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Performance indicators for microgrids during grid-connected and island operation

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***Abstract*—This paper discusses methods for quantifying the performance of microgrids during island operation. Such methods are essential for comparing different designs and different control algorithms. Performance indicators and objectives are proposed for voltage-quality variations, for individual dips and interruptions, and for the reliability during island operation.**

I. Introduction

MICROGRIDS consist of a number of loads or customers and the distribution network connecting them. The microgrid either contains sources of generation or curtailable load. The main emphasis in literature is on microgrids containing sufficient generation to supply the local load. The aim of a microgrid is to allow the control of active and/or reactive power independent from the grid. The development of microgrids is seen as an important part of the successful integration of massive amounts of distributed generation and renewable energy resources. A clear indication of this is that the transmission-system operatoror Energinet.dk in Denmark, which is moving away from central generation towards only windpower and small-scale CHP, is working to restructure system operation very much in line with the microgrid concept [1].

Possible applications of microgrids include: participation on the day-ahead and balancing market; providing system support during low operational security; controlled island operation during grid outages; and improving voltage quality. Microgrids have become possible through the developments in power-electronics, control and communication and are one of the completely new ways of thinking in design and operation of power systems.

However, the end-use of electrical energy hasn't changed and the performance requirements on microgrids are at least equal as those on the existing grid. There is however no reason to put excessive requirements on the performance of microgrids. Both overly low and overly high requirements could result in the erection of a barrier against the introduction of renewable sources of energy.

This paper aims to contribute to the use of microgrids by discussing some of the aspects of performance indicators in relation to microgrids.

II. Microgrid Control and Operation

Traditionally the lowest voltage levels of distribution systems are not explicitly controlled but governed by customer loads, local generation and control actions on higher voltage levels. The microgrid concept changes this passive role of the distribution network by introducing control. The more control and distributed energy resources, the more services can be considered. As a first step it becomes possible to control the exchange of power with the rest of the network at the connection point. With appropriate control and sufficient generation a microgrid may even operate autonomously as an island network.

A microgrid at island operation is a complete power system, yet very small. The functionality typically found at transmission level and associated with system operation such as frequency control must thus be available. The small size however makes operation more challenging and has physical implications for what performance can be achieved. In a small system the short-circuit capacity is normally very limited, which affects fault clearing and voltage regulation. Furthermore, load changes are large relative to the total load, which makes frequency control more challenging.

Since all power systems historically were small operating a small system is by no means impossible. The challenge rather lies in doing it economically. The strong coupling between performance and investments makes performance indicators and agreeing on acceptable ranges for these very important.

As an example, Fig. 1 shows the relationship between frequency deviation and load changes for a certain island system. If the frequency deviations are considered excessive adding a flywheel to the generating unit would help but has an associated investment cost.

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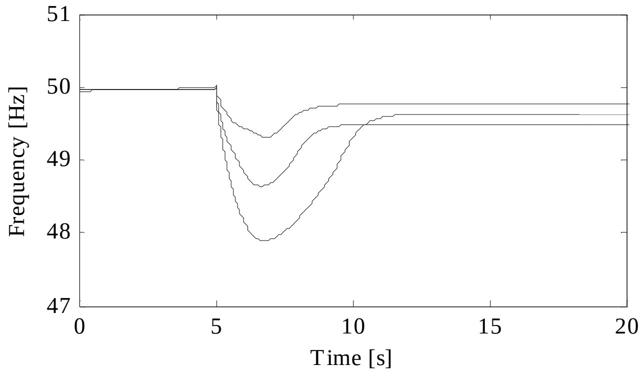

Fig. 1. Simulated frequency deviations in an island system for step changes in load. Rated output of the single hydro unit is 275 kW and the load steps are 7, 14 and 21 kW

Island operation may be reached through several sequences of events. The most straightforward is a breaker opening that disconnects the microgrid. This may also be preceded by a disturbance in the external system. If the generating units have fault ride through capability and the disconnection is swift island operation may be entered successfully. Alternatively the units may trip due to the disturbance. If one or more units have black-starting capability island operation may still be established but after an interruption to the electricity supply of the loads connected to the microgrid. These alternatives are different in terms of performance and necessary equipment. Also here a balance between investment and performance is needed.

III. Grid-Connected versus Island Operation

Microgrids will be connected to the rest of the grid most of the time. The voltage frequency, magnitude and distortion are in that case mainly determined by the performance of that grid. There is no need to do any additional studies.

However, microgrids may be connected to a remote part of the grid, where voltage magnitude and waveform are outside of acceptable limits during part of the time. The control of the microgrid can be used to improve the power quality. This is one of the applications of microgrids, where investments in the grid may be deferred by using the control options in the microgrid. The requirements on the performance of the microgrid in this operating mode will necessarily have to be the same as the requirements that are normally placed on the public grid.

Island operation of microgrids is used to prevent the interruption of the supply to important loads during grid outages. It may also be used to prevent voltage dips originating in the grid from propagating to the terminals of sensitive equipment. During such temporary island operation, lower requirements on performance may be appropriate. This is realistic particularly for frequency, which naturally will exhibit greater variations due to the relatively larger load variations as illustrated in [2]. However, the voltage at equipment terminals should not result in premature failure of any equipment, nor in the tripping or mal-operation of important equipment.

If a lesser performance of the supply is accepted during island operation, the amount of time that the microgrid is in island operation should be kept as small as possible. This calls for the introduction of performance indicators that quantify how much time the microgrid is in island operation without this being necessary.

IV. Performance Indicators

When studying power-system performance it is important to distinguish between variations and events. Variations concern small and slow deviations from the ideal voltages and currents. Variations are typically quantified by taking rms or average values over a certain period of time. Examples of variations are voltage frequency, voltage magnitude, voltage fluctuations and voltage distortion.

Events are sudden and large deviations from the ideal voltage and current. Individual events are quantified by characteristics like magnitude and duration, whereas the supply performance for events is quantified as the number of events that occur within a certain period. Examples of events are interruptions, voltage dips and voltage transients.

The terms “events” and “variations” are commonly used in power-quality studies, where experience has shown that they need to be treated in different ways.

A. Voltage Frequency

During island operation the balance between generation and load within the microgrid determines the voltage frequency. The control algorithm should be able to control generation and/or load fast enough to maintain the frequency within an acceptable range. According to existing quality standards [1][4] the frequency may deviate several Hz from its nominal value. Based on [1] the following performance criteria are proposed:

- ✓ The frequency should be between 49 and 51 Hz during at least 95% of the time.
- ✓ The frequency should not be less than 42.5 Hz and not exceed 57.5 Hz.

B. Voltage Magnitude

During grid-connected operation, the voltage magnitude is mainly determined by the public grid. Only if the grid performance is insufficient should performance requirements be set in place for the voltage control of the microgrid.

A typical acceptable range in voltage magnitude is between 90% and 110% of the nominal voltage. According to EN 50160, the 10-minute rms voltage should remain within this range for 95% of the time in low-voltage networks. Excursions down to 85% are allowed during 5% of the time. However, equipment immunity standards only require the equipment to function correctly between 90% and 110% of the nominal voltage. With modern power-electronics controllers, the voltage can be maintained within a narrow range. Based on this, the following performance requirements are proposed:

- ✓ The 1-minute rms voltage should be between 92 and 108% of the nominal voltage.

- ✓ The 1-second rms voltage should be between 90 and 110% of the nominal voltage.
- ✓ The 1-cycle rms voltage should be between 70 and 115% of the nominal voltage.

C. Voltage Fluctuations

Voltage fluctuations come in two types: continuous voltage fluctuations and occasional voltage fluctuations. Continuous voltage fluctuations are due to strongly fluctuating loads, where arc furnaces and welding are the most well known examples. Occasional voltage fluctuations are due to load switching. The starting of motor load is most notorious for this. Occasional voltage fluctuations are also referred to as “rapid voltage changes”. Both continuous and occasional voltage fluctuations will result in light-intensity variations for many types of lamps. Continuous voltage fluctuations may result in light flicker, to which incandescent lamps are most sensitive. The performance of the network with respect to continuous voltage fluctuations is quantified by the short-term and long-term flicker severity. Those indices are however based on the behavior of incandescent lamps. For non-incandescent lamps the flicker severity indices need to be redefined [5].

- ✓ The short-term flicker severity should not exceed 1.0 during grid-connected operation and during longer periods of island operation.
- ✓ During shorter periods of island operation, up to one hour, the short-term flicker severity should not exceed 1.5.

The flicker severity indices only cover voltage fluctuations at a time scale up to a few seconds. For slower fluctuations no indices exist. The “very-short variations”, as introduced in [6] are a possible index. The following performance criteria were concluded from the work presented in [6]:

- ✓ The 50 percentile of the 10-minute very-short variations during one week; should not exceed 1.0 Volt.
- ✓ The 95 percentile of the 10-minute very-short variations during one week; should not exceed 2.5 Volt.

For occasional voltage fluctuations (rapid voltage changes), no common methods of quantification exist at the moment. However it is appropriate the limit the size of rapid voltage changes. The number of rapid voltage changes cannot be limited by any control system as the number of switching actions of the load determines this.

A measured example of a rapid-voltage change is shown in Fig. 2. Within IEC standards, a rapid voltage change is described as a dynamic voltage drop (the worst drop in voltage magnitude during the event) and a steady-state voltage drop. This is shown schematically in Fig. 3, where d_{max} is the dynamic voltage drop and d_c the steady-state voltage drop.

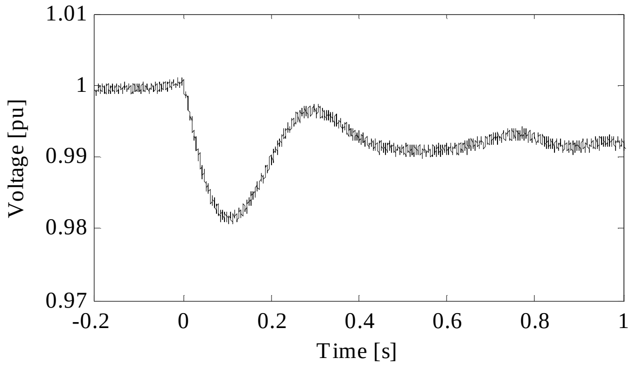

Fig. 2. Measurement of a rapid voltage change: voltage magnitude versus time.

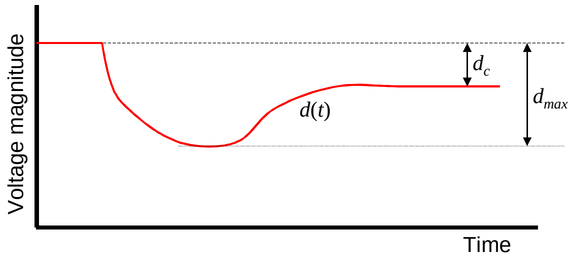

Fig. 3. Rapid voltage change: voltage magnitude versus time.

Limits are placed on the most severe rapid voltage change that may be caused by the switching of a device. Those limits are shown in Fig. 4.

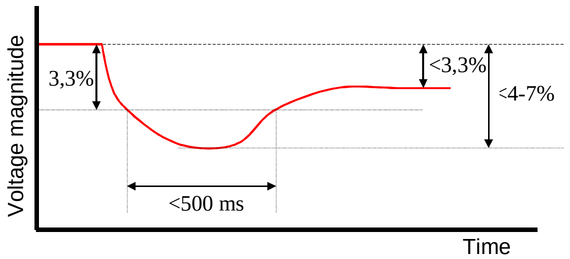

Fig. 4. Limits on rapid voltage change due to load switching.

The steady-state voltage drop should be less than 3.3% and the voltage magnitude should recover to within 3.3% in less than 500 ms; the dynamic voltage drop is limited to 4 to 7%, depending on how often the load is switched. Based on this, the following performance criteria are proposed for microgrids:

- ✓ After a switching action the one-cycle rms voltage should recover to within 3.3% of the pre-event value in less than 500 ms.
- ✓ The lowest 1-cycle rms voltage should not be more than 7% below the pre-event value, when the load switching is not likely to occur more than once during the island operation.
- ✓ The lowest 1-cycle rms voltage should not be more than 5% below the pre-event value, when the load switching is likely to occur several times during the island operation.

D. Voltage Distortion

Limits on voltage distortion for the public supply are given in [1] and [4]. Limits on equipment immunity against voltage distortion are given in IEC 61000-4-13 [7]. The levels in the latter document are higher than the ones in the former document. During short periods of island operation, there appears to be no need to impose more strict limits than the ones that hold for the public grid during normal operation. However, the immunity levels should never be exceeded, not even during short periods of time. The following performance criterion is proposed:

- ✓ The harmonic distortion, measured over a 200-ms window, should not exceed the levels in IEC 61000-4-13.

No limits exist for higher frequencies. This is a serious limitation and such limits should be developed. A discussion on limits for higher frequencies has started and some early results are presented in [8][9].

E. Grid Outages

Island operation of microgrids can be used to improve the reliability of the supply. During an outage of the distribution grid, the microgrid is disconnected from the rest of the grid and the generation connected to the microgrid takes over the supply. The number of island operation events is determined by the rest of the grid and cannot be controlled by the microgrid. However, the two following probabilities should be kept as low as possible:

- ✓ The probability that the microgrid is not able to successfully take over the load during a grid outage.
- ✓ The probability that the microgrid is disconnected from the rest of the grid when there is no outage in the rest of the grid.

The requirements on the latter probability will be less severe than on the former one; an unnecessary island operation event will in most cases not adversely impact the equipment.

To determine the first probability, a criterion is needed for what is a successful transfer to microgrid operation. The curve in Fig. 5 is based on the immunity tests in IEC 61000-4-11 and IEC 61000-4-34. The underlying assumption for this requirement is that equipment should be able to cope with any dip less severe than this.

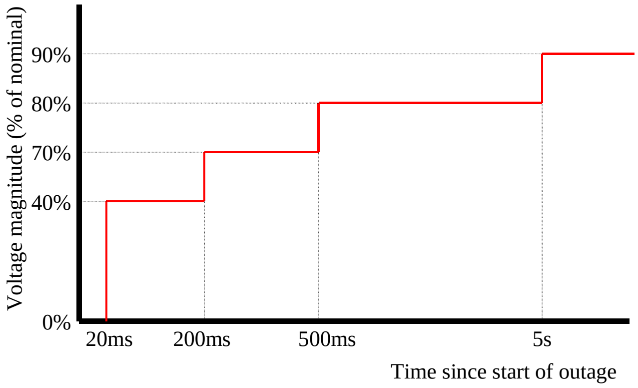

Fig. 5. Proposal for requirement on voltage recovery within the microgrid after a grid outage or a voltage dip.

The island operation of the microgrid may also start, manually or automatically, after a period of second to minutes. In that case other requirements than in Fig. 5 are needed.

F. Voltage Dips

Fast transfer from grid-connected to island operation allows for the mitigation of voltage dip. Upon the detection of a voltage dip, the microgrid goes into island operation, thus limiting the duration of the voltage dip. The same probabilities as in the previous section need to be determined and also here both need to be limited. The performance criterion in Fig. 5 also holds for the transfer due to a voltage dip.

The design of the dip detection method will have to be a trade-off between unnecessary island operation and failure to go into island.

G. Reliability and Island Operation

Being the autonomously-controllable parts of distribution networks, microgrids are normally operated as grid-connected. The reliability of the electricity supply to end-user in microgrids can be improved by allowing and enabling island operation of microgrids.

During island operation, the reliability of the supply is less than during grid-connected operation. As island operation is of limited duration, existing reliability indices like SAIFI and SAIDI are not useful. Other indices are needed.

Of importance for the improvement in reliability is the probability of successful island operation, i.e. successful disconnection, successful island operation as long as needed, and succesful reconnection. The probability that the island operation is not successful consists of:

- ✓ A fixed term associated with the disconnection and reconnection.
- ✓ A variable term proportional to the duration of the island operation.

The total probability of this should be less than a certain limit value. It is difficult to assess what would be a reasonable value for this probability. The value will however be strongly dependent on the kind of load. Rough values to be used as guidance, are:

- ✓ 5 to 10% for domestic customers

- ✓ 1 to 5% for commercial and industrial installations with high reliability requirements
- ✓ 1% or less for special applications where supply interruptions are absolutely not acceptable.

An alternative index is the maximum duration of an islanding state that the microgrid can stand with sufficiently high probability. Probabilities of 90%, 95% and 99% are reasonable values for use as performance indicators.

H. Impact on the Rest of the Grid

The motivation of connecting the microgrid to a large power grid is to improve the reliability and power quality of the power supply to the loads in the microgrid. The difference of a small distribution network with distributed generation and a microgrid is that the microgrid can be disconnected from (or islanded) the rest of the grid and operate autonomously during system emergency states. The microgrid is connected to the rest of the grid with a breaker at the point of common coupling (PCC). The breaker carries on the tasks of connecting to and disconnecting from the power grids.

The impacts of microgrids on the rest of the grid includes the dynamic impact of grid islanding, as well as the impact of the distributed generation in the microgrid on power grids. The IEEE Standard 1547 [10] has provided the standard for interconnecting distributed resources with electric power systems. Based on this standard, we will further discuss the requirements on the impact of the microgrid on the power grid. These requirements should be met at the point-of-common-coupling with other customers.

A. Grid-Connectioned Operation

During grid-connection operation, the distributed generation in the microgrid shall not cause voltage fluctuations at the PCC greater than ±5%. The voltage profile of the rest of the grid should satisfy the voltage requirement of power system operation. The interconnection system shall have the capability to withstand current surges caused by grid connection. When microgrids have DC energy sources and serve DC loads, the harmonic current injection into the power grids should satisfy the limit that the total demand distortion is not higher than 5% [10].

B. Islanding Operation

After detecting the formation of an unintentional interconnection of the microgrid, the generation sources in the microgrid should adjust their generation within 2 seconds to maintain power balance within the islanded microgrid; the power distribution grid shall do the same to keep power balance within the system. At the moment of reconnecting microgrid to the rest of the grid, the frequency difference, voltage difference and phase angle difference shall satisfy the requirement of interconnecting distributed generation to power grids [10].

I. Load Curtailment

During island operation of the microgrid, load curtailment (partial load shedding) may be needed to prevent the loss of the complete load. A typical case that requires load curtailment is when the total load demand exceeds the capacity of the generator.

To design a suitable, if possible optimal, load-curtailment algorithm, again a set of performance indicators is needed. Different indices are needed than the ones used in reliability studies. After all, the idea with load curtailment is to curtail load that has low reliability demands so as to save load that has high reliability demands. Different performance indicators will be needed for different types of load.

- ✓ Some load can be shifted a limited amount in time without impacting the function of the load at all. Examples are heating and cooling load, but also industrial processes using sufficient buffering. For this type of load curtailment does not impact the performance. Any performance index should consider only those cases when the load has to be shifted so much in time that its function can no longer be fulfilled. For heating or cooling loads, this would be when the temperature comes out of the acceptable range.
- ✓ With some loads the impact of curtailment is only minor inconvenience. This may be certain lighting in domestic enviroments or the background music in an elevator. After a while the minor inconvenience may become a major inconvenience. A performance index for this kind of load should trace the total number of curtailments and their average duration as well as the number of curtailments that cause major inconvenience if such occurs.
- ✓ With other loads some costs are associated with curtailment. The total costs due to curtailment are an obvious performance index.

The above indices may have to be refined, but an important aspect of the subdivision is that different indices should be kept for different types of loads.

V. Conclusions

In the design and study of microgrids it is important to quantify its performance. This holds especially during island operation, where the reliability and quality of supply are determined solely by the equipment present in the microgrid.

A number of performance indicators have been introduced for voltage-quality variations: voltage frequency; voltage magnitude; rapid voltage changes; and distortion of the voltage waveform. For each of the indices, objectives are proposed. These indices are mainly based on the performance requirements that exist for customers connected to the public grid. Those performance requirements are coordinated with the immunity requirements of end-user equipment. For equipment to perform during island operation without mal-operation or damage, the same performance requirements should be fulfilled during island operation.

Indices and objectives have also been introduced for the performance during individual dips and interruptions. No such requirements exist for the public grid. Instead the IEC standard for testing of equipment against voltage dips has been used as a reference.

Finally a number of possible reliability indices are discussed, including for load curtailment.

The indices and objectives proposed in this paper are very much open to discussion and the authors would very much encourage persons working on the development and study of microgrids to contribute to such a discussion.

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