ISSUES FOR RELIABILITY ANALYSIS OF ISLANDED MICROGRIDS WITH DISTRIBUTED GENERATION AND ENERGY STORAGE

Yu SUN
Strathclyde University – UK
yu.sun@eee.strath.ac.uk

Math BOLLEN
STRI AB – Sweden
math.bollen@stri.se

Graham AULT
Strathclyde University – UK
g.ault@eee.strath.ac.uk

ABSTRACT

This paper addresses a number of issues related to the reliability of microgrids powered by distributed generation (DG) and distributed energy storage units during periods of island operation. The load variations for small load groups (kW) are much larger and less predictable than in a large load group (MW). The overload capacity of micro-DG units is completely different than for conventional (large) generation units and this plays an important role in meeting the islanded microgrid load demand. An example is shown of a domestic customer supplied from a fuel cell. A moderate overrating of the fuel cell together with a limited amount of storage is, in the example, sufficient to guarantee a reliable supply.

INTRODUCTION

The UK Government has set targets for renewable energy and other forms of distributed generation to be achieved by 2010, and by 2020. These targets are mirrored in almost every developed country. In recent years, fuel cell and other forms of generation technology have been progressively evolving towards commercial status.

Intentional islanding, also referred to as "microgrid operation", is a situation where it is desirable that the distributed energy resources (DER) units maintain the stable operation of part of the distribution system after disconnection from the main system. This operating regime plays an essential role in providing higher reliability for individual customers [1][2][3]. This increased reliability is an additional advantage of DER possibly leading to a faster adoption of DER. The reliability of the microgrid operation depends on the capability of an islanded system to supply the load adequately.

Micro-DG technologies are different from conventional central station generation in a number of ways. An important difference for reliability during microgrid operation is in the overload limitations. All micro-DG require power electronics to interface with the power network and have limitations on their primary energy source. Too severe limitations would lead to islanded microgrids that were incapable of meeting the load demand requirements if energy storage were not included.

This paper discusses the main issues of reliability in islanded microgrid systems, presents approaches to modelling of micro-scale generation and load demand and presents a case study from which the conclusions are supported.

RELIABILITY OF ISLANDED SYSTEMS

During the island microgrid operation a number of failures may occur that endanger the electricity supply to the essential load. The microgrid does not only have to supply the essential loads but non-essential loads may be supplied by opening the local disconnector and closing the DG breaker. Upon opening of the islanding (interface) circuit breaker, the DG should take over active and reactive power (frequency and voltage) control quickly. Failure to take over the supply sufficiently fast will lead to tripping of the essential load. Different types of failures may be distinguished:

- Damage to the DG unit. This will require repair of the unit, which will take several hours through days.
- Tripping of the DG unit due to a fault induced voltage dip. This will require a restart of the unit, leading to an interruption between a few seconds (when an automatic restart is used) and a few hours (when restarting has to be done by staff not present on-site). The main concern is a dip in supply voltage at the beginning of an interruption, which could result in the DG unit not taking over supply of the load. When only the essential load is supplied by the DG unit, the number of dips due to local faults is likely to be limited, but once they occur the DG unit may trip.
- Tripping of the DG due to active and/or reactive power overload, either because of load variations or because of variations in the generation capacity. This will also require a restart of the unit, but only after appropriate load reduction has taken place. The load shedding may take longer than a simple DG unit restart.
- Tripping of the DG unit caused by poor power quality, such as voltage dips or transients. Transients in an electrical system can be generated by lightning, switching actions, or by faults. Lightning in a small-islanded area may be rare, but the same severe weather resulting in the interruption may also impact the islanded microgrid. Load switching transients may lead to tripping of the DG unit. The frequency of switching actions will increase when more loads are connected to the DG unit. Using the unit to supply non-essential loads

will reduce the reliability for the essential loads.

Adequacy is dominant in reliability analysis for traditional distribution systems, whereas the dynamic problem is identified as an important part of the analysis during island operation. DG units cannot safely pick up load greater than their dynamic characteristics. Simplified dynamic adequacy models have to be used to allow a reliability analysis to be performed concerning certain micro sources.

The basic reliability issues in a small island system are the same as in a large interconnected system: electricity has to be generated and transported to the end-users; interruptions may occur because a load increase exceeds the generation capacity or when a component in the system suddenly fails. However, the specifics of the reliability, like the kind of phenomena of importance, are completely different for small-islanded systems than for large interconnected systems.

DG interface control, of both rotating and inverter sources, is responsible for the control of voltage and frequency. The availability of the generation source depends on: technical availability dependent on the failure and operating characteristics of the units; energy availability dependent on the characteristics of the primary energy source; and commercial availability dependent on whether the owner of the plant considers it economically viable to offer the plant for service at any particular time [4][5].

STOCHASTIC LOAD MODELLING

Load variations take place at a number of time scales, ranging from milliseconds to months. The daily and annual variation is rather well understood as it corresponds to the average behaviour of the consumers. An example of the daily load variations is shown in *Figure 1*: the two curves are the average over all working or non-working days for an office building during a 30-day period in May and June. The working hours, from 8 to 5, dominate the curve for working days. The three peaks correspond to morning coffee, lunch and afternoon coffee. The high load between 10 pm and 4 am is the lighting in the entrance hall, triggered by a photocell.

However the load also varies strongly from day to day, as shown in Figure 2. The load at the same moment in time can be significantly different between different days. The load also shows fast variations in load during a day. Whereas the average load curve may appear rather smooth, the actual load is far from smooth. Some fast variations for domestic loads are shown in Figure 3 which shows 1-sec average currents during a period of about one hour. The load demand shows a number of steps of up to 3 kW. During a roughly 20-minute period the load changes fast between three different levels.

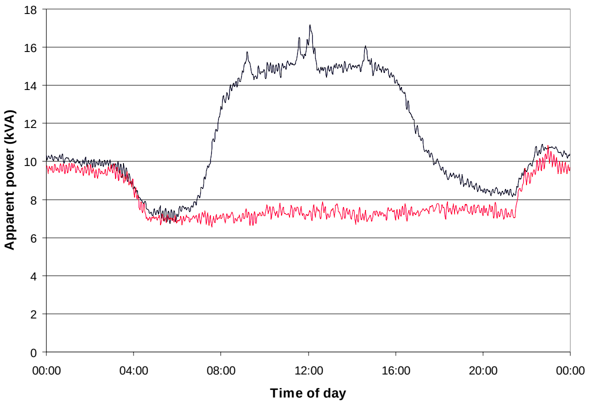

Figure 1, *Daily load variations for an office building; upper (black): working days; lower (red): non-working days.*

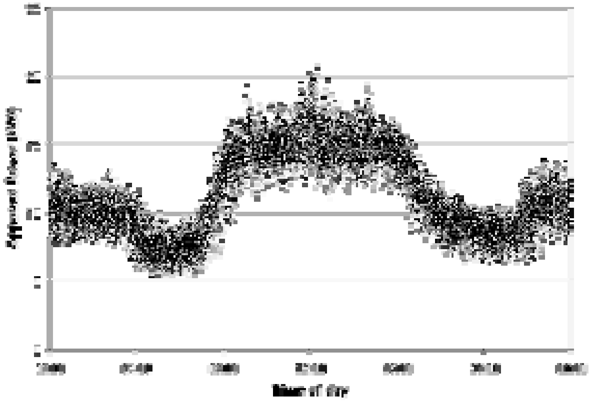

Figure 2, variations in load demand between different days.

A study of the reliability during island operation can be based on historical load demand series, but those are in many cases not available. Therefore stochastic load models are needed covering a range of possible customers. Historical load data from a number of customers could be used to form such a load model. The stochastic load model should accurately reflect the time-varying nature of active and reactive load demand and at least include the following phenomena:

- The daily, weekly and seasonal variations in load demand.
- Day-to-day variations in load demand.
- Fast changes in load demand on minute-to-minute and second-to-second time scales.
- Sudden changes in load demand.

A possible stochastic load model would consist of two parts:

1. An average load profile covering the first and second phenomena. This part of the model will generate “stochastic time series”, for example

resulting in a second-by-second prediction of active and reactive power demand.

2. Modelling potential load events, covering the third and fourth phenomena. This part of the model will generate occurrences of steps and peaks with their characteristics.

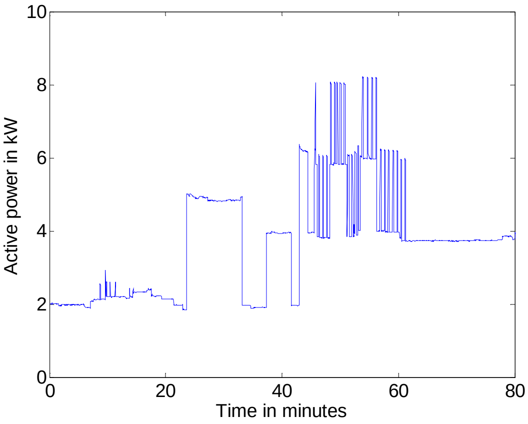

Figure 3, *Fast variations in active power demand.*

GENERATION MODEL

The load demand, as described in the previous section, has to be supplied by the generation connected to the islanded part of the distribution system. The strong variations in load require a serious overrating of the generation units to be able to supply the load during island operation. On the other hand island operation only takes place during a limited period of the year, so that the reliability requirements do not need to be as high as during grid-connected operation.

Consider as an example the combination of a fuel cell and a storage unit connected to a microgrid through appropriate interfaces. The following limits exist in this system :

- The active power limit of the fuel cell: the amount of active power that can be supplied by a fuel cell depends on the history. The way in which the fuell cell works limits to the rate-of-increase of the active power supply.
- The energy limit of the storage device. The storage takes over the supply of the load when the fuell cell has reached its limit.
- The rate of change limit of the storage device. With all types of storage there is a limit to the speed with which the energy can be extracted from the storage medium. This rate is often dependent on the amount of energy available in the storage device.
- The current limit of the fuell cell interface. This is typically a hardware or software setting in the interface controller.
- The current limit of the storage interface.

Note that in this example two interfaces are assumed. In some configurations, the storage and fuel cell share a dc bus, with a common interface to the ac grid.

CASE STUDY

A case study has been conducted for a single house in Sweden. The measured active-power demand, 1-second averages, is shown in Figure 4. The load shows a base level, due to electric heating and high spikes associated with various domestic activities. The average load is 3.12 kW, the peak load is 8.23 kW. DER based provision for the property with generation only would require a maximum generation capacity of at least 8.23 kW, whereas a storage-only solution would require 270 MJ of storage to ride through a 24-hour interruption with the active power demand as in Figure 4.

Various combinations of fuel cell and storage have been assumed, with the aim of riding through a 24-hour interruption. The maximum charging load of the storage device is assumed to be 1 kW. It is further assumed that the interfaces are of sufficient rating to supply the active and reactive-power demand at all times.

The quantity of energy in the storage unit as a function of time is shown in Figure 5 for a 24-hour interruption. The fuel cell rating is equal to 3.4 kW and the storage device size 13 MJ. The discharge of the storage unit takes place especially in the evening hours when electricity consumption is high. Slow fuel cell response and fast power demand rise in the morning contribute to the discharge of the storage unit.

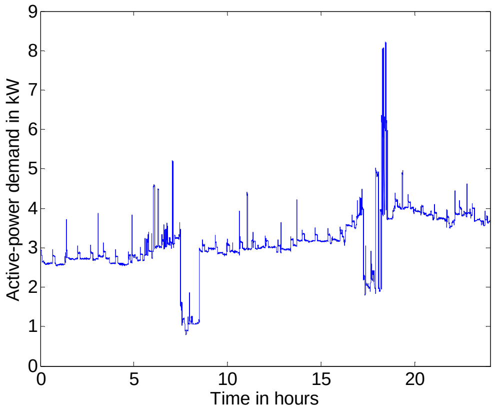

Figure 4, *Active power demand for a domestic load in Sweden during a 24-hour period.*

The required amount of energy storage has been calculated as a function of the fuel cell rating (the maximum amount of active power produced by the fuel cell). It has further been assumed that the storage capacity can be completely charged with a power of 1 kW and completely discharged at any required power level.

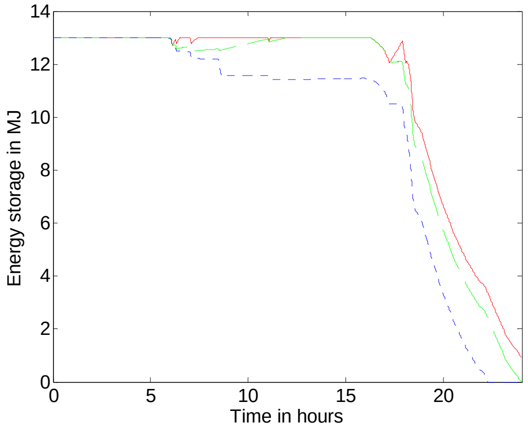

Figure 5, *Energy storage versus time for three levels of the maximum rate of change of active power for the fuel cell: 1/6s (red solid); 1/60s (green dashed); 1/600s (blue dotted).*

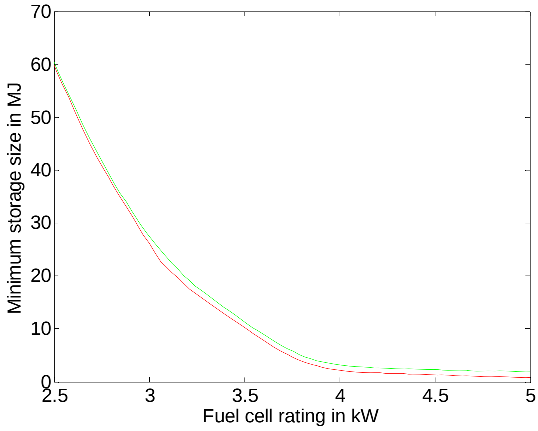

Figure 6, *Minimum storage capacity to ride through 24-hr interruption: 5%/s fuel cell response (lower red line) and 0.5%/s fuel cell response (upper green line).*

The results are shown in Figure 6, where the two curves correspond to a 5%/s and a 0.5%/s maximum increase in active power produced by the fuel cell. The difference between the curves is small in this case. The storage requirements can be significantly reduced by slightly overrating the fuell cell above the average load demand of 3.12 kW. Above about 4 kW the gain in reduced storage requirments becomes small as a certain amount of storage is needed to compensate for fast increases in load demand that the fuell cell cannot cope with. Note that 1 MJ of energy corresponds to 23 Ah at 12 V, about the size of a car battery.

CONCLUSIONS

The reliability analysis of microgrids during island operation requires a number of different approaches compared to the analysis of grid-connected systems. Although the basic principles are the same (the generation capacity has to be at least equal to the load demand) the differences in the details require a new look at reliability analysis.

The two main differences are in the overloading capacity of the generators and in the variations in load demand at different time scales. The overloading capacity of modern DER units like fuel cells is limited both in active power and current. For smaller loads, like one or a few domestic or commercial loads, the relative variations in load demand at short time scales (minutes or less) are much bigger than for aggregated loads. This calls for the development of stochastic load models covering a wide range of time scales and for accurate models of the overloading capacity of modern microsources. Dynamic models are needed to include very fast changes in load demand. A stochastic load model is proposed in which a distinction is made between continuous variations and sudden changes.

The case study shows that a trade-off can be made between the rating of the generation sources and the amount of energy storage to guarantee a reliable supply during island operation.

ACKNOWLEDGEMENTS

Part of the work was funded through the ‘Future Network Technologies’ consortium of the UK research councils funded SuperGen programme. Another part of this work was done within the EU-DEEP integrated project and funded by the European Commission, Svenska Kraftnät and the Swedish Energy Administration.

REFERENCES

[1] R.H.Lasseter, “MicroGrids”, *Proc. IEEE/PES Winter Meeting* 1, 27-31 Jan. 2002, 305-308.

[2] P.M.Costa and M.A.Matos, “Reliability of Distribution Networks with Microgrids”, *Proc. IEEE St. Petersburg Power Tech 2005*, St. Petersburg, Russia, June 26-30, 2005.

[3] Y. Sun, M.H.J. Bollen, G. Ault, “Improving distribution system reliability by means of distributed generation”, *this conference*.

[4] A. A Shakoor, G. Strbac, R.Allan, “Qualifying risk of interruptions and evaluating generation system adequacy with wind generation”, *9th International Conference on Probabilistic Methods Applied to Power Systems*, KTH, Stockholm, Sweden, June 11-15,2006

[5] Bagen, “Reliability and Cost/Worth Evaluation of Generating Systems Utilizing Wind and Solar Energy”, PhD Thesis, August 2005