DECENTRALISED SOURCE SCHEDULING IN A MODEL NANOGRID USING DC BUS SIGNALLING

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Abstract

A nanogrid is a small DC power system that uses distributed energy sources to power local loads. DC bus signalling, a novel control strategy that schedules sources in a decentralised fashion, brings the non-renewable sources in a nanogrid online when the renewable sources have been exhausted. This paper presents a prototype model nanogrid that uses power electronic converters to interface the sources and loads to the nanogrid. The design of the system is discussed and experimental results are presented. The results show that DC bus signalling allows the sources to be consumed in a prioritised fashion.

1 INTRODUCTION

Environmental concerns over burning fossil fuels have elevated the interest in renewable-based generation to a high level. Advances in power electronic systems and deregulation of the electricity industry have made it possible for renewable energy to move from niche to mainstream applications. Using power electronic converters, renewable energy sources can be interfaced to the existing power system or combined with local loads to form an independent power system [1]. A nanogrid falls into this category.

A nanogrid is a small scale power system that consists of two or more distributed sources that supply power to nearby loads. Typically, the total load on a nanogrid is less than 20kW, and the loads are located within 5km of the sources. The sources are primarily renewable based, although non-renewable sources such as battery storage and diesel generation may be included to ensure supply reliability in the presence of the fluctuating renewable sources. Fig. 1 shows the structure of a typical isolated nanogrid.

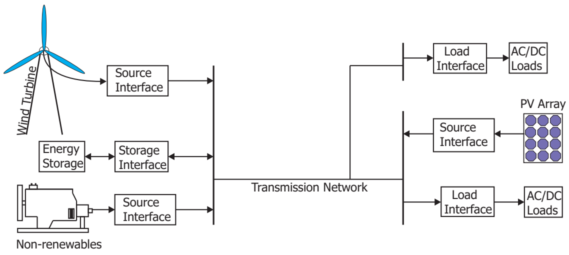


Figure 1: Structure of an isolated nanogrid

A nanogrid is a distributed power electronic based system. Step-up and step-down converters interface the sources and loads to the nanogrid, and a bidirectional converter allows the storage node to charge from and discharge into the nanogrid. Based on power electronics, a nanogrid is not restricted to operation at 50/60Hz. This paper considers the operation of a DC nanogrid since DC offers certain benefits [2]. Transmission at DC is more efficient, the magnetic components in the interface converters are small, and interfacing asynchronous sources to a DC network is simple.

To maintain the power balance in a nanogrid while minimising its operating cost, the sources should be scheduled in a prioritised fashion. The renewable sources should be used first, and any excess power used to charge the storage. The storage and non-renewable sources should come online only when the renewable sources have been exhausted.

A central controller and communications link are normally used for scheduling sources. However, to maintain the modularity and reliability inherent in the structure of a distributed system, a decentralised control strategy should be adopted. This paper discusses decentralised control options and proposes DC bus signalling as a means of generator scheduling. DC bus signalling uses discrete voltage levels on the system bus to indicate the state of the system and determine the behaviour of each the non-renewable sources. A case study and model system are presented to demonstrate the application of this novel control strategy.

2 BACKGROUND

2.1 Nanogrid Control Options

The main control issue in a nanogrid is one of power balance in the presence of fluctuating sources and loads. Power balance between the sources and loads can be achieved by either shedding loads [3], or by using storage and backup generation as an energy buffer. Load shedding smooths the load demand in large systems, but does not extract maximum power from the sources in a renewable system. Therefore this paper considers scheduling non-renewable sources as a means of maintaining the power balance in a nanogrid.

The sources, storage, and backup generation can be scheduled in a centralised or decentralised fashion. Centralised control uses a central controller and communications link to schedule the sources [4]. Centralised control readily allows optimal operation since the controller is aware of each node in the system, but reliability is degraded since the system is dependent on the controller and communications link. Decentralised control is fast and reliable, as the output of each source is based on terminal quantities alone. Although, optimisation of the system is difficult, decentralised control is suitable for simple distributed systems as it maintains the modularity and reliability inherent in the structure of the system. Two decentralised control options are droop and DC bus signalling.

2.2 Voltage Droop

Numerous schemes have been proposed to accomplish power sharing in modular systems. The two most common methods are the master-slave and droop control schemes [5]. The droop method is commonly used in distributed DC systems to maintain the modularity and reliability inherent in its structure [6, 7]. The droop method is one in which the output voltage of a module, V_o, decreases as its load current, I_o, increases.

$$V_o = V_{ref} - k \cdot I_o \tag{1}$$

The slope of the module's droop curve, k (V/A), determines the share of the load power it supplies. The droop curves are set as a compromise between accurate power sharing in the presence of line impedance, and good voltage regulation. Voltage droop is well suited for systems with a consistent supply and load. Power sharing can generally be achieved with minimal voltage deviations on the supply bus. However voltage droop has limited use in renewable systems where power must be consumed in a prioritised fashion. Droop does not allow modules to be scheduled; it merely allows the power sharing ratio between the modules to be set.

2.3 DC Bus Signalling

DC bus signalling is a nonlinear form of voltage droop that allows groups of sources to be scheduled in a prioritised fashion. Discrete voltage deviations on the bus provide information about the generation mix to facilitate source scheduling. Significant voltage deviations are permitted since the system is power electronic based and the source and load interfaces can be designed to operate satisfactorily within a specified voltage window.

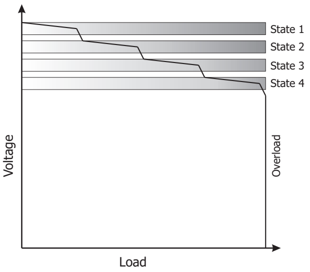


Figure 2: DC bus signalling

The mechanism of DC bus signalling in a system comprising four groups of sources is shown in Fig. 2. The system includes four voltage states and the current state is dependent on the load on the system. Each group of sources is assigned to come online in a particular state in order to meet the load demand in a prioritised fashion. The voltage states are designed with a large enough voltage window to ensure that the voltage drop across the transmission line impedance does not interfere with the source scheduling.

The group of sources with the highest utilisation priority begins operation in state 1. Because voltage droop allows power sharing between the sources that are active in this state, the system's voltage decreases in proportion to the load. When the load demand increases beyond the maximum power capacity of the sources operating in state 1, the sources are forced into current limiting mode and the bus voltage sharply decreases to the upper threshold of state 2. The second group of sources now come online to supply the balance of the load power. Thus as the load increases, the bus voltage decreases in discrete levels to bring additional sources online to meet the load demand.

3 CASE STUDY

This section presents a simple nanogrid that encompasses two remote farms and derives a suitable control law for the system. The nanogrid, shown in Fig. 3, relies on wind and solar energy in conjunction with battery storage. No backup generation is included in the system.

3.1 System Characteristics

The system includes two load nodes 2 km apart. The combined average energy consumed by the loads is 20 kW-hr per day, and the combined peak load is 15 kW. The system operates at 700V to allow for an efficient transmission system [8].

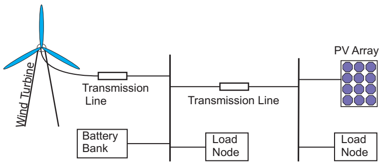


Figure 3: Nanogrid used for case study

The primary source of generation for the nanogrid is a wind turbine and photovoltaic array. The wind turbine is situated on a hill 2 km from one load node, while the photovoltaic array is located at the second load node itself. For this case study, the renewable generation is sized to provide approximately 25% more energy that that required by the load. This allows the renewable sources to meet the average load in spite of system losses, and helps reduce the use of the storage node to improve the overall system efficiency.

Although average load demand can be met using renewable generation, storage is essential because the generation and load power fluctuate significantly around their average values. In this scenario, a battery bank is used as the energy buffer.

The battery takes second priority to the renewables because its operating cost is higher, and using the storage is less efficient. The life-expectancy of the battery bank is 5-10 years, significantly less than that of the wind turbine and photovoltaic array, and two stages of power electronic conversion are required to charge and discharge the batteries.

3.2 Control Law

The control law is designed to consume the renewables sources before drawing from the storage. When the storage node is not fully charged, any excess power available from the renewable sources should be used to charge the battery bank. Fig. 4 expresses the control law in the form of an operational state diagram.

In this instance, the control law is simple since only two types of sources are present in the system. Two states are sufficient to account for all possible operating conditions. It should be noted that the control law can easily be extended to accommodate all operating states in more complicated systems that use backup generators in addition to battery storage [9].

The state diagram consists of two operating states. State 1 contains a substate to allow the storage to charge from any excess renewable energy without forcing a change in states.

The main input to the system is the load power, P_L, as a change in this input may force a transition between states. The storage energy, E_S, is also an input to the system. However, this input is a passive input as it does not cause the system to change states. It merely allows transitions between substates. The system outputs are the renewable power, storage power, and non-renewable power, which are denoted by P_R, P_S and P_N respectively.

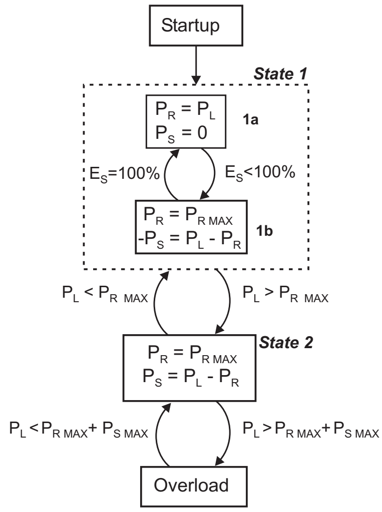


Figure 4: Nanogrid operational state diagram

At startup, the renewable sources turn on while the load remains off. When the system voltage has stabilised in state 1, the load converters become active. Once the system is running, the load demand and power available from the sources dictate the operating state of the nanogrid.

The system operates in state 1 when the load demand is less than the available renewable power. State 1 comprises two substates to allow the storage to charge from the renewables when excess power is available. In substate 1a, the storage is fully charged and renewable sources share power using voltage droop. If however the storage is not fully charged, the storage node charges by forcing the system to operate in state 1b. This substate occurs at the boundary of states 1 and 2 and corresponds to the maximum power point of the renewable sources.

In state 2, the load demand exceeds the available renewable power, and the storage is drawn upon to provide the power balance.

4 EXPERIMENTAL SYSTEM

Simulation results have shown the feasibility of using DC bus signalling to schedule storage and non-renewable backup generation in a 700 V nanogrid [9, 8]. This section presents a low power experimental nanogrid to demonstrate the practicality of DC bus signalling. The model nanogrid, shown in Fig. 5, is a representation of the nanogrid presented in the case study, scaled down by a factor of ten. The system operates at 70 V and has an average load demand of 200 W. The transmission network has a resistance of 0.01 Ω/km.

4.1 Sources

For simplicity, 12 V laboratory power supplies are used in place of the wind turbine and photovoltaic array. Unlike the renewable sources, these supplies do not have a fluctuating power output. This phenomenon can be accounted for by varying the maximum power points (MPPT) of the source interface converters.

4.2 Source Interface

The key element in the model nanogrid is the source interface, a step up DC-DC converter that connects each source to the transmission system by boosting the supply voltage from 12 V to 70 V. The source interface converters are identical full-bridge, hard-switching converters rated at 100 W.

The source interfaces are current-controlled converters, and a two-tiered control structure is used to regulate the output voltage. A slow outer PI control loop regulates the output voltage by providing a reference current to a fast inner current loop, which uses average current mode control to regulate the inductor current. Fig. 6 shows a simplified form of the source interface controller with the current loop replaced by its idealised form. The voltage loop governs the response of the converter, and has a droop characteristic of 0.1 V/A to allow power sharing between the renewable-based sources.

The DC bus signalling strategy relies on the MPPT characteristic of the source interfaces to reduce the bus voltage when the renewable sources have been exhausted, and signal to the storage node to begin discharging. The MPPT characteristic of each source is implemented by limiting the reference current for the current loop. The maximum reference current is given by

$$I_{refmax} = P_{max}/V_o \tag{2}$$

where P_{max} is the maximum power output of the source, and V_o is output voltage of the converter. It is worth noting that I_{refmax} has an upper limit of 1.5A to prevent excessively large currents flowing when V_o is small.

4.3 Loads

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. The load banks exhibit constant power characteristics because load interface converters connect the load banks to the system.

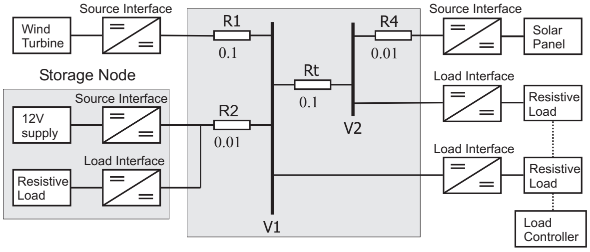


Figure 5: Block diagram of the model nanogrid

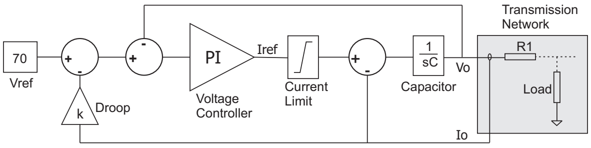


Figure 6: Simplified block diagram of source interface controller

The construction of the load interface is similar to that of the source interface. The main difference is that the load interface is a step down converter rated at 200W, with a voltage transformation ratio of 70:12 V.

The controller for the load interface is also similar to that of the source interface controller shown in Fig. 6. A two-tiered control structure is adopted; however, voltage droop is not included and a MPPT characteristic is not imposed on the load interface.

4.4 Storage Node

The storage node is constructed by connecting a source interface and load interface in parallel. The load interface converter connects the nanogrid to a resistive load to allow charging action while the source interface and 12 V supply allow the storage node to discharge into the nanogrid.

The load and source interface are modified slightly to allow charging and discharging action. The main difference between the storage charger and the load interface is that the storage charger regulates the bus voltage to the threshold of state 1b rather than regulating the output voltage to 12 V. The storage discharger is identical to the source interface aside from one respect: the reference voltage is set to the upper threshold of state 2 rather than 70 V.

4.5 Transmission Network

The transmission system is constructed as a resistive only network. Transmission line inductance and capacitance are not included as these parasitic components produce transient phenomena outside the timeframe of interest.

4.6 Control Law Implementation

Two steps are needed to implement the control law using DC bus signalling. The first step involves mapping each operating state to a voltage state. This implementation is shown in Fig. 7. The highest priority operating state is mapped to the voltage state with the highest level. It should be noted that the voltage window of state 1 is made larger to allow the inclusion of substate 1b.

A load line is drawn in Fig. 7 to allow the operating point of the system to be determined. Since the load

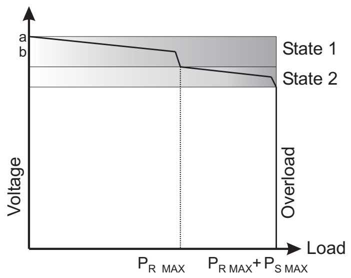


Figure 7: Nanogrid voltage state diagram

line changes shape as the maximum generation available changes, the operating point not only depends on the load, but also on the generation.

The second step of the implementation involves deriving a control law for the storage node based on the voltage states. A control law is not derived for the renewable sources as the MPPT characteristic of these sources causes the voltage state changes themselves. The storage node has two modes of operation. It charges in state 1, when the bus voltage is greater than V1b, and discharges when the bus voltage decreases to the upper threshold of state 2.

4.7 Setting the voltage thresholds

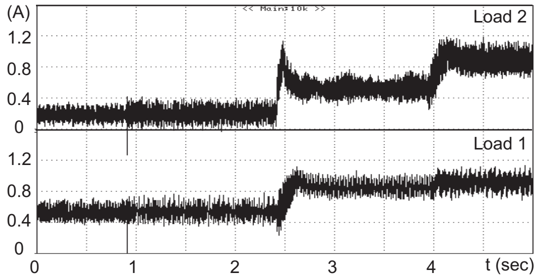
A key aspect in the design of the experimental system is setting the charge and discharge thresholds for the storage controller. The thresholds must be set to appropriate voltage levels to prevent the storage node from discharging prematurely due to voltage drop caused by source droop and transmission line resistance, and to ensure the charging threshold of the storage node corresponds to the maximum power point of the renewable sources.

In the model system, the thresholds for states 1b and 2 are derived experimentally. The minimum voltage at the storage node when both sources are operating at their MPPT is 68.6 V. The threshold for state 1b is therefore arbitrarily set below this value to 66 V. Theoretically, the threshold for state 2 could be set just below the threshold of state 1b; however, state 2 is set to 62 V, and hysteresis is included the the transition between states 1 and 2 to prevent jitter when the system operates at this boundary point.

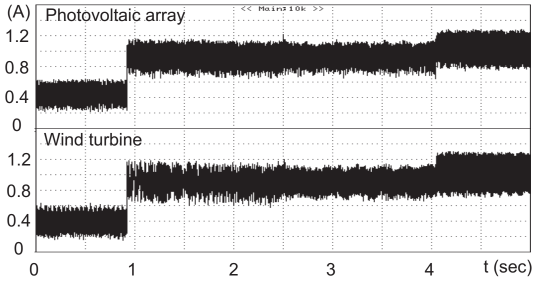
In a system with a more complex transmission network and multiple storage nodes, experimental derivation of the state thresholds for the storage nodes may not be possible. For such situations however, a DC load flow technique has been developed to determine the maximum voltage for the charge and discharge thresholds. Based on the Newton-Rapheson technique, the load flow calculates the the voltage at each point in the system for a given set of source and load powers, allowing the threshold settings to be identified readily.

5 RESULTS

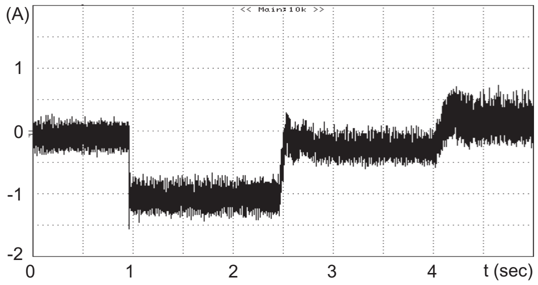
Step changes in the load demand are applied to the system to demonstrate how the voltage on the nanogrid varies to schedule the storage node. The results are portrayed in Fig. 8.



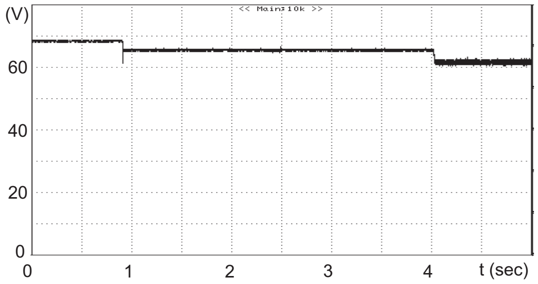
(a) Load currents



(b) Supply currents



(c) Storage current



(d) Voltage at bus V1

Figure 8: Experimental results

Fig. 8(a) shows the variations in the load currents, and Fig. 8(b) shows the supply currents. The storage current required to balance the load demand is shown in Fig. 8(c), while Fig. 8(d) shows the voltage level changes on the model nanogrid at bus V1.

Initially, load 1 operates at 50 W and load 2 at 25 W while the storage remains offline. The maximum power available from each renewable source during the step changes is 70 W, hence the system operates in state 1a. The bus voltage is approximately 68 V, and the renewable sources share the total load current due to their voltage droop characteristic.

At t = 1s, the storage node is brought online and begins to charge using the excess energy available from the renewable sources. Fig. 8(c) shows the storage charging current is approximately -1 A at this point and Fig. 8(b) shows that the supply currents have increased to their maximum values of 1 A. The bus voltage is now regulated at 66 V, the threshold of state 1b, as shown in Fig. 8(d)

At t = 2.5s, load 1 is increased to 75 W and load 2 to 50 W. Fig. 8(a) shows the corresponding change in load currents. The system remains in state 1b, as the load demand does not exceed the available source power and the bus voltage remains at 66 V, while the sources operate at their maximum capacity. However, the storage charging current is reduced as shown in Fig. 8(c).

At t = 4s, load 2 is increased to 75 W, while load 1 remains unchanged. The storage node now discharges to meet the load demand, as the load demand exceeds the available source power. The bus voltage drops to 62 V, the upper threshold of state 2.

The experimental results have shown that the storage node maintains the power balance in the system despite changes in the load demand. However the results also highlight some high-frequency stability issues that need to be addressed.

The current waveforms shown in Fig. 8(a) - Fig. 8(c) contain a significant high-frequency ripple component. This ripple component is generated by interaction between the ripple voltages across the source interface converters' output capacitors. The differences between the ripple voltages are only limited by the small resistance of the transmission line. With the addition of transmission line inductance however, this ripple component would be attenuated.

The ripple voltage on the DC bus increases significantly at t = 4s as shown in Fig. 8(d). At this point, the storage node begins to regulate the bus voltage. Small voltage oscillations appear on the bus because the voltage loop of the storage node's source interface controller is slightly unstable under these conditions. This problem can be eliminated by careful design and tuning of the voltage control loop.

6 CONCLUSION

A nanogrid is a distributed power system that uses power-electronic converters to interface renewable sources and storage devices to a DC network. An isolated nanogrid requires intelligent scheduling of a storage node due to fluctuations in the source power and load demand. This paper has introduced a novel control strategy, DC bus signalling, as a method of scheduling the storage node in a decentralised fashion. The storage node infers the operating state of the system from the voltage level on the nanogrid. Changes in the supply power and load demand change the voltage level on the nanogrid and allow the storage node to charge or discharge to balance the load demand. Experimental results obtained from a model nanogrid have verified the practicality of this new concept.

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