DETERMINATION OF LOAD FREQUENCY DEPENDENCE IN ISLAND POWER SUPPLY

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ABSTRACT

The measurement results of a field test in an isolated network show that the quasi-stationary load frequency dependence in small isolated grids can be more pronounced than in large interconnected systems. In a droop based control strategy of the power plants, the load frequency dependence has an influence on the steady state operating point. Therefore, a methodology for the determination of frequency-dependent characteristics of loads is presented. In the examined network, another effect occurs which is considered in the paper. Transient frequency deviations have a relevant impact on the consumption of reactive power caused by transformers.

INTRODUCTION

A study by the German government has shown that long-term and wide spread blackouts can have a serious impact on society and even lead to national crises [1]. The potential for damage would be immensely decreased, if the provision of electrical energy for the most critical consumers could be maintained with help of decentralized power units (e.g. hydro power, wind, biomass or photovoltaic).

LINDA is a German research project that focusses on “Local Island Power Supply and Accelerated Grid Restauration with Distributed Generation Systems in Case of Large-Scale Blackouts”. The aim of the project, which is funded by the German government (Federal Ministry for Economic Affairs and Energy), is the development of a concept for establishing and operating a stable island system that is supplied by the locally available mixture of distributed generation units. As described in [2], the balance of active and reactive power is based on droop curves.

One generation units act as a leading power plant (LPP) and is responsible for the balance of active and reactive power, what is coherent with the regulation of frequency and voltage. The droop curve of the LPP determines the load distribution between LPP and the other distributed energy resources (DER). The DER-droop curves in the range 50.2 Hz < f < 51.5 Hz are based on German and European grid codes [3-8]. Therefore, no adaption of the DER for operation in the local grid island is required.

The research methodology of LINDA is based on a transient simulation model of an exemplary grid section in southern Germany and staggered field trials. The tests are used to proof the concept in a real grid and collect data for optimization of the transient simulation model.

In contrast to the usual network operation, the frequency in island power supply according to the LINDA-concept varies in the whole range between 47.5 Hz and 51.5 Hz. Therefore, the frequency dependence of the load has an important influence on the steady state operating point. Furthermore, large load steps in relation to available generation power as well as the reduced rotational inertia lead to potentially higher frequency deviations in isolated grids. Therefore, load frequency dependence is of greater significance and must be taken into consideration.

QUASI-STATIONARY LOAD FREQUENCY DEPENDENCE

In the field Test 1A of LINDA, the quasi-stationary load frequency dependence of a drinking water supply facility in an isolated grid was determined.

Field Test

The pump station was supplied by one generator (G) of a hydro power plant (Figure 1). The load of the islanded grid is dominated by two pumps which are driven by grid coupled slip ring motors M_1 and M_2 with a rated power of 700 kW and 1200 kW. Further loads are the squirrel-cage motors of the well pumps M_W with approximately 100 kW, each. Switch S1 was opened and S2 closed.

To prepare for the measurements, a black start of the isolated grid was performed. At connection of large transformers, the inrush-effect must be considered. According to [11] the voltage dip caused by the inrush-effect, can lead to a dynamic stimulation of the automatic voltage regulation (AVR) which can result in a dynamic over-voltage caused by the LPP. A countermeasure is the transition to field current regulation of the excitation system before connecting the transformers. This method was sucessfully applied in a field test of LINDA. Since the 150 kvar capacitor banks are connected with the transformers T2 - T4, it leads to a static voltage increase. This effect was compensated by a previous reduction of the supply voltage. After the connection process, the excitation mode was changed to AVR again.

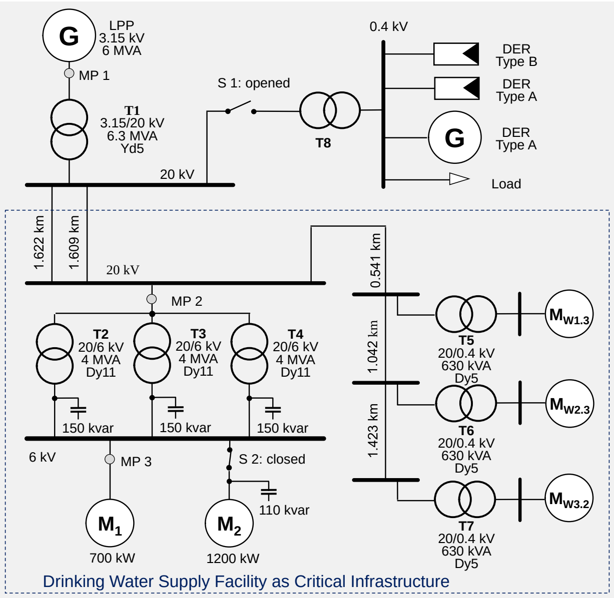

Figure 1: Schematic of isolated grid in field test 1A

For determination of the quasi-stationary load frequency dependence, the load was measured at measurement point MP 1, while the frequency was slowly varied in the range between 47.5 Hz and 52.5 Hz, with the synchronous generator of the LPP. The measurement results, displayed in Figure 2, show an active load change of approximately 8.5 %/Hz which is mainly caused by the speed-torque characteristics of the pumps connected to the asynchronous machines M_1 and M_2. Typical literature values for active load changes at frequency deviations in 50 Hz-distribution systems are 2 %/Hz [9].

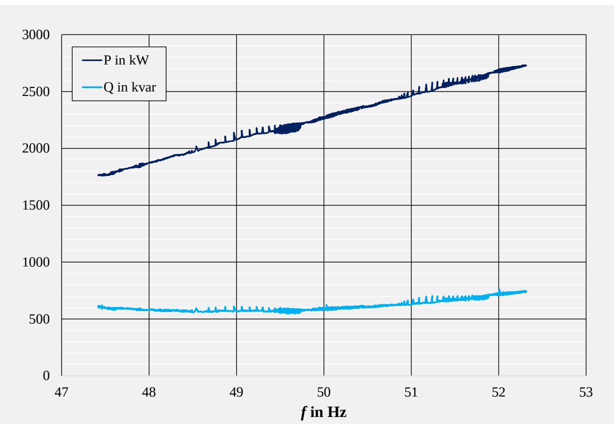

Figure 2: Quasi-stationary load frequency dependence of a drinking water supply facility

In contrast to the active load, the reactive load shows no linear dependency on the stationary frequency, as a result of the interaction between frequency-dependent inductive and capacitive loads in a complex network. The inverter driven well pumps must also be considered. For a detailed analysis of the behavior, more measurement points are required.

The measurements of the field test show that the load frequency dependence can be more pronounced in small isolated grids compared to interconnected grids. This effect is related to the ratio of load types which can differ from their mixture in the interconnected grid, especially in islanded grids with specific infrastructure. Since the load increases with the frequency, this effect supports the stability of the isolated grid.

Steady State Operating Point

Figure 3 displays the influence of the *P(f)*-dependence on the steady state operating point (OP) in a droop-based control concept according to [2]. With the knowledge of the *P(f)*-dependence-quantity, the droop for the controler of the leading power plant can be designed for achieving a suitable point of steady state operation, considering the supply capacity of the DER, if present. Figure 3 exemplifies the resulting droop which consists of the LPP droop curve and the DER droop according to grid codes.

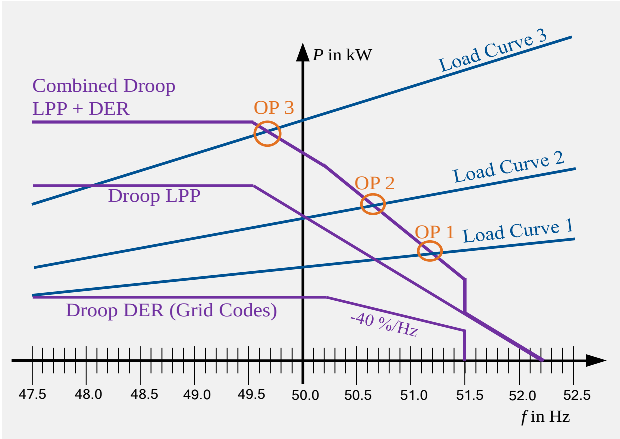

Figure 3: Determination of the droop curve for the leading power plant

The field test 1A of LINDA was a special case with the LPP as exclusive generation unit in the grid section. Figure 1 shows an example for a grid section with LPP and DER, when S1 is closed. Since the presence of further DER makes the determination of the load-frequency dependence more complex, a general applicable methodology is presented.

Methodology for Determination of the Quasi-Stationary Frequency Dependence of Load

The methodology displayed in Figure 4 is based on the field tests of LINDA and is transferable to other grid sections with minor adaptions. In the first step, the island supply mode is activated which allows the operation of the isolated grid section without linkage to the interconected grid. This includes the changeover to a optimized set of parameters for island power supply. Then the leading power plant (LPP) is started in order to supply its own demand. The control mode is set to constant speed control with a frequency of more than 51.5 Hz to prevent connection of DER related to their grid code restrictions.

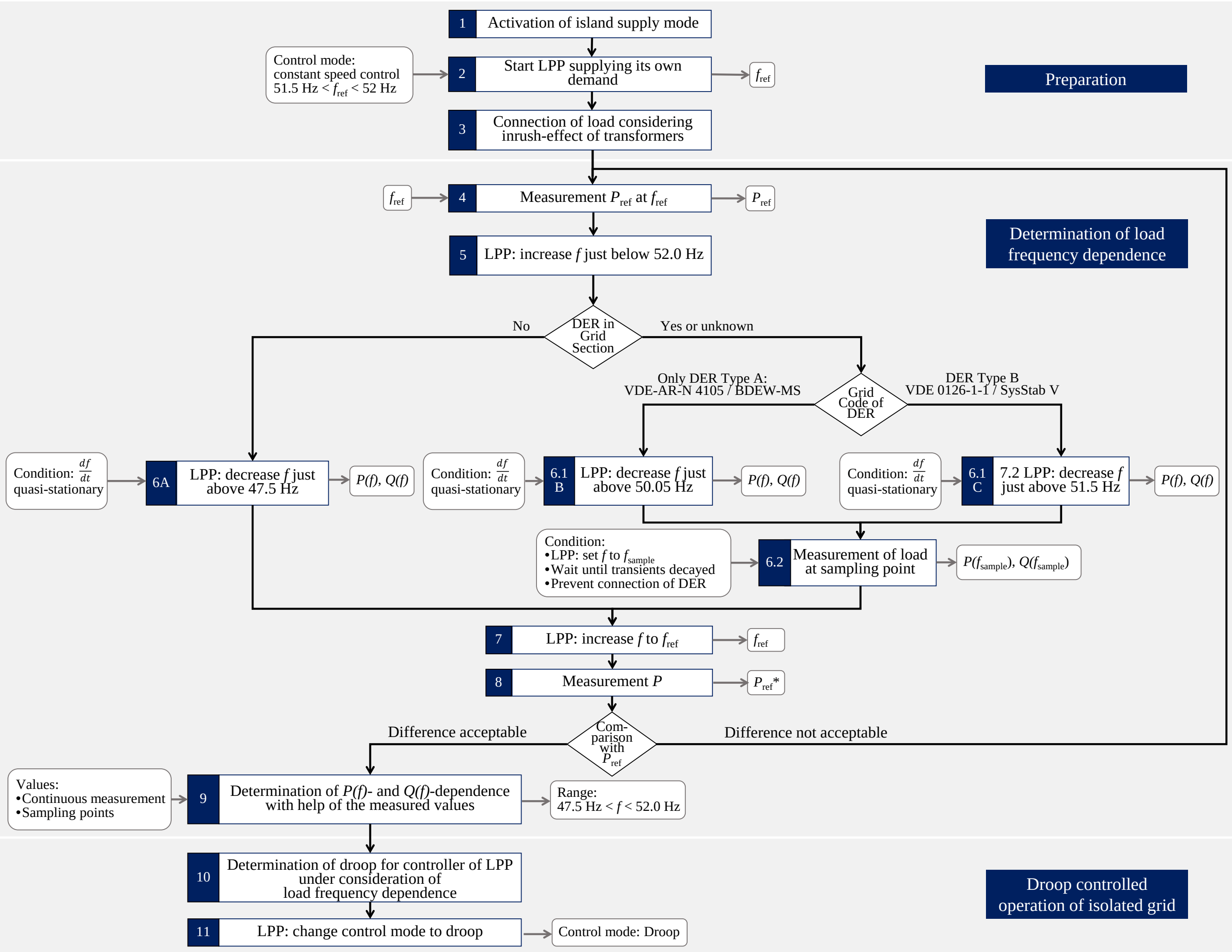

Figure 4: Methodology for determination of quasi-stationary frequency dependence of the load

To meet the requirements of DIN EN 50160, the frequency should be less than 52.0 Hz for grid sections, which are typically connected to the main grid, even though the grid section is currently islanded [10]. So the reference frequency has to meet the boundary conditions 51.5 Hz < f < 52.0 Hz, e.g. f_{ref} = 51.7 Hz.

In step 3, loads are connected to the leading power plant, considering the inrush-effect of transformers. Afterwards, a reference power P_{ref} at f_{ref} is measured at step 4. This value is required for validation of the measurement results later on. Next, the LPP increases the frequency just below 52.0 Hz.

At step 6 it must be distinguished whether DER are in the grid section or not. Step 6A represents the method if there are no DER in the grid section. In this case the leading power plant decreases the frequency just above 47.5 Hz, while measuring *P(f)*, and *Q(f)*. To achieve a quasi-stationary behavior, the speed of the frequency variation must be noted. Transient simulations of the determined grid section according to Figure 1 show a quasi-stationary behavior for $|df/dt|$ < 0.5 Hz/min. The load behavior is mainly influenced by the main hydro pumps and can differ in other grid sections.

If there are DER present, the method for measurement of the frequency dependence of the load is adapted, as the connection of DER should be avoided. For the methodology, the DER are sorted in two Types. Type A means parametrized according to [3] or [4]. If there are only DER of Type A in the grid section, the determination of data from constant measurement is valid in the range 50.05 Hz < f < 52.0 Hz, because Type A units can reconnect, if f < 50.05 Hz for 60 s.

According to [12], many DER which have an automatic disconnection device according to [13] were retrofitted with fixed shutdown thresholds at equally distributed frequencies in the range 50.2 Hz < f < 51.5 Hz. This DER of Type B reconnect when f < threshold value for 30 s. Therefore the determination of data from constant measurement is valid for 51.5 Hz < f < 52.0 Hz, if Type B units are in the grid section.

For determination of measurement values in the frequency range in which the DER have the ability of grid connection, the method is changed to prevent connection (step 6.2). In the range 47.5 Hz < f < 50.05 Hz (Type A) or 51.5 Hz (Type B), a set of sampling points at equally distributed frequencies f_{sample} has to be defined.

Linear interpolation of measurement values *P(f)* and *Q(f)* at f_{sample}, allows an approximation of the load frequency dependence in the named range, later on.

For measurement of *P(f)*, and *Q(f)* at a sampling point, the frequency is changed to f_{sample}, with help of the leading power plant. After transient osciallations have decayed, the desired quasi-stationary values can be measured. To prevent connection of the DER, the frequency has to be increased above the reconnection frequency f_{rc} = 50.05 Hz each t < 60 s for Type A and f_{rc} = 51.5 Hz each t < 30 s for Type B. This procedure is repeated until load values are determined for all sampling points.

Since switching of loads can distor the measurement, the active power at reference frequency f_{ref} is measured again and compared with the values of step 4. If the difference is acceptable, the determination of the load frequency dependence is valid. Otherwise, a repetition of the procedure from step 4 is required.

In step 9, the *P(f)*- and *Q(f)*-dependence is determined in the whole range 47.5 Hz < f < 52.0 Hz with the values from continuous measurement and, if applicable, linear interpolation of the sampling points. The minimum frequency is set to 47.5 Hz, because the current grid codes allow a disconnection of the generation units at this value. So this is the minimum frequency which allows a stable operation of the isolated grid according to the LINDA-concept.

Step 10 allows the determination of the LPP-droop curve under consideration of the load frequency dependence. Now, the control mode of the LPP is changed from constant frequency control to droop control which allows the operation of the isolated grid supplied by the LPP and further DER.

The explained methodology allows the determination of the quasi-stationary load frequency dependence, but transient effects must also be considered.

LOAD DEPENDENCE ON TRANSIENT FREQUENCY DEVIATIONS

Transient frequency deviations have a sizeable impact on the consumption of reactive power caused by large transformers in the examined network area.

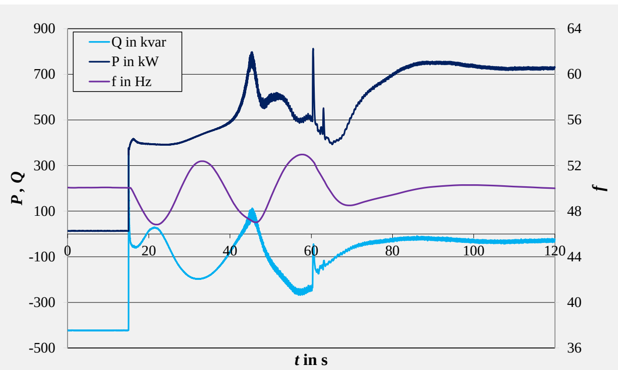

Figure 5: Load of MP 2, at start of M_1

Figure 5 shows the load of the measurement point MP 2 and the frequency of the grid section at start of M_1, while S1 and S2 are open. The load steps at the start of M_1 cause frequency fluctuations in the isolated grid which result in in variations of the reactive power consumption.

Figure 6 shows the exclusive behaviour of the transformers T2, T3 and T4 with the three 150 kvar capacitor banks at these frequency variations. The values are determined by subtraction of the load of MP 5 from the load of MP 2. With decreasing frequency, the consumption of reactive power of the transformers with their capacitor banks is increasing and vice versa. The effect is related to the parallel connection of reactive loads.

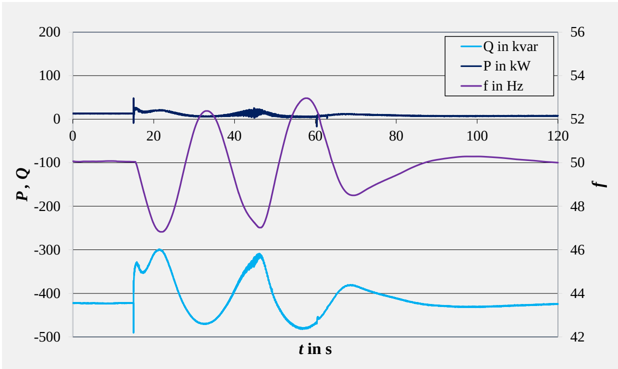

Figure 6: Measurement - Transient frequency dependence of transformers with capacitor banks

In the transient simulation with the program DIgSILENT PowerFactory®, the effect can be reproduced with EMT-simulation but not with RMS-simulation (Figure 7), as EMT-simulations consider the transient behavior of passive loads. In difference, RMS-simulations use the parameters of passive loads in steady-state condition as base for the transient simulation [14].

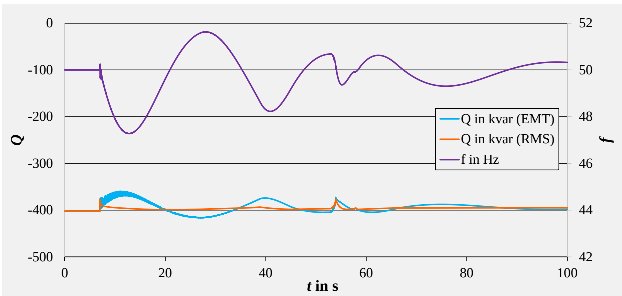

Figure 7: Simulation - Transient frequency dependence of transformers with capacitor banks

The used library models of the transformers allow the reproduction of the general effect, but not the absolute values. Further research is required on this topic.

CONCLUSION

The concept of LINDA focusses on island power supply with prioritization of critical infrastructure in case of large-scale blackouts. Measurements at a drinking water supply facility show that the load frequency dependence of critical infrastructure in small isolated grids can differ from typical literature values for distribution systems. Therefore, a methodology for the determination of the load frequency dependence in isolated grid sections is presented. Since the frequency-dependent characteristics of loads have an influence on the steady state operating point, the knowledge of this characteristics is important for the design of the droop curve of the leading power plant in a droop based control concept with small slopes according to [2].

Transient frequency deviations, caused by switching processes, have an influence on the reactive power consumption of large transformers in the examined isolated grid. Reproduction of this effect with the program DIgSILENT PowerFactory® show a significant difference between RMS- and EMT-simulation.

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