeding the capacity of PV rooftop systems connected to a residential LV grid. Furthermore, in research projects or in practical applications, the frequency control oftentimes relies on communication between diesel generator and the distributed energy resource [5]. Furthermore, various research activities are going on in the field of frequency control in island grid with renewable energy resources [6].

In Germany, the standard procedure during maintenance at the MV/LV transformer is to operate the diesel generator at such a high frequency, that all PV systems disconnect from the grid due to overfrequency protection. Thus, the diesel generator is usually operated in isochronous frequency control mode above 51.5 Hz. After that, the frequency set-point is slightly reduced to a value above 50.05 Hz which is the threshold value for reconnection. In Germany, PV systems will not reconnect if the frequency is above this value.

The contribution of this paper is the investigation of the reconnection behavior of small-scale PV systems in a German residential LV network without the presence of communication. The focus is on PV systems that adhere to the German LV grid code VDE 4105 [7] from 2011 (here called new PV systems) and on PV systems that are built prior to 2011 (here called old PV systems). Furthermore, the goal of this paper is to investigate the reconnection of a mix of old and new PV systems in a diesel powered residential LV network considering the impact of different grid code designs.

The paper is structured as follows: In Section II the modelling of the PV system and the diesel generator is explained. Furthermore, the modelling environment is described briefly. Also, the networks, that are used for this study, are introduced. In Section III and IV the reconnection of new and old PV systems is explained, respectively. In Section V the reconnection of a mix of new and old PV systems is investigated. The conclusion and outlook of this work is given in Section VI.

II. MODELLING AND SIMULATION ENVIRONMENT

A. Photovoltaic system

The structure of the PV model used in this paper is displayed in Fig. 1. It has two electrical inputs (bus voltage \underline{V} and system frequency f) and one electrical output (current

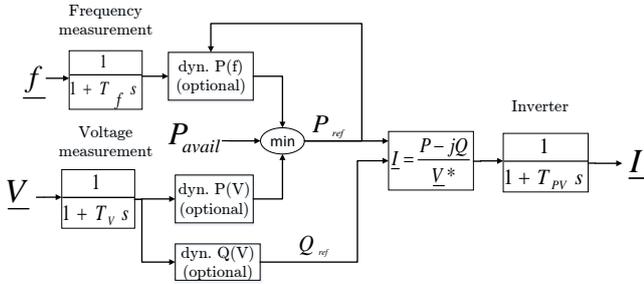


Fig. 1. Overview of PV model.

D). Furthermore, the model contains an input for a time series of available PV power P_{avail} . Moreover, the model contains blocks for the emulation of the voltage and frequency measurement, as well as the blocks *dyn. P(V)* and *dyn. Q(V)*. These blocks represent the calculation of voltage dependent active and reactive power injection. The block *dyn. P(f)* contains the model for frequency dependent active power injection. The actual active power set-point is calculated as the minimum of the output of the *dyn. P(f)* and *dyn. P(V)* block and the P_{avail} input. It has to be noted that this model is suited for RMS simulations in the range of seconds up to minutes. It does not include effects of electromagnetic transients (EMT), such as inverter switching. Furthermore, this model does not include LV fault ride-through behavior as it is not mandatory for LV connected PV systems yet [8]. However, this could be included in a future version of the model.

The PV model used in this study is a modified and extended version of [9] which is originally based on the model described in [10]. The major modification, compared to [9], is situated in the dynamic *P(V)* and *Q(V)* block. In this model the *P(V)* and *Q(V)* characteristic is placed behind the PT_1 block. This allows to omit the dead time, which was introduced in [9]. Moreover, the model of [9] was extended by a dynamic *P(f)* block and a frequency measurement block. The frequency measurement block is an emulation of phase-locked loop (PLL) and simply consists of a PT_1 element with a rise time of 20 ms.

The *P(f)* and reconnection behavior was implemented such that two options can be chosen. One option is to choose a PV behavior according to VDE 4105 from 2011 [7] (new system). For PV systems that went into operation prior to 2011, a modified behavior can be chosen (old systems). From now on, these two types of PV system models are referred as new and old PV systems. In the following subsections, they are described in more detail.

B. Modelling of new PV systems

The behavior of new PV systems is described in [7]. In the following list, the properties, relevant for the studies conducted in this paper, are described:

- The PV system is reconnected if the frequency is in the range $47.5 \text{ Hz} \leq f \leq 50.05 \text{ Hz}$ for a duration of 60 s.
- During the first 10 min of the reconnection process, the output power is limited. The limit is time varying

according to

$$P_{lim,new} = \frac{10\%P_n}{\min} \cdot t \quad (1)$$

where P_n is the nominal inverter power.

- At the instant \tilde{t} , at which the frequency exceeds 50.2 Hz, the present active power output is stored in the variable $P_M = P_{ref}(\tilde{t})$. If the frequency rises above 50.2 Hz, the output power is limited as displayed in Fig. 2. This can be expressed via a power limit $P_{lim,new}$ that varies with the frequency according to

$$P_{lim,new} = P_M - \frac{0.4}{\text{Hz}} \cdot P_M (f - 50.2 \text{ Hz}) \quad (2)$$

- If the frequency falls again below 50.2 Hz, and the available power is above P_M , the maximum allowable output power of the PV system can only increase with $10\%P_n/\min$ until the available power is reached.
- The *P(f)* behavior according to [7] is implemented in the simulation via a Stateflow[®] diagram in Simulink, as illustrated in Fig. 3. The implementation consists of the four states Normal operation, Active power reduction, Disconnected and Reconnection. A transition from one state to another is triggered as soon as a transition condition is fulfilled. For example, a transition from the state Reconnection to the state Disconnected occurs if the frequency exceeds 51.5 Hz.

C. Modelling of old PV systems

The behavior of inverter coupled systems in LV grids is not well defined for systems that are older than 2011. For example the German grid code VDEW [11] from 2001 defines no behavior for active power reduction in case of over frequency. Also, no reconnection behavior is defined. Previously, PV systems disconnected within 20 ms if the frequency is above 50.2 Hz. The cut-off frequencies of these old PV systems was updated such that the disconnection of all installed PV systems in Germany occurs equally distributed between 50.2 Hz and 51.5 Hz. Thus, the features of old PV systems were modelled based on information from industry experts, which resulted in the following assumed behaviors:

- After disconnection of the PV system, the system is allowed to reconnect to the network whenever the

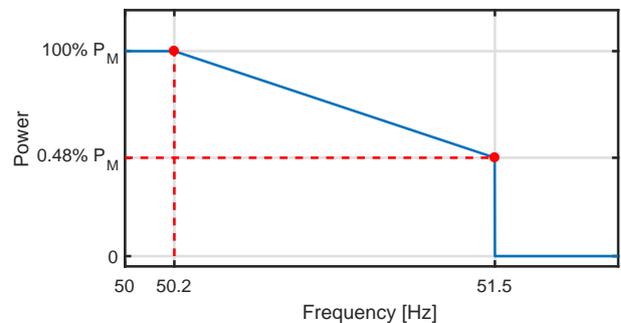


Fig. 2. Frequency dependent active power limitation of PV systems according to [7]. P_M is the output power of the PV system at the instant, at which the frequency exceeds 50.2 Hz. The upper limit of the output power is reduced by $40\% P_M/\text{Hz}$. The output power of the PV system is limited by blue line as long as the frequency is above 50.2 Hz.

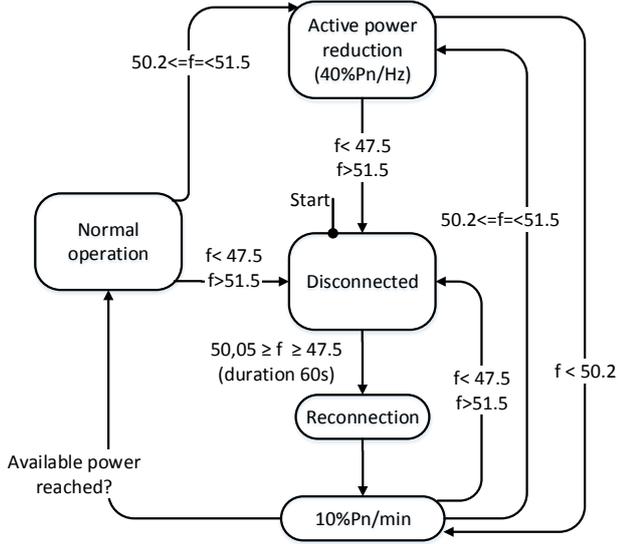


Fig. 3. State diagram of the P(f) portion of the model of a new PV system.

frequency is in the range of $47.5 \leq f \leq 50.05$ Hz for 40 s.

- After reconnection, the output power is limited with a time varying maximum power of

$$P_{\text{lim,old}} = \frac{25\%P_n}{s} \cdot t \quad (3)$$

for the first 4 seconds. Thus, the full PV infeed is reached after 4 s.

- The implementation of the P(f) behavior of PV systems produced before year 2011 is displayed in Fig. 4. The main difference to Fig. 3 is the lack of the state Active power reduction. Instead of that, the model changes its state from Normal operation to Disconnected if the frequency increases above a configurable cut-off frequency $f_{\text{cut-off}}$.

D. Diesel generator

The diesel generator, used for this study, has a nominal power of $P_{n,\text{diesel}} = 250$ kW. The minimal permanent load of a diesel generator is typically 30% of the nominal power,

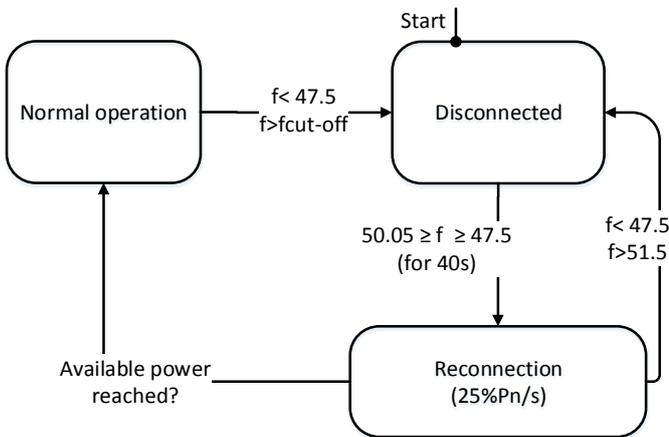


Fig. 4. State diagram of the P(f) portion of the model of an old PV system.

which is $P_{\text{min}} = 75$ kW for this engine. If the output power falls below P_{min} for longer time periods, e.g. for many hours, the maintenance requirement of the diesel generator is increased and its lifetime is compromised.

The model of the diesel generator is displayed in Fig. 5. It is based on the model used in [12]–[14] and is complemented with a frequency control option. The main part of the model (upper part of Fig. 5) consists of an electric control box, an actuator model and an engine model. The parameters used in this work can be found in Table I.

The frequency control (lower part of Fig. 5), which is referred to as f(P) control, works as follows: If the mechanical output power $\omega_N T_m$ is above a threshold P_{set} , the boolean signal (orange, dashed and dotted line) is zero and $\Delta f_{\text{ref}} = 0$. Thus, the reference frequency f_{ref} is not changed. If $\omega_N T_m \leq P_{\text{set}}$, the boolean signal (orange, dashed-dotted line) is one and the reference frequency f_{ref} is changed by the value

$$\Delta f_{\text{ref}} = (\omega_N T_m - P_{\text{set}}) \cdot \text{Droop}. \quad (4)$$

where T_m , P_{set} , Droop and Δf_{ref} are expressed in per unit. T_m is the mechanical output torque of the diesel generator, f the frequency at the point of common coupling and Δf_{ref} is the deviation from the reference speed of the diesel generator. By defining P_{set} and Droop accordingly, the desired f(P) behavior can be chosen. Here, ω_N is the nominal rotational speed of the synchronous generator shaft in per unit. As the rotational speed of the generator shaft

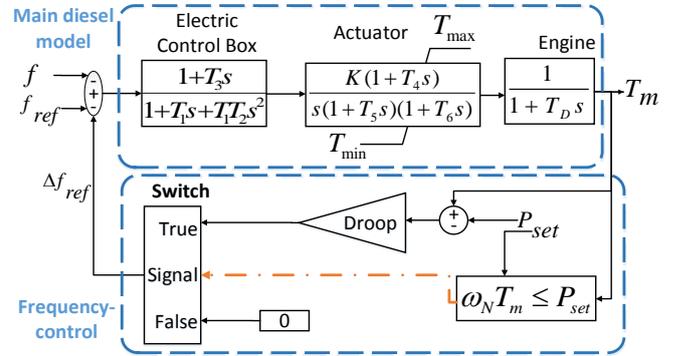


Fig. 5. Block diagram of diesel generator. Note that all variables are in per unit.

TABLE I
PARAMETERS OF THE DIESEL GENERATOR

Parameter	Value
T_1	0.2 s
T_2	0.1 s
T_3	0.5 s
T_4	1 s
T_5	0.1 s
T_6	0.2 s
K	0.01
T_D	0.01 s
T_{min}	0 pu
T_{max}	1.1 pu
<i>Droop</i>	0.0375 Hz/kW

is $\omega \approx 1$, the error that is made for the calculation of the mechanical output power is negligible.

There are two main design goals for the $f(P)$ control of the diesel generator:

- 1) The $f(P)$ control of the diesel generator should be attuned to the $P(f)$ behavior of the PV system such that the infeed of PV power is as high as possible.
- 2) The $f(P)$ control should reduce the time in which the diesel generator is operating below its minimal power P_{\min} .

For obtaining a reasonable engineering compromise between the two goals, the operation of the diesel generator in the range from 40 kW to 75 kW is assumed to be acceptable for a couple of hours, but not for long-term operation.

The $f(P)$ control characteristics chosen for the investigation in this paper is shown in Fig. 6. It can be seen that the diesel generator increases its output frequency when the output power falls below 80 kW. The droop is chosen in such a way, that the output frequency is 50.2 Hz at an output power of 75 kW. This value is chosen because new PV plants, that adhere to VDE 4105 [7], start to reduce their output power at frequencies above 50.2 Hz. Furthermore, the frequency is controlled to 51.5 Hz at an output power of 40 kW. Above 51.5 Hz, all PV systems disconnect from the system. It can be assumed that the operation in the region of 40 kW to 75 kW is indeed temporary, meaning not longer than a couple of hours. This assumption is reasonable if the minimal load demand of the grid is well above P_{\min} during night, when no PV in-feed is present and all load is covered by the diesel generator. This is the case for the 120-node LV grid investigated in this study.

E. Networks

The investigations are carried out with a 3-bus network and a 120-bus LV grid, provided by a German grid operator. In both grids, the diesel is connected to the LV side of the MV/LV transformer.

1) *3-bus network*: The 3-bus grid is displayed in Fig. 7. The diesel generator is connected to bus 1. Bus 1 is connected to a load at bus 3 and to a PV system at bus 2 via two NAYY 4x150 cables of length 100 m.

2) *120-bus network*: The 120-node network is shown in Fig. 8. In its basic configuration, it has a maximum load of 230 kVA, distributed among 150 households and 3 PV systems with total installed power of 90 kVA. In the configuration with increased PV installation, 21 PV systems

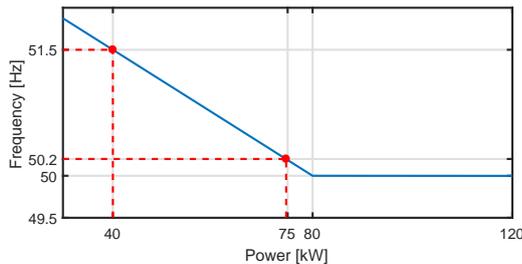


Fig. 6. Frequency control scheme of the diesel generator. Above an output power of 80 kW, the frequency is controlled to 50 Hz. Below that, the frequency increases with a droop of 0.0375 Hz/kW.

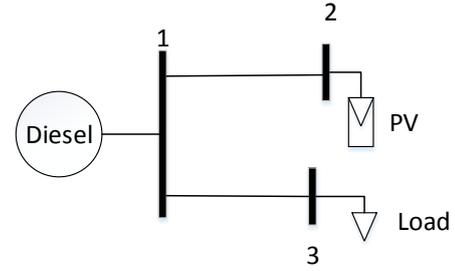


Fig. 7. 3-bus network.

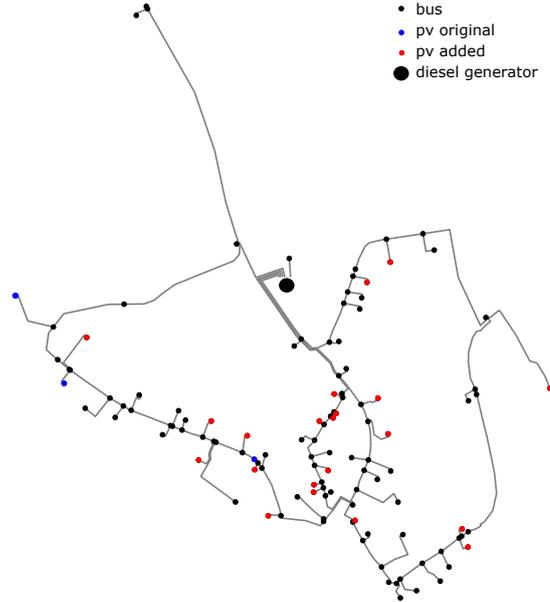


Fig. 8. 120-bus LV grid (original PV systems in blue, PV systems added for this study in red).

with a total power of 210 kVA (10 kVA each) are present in the system.

F. Simulation environment

The case studies are carried out via phasor-based simulations, also called Root-Mean-Square (RMS) simulations. For these simulations, a self-developed RMS-framework presented is used. It is completely based on MATLAB/Simulink® [15].

III. RECONNECTION OF NEW PV SYSTEMS

In this section, the reconnection of a new PV system is investigated. The PV system is modeled according to VDE 4105 as described in Section II-A. For the investigation, the 3-bus system introduced in Section II-E and displayed in Fig. 7 is used. The PV system at bus 2 is assumed to be an aggregated PV system. Also, the load at bus 3 is assumed to be an aggregated load. Furthermore, the following steps are assumed for the investigation:

- 1) The LV network is not supplied with power from the MV grid, for example due to a blackout.

- 2) An emergency diesel generator is connected to the LV side of the MV/LV transformer to resupply the LV system and form an island grid. The diesel generator is initially operated at 50.1 Hz in isochronous control mode. This control mode is maintained until the cold-load pickup phenomenon decayed.
- 3) The frequency control mode of the diesel generator is switched from isochronous control mode (50.1 Hz) to the f(P) control scheme explained in Section II-D and displayed in Fig. 6. This third step marks the start of the investigation of this paper. As the cold load pickup phenomenon is not part of this investigation, the first two steps will not be presented and discussed here as they are presented in [16]

Three scenarios are investigated. In the first scenario, the available power of the PV system is smaller than the load. In the second scenario, the available PV power is bigger than the load consumption. In the third scenario, the total load is below the minimal power P_{\min} of the diesel generator. During all investigations in this paper, it is assumed that the available PV power P_{avail} is equal to the nominal power of the PV inverters. This corresponds to a weather situation on a sunny day during noon.

A. Available PV power smaller than load

In this scenario, the reconnection of the PV system is investigated for the case in which the load power is $P_{\text{Load}} = 200$ kW and the nominal PV inverter power is $P_n = 100$ kW. The results of the simulation can be seen in Fig. 9. In the first seconds, the frequency control mode of the diesel generator is switched from isochronous operation at 50.1 Hz to the f(P) control mode. After the frequency is controlled to 50 Hz and the reconnection condition is fulfilled, the PV system is reconnected and the PV power is ramped up. Furthermore, it can be seen that the power infeed of the PV is limited by a gradient of 10 % of the nominal inverter power per minute, which is 10 kW/min. Thus, it takes 10 min until the maximum power is reached.

B. Available PV power bigger than load

In this scenario, the PV plant has a nominal and available power of $P_n = P_{\text{avail}} = 300$ kW. The simulation results are shown in Fig. 10. It can be seen that the PV power increases until the frequency reaches 50.2 Hz. At this point, the current

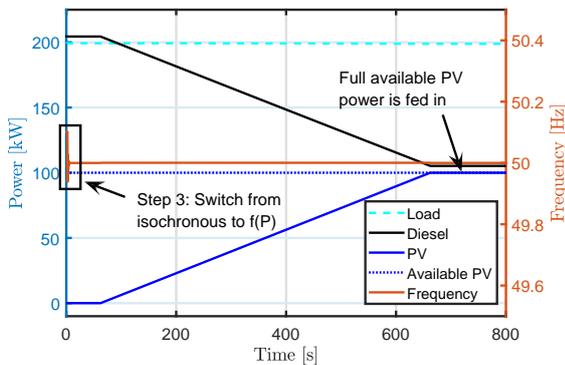


Fig. 9. PV reconnection for the case $P_{\text{Load}} = 200$ kW and $P_{\text{avail}} = 100$ kW (new PV system).

PV power is frozen at a value $P_M = 131$ kW and kept constant. It has to be noted that freezing the output power of the PV system is the key factor for assuring a successful reconnection. If the power was not frozen, the PV power would continue to increase. Eventually the diesel generator would increase its frequency due to the f(P) control until $f = 51.5$ Hz and the PV system would disconnect. This happens in case of old PV systems as will be shown in Section IV.

C. Load smaller than minimal diesel power

In this scenario, the reconnection of a new PV system with $P_n = P_{\text{avail}} = 100$ kW is investigated for the case in which the load is less than the minimal power of the diesel generator, namely $P_{\text{Load}} = 50$ kW. The simulation results are displayed in Fig. 11. It can be seen that the f(P) control of the diesel generator shifts its frequency to a value above then 50.05 Hz. Thus the reconnection condition of the PV system is not fulfilled and the PV system does not connect.

IV. RECONNECTION OF OLD PV SYSTEMS

In this section, the reconnection of old PV systems is investigated. The modelling of old PV systems was described in Section II-C. This investigation uses the same three steps, as already used in Section III and is conducted with the 3-bus system displayed in Fig. 7. Two scenarios are investigated. In the first scenario, the available PV power is smaller than the load and in the second one, the PV power and the load power are of the same size. In both cases an old PV system with a cut-off frequency of 50.6 Hz is used.

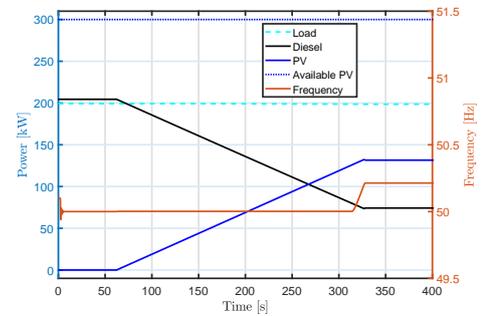


Fig. 10. PV reconnection for the case $P_{\text{Load}} = 200$ kW and $P_{\text{avail}} = 300$ kW (new PV system).

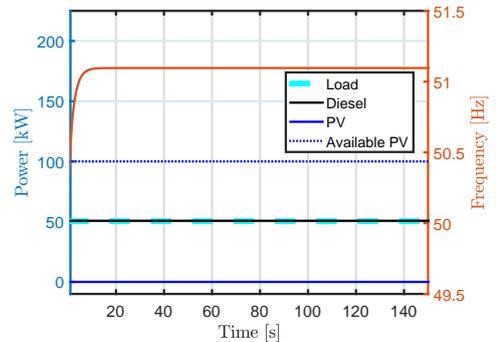


Fig. 11. PV reconnection for the case $P_{\text{Load}} = 50$ kW and $P_{\text{avail}} = 100$ kW (new PV system).

A. Available PV power smaller than load

In this scenario, the nominal and available PV power is $P_n = P_{avail} = 100$ kW and the load is $P_{Load} = 200$ kW. It is expected that the PV can reconnect without any problem because the diesel generator will supply the difference between the load and the PV power, which is about 100 kW. Thus, the frequency will stay at 50 Hz. The system behavior can be seen in Fig. 12. At about $t = 40$ s the PV system increases its output power with a gradient of 25 % of the nominal power per second as described in Section 3. At the same time, a slight frequency rise occurs due to the fast increase of the PV infeed. The short frequency increase is due to the response of the spinning reserve to the excess of electric power in the system which is due to the increase in PV power. However, as the diesel generator has a very fast response time, the control is able to reduce the mechanical torque of the diesel generator within a few seconds and restore operation at 50 Hz. All in all, the reconnection process is successful in this situation and at about 45 s the available PV infeed is reached.

B. Available PV power same size as load

The simulation results for $P_n = P_{avail} = 100$ kW and $P_{Load} = 100$ kW are shown in Fig. 13. The cut-off frequency of the PV system is 50.6 Hz. With the increase of PV output power, the diesel reduces its output power. Due to the $f(P)$ characteristics, the diesel generator increases the system frequency to 50.6 Hz (at about $t = 44$ s). Therefore, the PV system disconnects from the network, the diesel generator takes over the complete load and restores the original frequency of 50.0 Hz. At $t \approx 55$ s the same operating condition is present in the system as before the reconnection of the PV system. The process of reconnection and immediate disconnection of the PV system can be seen in more detail in Fig. 14. Furthermore, the PV system reconnects once again (at about 85 s) and the whole procedure repeats. Thus, a periodic process of reconnection and disconnection of the PV system occurs. This is an oscillatory instability and needs to be avoided if possible.

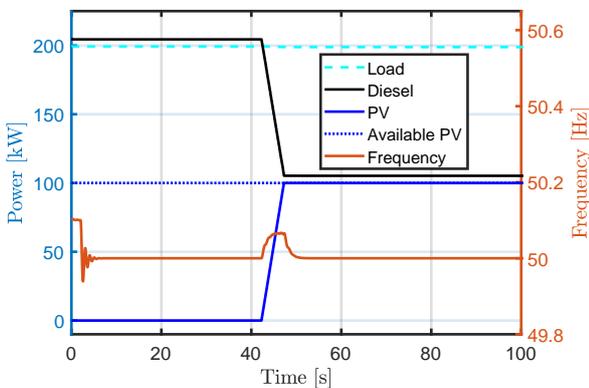


Fig. 12. PV reconnection for the case $P_{Load} = 200$ kW and $P_{avail} = 100$ kW (old PV system with cut-off frequency of 50.6 Hz).

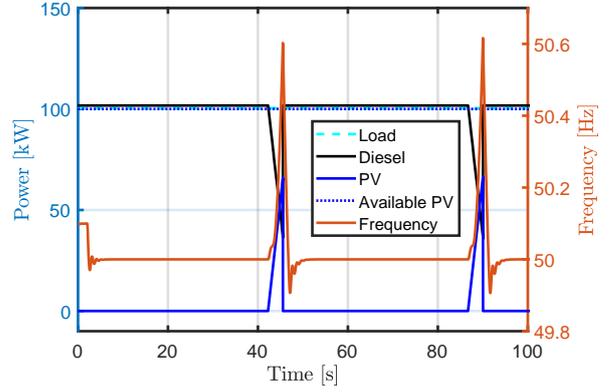


Fig. 13. PV reconnection for the case $P_{Load} = 100$ kW and $P_{avail} = 100$ kW (old PV system with cut-off frequency of 50.6 Hz).

V. RECONNECTION OF A MIX OF OLD AND NEW PV SYSTEMS

The reconnection of new and old PV systems was investigated in a 3-bus system in Sections III and IV, respectively. In real LV grids, both types of PV systems are present. Therefore, the connection of a mix of old and new PV systems is now investigated. For that, the 120-bus LV grid described in Section II-E is used. Two scenarios are shown. In the first scenario, 12 new and 8 old PV systems are present. In the second one, 3 new and 17 old PV systems are present. Each PV system has a nominal power of 10 kW. The load is $P_{Load} = 175$ kW in each case. The cut-off frequencies of the old PV systems are distributed in a range between 50.2 Hz and 51.5 Hz. For the reconnection behavior a worst case assumption is made in which all old PV systems reconnect after 40 s with a time varying maximum power as described in (3).

A. 12 new and 8 old PV systems

In this scenario the 8 old PV systems have cut-off frequencies of $f=[51.1, 50.8, 51.4, 50.3, 51.2, 50.9, 50.4, 51.0]$ Hz. The simulation results are displayed in Fig. 15. At about 45 s an increase in PV power is observed. This is due to the rapid connection of the old PV systems which causes a temporary frequency increase as explained in Section IV. Because of this frequency increase, the new PV systems wait another 60 s until they also reconnect at time $t = 108$ s. As the power of the diesel generator drops below 75 kW,

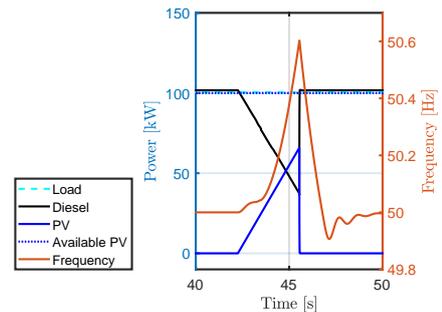


Fig. 14. Zoom of Fig. 13.

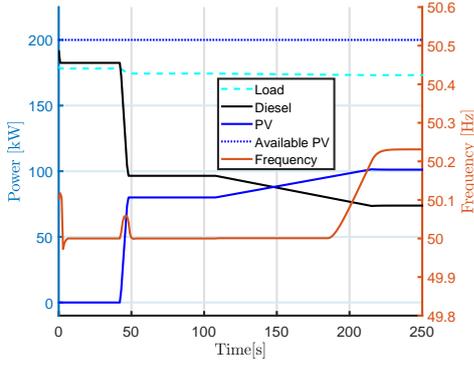


Fig. 15. PV reconnection in a 120-bus LV network with 12 new and 8 old PV systems. Each PV system has a nominal power of 10 kW. The load is $P_{Load} = 175$ kW. Displayed is the accumulated PV and load power

the frequency is increased to above 50.2 Hz and the output power of the new PV systems is frozen. A detailed view on the infeed of each PV system can be seen in Fig. 17. All old PV systems with a fixed cut-off frequency connect with their full power of 10 kW. Furthermore, all new PV systems, that behave according to VDE 4105, freeze their output power at about 2 kW. The reconnection process is successful for this configuration. The main reason for this is that the total available power of all old PV systems is low enough such that the diesel generator still feeds in more than its minimal power P_{min} and does not increase its frequency above the cut-off frequencies of any old PV system.

B. 3 new and 17 old PV systems

In this scenario, the total available power of the old PV systems is 170 kW which corresponds to 17 old PV systems. The 17 old PV systems have cut-off frequencies of $f=[51.1, 50.8, 51.4, 50.3, 51.2, 50.9, 50.4, 51.0, 50.6, 50.4, 50.5, 51.4, 50.3, 50.5, 50.3, 50.8]$ Hz.

As the total load is only 175 kW, a periodic connection and disconnection of the old PV system occurs. This can be seen in Fig. 16. At $t = 42$ s the old PV systems reconnect to the system. Shortly after, the output power of the diesel generator is below its minimal output power P_{out} and the frequency is increased. As the cut-off frequency of some of the old PV systems is reached, they disconnect and the frequency drops again to 50 Hz. This procedure is then repeated over and over again. The new PV systems do not connect during this scenario because the condition for reconnection (Frequency between 47.5 Hz and 50.05 Hz for 60 s) as shown in Fig. 3, is never fulfilled. A detailed plot of the power output of each PV system is shown in Fig. 18. It can be seen, that most of the old PV systems have an oscillatory behavior. Only the old PV systems with cut-off frequencies of at least 50.6 Hz stay connected.

VI. CONCLUSION

In this paper, case studies of LV PV-diesel island networks were conducted. The case studies focused on the reconnection of old and new PV systems with focus on power balance during reconnection. The reconnection of new PV systems was successful in all cases due to the power freezing at the instant at which a frequency increase above 50.2 Hz occurs.

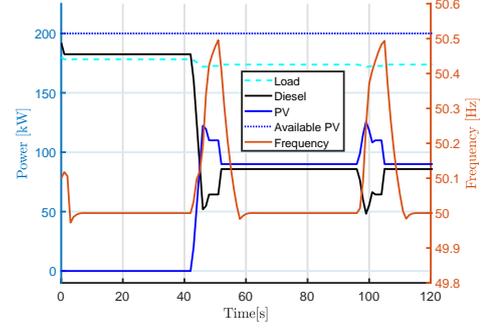


Fig. 16. PV reconnection in a 120-bus LV network with 3 new and 17 old PV systems. Each PV system has a nominal power of 10 kW. The load is $P_{Load} = 175$ kW. Displayed is the accumulated PV and load power.

The reconnection of old PV systems can lead to a periodic connection and disconnection. This can occur if the power infeed of the old PV systems leads to a reduction of the infeed of the diesel generator below its minimal power P_{min} and thus to a frequency increases which is above the cut-off frequency of the old PV systems.

The main finding of this paper is that grid codes for microgrids should contain a freezing of the PV power in case of over-frequency and an active power reduction according to a $P(f)$ characteristics. The optimal slope of the active power reduction is a topic for further investigations.

A general rule of thumb can be deduced from the case studies conducted in this paper: The reconnection process of PV systems in a LV network is (under the considered $f(P)$ control presented in this paper) successful, if the output power of the diesel generator stays above its minimal power under consideration of a full infeed of the available power of all old PV systems. The available power of the new PV systems does not need to be considered due to the freezing of their power and their slower reconnection. This can be stated as

$$P_{diesel} = P_{Load} + P_{loss} - P_{avail, old} > P_{min} \quad (5)$$

where P_{diesel} is the current power infeed of the diesel generator, P_{loss} is the loss power in the network, $P_{avail, old}$ the available power of the old PV systems and P_{min} the minimal power of the diesel generator. Therefore, a rough estimation of the allowed upper limit for total available power of old PV systems can be deduced:

$$P_{avail, old} < P_{Load} + P_{loss} - P_{min} \quad (6)$$

To increase the security margin and to cover most times of the year, worst case assumptions can be made for the load and the PV infeed. Thus, P_{Load} can be assumed as the minimal load of the LV grid during the year. The calculated $P_{avail, old}$ is then the maximum value of the nominal power of old PV systems, with which a reconnection would work safely.

As state-of-the-art inverters are all expected to have the freezing functionality, it is expected that the amount of old PV inverters will decrease over time. This is due to the replacement of old or damaged inverters with new ones.

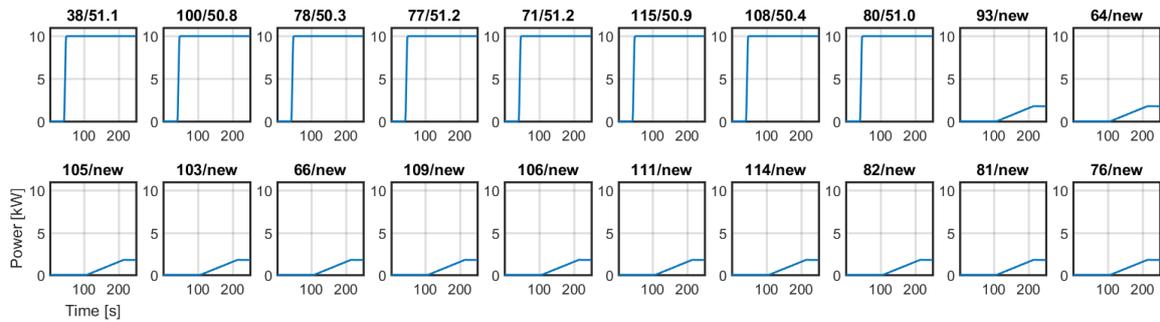


Fig. 17. PV reconnection in a 120-bus LV network with 8 old and 12 new PV systems. Displayed is the output power of each PV system. The title of each graph displays the bus number of the PV system and the $P(f)$ behavior in a format *BusNo / P(f) behavior*. The $P(f)$ behavior is either a fixed cut-off frequency (e.g. 50.8 Hz at bus 100; old systems) or according to VDE 4105 (new PV system).

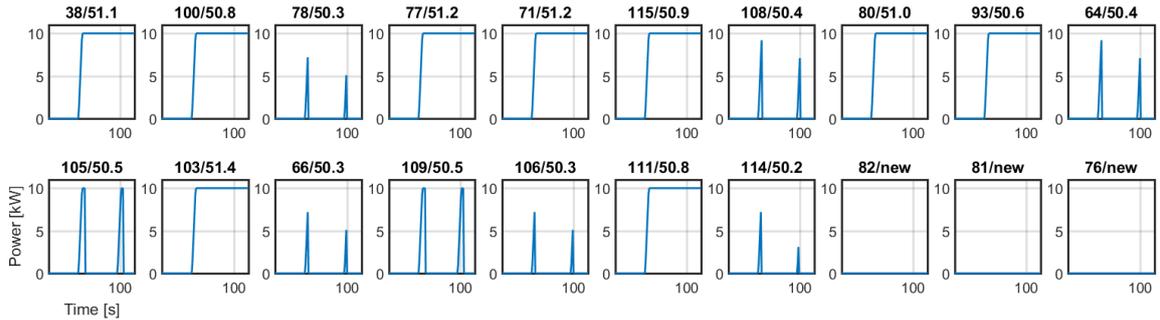


Fig. 18. PV reconnection in a 120-bus LV network with 17 old and 3 new PV systems. Displayed is the output power of each PV system. The title of each graph displays the bus number of the PV system and the $P(f)$ behavior in a format *BusNo / P(f) behavior*. The $P(f)$ behavior is either a fixed cut-off frequency (e.g. 50.8 Hz at bus 100; old systems) or according to VDE 4105 (new PV system).

Thus, the problem will become less severe during the next years.

As this paper only investigated the reconnection, studies concerning the operational behavior are ongoing. These studies consider steps in load and PV generation and contain time series for load and PV generation.

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