Demand Response for Increasing Renewable Energy Penetration in Isolated Power Systems

Michael Negnevitsky
University of Tasmania
Hobart, Australia
e-mail: Michael.Negnevitsky@utas.edu.au

Dusan Nikolic
Hydro Tasmania
Hobart, Australia
e-mail: Dusan.Nikolic@entura.com.au

Martin de Groot
CSIRO
Sydney, Australia
e-mail: Martin.deGroot@csiro.au

***Abstract*— Electric power industry is undergoing a profound change. The change is driven by technical, economic and environmental factors. The emerging challenges are particularly significant for distribution grids, where the level of automation or "smartness" is relatively low. With the push for energy conservation, demand response is becoming a vital tool under the smart grid paradigm. This paper outlines some experience obtained at the University of Tasmania, Hydro Tasmania and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia in developing fast DR for isolated power systems. The paper presents results of the implementation of DR for enabling higher wind energy penetration in isolated power systems. The presented approach is based on the centralized control of residential and commercial loads with the DR execution time of 1 second. The technology discussed in the paper has been implemented in the King Island power system in Australia.**

Keywords-smart grid; distribution system; demand response.

I. INTRODUCTION

Electric power systems are undergoing a profound change. This change is driven by several factors that include technical, economic and environmental factors. We need to deal with an aging infrastructure of power systems and maintain the required level of grid reliability. We need to integrate renewable energy sources, particularly wind and solar, and provide secure power supply to our customers, and at the same time improve operational efficiency. The emerging changes and challenges are particularly significant for distribution grids, where the level of automation or "smartness" is relatively low. Manual and "blind" operations along with old electromechanical relays are to be transformed into a "smart grid". This transformation is necessary to meet environmental targets, accommodate distributed generation, and support plug-in electric vehicles. In fact, these needs present the power industry with the biggest challenge it has ever faced. On one hand, the transition to the "grid of the future" has to be evolutionary – we still need to supply electricity to our customers to keep the lights on. On the other hand, the challenges associated with the smart grid are significant enough to expect revolutionary changes in power system design and operation.

With the push for energy conservation, demand-side management and demand response are becoming vital tools under the broad smart grid paradigm.

The term "demand-side management" (DSM) was first introduced by Electric Power Research Institute (EPRI) in the 1980s, and since then has been widely used around the world. In fact, DSM is a term that implies many activities such as direct load control, peak shaving, peak shifting, and various load management strategies. Effective load management programs are often referred to as demand response (DR). According to the US Federal Energy Regulatory Commission, DR is defined as:

"Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."

Customers living in remote areas often cannot be supplied from conventional interconnected power systems. These customers are usually serviced by a local electricity generation and distribution system with electricity generated using diesel fuel. Due to remoteness and consequent high cost of diesel fuel supply, the cost of electric energy in isolated power systems is high compared to conventional interconnected systems. In some locations, the price exceeds US $1/kWh, which is an obvious incentive for introducing renewable energy (RE) generation. Unfortunately, RE from the two most abundant energy sources – wind and solar – incurs significant stability and reliability issues due to the intermittency of those sources.

This paper outlines and builds on recent research in utilizing DR in power systems. It presents fast (i.e., sub-second) DR as an enabling technology for increasing renewable energy penetration in isolated power systems (IPS). The contribution of this paper lies in presenting the concept of implementing fast DR in a real IPS case study, presenting preliminary results proving the concept of fast DR and outlining its potential future applications.

The paper has the following structure. In Section II, we discuss potential benefits of the DR application in isolated power systems. In Section III, we consider DR as a virtual power plant, or a DR generator, for supporting higher RE

Copyright (c) IARIA, 2015. ISBN: 978-1-61208-406-0

penetration by providing required spinning reserves. We present the architecture of the DR generator, communication protocols and the structure of the control system. In Section IV, we present a case study based on the King Island Renewable Energy Integration Project. Finally, in Section V, we report our conclusions.

II. DEMAND RESPONSE IN POWER SYSTEMS

A. *Standard approach to DR*

Recent research has shown that DR can provide benefits to power systems and their customers by:

- Supporting frequency and/or voltage regulation [1, 2];
- Reducing operational costs and emissions by increasing utilization of RE sources [3]. Note that reducing operating costs in turn leads to a greater return on investment which would incentivize expansion of the RE industry;
- Reducing operational costs and emissions caused by traditional generators installed to provide spinning reserve for RE [4];
- Relieving stress from transmission and distribution infrastructure by coordinating loads close to RE sources [4];
- Reducing utility operating costs through advanced metering infrastructure installed to enable DR [5].

Most of the research is focused on large systems, price-driven signals to DR [6], day-ahead scheduling [7], or demand response which responds in period of 10-minutes or longer [8].

In recent years, researchers have started recognizing the need for fast direct load control; one which does not depend on price responsiveness [9]. Benefits of this fast DR was taken further by showing that sub-second response of DR can support primary frequency regulation [10].

This paper focuses on benefits of fast DR in IPS.

B. *Special case of IPS*

Most DR applications focus on large power systems, which have a steady and predictable load profile defined by morning and evening peaks. The time and size of these peak periods can be accurately estimated using historical load data and weather forecasts. In contrast, isolated power systems not only supply less power (MWs, rather than GWs) they are also geographically much smaller. Being smaller in capacity means that demand is less predictable. Being smaller in area means that supply from RE sources is more variable, as a larger percentage of the RE generators are likely to be affected by the same weather events (e.g., a lull in the wind or passing clouds). Due to their reduced demand predictability and increased variability of RE supply, conventional generation scheduling in isolated systems with RE is more challenging. From a generation scheduling perspective - where RE generation is usually treated as a load offset – the daily load curve becomes extremely volatile. An example of an IPS with RE load curve is giving in Figure 1. Notice that it does not even have predetermined daily peaks.

High load variation makes scheduling of diesel generation more difficult and less efficient, as diesel engines will rarely operate at their peak efficiency, and more generator start-ups are required. This is where fast DR can help. It can smooth the variability of required diesel generation by quickly adjusting system load. To be able to do that, fast DR cannot rely on typical load patterns – it must be executed in real-time. If DR is to complement RE in an isolated system, it has to be as fast as the speed at which RE generators change their power output.

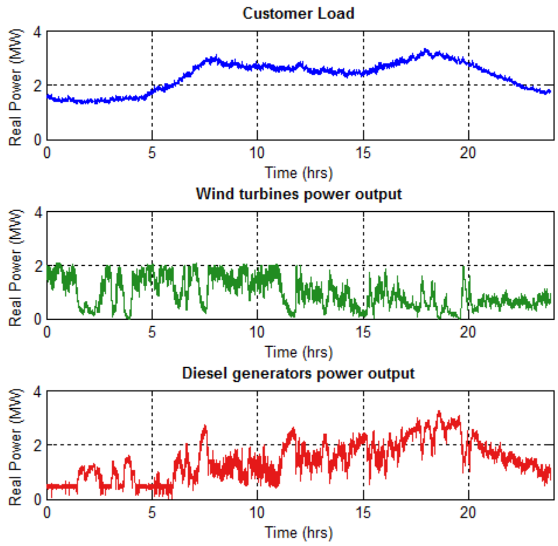

Figure 1. Daily load diagram in an isolated power system.

III. DEMAND RESPONSE AS A VIRTUAL POWER PLANT

The idea of aggregating and controlling small loads to create a large block of variable demand has been discussed in the power engineering literature where it is often referred to as a 'virtual power plant' [11]. Since isolated power systems generally have only one power station, the idea of adding another (virtual) power plant to this system might be a bit misleading. However, isolated systems with RE might have several generating sources (e.g., diesel, wind, solar, etc.). Therefore, aggregated DR could be treated as a 'virtual generator'. Although such a 'DR Generator' (DRG) is not generating real power, the power system controller perceives it as one due to the DRG's ability to decrease the amount of energy needed from other generating sources.

Isolated systems are usually controlled by a single controller. The controller is typically implemented with a programmable logic controller (PLC). The role of the controller is to schedule available generation in accordance with the current power system constraints, and to maintain system stability. In addition, the controller can be programmed to maximize the amount of RE generation and, consequently, minimize running costs. The controller

Copyright (c) IARIA, 2015. ISBN: 978-1-61208-406-0

effectively controls the entire system by collecting data on the current system status and by issuing commands to various generation sources, as shown in Figure 2.

When the controller has a goal to maximize the use of RE, it will dispatch as much renewable generation as the power system can handle while simultaneously maintaining an appropriate level of spinning reserve to ensure system stability. If the amount of RE drops and the system suddenly does not have enough spinning reserve, the controller starts a diesel generator. The role of the DRG is to support higher RE penetration by providing additional spinning reserve. If sufficient spinning reserve is provided by the DRG, diesel generator start-up is prevented.

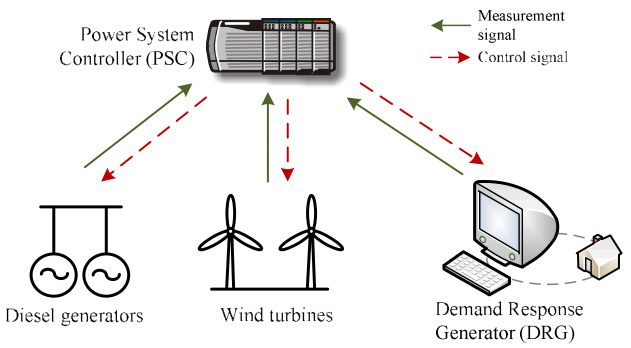

Figure 2. Smart Grid generator in IPS control system.

A DRG consists of three main components, as shown in Figure 3:

- DRG Master controller,
- communications network, and
- Slave controllers.

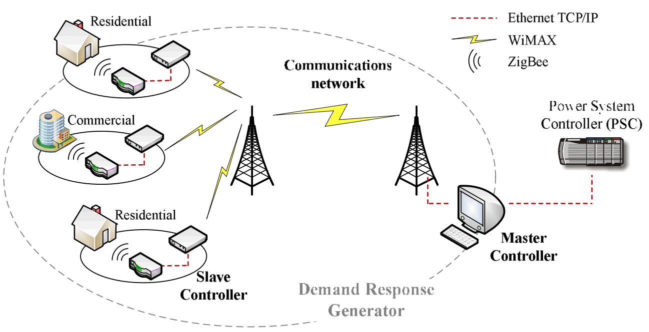

Figure 3. The DRG architecture.

A. DRG Master Controller

The master controller collects metering data (voltage, current, real and reactive power) from each available load and aggregates it into predefined virtual loads (e.g., feeders, geographical regions). It only aggregates the loads, which are currently consuming energy.

The Master controller then communicates available DR capacity to the power system controller (PSC) while checking for DR dispatch requests from the PSC. DR requests identify a target virtual load and the amount of demand to curtail. The master controller selects the individual loads to curtail from the virtual load, and immediately sends a switch-off signal to each. It also ensures that customers are not greatly affected by load curtailment, and that all customers are treated evenly. This is achieved by imposing constraints on the maximum length of control for each individual load.

Finally, Master controller controls only individual consumer loads and not entire feeders or their parts.

B. Communications Network

A multi-protocol bidirectional communications network delivers information between all elements of the DRG. Ethernet is used within the control system. A dedicated WiMAX network provides the backhaul capability. Within individual customer sites, a WiMAX gateway is connected by Ethernet to a ZigBee gateway for the final link to the load metering and switching devices. This communications configuration is configured to ensure a sub-second round trip for DR requests from the PSC out to the load control devices and back again.

C. Slave Controllers

Slave controllers are located in each DR capacity providing site. They consist of a pair of gateways to provide WiMAX-Ethernet-ZigBee signal translation between the backhaul network and the individual load control devices. The load control devices perform both metering and load switching. They provide a range of power metrics and also support set-points.

A DRG providing spinning reserve must be extremely responsive and reliable. The master controller must be able to monitor and dispatch slave controllers at all times. This critical requirement becomes obvious in the two most common scenarios:

- If the PSC requests DR for extended periods of time, some slave controllers may override the dispatch as they exceed their maximum dispatch duration. In this situation, the master controller must quickly identify and dispatch another device (or devices) with an equivalent load.
- If a slave controller or communication link is unreliable, the DRG may be forced to always dispatch more DR than requested to ensure a suitable margin of error in either load switching or reporting. This is not an efficient use of capacity and may reduce the overall effectiveness of the DRG.

IV. CASE STUDY

The fast DR technology discussed above was implemented in an IPS as part of the King Island Renewable

Copyright (c) IARIA, 2015. ISBN: 978-1-61208-406-0

Energy Integration Project [12]. King Island lies in the Bass Strait between Tasmania and the Australian mainland. It has a population of approximately 2000 people, and an economy based on agriculture and food processing.

A. The King Island Power System

Customer load on King Island ranges between 1 MW and 3 MW, with an average of around 1.5 MW. The King Island power system is shown in Figure 4. There is one power station on the island with four distribution feeders delivering electricity to customers. The power station houses four diesel generators with a total generation capacity of 5.8MW. Three fixed speed Nordex N29 (250kW each) wind turbines are installed on a nearby hill, together with two Vestas V52 turbines (850kW each) with doubly fed induction generators. Two 800kW diesel engines with flywheels are also connected to the system. In these generators the flywheels are separated by a clutch from a diesel engine and provide system with additional inertia.

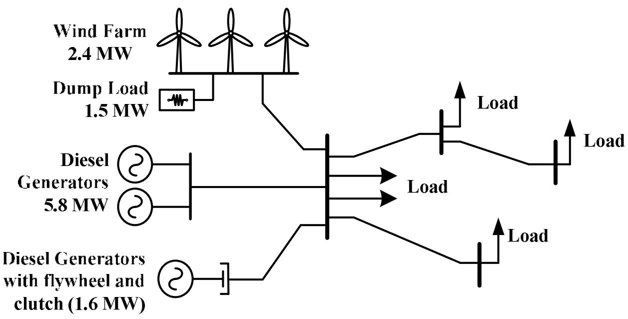

Figure 4. The simplified schematic of the King Island power system.

Normally the spinning reserve in the King Island power system is provided by diesel generators. During the wind-only operation of the system, the spinning reserve is equal to the dump load, as it represents the surplus of renewable energy in the system. If wind power suddenly drops, quick start-up of diesel generation is needed.

By adding to the spinning reserve (represented by dump load) during the wind-only operation of the system, the available DR has the opportunity to delay or prevent diesel generation start-ups, and by doing so, increase RE penetration in the system.

B. The King Island Smart Grid Project

The ongoing King Island Smart Grid project has the goal of supporting higher levels of wind energy integration in the King Island power system by providing:

1. Spinning reserve by implementing the DRG concept, and

2. Fast fine-grained under frequency load shedding (based on the slave controller level).

The master controller constantly monitors each available load, aggregates it and passes this information to the PLC-based power system controller (PSC). At the same time, the PSC monitors the current level of power system spinning reserve.

If the spinning reserve falls below a predefined threshold, the controller instructs the DRG to curtail some load and effectively raise the spinning reserve. This function can be observed in Figure 5, where due to a sudden drop in wind generation, the spinning reserve falls. The reduction in spinning reserve causes the power system controller to initiate a request for all available DR, as shown in the lower graph.

The results shown in Figure 5 demonstrate that the implemented DRG was able to respond accurately to given set-points. It also shows that DR capacity can be dispatched reliably in 1 second.

C. Selection of Smart Grid technology

As presented in Section III, there are three components of the Smart Grid project: master controller, communications network and slave controllers. The King Island Smart Grid project is, in fact, a research and development project. However, all the equipment installed during the project duration is meant to be industrial grade and capable of operating in real power systems for extended periods of time. Having this in mind, ruggedized and proven equipment has been used during in the Smart Grid project:

- Master controller is an industrial in-rack server computer with operating systems for embedded devices. It requires very little or no maintenance.
- Communications network is built using widely available and proven telecommunications technology. Since the requirements of the King Island Smart Grid are much lower than usual operating requirements to communication networks, the network maintenance cost is also very low. To ensure the minimum response time, a proprietary long-polling protocol has been developed by CSIRO and used for communications between master and slave controllers. This protocol maintains a permanent open communication link between devices. There is no need for opening and closing the communication link, which provided an obvious advantage in the overall response time compared with industrial standards.
- Slave devices are modem, gateway and miniature circuit breaker (MCB) switch capable of at least 50,000 operations. If any of these devices malfunctions, their replacement is relatively inexpensive and fast.

An essential part of the King Island Smart Grid project is to provide training to local electricians in maintaining the system including its repair when equipment fails. The Smart Grid has been in operation for over a year now, with no serious equipment failures. The outcome of selecting widely available devices is a relatively low capital cost of the installed equipment. Selecting proven and ruggedized equipment resulted in very low maintenance costs.

Copyright (c) IARIA, 2015. ISBN: 978-1-61208-406-0

D. Preliminary Implementation Results

Currently the King Island DRG has 50 sites under management and has been fully integrated into the power system. When complete, the DRG will be extended to include 150 households and several commercial loads.

Prior to roll-out on King Island, the DRG was tested with 10,000 simulated customer loads with minimal performance degradation [13]. This implies that the full DRG will supply more than 100 kW of sub-second DR capacity.

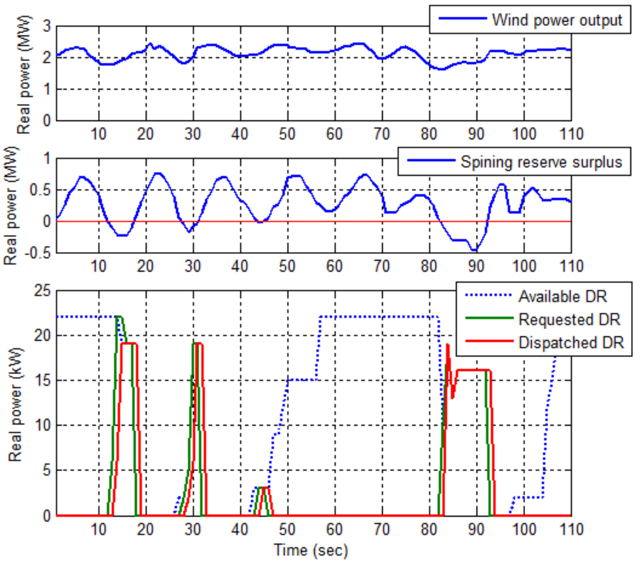

Figure 5. Results of the King Island DRG operation.

The effectiveness of the King Island DRG depends largely on its integration with the power system controller. Figure 6 demonstrate how the controller requests for the DRG and uses it as a tool for regulating demand accurately.

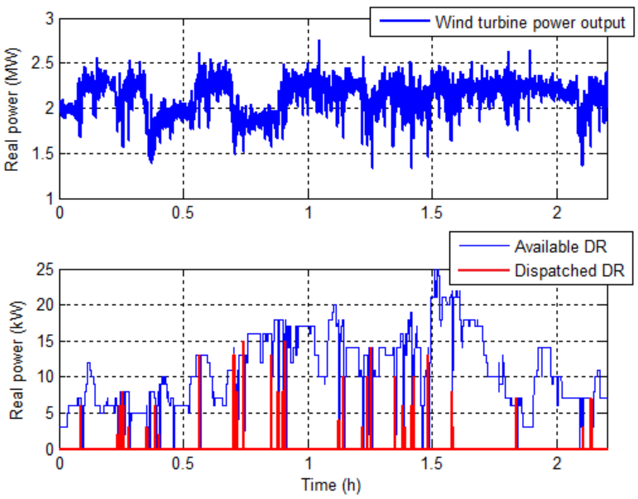

Figure 6. Operation of the King Island DRG.

During the period of over 2 hours, the King Island power system was running in zero-diesel operation and the DRG was used under small and short dips in wind power generation. In this mode of operation, the power system controller prioritizes DRG dispatch, and thus postpones unnecessary start-ups of a diesel generator.

V. Conclusion

With a strong drive for energy conservation, demand-side management and demand response are becoming vital for the implementation of the smart grid concept. This paper outlines some experience obtained at the University of Tasmania, Hydro Tasmania and the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia in developing fast DR for isolated power systems.

The paper presented DR as an enabling technology for higher penetration of renewable energy in isolated power systems. These systems are often based on diesel generators. However, due to high costs of diesel fuel supply, the cost of electricity in isolated power systems is much high compared to conventional interconnected systems. This presents an incentive for introducing renewable energy generation in isolated power systems.

Unfortunately, the integration of renewable generation presents significant stability and reliability challenges due to their intermittency. The solution proposed in this paper is based on centralized two-way communication and control of residential and commercial loads. DR can be dispatched and confirmed within 1 s. The technology has been installed and successfully tested in an isolated power system on King Island in Australia.

Acknowledgment

The authors would like to thank power operators of the King Island system, Australia for sharing insights their extensive knowledge and experience in operating isolated power systems.

References

[1] J. A. Short, D. G. Infield, and L. L. Freris, “Stabilization of Grid Frequency Through Dynamic Demand Control,” IEEE Transactions on Power Systems, vol. 22, no. 3, pp. 1284-1293, 2007.

[2] T. L. Vandoorn, B. Renders, L. Degroote, B. Meersman, and L. Vandevelde, “Active Load Control in Islanded Microgrids Based on the Grid Voltage,” IEEE Transactions on Smart Grid, vol. 2, no.1, pp. 139-151, 2011.

[3] M. de Groot, J. Forbes and D. Nikolic, “Demand Response in Isolated Power Systems”, Australasian Universities Power Engineering Conference, Proc. AUPEC 2013, Hobart, Tasmania, Australia, 29 Sep. – 3 Oct. 2013, pp. 1-6.

[4] D. Westermann and A. John, "Demand Matching Wind Power Generation With Wide-Area Measurement and Demand-Side Management," IEEE Transactions on Energy Conversion, vol. 22, no. 1, pp. 145-149, 2007.

Copyright (c) IARIA, 2015. ISBN: 978-1-61208-406-0

[5] N. Rajakovic, D. Nikolic, and J. Vujasinovic, “Cost benefit analysis for implementation of a system for remote control and automatic meter reading,” Proc. PowerTech, 2009 IEEE Bucharest, 2009, pp. 1-6.

[6] A. J. Conejo, J. M. Morales, and L. Baringo, "Real-Time Demand Response Model," IEEE Transactions on Smart Grid, vol. 1, no. 3, pp. 236-242, 2010.

[7] A. S. Kowli and S. P. Meyn, "Supporting wind generation deployment with demand response," Pros. the IEEE/PES General Meeting, Detroit, MI, USA, 24-28 July, 2011, pp. 1-6, IEEE Catalog Number CFP11POW-USB, ISBN 978-1-4577-1001-8.

[8] B. J. Kirby, "Spinning Reserve From Responsive Loads," Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, March 2003.

[9] D. S. Callaway and I. A. Hiskens, "Achieving Controllability of Electric Loads," *Proceedings of the IEEE,* vol. 99, pp. 184-199, 2011.

[10] S. A. Pourmousavi and M. H. Nehrir, "Real-Time Central Demand Response for Primary Frequency Regulation in Microgrids," *Smart Grid, IEEE Transactions on,* vol. 3, pp. 1988-1996, 2012.

[11] J. Kumagai, “Virtual power plants, real power,” IEEE Spectrum, vol. 49, pp. 13-14, 2012.

[12] Hydro Tasmania. (2013). King Island Renewable Energy Integration Project (KIREIP). [Online]. Available from: www.kireip.com.au 2015.04.10

[13] D. Nikolic, M. Negnevitsky, M. de Groot, S. Gamble, J. Forbes and M. Ross, “Fast Demand Response as an Enabling Technology for High Renewable Energy Penetration in Isolated Power Systems”, Pros. the IEEE/PES General Meeting, Washington DC, USA, 27-31 July, 2014, pp. 1-5, IEEE Catalog Number CFP14POW-USB, ISBN 978-1-4799-6414-7.