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Controlled island operation of part of the 50-kV grid in Southern Sweden

Math Bollen and Olof Samuelsson

***Abstract*—This paper is based on measurements obtained during a test of controlled islanding of part of the 50-kV grid in Southern Sweden. The purpose of the test was to verify operation of generator controls during islanding. The variations in voltage magnitude and frequency are shown as well as flicker severity and very-short variations. A number of performance indices have been calculated and compared with limits. Voltage magnitude and frequency have been studied in some detail around the disconnection and reconnection instants. The frequency varies much more during the island operation than during grid-connected operation. Voltage magnitude variations and flicker remain within their normal range. However the variations in the time range between 3 seconds and 10 minute appear to be higher than normal.**

I. INTRODUCTION

AN island operation field test was performed in the south of Sweden. The purpose of the test was to verify correct operation of generator controls during island operation, which is used as backup when the single infeed fails. The islanded part of the system has a highest voltage level of 50 kV and supplied 15 MW of load. Generation capacity connected to the island consisted of 30 MW hydropower (equipped with voltage and frequency control) and 0.9 MW of wind power.

Island operation started around 22:00 local time and reconnection took place around 00:15. At 23:00 the wind power tripped on over frequency. At 23:44 one of the generators in the island system was intentionally tripped leading to a loss of 2.2 MW. Around 23:50 the voltage in the island system was reduced significantly towards the same level as in the surrounding grid. After reconnection some of the generators that had been out of operation during the island experiment were reconnected.

During the experiment voltage and frequency values were recorded at 50 kV every 20 ms (i.e. every cycle of the power-system frequency) using an ABB RES 521 PMU. The recording started one hour before disconnection and continued until 45 minutes after reconnection. This paper presents some of the voltage and frequency measurements performed during the experiment.

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M.H.J. Bollen is with STRI AB, 771 80 Ludvika, Sweden and with Luleå University of Technology, 931 87, Skellefteå, Sweden (e-mail: m.bollen@ieee.org). O. Samuelsson is with Lund University, 221 00 Lund, Sweden.

II. FREQUENCY VARIATIONS

The 20-ms frequency values are shown in Fig. 1. A visual inspection of the figure immediately shows that the frequency variations during island operation are much larger than during grid-connected operation. Not only is the range in frequency larger, the frequency also shows much faster variations during island operation than during grid-connected operation.

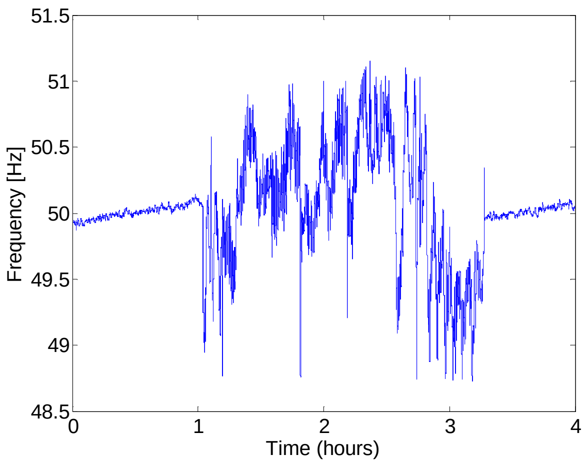

Fig. 1. Frequency variations before, during and after the experiment.

At 23:00, the frequency reaches 51 Hz, which makes over frequency protection of the wind farm trip 0.9 MW. This causes a frequency drop to 50.3 Hz. The loss of a 2.2 MW generator unit during the island operation resulted in the frequency swing shown in Fig. 2. The frequency dropped quickly by about 2 Hz to a value around 48.8 Hz. The frequency control of the other generators picks up the frequency drop very well.

The initial frequency drop is around 0.5 Hz per second. As this is due to the loss of 7.3% of generation (2.2 MW on a 30 MW base) the inertia constant of the system is estimated as 3.7 seconds.

Note that the loss of generator event takes place when the frequency is around 51 Hz. If the event would have taken place for a lower frequency, e.g. 49.4 Hz, the initial frequency drop would still have been significant and a frequency as low as 48 Hz could have occurred. A stochastic study is needed to estimate the risk that the loss of a generator unit will lead to an unacceptably low frequency in the system.

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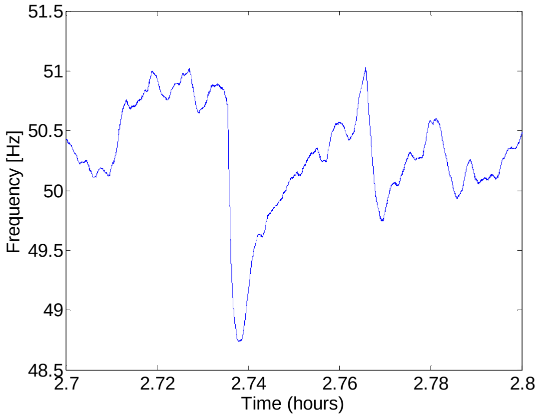

Fig. 2. Frequency swing due to the loss of a 2.2 MW generator during island operation.

The 10-second frequency values have been calculated as the average of 500 20-ms values. The resulting probability distribution function is shown in Fig. 3. The probability distribution function is calculated separately for the island-operation part of the experiment and for grid-connected operation. As expected the frequency spread during island operation is significantly larger.

The relevant frequency indices for the island-operation part of the experiment are presented in Table I. The grid-connected operation values, shown for comparison, are 3-second values obtained during a 198-hour measurement period in the same interconnected system as the experiment. No 10-second values were available, but the difference between 3-second and 10-sec ond values is small. The objectives, based on the voltage characteristics in EN 50160, are fullfilled during the experiment. This experiment involved an island with 30 MW generation on-line corresponding to 100 % spinning reserve. It is expected that the frequency variations increase when this reserve decreases. For smaller islands, there is thus a serious risk that the limits will be exceeded.

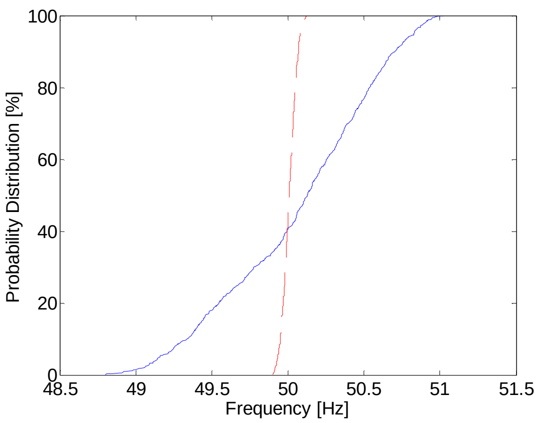

Fig. 3. Probability distribution function of the 10-second average frequency during the experiment: island-operation (blue solid curve); grid-connected operation (red dashed curve)

TABLE I.
FREQUENCY INDEX FOR ISLAND OPERATION IN COMPARISON WITH THOSE FOR GRID-CONNECTED OPERATION IN SWEDEN.

Index	Grid-connected	Islanded	Objectives
Lowest frequency	49.76 Hz	48.80 Hz	47.5 Hz
Lower limit of 95% interval	49.92 Hz	49.07 Hz	49 Hz
Upper limit of 95% interval	50.08 Hz	50.89 Hz	51 Hz
Highest frequency	50.19 Hz	51.02 Hz	52.5 Hz

III. VOLTAGE VARIATIONS

The voltage values, before, during and after the island operation are shown in Fig. 4. Like with the frequency values, the rms voltage was obtained every 20 ms. The disconnection and reconnection instants are not as clearly visible in the voltage as in the frequency (Fig. 1). To better emphasize the island-operation period, the values during island operation are shown in red (grid-connected operation in blue). A small black open circle further indicates the disconnection and reconnection instants.

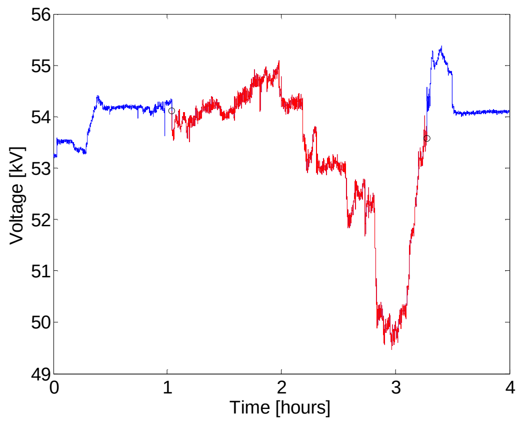

Fig. 4. Voltage values before, during and after the experiment (20-ms values). Circles indicate forming of the island and reconnection respectively.

To enable comparison with the voltage at the terminals of low-voltage equipment, the rms voltages have been scaled to values for a hypothetical 230-Volt system. For this scaling the average rms voltage before island operation is scaled to 230 Volt.

A sharp drop in voltage magnitude occurs at the tripping instant of the 2.2 MW generator unit. The synchronous machine gives a voltage proportional to the speed. The voltage control of the remaining generators makes however that the voltage drop is about half the drop in frequency. This voltage drop is shown in more detail in Fig. 5. Note the strong similarity between the variations in voltage frequency (Fig. 2) and the variations in voltage magnitude (Fig. 5) at this time scale.

In Fig. 4 the voltage magnitude shows a rather large step about 15 minutes after the end of the island-operation period. This step is related to the rescheduling of the generators to their normal schedule. Most likely the drop is due to the disconnection of a generator unit. No clear explanation is available for the continuing rise in voltage before and after reconnection, but manual excitation control is likely.

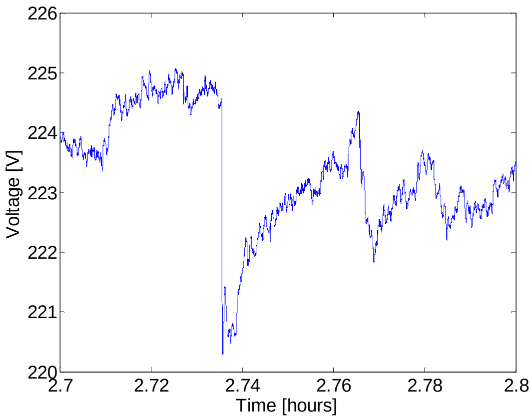

Fig. 5. Voltage drop due to the loss of a 2.2 MW generator unit during island operation.

IV. Very-Short Variations in Voltage

The very-short variations, as introduced in [1][2], have been used to quantify voltage variations at a medium-term time scale (i.e. between 3 seconds and 10 minutes). The 3-second and 10-minute very-short variations, as calculated from the measured rms voltages, are shown in Fig. 6 and Fig. 7. The values during island operation are indicated differently to distinguish them from the values during grid-connected operation. The 3-second very-short variations (Fig. 6) are shown dotted blue during grid-connected operation and solid red during island operation. The 10-minute very-short variations (Fig. 7) during island operation are indicated by a red star.

The highest values are obtained towards the end of the island operation and upon reconnection to the grid. The values during most of the island operation are normal.

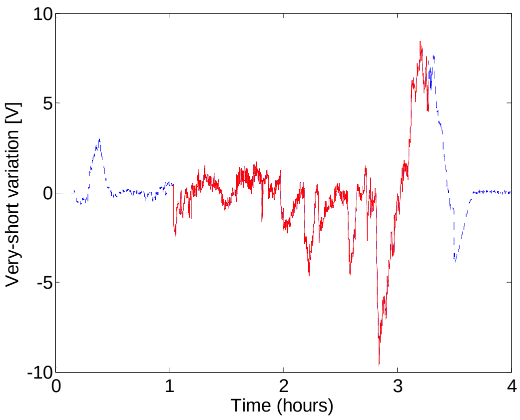

Fig. 6. Very-short variations during the experiment: 3-second values.

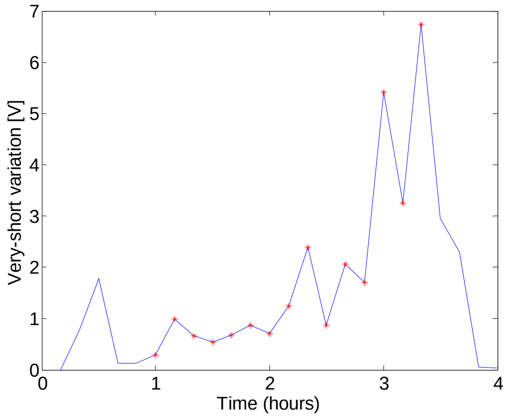

Fig. 7. Very-short variations during the experiment: 10-minute values.

V. Flicker

The flicker severity has not been measured directly during the experiment. Instead the instantaneous flicker severity has been calculated from the recorded 1-cycle rms voltages. The short-term flicker severity has been calculated from the probability distribution function of the instantaneous flicker sensation using the standard expressions [3]. The algorithm for calculating the instantaneous flicker sensation has been calibrated using the signals prescribed in the flickermeter standard [3]. The results are within 10% of the ideal value, with the exception of the value for 4000 changes per minute, which is too fast to be recorded using 1-cycle rms voltages.

The instantaneous flicker sensation is shown in Fig. 8; the short-term flicker severity is shown in Fig. 9. The values during island operation are again marked red. Neither the instantaneous flicker sensation nor the short-time flicker severity is significantly higher during island operation than during grid-connected operation.

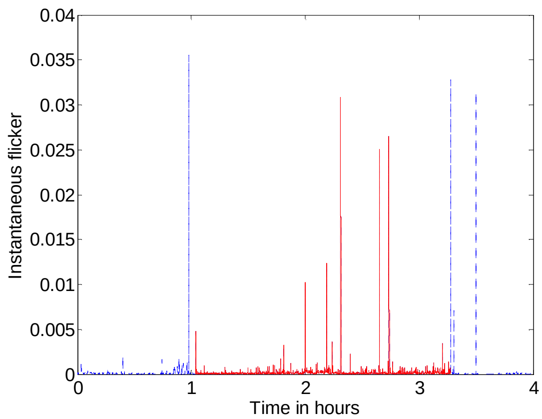

Fig. 8. Instantaneous flicker sensation calculated from the 1-cycle rms voltages recorded during the experiment.

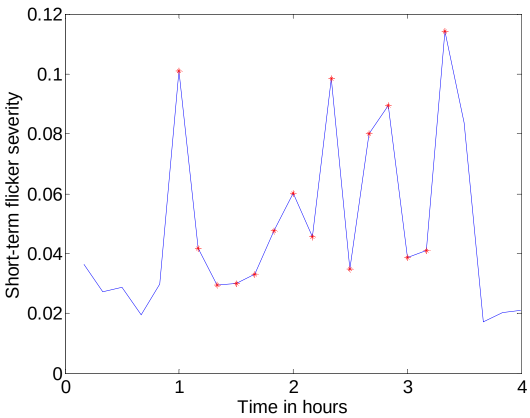

Fig. 9. Short-term flicker severity (Pst) during the experiment.

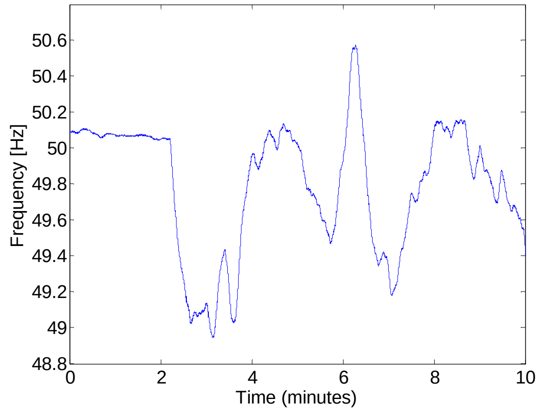

Fig. 10. Frequency recording around the disconnection instant.

VI. Overview of Voltage Indices

All the voltage variation indices, together with their values and objectives, are summarized in Table II. Apart from the very-short variations, all values are within their limits.

TABLE II
VOLTAGE VARIATION INDICES: MEASURED VALUES AND OBJECTIVES

Index	Value (V)	Value (%)	Limit
Highest 10-min rms voltage	234.69 V	102%	110%
Lowest 10-min rms voltage	213.03 V	92.6%	85%
Lower limit 95% interval 3-second voltage	212.4 V	92.4%	85%
Upper limit 95% interval 3-second voltage	233.7 V	101.6%	115%
Lower limit 95% interval 1-minute voltage	212.4 V	92.4%	86%
Upper limit 95% interval 1-minute voltage	233.6 V	101.6%	114%
Highest 10-min very-short variation	6.7 V		2.5 V
Highest long-term flicker severity		7.2%	100%

VII. Disconnection and Reconnection

The above discussion was concentrated on the performance of the grid during the island operation. If island operation is initiated and ended without an intermediate blackout, disconnection and reconnection of the islanded grid to the rest of the grid are critical instants. During disconnection the voltage and frequency control of the generators should be able to handle the possible reactive and active power mismatch between generation and load in the island. During reconnection the differences in voltage and frequency between the islanded grid and the rest of the grid can result in transients that result in protection operation.

A. Disconnection

The frequency, measured every 20 ms, for a period of 10 minutes around the disconnection instant, is shown in Fig. 10. Immediately after disconnection the frequency in the islanded grids drops slowly but gradually (see Fig. 11 for a detailed view). A frequency around 49 Hz is reached after about 25 seconds, at which balance between active power generation and consumption within the islanded grid is reached.

The frequency drop immediately after disconnection is shown in more detail in Fig. 11. The frequency drops from slightly above 50 Hz to slightly above 49 Hz. End-user equipment is rarely impacted by such frequency variations. However, the underfrequency protection of distributed generation like wind power or CHP is often set at 49 Hz. Also the first stage of underfrequency load shedding has a typical setting around 49 Hz. If the grid frequency just before the disconnection would have been 49.9 Hz the frequency would have dropped to below 49 Hz and load or local generation could have been impacted. The frequency drops below 49 Hz a few times during the islanding period, so that the disconnection does not seem to result in more severe demands on the control system than the islanding operation itself.

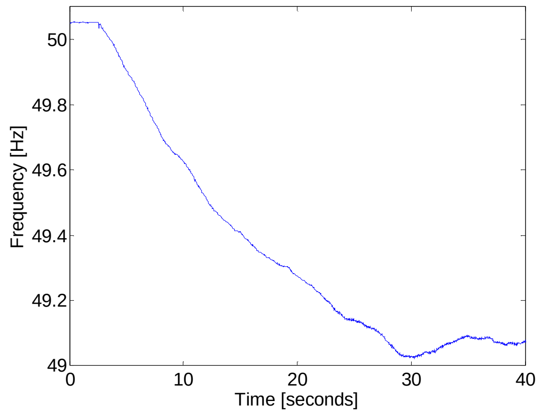

Fig. 11. Details of the drop in frequency immediately after disconnection.

The voltage during disconnection is shown in Fig. 12. The voltage drops about 1 Volt within a few cycles and shows a slow decrease for about 10 seconds after that. The latter may however also be due to normal load variations as the range in voltage magnitude variations is similar to what is recorded during the rest of the island operation.

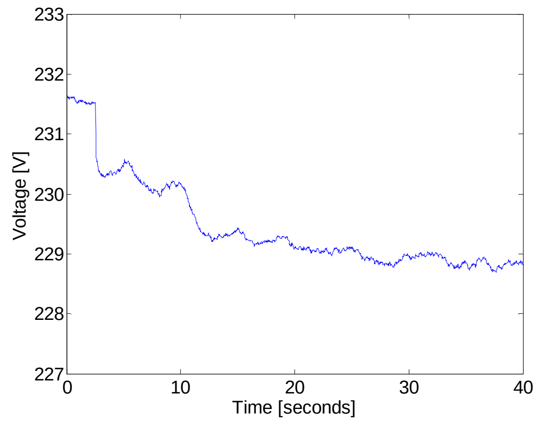

Fig. 12. Voltage recording around the disconnection instant.

There are no indications that the disconnection was associated with any risk as far as the voltage control was concerned.

B. Reconnection

The recordings of the voltage magnitude and frequency around the reconnection instant are shown in Fig. 13 and Fig. 14, respectively. The voltage magnitude shows a step of about 2 Volt followed by an oscillation with a frequency between 1 and 1.5 Hz. .

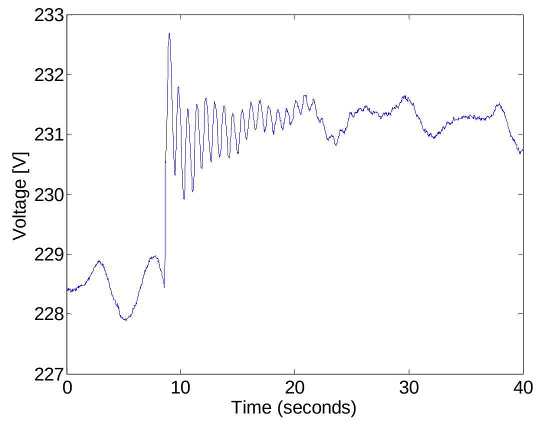

Fig. 13. Voltage recording around the reconnection instant.

The same oscillations are visible in the frequency (Fig. 14). This is a typical local electromechanical mode, where the generating units in the island oscillate against those in the rest of the system. The damping of this mode is modest but acceptable.

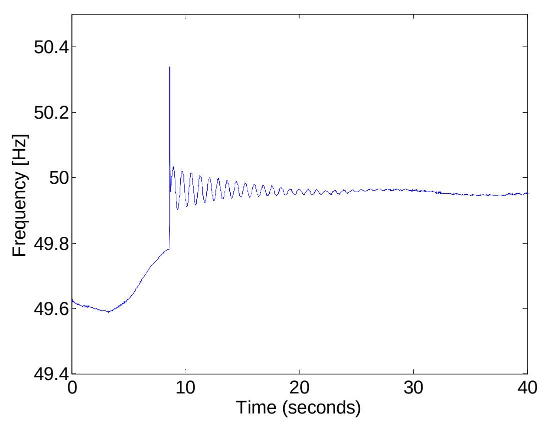

Fig. 14. Frequency recording around the reconnection instant.

Since a PMU determines frequency from rate of change of phase angle, the spike in frequency at the reconnection instant can be explained from a jump in phase angle of the voltage at the reconnection [7]. It should be noted that some frequency and rate-of-change-of-frequency (ROCOF) relays measure the frequency in the same way. This has resulted in several documented cases of industrial installations tripping due to a phase-angle jump. Such relays might trip when the reconnection results in a significant jump or oscillation in the phase angle of the voltage. Note that a jump of only 10 degrees in voltage phase angle in 20 ms would give an apparent frequency of 48.6 or 51.4 Hz.

VIII. Conclusions

The measurements performed during the islanding test show that the frequency range is much larger than during normal, grid-connected, operation. The frequency drops below 49 Hz a number of times during the 2-hour experiment. The impact of this on the load or on local generation is not clear and requires further scrutiny.

The range of 3 second and 10 minute voltage magnitude values remains within their normal range. Also voltage flicker remains within its normal range. However an increase has been observed in the medium-term voltage variations at a timescale between 3 seconds and 10 minutes. There is not enough experience with using these values to draw any further conclusions from this. It however confirms that this time scale deserves some more attention than it receives today.

The changes in voltage magnitude and frequency due to disconnection and reconnection were not more severe than during the rest of the island operation.

Immediately after reconnection the measured frequency showed oscillations that were typical for a local electromechanical mode. The measurements also illustrate that phase jumps lead to spikes in the frequency signal from a PMU, since it determines frequency as rate of change of phase angle. This same phenomenon may affect protection

Another important conclusion from the experiment is that dedicated performance indicators and limits should be developed for island operation This is treated in [5] and [6].

This experiment concerned a rather large islanded system, with 30 MW of generation capacity and 15 MW of load. Furthermore it was a staged test where it was ensured that the risk of interruption for end customers was sufficiently small. The islanding operation of smaller parts of the grid will likely result in even bigger variations in frequency.

The frequency control performance reflected by these measurements proves acceptable, but could be improved considerably. One reason for the limited performance is that the test was targeted at testing frequency control by a few units and therefore the controllers of other units were disabled. Also note that optimal frequency control parameters for island operation are not the same as for normal operation.

One of the challenges of the ongoing work on island operation of microgrids is to be able to switch fast between control suitable for grid-connected operation and control suitable for islanding operation.

IX. References

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