Multidimensional droop control for wind resources in dc microgrids

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Abstract: Two important and upcoming technologies, wind resources and microgrids, are increasingly being combined. Various control strategies can be implemented, and droop control provides a simple option without requiring communication between microgrid components. However, traditional droop control does not allow the microgrid to maximise the power available from the wind. This study proposes a novel droop control strategy, which implements a droop surface in higher dimension than the traditional strategy. Simulation results show that power from the wind can be maximised, while maintaining the system’s bus voltage around a nominal value using a distributed multidimensional droop approach. Selection of the optimal droop relationship is discussed and simulation results are presented.

1 Introduction

The use of wind to generate electricity has become more and more common in recent years. Using renewable energy sources such as wind resources is one way to help preserve our planet for future generations. Wind power provides a clean, sustainable energy source for generating electricity. Wind and other sources of renewable energy are often used as distributed resources and are increasingly being applied in connection with microgrids [1].

Some advantages of using distributed generation sources such as wind include cost and energy savings, since distributed sources are located physically closer to load centres than traditional power plants tend to be. Distributed sources such as the wind can also provide power more easily to rural or remote locations [2]. Distributed sources are a good fit with the relatively new power system topology of microgrids.

Microgrids are small-scale power systems that are able to operate with a connection to the main power grid, but can also operate in an islanded mode [3]. This capability to run separately can be especially beneficial during a blackout on the main grid, since the microgrid is able to continue operating. Microgrids also allow for a more efficient and reliable power system, since generated electricity does not have to travel long distances through transmission lines to reach consumers.

The size of microgrids can vary greatly, from single homes or buildings, to university or corporate campuses, for example. Microgrids can also be mobile such as on an electric ship. Regardless of the size, a microgrid must contain distributed sources of generation in order to operate in an islanded mode. In this paper, a sample microgrid is presented that could represent a home or other building.

Droop control is commonly chosen as the control method for power systems including microgrids. The main benefit of droop control is that communication between sources and loads is not required [4]. While communication systems have been designed for the control of smart microgrids [5], removing the reliance on communication also eliminates a single source of failure in the control system. In a dc distribution system, each source is given a droop setting so that the power supplied from each source changes as the load in the system changes. All of the sources and loads are connected to a common bus, so changes in the load cause changes in the bus voltage. The bus voltage is common for all sources, but using different droop settings for each can allow the different sources to supply more or less power as the bus voltage varies [4].

Another common type of control for wind and other non-deterministic resources is maximum power point tracking (MPPT); this paper presents an alternative approach using a modified droop control method. The goal of this paper is not to compare the proposed control method to MPPT, but to present a new alternative droop control method for use in situations when something other than MPPT is required. In [6], Gu et al. describe this situation as a ‘power limiting’ mode of operation where the non-deterministic sources have to switch from MPPT to an alternative method to maintain the power balance in the isolated system. This paper focuses on the ‘power limiting’ mode in which the renewable sources use the proposed novel droop control to balance the power in an isolated microgrid.

Droop control has been applied to with microgrids and specifically with wind resources in microgrids [7]. The advantage of using some type of droop control in a microgrid is the simplicity, and the fact that communication between the system components is not necessary. However, when implementing droop control with wind resources in microgrids, a large disadvantage is the fact that the wind speed is not considered – during times of higher wind speed, more power is available from the wind that is not utilised with traditional droop control.

Various adjustments to traditional droop control have been proposed, in order to achieve better operation when applied with microgrids, and with wind resources. Luo et al. [8] propose an offset \( P^* \) be added to the linear droop setting for sources connected to the dc bus in a microgrid. An alternative optimal ac droop control method has been proposed by Rokrok and Golshan [9], where the voltage reference for each source is drooped as a function of the active and reactive power outputs of that source.

In one study of droop control applied with wind resources in microgrids, two droop settings are recommended: one for grid-connected operation and one for microgrid operation in islanded mode [10]. Control methods have also been proposed that allow the energy storage system to operate using the same control architecture, regardless of whether the microgrid is operating in islanded or grid-connected mode [11]. To improve frequency regulation of wind turbines, another approach which gives lower droop settings to those sources with higher power margins is proposed [12]. While previous research, with some examples
discussed here, has shown possibilities for modifying droop control for wind resources, these still do not allow the wind speed to be taken into account.

This paper proposes an improved method for applying droop control with wind resources that substantially improves wind resource utilisation in dc microgrids using multiple dimensions. The main limitation of the proposed multidimensional droop control is that it is an open-loop control and design method based on an a priori assumption of system parameters and operating scenarios. If system parameters change or operating scenarios are different from the design, then a non-optimal operating point may result. However, just as in traditional droop control methods, a secondary control loop could be implemented to adjust the multidimensional droop surface during operation.

In this paper, Section 2 describes the modelling method used for each microgrid component, whereas Section 3 includes details on the overall example microgrid. Section 4 presents the new research contribution of this paper, a method of multidimensional droop control. One approach for selecting droop constants for this new proposed method is described in Section 5. Simulation results comparing traditional and multidimensional droop control operation with a wind resource are shown in Section 6 and conclusions are presented in the final section.

2 Microgrid modelling and control

This section will present the model and control method proposed for general microgrid components including conventional sources, wind sources, energy storage devices, variable loads, and constant impedance loads. All power electronics will be modelled using average mode methods [13]. The complete microgrid model is shown in Fig. 1, and the details for each of the components are discussed in the following sections. The purpose of this paper is to introduce the multidimensional droop control method concept. For clarity, the simplest system that still includes the relevant sources, load, and storage was used, as shown in Fig. 1. The proposed method would be implemented in a similar way for a multi-bus dc microgrid, with the objective remaining the same: to optimise the wind energy utilisation. In a multi-bus microgrid, the power and energy losses that impact the objective are quantified by the losses calculated in the distribution system through the \( V_{\text{bus}} \). In addition, though consistent variable names are used for each circuit element of the microgrid in Fig. 1 across the various components, different values can be and are implemented in the simulation results presented in this paper.

2.1 Sources

In this paper, microgrid sources are modelled with buck converters which step the high voltage of the sources down to match the bus voltage. Two sources are included in the example microgrid: one wind source and one conventional voltage source. Both sources interface to the bus through a dc–dc buck converter. However, the wind source is a simplified dc model of a permanent magnet synchronous generator (PMSG) wind turbine behind a rectifier, resulting in a variable voltage that models wind cycles. The model for each source contains five states

\[
\frac{dV_{cl}}{dt} = C_i \left( i_{th} - D_i v_{cl} \right) \quad (1)
\]

\[
\frac{dI_{cl}}{dt} = D_i v_{ch} - v_{cl} \quad (2)
\]

\[
\frac{dV_{cl}}{dt} = C_i \left( I_{cl} - i_{out} \right) \quad (3)
\]

\[
\frac{dI_{th}}{dt} = V_s - R_{th} I_{th} - v_{ch} \quad (4)
\]

\[
\frac{dI_{out}}{dt} = V_{cl} - R_{out} I_{out} - V_{bus} \quad (5)
\]

The proposed control methods for both conventional and wind sources are discussed in the next section.

2.1.1 Traditional droop control implementation: For conventional sources, traditional dc voltage droop control is used. In traditional droop control for a dc system, the power supplied from each source changes as the bus voltage changes, with movement along a line with a chosen slope. The equation for the reference current from a source is

\[
i_{\text{ref}} = \frac{V_{\text{ref}} - V_{\text{bus}}}{R_d} \quad (6)
\]

where \( V_{\text{ref}} \) is the desired bus voltage and \( R_d \) is the droop setting which represents a virtual series line resistance.

To implement droop control with the source modelled above, two additional states are added. The first compares the current command from (6) to the actual output current of the source

\[
\frac{d\text{error}_1}{dt} = i_{\text{ref}} - i_{\text{out}} \quad (7)
\]

The second compares the voltage command for the source output voltage, which will be set in the controller as explained next, to the actual voltage at the output of the converter

\[
\frac{d\text{error}_2}{dt} = v_{\text{cl, ref}} - V_{\text{cl}} \quad (8)
\]

A proportional–integral (PI) control loop can then be implemented to replace \( v_{\text{cl, ref}} \) in (8) as

\[
v_{\text{cl, ref}} = k_p (i_{\text{ref}} - i_{\text{out}}) + k_i \text{error}_1 \quad (9)
\]

A second PI control loop is then implemented to replace the average value of the duty cycle, \( D \), and allow the converter to track the reference voltage

\[
D = k_p (v_{\text{cl, ref}} - V_{\text{cl}}) + k_i \text{error}_2 \quad (10)
\]

Fig. 2 shows the traditional linear droop control implemented for conventional sources.

2.2 Energy storage devices

Microgrids often contain energy storage devices to balance the power supplied from the sources and demanded from the loads while operating in islanded mode [14]. As the microgrid concept is increasingly implemented, the importance of energy storage and the impacts it can have on system stability become clear [13]. One of the key benefits of microgrids is their capability to operate in islanded mode disconnected from the main electricity grid. This is especially important during times of disturbance on the main grid, which would disrupt electricity service to many customers. With a microgrid, the option to operate as an island allows many of those customers to continue with uninterrupted electricity. Microgrids also provide the capability to supply power to critical loads, for example, providing power to hospitals during a natural disaster that causes a blackout on the electricity grid [16].

In both of these cases, the fact that there are nearby distributed generation sources allows the microgrid to continue operating while the main electricity grid is not. When some of those distributed sources are renewable energy options with variable resources such as sunlight or wind, it is difficult to predict how much electric power the microgrid can supply, and when. The addition of some form of energy storage alleviates this concern, allowing excess energy produced to be stored, and used as needed [17]. The importance of including energy storage when wind sources are included in the system is detailed in [18]. Since energy storage is a key part of a successful microgrid, it is important to
ensure that any proposed control design for a microgrid component would function well alongside an energy storage device. Therefore, energy storage is included in the sample microgrid used in simulation to test the proposed multidimensional droop control for wind resources.

While many options are available for energy storage in microgrids, in this paper a battery is simulated. The battery model used is based on the FreedomCAR design [19]. The battery model is included in Fig. 1, with the bi-directional dc–dc buck converter as the interface to the microgrid dc bus. A reasonable size for the battery was chosen to match the size of the example microgrid described in Section 3. During all simulations, the battery state of charge is monitored to ensure that it remains within desired operating limits.

The model for the energy storage system is similar to the model for each source. There are again five states for the converter, with an additional state for the battery defined as

\[
\frac{dv_{ch}}{dt} C_h = i_{lh} - D_i l_l
\]

\[
\frac{di_{lh}}{dt} = D v_{ch} - v_{cl}
\]

\[
\frac{dv_{cl}}{dt} C_l = i_{ll} - i_{out}
\]

\[
\frac{di_{ll}}{dt} L_l = v_{batt} - R_{lh} i_{lh} - v_{ch}
\]

\[
\frac{di_{out}}{dt} L_B = v_{cl} - R_B i_{out} - V_{bus}
\]

\[
\frac{dv_{batt}}{dt} C_{batt} = i_{lh}.
\]

Defining the equations in this way results in a positive current \(i_{out}\) when the battery is discharging or supplying power to the microgrid. The current \(i_{out}\) is negative when the battery is charging or absorbing power from the microgrid. The numeric values used in the energy storage model are shown in Table 1.

Droop control can be implemented for the energy storage in a similar manner as for the traditional source, as in (6)–(10). When the bus voltage is above the reference value the battery absorbs current and charges. When the bus voltage is below this reference, the battery discharges. Fig. 3 shows the droop control as implemented for the battery in this simulated microgrid.

This simple control implementation will allow the system to operate without a communication link necessary between the energy storage system and the rest of the microgrid. More complex control designs could be implemented to schedule the charging of the battery; however, this is beyond the scope of this research.

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**Fig. 1** Example microgrid for demonstration of droop control methods

**Fig. 2** Traditional, 2D droop settings for implementing droop control
2.3 Loads

In this paper, two general types of loads are considered: constant impedance loads and variable impedance loads. The modelling approach for both load types is discussed here. The resistive load model used here is similar to an actual lighting type load.

2.3.1 Variable loads: The general load is modelled with a buck converter to step the bus voltage down to the level of the load. Fig. 1 shows the buck converter model for the variable load. The load model contains four states with equations defined as

\[
\frac{dV_{ch}}{dt} = i_n - D_i \quad \text{(17)}
\]

\[
\frac{di}{dt} L_i = D_i (V_{ch} - v_{cl}) \quad \text{(18)}
\]

\[
\frac{dv_{cl}}{dt} C_l = i_l - \frac{v_{cl}}{R_{load}} \quad \text{(19)}
\]

\[
\frac{dl}{dt} L_h = V_{bus} - R_{load} i_n - v_{ch} \quad \text{(20)}
\]

The numeric values used for the variable load parameters are shown in Table 2. A PI controller can be implemented to keep the load at a desired nominal voltage. This adds one state to the model

\[
\frac{d\text{error}}{dt} = V_{nom} - v_{cl} \quad \text{(21)}
\]

The duty cycle \(D\) can then be replaced with the PI controller such that

\[
D = k_D (V_{nom} - v_{cl}) + k_i \text{error} \quad \text{(22)}
\]

2.3.2 Constant impedance loads: Fig. 1 also includes the model used for constant impedance loads. There is just one state for the constant impedance load model

\[
\frac{dV_{bus}}{dt} C_{load} - \Sigma i_{sources} - \Sigma i_{loads} + V_{bus} \frac{v_{load}}{R_{load}} \quad \text{(23)}
\]

where the currents from the sources, energy storage devices, and other loads are summed together. The numeric values used for the constant load parameters are shown in Table 3.

3 Example microgrid

The microgrid system used in this paper is on the scale of a home or other building, and is shown in Fig. 1. The wind source is a small-scale wind turbine, while the conventional source is a liquid-fuel generator. The constant impedance load has an impedance which remains the same throughout the simulation, while the variable load changes with time. A timeframe of 1 day is simulated, and a load profile throughout the day was chosen by scaling actual residential load data from an existing power system [20]. A wind speed profile for the day was approximated by calculating an average of daily wind speed measurements [21]. The load and wind speed profiles used for this 24 h simulation period are shown in Fig. 4. The wind source is based on a 12 kW wind turbine, with a power curve as shown in Fig. 5 [22]. As simulation results will demonstrate, using traditional linear droop control will not allow all of the energy available from the wind to be utilised. Fig. 4 shows that for this specific example, there are high wind speeds that coincide with high load demand during the evening hours. While linear droop control provides a simple method for controlling the system, it does not use this available wind energy. The proposed multidimensional droop control method maintains the overall control simplicity, while allowing the energy available from the wind to be utilised.

4 Multidimensional droop control method

For wind sources, the linear droop control method presented above is expanded into three dimensions to create a droop surface as shown in Fig. 6. Variation in bus voltage still causes adjustments in power supplied from the source. However, variation in wind speed also causes changes in power supplied. The reference current for a

Table 1 Energy storage parameter values

| Component | Value | Unit |
|-----------|-------|------|
| \(C_h\)   | 1     | mF   |
| \(L_h\)   | 0.2   | mH   |
| \(C_l\)   | 0.08  | F    |
| \(L_l\)   | 1     | mH   |
| \(R_l\)   | 1     | \(\Omega\) |
| \(L_{\text{bus}}\) | 1.2 | mH |
| \(C_{\text{bus}}\) | 10  | mF |
| \(R_{\text{bus}}\) | 0.001 | \(\Omega\) |
| \(V_{\text{bus}}\) | 293  | V |
| \(R_s\)   | 1.5   | –    |
| \(k_{pi}\) | 1     | –    |
| \(k_{li}\) | 10    | –    |
| \(k_{pv}\) | 1     | –    |
| \(k_{ic}\) | 10    | –    |

The duty cycle \(D\) can then be replaced with the PI controller such that

\[
D = k_D (V_{nom} - v_{cl}) + k_i \text{error} \quad \text{(22)}
\]

Table 2 Variable load parameter values

| Component | Value | Unit |
|-----------|-------|------|
| \(V_{nom}\) | 200  | V |
| \(R_{nom}\) | 0.2  | \(\Omega\) |
| \(C_{nom}\) | 10   | \(\mu F\) |
| \(L_{nom}\) | 0.15 | mH |
| \(C_l\)   | 0.8   | mF   |
| \(L_l\)   | 7.5   | mH   |
| \(k_{pl}\) | 1     | –    |
| \(k_{ll}\) | 10    | –    |
| \(k_{pl}\) | 1     | –    |
| \(k_{cl}\) | 10    | –    |

Table 3 Constant load parameter values

| Component | Value | Unit |
|-----------|-------|------|
| \(C_{load}\) | 1    | mF |
| \(R_{load}\) | 30   | \(\Omega\) |
source is now determined by a plane

\[ i_{\text{ref}} = \frac{V_{\text{ref}} - V_{\text{bus}}}{R_{d1}} + \frac{v_w}{R_{d2}} \]

where \( v_w \) is the wind speed and \( R_{d1} \) and \( R_{d2} \) represent the droop settings in two dimensions. \( R_{d1} \) is with respect to voltage and \( R_{d2} \) is with respect to wind speed. In Fig. 6, the two droop settings are 10.8 for \( R_{d1} \) and 0.28 for \( R_{d2} \). The selection of these droop control parameters will be discussed in Section 5. This multidimensional approach allows more power from the wind to be utilised, since the current reference increases with wind speed. The droop control relationship in (24) is valid within the operating parameters of the wind turbine, specifically within the range of wind speeds where the wind turbine is able to operate.

For each of the sources, the numeric values of the various circuit parameters are shown in Table 4. The complete state model of the wind source and controller is

\[ \frac{di_{\text{th}}}{dt} L_i = \left( k_p \left[ k_p \left( \frac{V_{\text{ref}} - V_{\text{bus}}}{R_{d1}} + \frac{v_w}{R_{d2}} - i_{\text{out}} \right) + k_i \text{error}_1 - v_{cl} \right] + k_i \text{error}_2 \right) i_{\text{th}} \]

\[ \frac{dv_{ch}}{dt} C_i = i_{\text{th}} - i_{\text{out}} \]

\[ \frac{dv_{ch}}{dt} = k_p \left[ k_p \left( \frac{V_{\text{ref}} - V_{\text{bus}}}{R_{d1}} + \frac{v_w}{R_{d2}} - i_{\text{out}} \right) + k_i \text{error}_1 - v_{cl} \right] + k_i \text{error}_2 - v_{cl} \]

To analyse the stability of the system with the proposed multidimensional droop controller, the Jacobian matrix was formed by calculating the partial derivative of each state equation with respect to each of the states. The numeric values in Table 4 were included, and a reasonable operating point of 295 V for the bus voltage, and 8 m/s for the wind speed was chosen. The equilibrium point was found using these numeric values. The eigenvalues of the system were then calculated, and are shown in Table 5. Since all of the eigenvalues have negative real parts, the stability of the source model with the proposed controller is confirmed for this equilibrium point. The eigenvalues remain negative when bus voltage and wind speed are varied within reasonable ranges as well.

5 Selection of multidimensional droop surface

With the proposed multidimensional droop control, the control designer has an additional component to choose, since there are droop constants in two dimensions instead of just one. Choosing different values for these parameters changes the orientation of the droop plane and the operation of the system. One method for choosing the optimal droop constants is presented here.

The generalised cost function to be minimised is

\[ J = \int_{t_0}^{t_1} \left( P_s(v_w) - P(i_{\text{ref}}, v_{cl}) \right) dt \]

where \( P_s \) is the power available from the wind, \( v_w \) is the wind speed, and \( P \) is the power generated by the wind source (power utilised from the wind). The power available from the wind \( P_s \) was determined using the wind speed profile as shown in Fig. 4b and the wind turbine power curve as shown in Fig. 5. The time interval of the problem \( t_0 < t < t_1 \) is the scenario period such as the operation over 1 day or week.

It is likely that there are some constraints on the microgrid operation. For example, it maybe undesirable to allow the conventional source to stop providing any power, so there is a minimum output power that should be maintained from this source. There is likely also a limit to the charging current for the
battery. Then the optimisation problem becomes

\[
\begin{align*}
\text{minimise} & \quad J = \int_0^T (P_i(v_i) - P_{\text{ref}}(V_{\text{ref}}, V_{\text{cl}})) \, dt \\
\text{subject to} & \quad V_{\text{low}} < V_{\text{bus}} < V_{\text{high}}, \\
& \quad I_{\text{b,low}} < I_{\text{b,bar}} < I_{\text{b,high}}, \\
& \quad I_{\text{b,low}} < I_{\text{b,bar}} < I_{\text{b,high}}, \\
& \quad \dot{x} = f
\end{align*}
\]

where \( \dot{x} = f \) is the microgrid model from (25) to (31). This optimisation is then performed on a range of wind speeds \( v_w \) and voltages \( v_{cl} \) to define a droop surface of \( i_{\text{ref}} \) for each wind source in the system.

There are multiple options for solving the optimisation problem presented above. One method is the minimum principle, which involves adding a co-state variable for each state and creating a Hamiltonian function [23]; many other approaches to numerical optimisation have been developed [24]. For this work, a direct numeric search method was utilised to find the minimisation of (32); other numeric search methods could certainly be utilised, but a direct numeric search method suffices to solve the optimisation problem presented above and demonstrate the proposed multidimensional droop control method.

The slopes of the droop surface \((1/R_{d1})\) with respect to voltage and \((1/R_{d2})\) with respect to wind speed) were varied at discrete intervals, with the constraints in (33) included: a 500 W minimum output from the conventional source, a 10 A maximum charging current

| Component | Value | Unit | Component | Value | Unit |
|-----------|-------|------|-----------|-------|------|
| \( R_1 \) | 0.2 | \( \Omega \) | \( R_1 \) | 0.2 | \( \Omega \) |
| \( C_1 \) | 0.2 | mF | \( C_1 \) | 0.2 | mF |
| \( L_1 \) | 1.5 | mH | \( L_1 \) | 1.5 | mH |
| \( C_2 \) | 0.08 | F | \( C_2 \) | 0.08 | F |
| \( L_2 \) | 5 | mH | \( L_2 \) | 5 | mH |
| \( R_3 \) | 0.1 | \( \Omega \) | \( R_3 \) | 0.23 | \( \Omega \) |
| \( L_3 \) | 1.2 | mH | \( L_3 \) | 0.8 | mH |
| \( V_{\text{ref}} \) | 300 | V | \( V_{\text{ref}} \) | 300 | V |
| \( k_{cl} \) | 0.8 | – | \( k_{cl} \) | 0.8 | – |
| \( k_p \) | 1 | – | \( k_p \) | 1 | – |
| \( k_i \) | 10 | – | \( k_i \) | 10 | – |
| \( k_{pv} \) | 1 | – | \( k_{pv} \) | 1 | – |
| \( k_{cl} \) | 10 | – | \( k_{cl} \) | 10 | – |

6 Simulation results

To test the proposed droop control scheme, the example microgrid described above was modelled using MATLAB/Simulink. The system was first simulated using a traditional droop control technique for both the conventional and wind sources, with droop settings similar to Fig. 2. This paper compares the proposed multidimensional droop control approach to traditional droop control; the focus is on microgrid applications where droop control is preferred, with an understanding that there are other control options such as MPPT for renewable resources that maybe preferred in other situations.

Next, the system was simulated using the proposed multidimensional droop surface for the wind source, with a traditional droop setting for the conventional source. The optimal droop surface was chosen as described above, with the constraints as shown in Table 6. The resulting slopes are \( 1/R_{d1} = 0.0926 \) in the bus voltage direction and \( 1/R_{d2} = 3.5714 \) in the wind speed direction.

Future work will present a more generalised method for determining an optimal droop control plane (instead of an optimal droop plane as demonstrated here) for all scenarios.

![Fig. 6 Plot of 3D surface for implementing multidimensional droop control for wind sources](image)

![Fig. 7 Cost from (32) with varying slopes in wind speed and bus voltage directions including constraint conditions. Minimum cost point given constraints is shown](image)

Table 5 Eigenvalues for source and controller state model

| Source 1 | Source 2 |
|----------|----------|
| \(-57.26 + 1970.61\) j | \(-57.26 - 1970.61\) j |
| \(-20.04 + 138.91\) j | \(-20.04 - 138.91\) j |
| \(-54.25\) | \(-6.85\) |
| \(-0.97\) | \(-0.97\) |
the simulation. The points marked A, B, and C provide a reference for the plot of the source’s output with respect to time, which will be shown in Fig. 11.

The power from each source for the two cases is shown in Fig. 9. The power available from the wind is included, and it is clear that using the planar droop surface allows more of the available wind power to be utilised (and requires less liquid fuel).

A summary of the simulation results using traditional droop control is shown in Fig. 10 and Fig. 11 shows a summary of the simulation results using multidimensional droop control. The points marked A, B, and C provide a reference back to the plot of the source’s movement along the droop control plane, as shown in Fig. 8. The power supplied by each source, consumed by each load, and supplied from the battery is shown in both cases. For this example scenario, the battery is supplying power to the system when traditional droop control is used. When multidimensional droop control is implemented instead, the battery is able to charge during times of high wind and/or low load. The battery reverses its power flow and supplies power during the morning hours, when the load is increased, but the wind speed has dropped.

| Component       | Parameter              | Constraint  |
|-----------------|------------------------|-------------|
| conventional source | minimum power output  | 500 W       |
| battery         | maximum charging current | -10 A     |
| microgrid       | bus voltage            | ±5%         |

Fig. 8 Plot of 3D droop surface for wind source

Fig. 9 Power supplied from
a Wind source
b Conventional source using 2D and 3D droops. Power available from the wind is also shown

c Power supplied by the battery

d Power supplied by each source

e Power consumed by each load

Fig. 10 Simulation results using traditional droop control
a Power supplied by each source
b Power consumed by each load
c Power supplied by the battery

d Power supplied from
a Wind source
b Conventional source using 2D and 3D droops. Power available from the wind is also shown

c Power supplied by the battery

d Power supplied by each source
e Power consumed by each load

Fig. 11 Simulation results using multidimensional droop control
a Power supplied by each source
b Power consumed by each load
c Power supplied by the battery

d Power supplied from
a Multidimensional droop control
b Traditional droop control

c Power supplied by the battery

d Power supplied by each source

e Power consumed by each load

The microgrid bus voltage for each simulation is shown in Fig. 12. When multidimensional droop control is used, the bus voltage varies more than in the traditional droop case. This is one trade-off that
must be considered when choosing the droop surface. In this example with multidimensional droop, more power from the wind is utilised and the bus voltage still remains within ±5% of the nominal value of 300 V. If less variation in bus voltage were desired, the design parameter in (33) could be altered, and new slopes for the multidimensional droop control plane calculated.

The cost was calculated for each simulation using (32), and the results are shown in Table 7. The cost is reduced significantly when the multidimensional droop surface is used instead of traditional droop control, even when realistic constraints on the system are considered. When traditional linear droop control is utilised, a significant amount of the energy that is available from the wind resource goes unused. With the proposed multidimensional droop control method, the amount of unused energy that was available from the wind is reduced by over 5.5 times. Meanwhile, the simplicity of the control implementation and operation is maintained.

7 Conclusions

The results presented in this paper show that using a multidimensional droop surface to control a wind turbine connected with a dc microgrid allows the wind speed at the current time to be considered as a part of the control. This new proposed control method retains the simplicity of traditional droop, while allowing more of the available power from the wind to be utilised.

The proposed multidimensional droop control for wind resources was demonstrated here in a simulation of a small microgrid, with a size representing a home or other small building. Actual wind speed and load profile data was used to ensure a realistic simulation of the microgrid over a 24 h period.

As discussed, energy storage is a key factor in a microgrid containing renewable resources such as wind. The results presented here show that the proposed multidimensional droop control for wind resources works well in conjunction with an energy storage system. In times of high wind, energy is stored in the battery, and that energy is used to supply the microgrid in times of lower wind speed. This is accomplished without the need for communication between the wind source and the battery, resulting in a simple and reliable control strategy for a dc microgrid.

The work presented in this paper is confined to using a linear droop control surface (plane) in three dimensions. The optimal plane was found for average profiles of changing load and wind speed over a 24 h period. Since both load and wind speed can vary and be uncertain, future work will present a method for optimizing a droop surface for general operation of a microgrid system, rather than a specific case.

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9 References

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