Autonomous Load Shedding in a Nanogrid using DC Bus Signalling

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***Abstract*— Including load shedding in the system control strategy for a small standalone hybrid power system such as a nanogrid is beneficial since the peak generation requirement is reduced and the system is protected from a complete collapse under overload conditions. Autonomous load shedding can be implemented in a nanogrid that uses DC bus signalling for source scheduling by shedding loads when the dc bus voltage decreases to a level that signals an overload condition. This paper explains the control requirements for the system interface converters that is required to permit load shedding and explains a procedure for implementing a prioritized load shedding scheme in a practical system. Experimental results are included to illustrate the operation of this control strategy.**

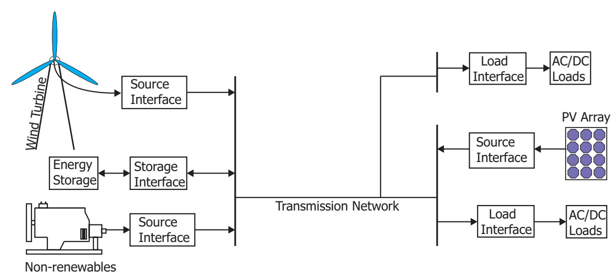


Fig. 1. Structure of a standalone hybrid renewable nanogrid

I. Introduction

The use of renewable sources for supplying remote loads is gaining popularity since the need for burning fossil fuels to power remote generators is reduced. With the aid of power electronic converters, renewable sources can be combined with storage and backup generation to form a hybrid standalone power system that requires minimal use of fossil fuel-based generation. A nanogrid, shown in Fig. 1, is one such system.

This paper uses the term nanogrid to describe a distributed hybrid renewable system that is based completely on power electronic converters and uses dc transmission for ease of interfacing asynchronous sources such as wind turbines to the system [1]. The nanogrid employs step-up converters to allow low-voltage sources to supply power to the nanogrid and step down converters to allow the loads to draw power from the nanogrid. Bidirectional converters allow storage devices to charge from and discharge into the nanogrid.

The intended application for a nanogrid is for small, remote power systems in both industrialized and developing countries. In these applications, the economics of the system become viable since the cost of connecting to the grid is prohibitive. A nanogrid intended for these remote applications will typically supply a peak load in the order of 2-20 kW. The renewable generation is sized to supply the average load demand, and the storage, acting as an energy buffer, is sized to balance short-term differences between the source and load powers. Non-renewable generation is included to improve system reliability in the event of a long-term shortfall of renewable power.

The main system control aim in a nanogrid is one of maintaining the power balance in the presence of stochastic renewable sources and loads and maximizing use of the renewable sources. The primary system control strategy used for achieving power balance is source scheduling to ensure that maximum power is extracted from the renewable sources. With source scheduling, the storage is controlled to charge from the system during periods of excess renewable power and discharge into the system during power shortfalls. Backup generation is brought online when the storage is incapable of meeting the load demand alone.

Although a source scheduling strategy alone is sufficient for maintaining the power balance in a nanogrid, the addition of load shedding provides two major benefits. Load shedding reduces the peak load demand which is often at least five times the average load in a small standalone system [2]. With load shedding, the generation does not have to be sized to cope with extreme loading situations, hence the cost of the system is reduced. Load shedding also prevents the dc bus from collapsing under overload conditions, ensuring that critical loads enjoy an uninterrupted supply of power.

This paper presents a method for including an autonomous load shedding strategy in a system that uses DC bus signalling (DBS) for source scheduling. DBS is a strategy which uses the level of the dc bus to convey control information. The source and storage interface converters are designed with a constant power limiting characteristic such that the bus voltage decreases when the load exceeds the current generation that is online. This information is then used by the source and load interface converters for autonomous source scheduling and load shedding. The concept of using DBS for source scheduling was developed by the author and its efficacy has been verified experimentally [3], [4].

The concept of load shedding based on the bus voltage level in a dc system has been proposed to ensure that the high-priority loads enjoy an uninterrupted supply of power under overload conditions [5], [6]. However, this research assumed an ideal transmission impedance and was verified using simulation results only. This paper demonstrates the application of DBS to load shedding in a practical system which is affected by the presence of transmission line impedance. The converter control requirements needed for DBS to function in a nanogrid are explained and a procedure for implementing a prioritized load shedding strategy is given. The operation of the load shedding strategy is verified with experimental results.

II. Background

A number of different control topologies can be used for system control of a nanogrid, and the control topology of choice should ideally maintain the modularity and reliability inherent in the distributed structure of the system and be low-cost to help improve the economic viability of the system. The three basic control topologies, decentralized, distributed and central control tend not to be used alone for system control but are combined with other strategies to form a hybrid system control strategy. Two such hybrid strategies are hybrid central and hybrid distributed control.

Hybrid central control, a combination of central and decentralized control, is a topology that is widely used in the control of the 50/60 Hz power system and is often applied to the control of small renewable systems [7], [8]. A central controller and communications link are used for coordinating the system and decentralized control is used for managing the instantaneous power sharing between the sources. The advantage of this strategy is that the central controller allows flexible control of the system and the decentralized control strategy relieves the control burden on the central controller. However, the system is dependent on the central controller and communications link for correct operation. To improve the reliability of this control strategy, redundant controllers and communications links must be included at an extra cost.

Another hybrid control strategy, hybrid distributed control, has the potential to offer a similar performance to hybrid central control with cost and reliability advantages. Hybrid distributed control is a strategy in which the system control function is distributed among the system nodes and communication takes place over the system power bus. Due to the lack of a central controller and external communications link, this strategy maintains the modularity and reliability inherent in the structure of the nanogrid; however, the control flexibility is not as great. Since the control law is embedded in the design of the system nodes, it must remain fixed for all operating conditions. This is generally not a problem in a nanogrid since the utilization priority of the different nodes does not change.

An implementation of hybrid distributed control that is well-tailored for use in a nanogrid is DBS. DBS uses the voltage level of the system to convey system control information between nodes. The mechanism behind its operation is reliant on controlling the storage interface converters to exhibit different modes of operation based on the level of the dc bus. Each converter remains off until the bus voltage decreases below its discharge threshold. At this point the converter comes online, acting as a constant voltage source with a constant power limit. Source scheduling is achieved by prioritizing the discharge thresholds and load shedding is achieved by controlling the load interface converters to turn off when the voltage level of the dc bus decreases to a value that indicates an overload condition.

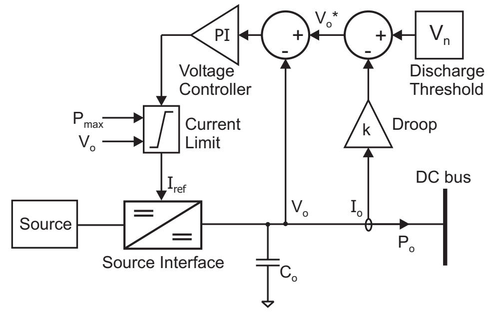


Fig. 2. Source interface controller

III. Load Shedding Implementation

The implementation of a load shedding strategy using DBS not only requires control of the loads based on the level of the dc bus, but also control of the source and storage interface converters such that the level of the dc bus decreases as the total load increases in relation to the available source power.

A. Source Interface Control

The source interface converters are designed to exhibit three modes of operation when supplying power to the system: off, constant voltage, and constant power. The control structure required to implement these modes of operation is shown in Fig. 2.

Each converter remains off until the bus voltage decreases below its discharge threshold. At this point, the PI controller regulates the converter such that it acts as a constant voltage source. A droop characteristic is included to allow multiple sources to share power at the same voltage threshold. The current limit limits the output power of the converter when the load exceeds the output power of the source. This mode of operation is of particular interest since it forces the bus voltage to collapse when the output power of the source is exceeded. With source scheduling using DBS, this collapse is a trigger signal that brings the source with the next priority online. However, once all sources are active, the load interface converters use this signal for load shedding.

B. Storage Interface Control

With DBS, the storage interface converter exhibits two modes of operation: charge and discharge. In charge mode, the storage interface acts as a slack bus, charging using any excess power. When the bus voltage is high, indicating an excess of

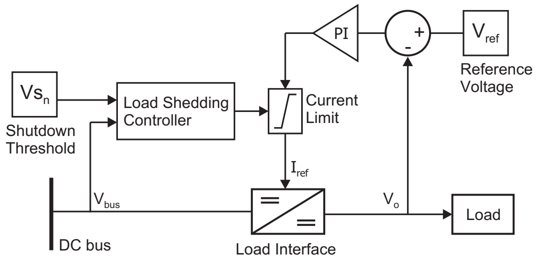


Fig. 3. Load shedding controller

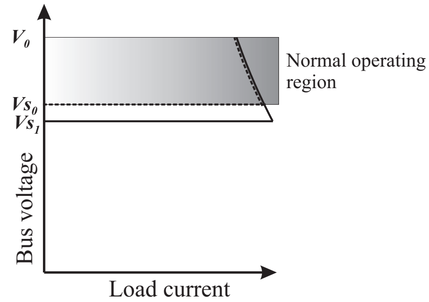


Fig. 4. Load shedding operation

renewable power, the storage controller draws power from the system by attempting to regulate the dc bus down to its charge threshold. This mode of operation has no impact on the load scheduling strategy, but when the bus voltage decreases below its charge threshold, indicating a power deficiency, the storage interface ceases to charge and begins discharging in the same manner as a source interface.

C. Load Shedding Control

The control mechanism required to implement a prioritized load shedding strategy is shown in Fig. 3. A local load shedding controller monitors the bus voltage and disconnects the load from the system when the bus voltage decreases below the shutdown threshold. The load shedding controller can be included with the load interface controller as shown in Fig. 3, shedding the load by imposing a zero current limit on the total load, or it can be a separate controller that switches out a certain portion of the load. Either way, prioritizing the thresholds ensures that low-priority loads are shed first under overload conditions. A graph illustrating the operation of load shedding using DBS in a system with two loads having different priorities is shown in Fig. 4. A low-priority load is assigned to shutdown threshold Vs_0, and a high-priority load to Vs_1.

Under normal operating conditions, the system operates in the normal operating region where source scheduling is used for balancing increases in the load demand. In this region, the load interface converters act as constant power loads on the system since they maintain a supply of constant power to their loads regardless of the bus voltage. When the bus voltage collapses due to an overload condition, the low priority load assigned to shutdown threshold Vs_0 is the first to detect this, and it trips out immediately rather than entering a voltage dependent current limit (VDCL) mode to prevent sensitive loads from experiencing less than their nominal rated voltage while the converter is shutting down. If this load decrease is sufficient to restore the system to normal operating conditions, the bus voltage increases and the low priority load remains off for a specified time period. If the overload condition persists, the bus voltage continues to decrease and the high priority load assigned to shutdown threshold Vs_1 is shed when the bus voltage decrease below this value.

D. Implementation Procedure

To implement load shedding in a nanogrid the shutdown thresholds are first prioritized according to the utilization priority of the loads. Next the shutdown thresholds must be calculated to ensure that steady-state voltage drop on the transmission line does not cause any loads to trip out prematurely. The shutdown thresholds are calculated such that the shutdown priority of the loads remains unaffected by the unequal propagation of the dc bus voltage throughout the system. The shutdown threshold for the lowest priority load is calculated first as follows:

$$Vs_0 = V_n - Vd_n - V_e \quad (1)$$

where V_n is the value of the lowest discharge threshold, Vd_n is the worst-case voltage drop that occurs in the system with the system operating in state n, and V_e is a margin of error to account for ripple on the dc bus and measurement tolerances. A dc load flow program, which is a one-dimensional version of a conventional ac load flow, is used to calculate the voltage drop, Vd_n. The voltage drop is found by analyzing the system for all possible loading conditions in state n. It is the difference between V_n and the lowest voltage at the connection point of a load assigned to shutdown threshold Vs_0 with the system.

Each successive shutdown threshold is calculated using

$$Vs_n = Vs_{n-1} - Vd_n - V_e \quad (2)$$

where Vs_{n-1} is the previous shutdown threshold. In other words, each successive threshold is calculated by subtracting the maximum steady-state difference in the bus voltage between the load interface converters assigned to adjacent shutdown thresholds from the previous threshold.

IV. Experimental System

A. System Design

A block diagram of the experimental system used to test the load shedding strategy is shown in Fig. 5. It should be noted that the system normally includes a renewable source connected to each bus, but these are omitted from Fig. 5 since they are not needed for the load shedding experiment.

The system is designed to be one-tenth the size of a full-scale system that operates at 700 V, has an average load of 2 kW and uses an overhead transmission line with a dc

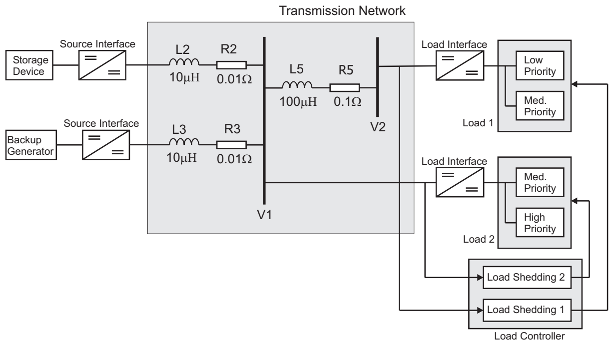


Fig. 5. Experimental setup for load shedding

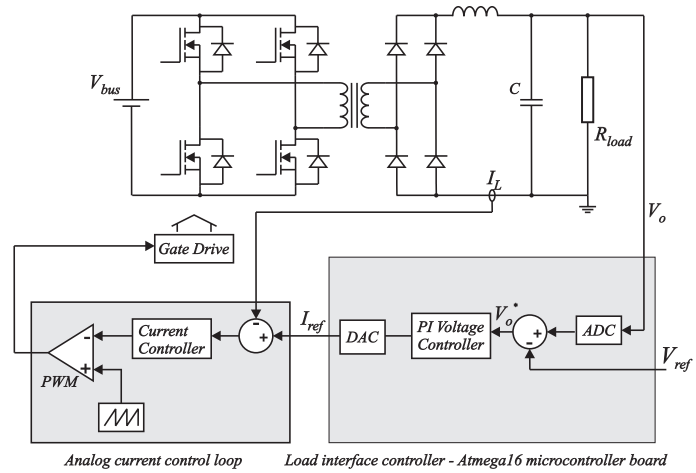


Fig. 6. Load interface and controller implementation

TABLE I
SYSTEM DESIGN

Source	Vout: 12 V
Source Interface	Vin: 10-15 V Vout: 70 V Pmax: 100 W
Load Interface	Vin: 55-70 V Vout: 12 V Pmax: 200 W
Load Bank	Resolution: 25 W Pmax: 200 W
Transmission Network	Resistance: 0.1 Ω/km Inductance: 0.1 mH/km

resistance of 0.783 Ω/km and an inductance of 0.983 mH/km. The voltages, resistances, and powers are all scaled down by a factor of ten causing the current levels to remain the same. The key parameters of the system modules are given in Table I.

For simplicity, 12 V laboratory power supplies are used in place of the renewable and non-renewable sources. The source interface is a step-up dc-dc converter that boosts the supply voltage from 12 V to 70 V for connection to the system. A full-bridge, hard-switched topology is used, and the converter is controlled using an inner analog current loop and an outer microcontroller-based voltage loop. This combination of analog and digital control allows easy customisation of the voltage threshold using a low-cost microcontroller instead of a DSP. The bandwidth of the voltage loop is set to 1 kHz to provide a fast transient response.

The construction of the load interface is similar to that of the source interface. The load interface is a full bridge converter that is controlled using an analog inner current control loop and a microcontroller-based outer voltage control loop. The control scheme used for the load interface is shown in Fig. 6.

The outer voltage control control loop of the load interface controller is implemented using an Atmel Atmega16 8-bit microcontroller and the inner analog current loop is based on average current mode control. The PI voltage control function implemented in the microcontroller controls the output voltage of the converter by controlling the reference current for the inner loop. It should be noted that in order to permit stable operation of the system the bandwidth of the voltage loop was decreased to 200 Hz and input filters were added to the input of the load interface and such that the input impedance of the load interface converters did not react with the output impedance of the source interface converters causing transient stability problems [9], [10].

A bank of incandescent lights is used for each load node. Consisting of six 12 V lights rated at 25 W, each load bank can be controlled in discrete steps of 25 W up to a peak of 150 W using the microcontroller-based load controller. The loads are divided into three different priorities: low, medium, and high.

The bidirectional storage node is constructed by connecting a source interface and load interface converter in parallel. The load interface converter connects the nanogrid to a resistive load to allow charging action while a source interface converter and 12 V supply allow the storage node to discharge into the nanogrid. It should be noted that the power ratings for charging and discharging are different due to the ratings of the source and load interface converters.

The transmission line is constructed as a series R-L network, with its parameters derived from the transmission line used in the case study. The parameters of the transmission line are scaled down by a factor of ten such that the per unit resistance of the line in the experimental system is approximately the same as that of the line in the full-scale system it represents.

B. Implementation of Load Shedding Strategy

To implement the load shedding strategy, the shutdown thresholds are prioritized as shown in Table II and the spacing between thresholds is calculated using (1) and (2). The value of V_n used in the calculation is 60 V, the value of the discharge threshold of the backup generator.

Load shedding is implemented in the system by programming the shutdown thresholds into the load controller. The load controller is used rather than the load interface controller since the load banks have multiple loads with different priorities and

TABLE II

LOAD SHEDDING IMPLEMENTATION

Shutdown Threshold	Value (V)
V_{s1}	58
V_{s2}	56
V_{s3}	54

must be shed in stages. The load control functions operate such that they deactivate the loads when the bus voltage decreases below the appropriate discharge threshold. the system is in danger of an overload. Two separate load shedding functions, Load Shedding 1 and Load Shedding 2, are written to ensure that the load shedding is performed based on the voltage at each load's point of connection with the system. Load 1 is controlled based on the voltage level at bus V2, and load 2 based on the voltage level at bus V1. A time delay of 100 ms was added to each load shedding function to prevent brief bus voltage transients from causing load shedding.

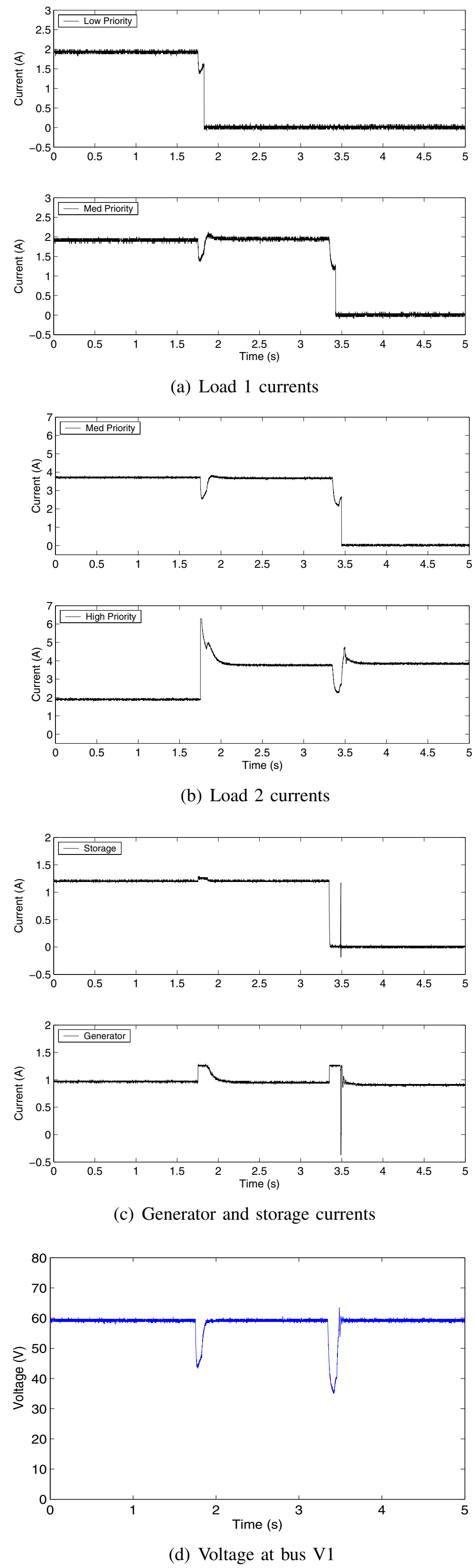
V. RESULTS

The load shedding strategy is verified by creating overload conditions and monitoring the response of the loads to the overload conditions. The overload conditions are created by reducing the available supply or increasing the load such that the total load demand exceeds the available generation. The results are shown in Fig. 7.

Initially the system operates close to its available output capacity, with a total loading on the system of 125 W. The total load is divided into two banks of two loads taking three different utilization priorities. Load 1, comprising 25 W of both low and medium-priority load, contributes 50 W to this total, and Load 2 contributes 75 W to the total load in the form of 50 W of medium-priority load and 25 W of high-priority load. The supply currents of loads 1 and 2 are shown in Fig. 7(a) and 7(b) respectively. It should be noted that the load currents are monitored at the 12 V output side of the load interface converter rather than at the 70 V input side to allow the portion of current the load interface converter supplies to each load to be distinguished.

In order to supply power to the loads, the storage node supplies its peak output of 75 W to the system and the generator acts as a slack bus, providing power to supply the remaining load demand and to compensate for the power losses in the system. The supply currents are shown in Fig. 7(c). Because the generator acts as a slack bus, the bus voltage is regulated at the generator's discharge voltage threshold of 60 V as shown by the bus voltage at bus V1 in Fig. 7(d). The plot of the voltage at bus V2 is not included since it is approximately equivalent.

The first overload condition is created at 1.75 s by increasing the high-priority portion of load 2 from 25 W to 50 W. As shown in Fig. 7(b), the current drawn by the high-priority load peaks before settling to its new value due to the startup current surge of the incandescent lamp used as the load. The output



(a) Load 1 currents

(b) Load 2 currents

(c) Generator and storage currents

(d) Voltage at bus V1

Fig. 7. Experimental load shedding results

of the generator interface briefly increases to its peak value in a bid balance the increased load. However, since this supply increase is insufficient to maintain the power balance in the system, the bus voltage collapses. The load controller therefore sheds the low-priority load to restore the power balance. Power is therefore maintained to the medium and high-priority loads during the overload. It should be noted that because the bus voltage briefly deviates outside the designed operating window, decreasing to 40 V during the overload. This causes the load interface converters to briefly lose regulation of their output, as can be seen by the glitch in the current drawn by the medium-priority load.

The second overload condition is created by removing the storage from the system at 3.25 s as shown in Fig. 7(c). The load once again exceeds the maximum generation and consequently the bus voltage decreases. When the load controller has detected that the voltage at each load bus has decreased below the shutdown threshold of the medium-priority loads, V_{s2}, the medium-priority loads are shed, restoring the power balance in the system. Thus the power to the high-priority loads remains uninterrupted aside from a brief transient glitch.

VI. Discussion

The experimental results show that under overload conditions, the prioritized load shedding scheme prevents the dc bus from collapsing. Because the load shedding strategy only responds to voltage decreases caused by overload conditions and does not regulate the system voltage itself, the steady-state value of the dc bus voltage does not change for the duration of the experiment. However the transient response is not as ideal with the bus voltage briefly decreasing to approximately 50% of its nominal value under overload conditions. Since this deviation is outside the operating range of the load interface converters, they briefly lose regulation of the loads. The main reason for this anomaly is the time delay added to the load controller to prevent brief glitches in the supply voltage from causing load shedding.

This brief collapse of the supply voltage is unlikely to pose any problems for loads such as heating and lighting. However, for sensitive electronic equipment, this brief decrease in the bus voltage may be an issue since these loads require a constant supply voltage. To circumvent this problem, the load converters can be redesigned to regulate the output voltage over a wider operating window. Alternatively, additional storage can be combined with sensitive critical loads to ensure they enjoy a constant supply of power.

Overall, the concept of load shedding using DBS has been verified using the experimental system, and the strategy can be adopted for use in a full-scale practical system by using the same control structure for the interface converters. It should be mentioned that the practical issues associated with operating a practical system at higher voltage and power levels extend beyond small signal stability. Issues such as interface converter design, operation under fault conditions and sizing the voltage window must also be taken into account [2].

VII. Conclusion

DBS is a control strategy that is well-suited for controlling a nanogrid used in remote power applications, being simple, reliable and cost-effective. This paper has presented a method for incorporating a prioritized load shedding strategy in a nanogrid that uses DBS for scheduling renewable sources, storage and backup generation. The strategy is implemented by shutting down loads when the level of the dc bus decreases to a level that signals an overload condition. Prioritized load shedding is achieved by assigning different shutdown thresholds to the loads. Experimental results demonstrated that this method of autonomously shedding loads based on the level of the dc bus functions successfully, even in the presence of transmission line impedance.

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