MANAGEMENT OF HYBRID (AC-DC) MICRO-GRIDS

By

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Management of Hybrid (AC-DC) Micro-Grids

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Abstract

The objective of this thesis is to demonstrate the sharing demanded power in a single-phase hybrid micro grid operating in autonomous island mode. We assume that we have DC power sources such as a photovoltaic array and wind turbine in the DC sub-grid that is tied to the AC sub-grid consisting of two uninterruptible power sources (UPS) through a bi-directional single phase inverter.

Demand-droop control is used to manage power sharing between power sources in each sub-grid; however, managing the power flow through the entire grid is still a challenge. To overcome this we develop droop control strategies for each sub-grid, and droop control for the interfacing converter. The latter, can be formed using available information from each sub-grid and a specific normalization technique for the droop control of the interfacing converter. In this thesis it is assumed that supply and demand are matched at all times, and the major problem addressed is managing power sharing.

Simulation results using MATLAB are used to demonstrate the performance of the power sharing methodology developed in the thesis. Four different scenarios have been tested: (1) Both sub-grids have a heavy load, (2) both sub-grids have a light load, (3) a heavy DC load with a light AC load, and (4) a heavy AC load with a light DC load.

Chapter 1: Introduction

1.6 Micro-Grid Power System Concept

A micro-grid includes a small-scale power supply such as a wind turbine, photovoltaic array or diesel generator, connected to serve the demand of small communities [1]. Precisely, we can say it is a distributed generation (DG) network work as group or individually to provide energy. Fig.1-1 shows the simplest structure of a micro-grid, in which the house has been tied with green energy sources, e.g. a wind turbine and photovoltaic, array and all are connected to conventional utility through bidirectional inverter. This mode of micro-grid operation is called grid-connected mode, unlike the autonomous island mode where the conventional utility is disconnected from the micro-grid [2]. In fact, a micro-grid can include AC sources, DC sources or both of them to form a Hybrid Micro-Grid.

Fig 1-1: Simplest structure of micro-grid.

1.2 Why Micro-Grids?

Most of the countries around the world rely on centralized power system for energy, usually from fossil fuel or nuclear power stations. Even though this type of power system is reliable; however, large amounts of energy (up to 60%) are lost [1] as the result of transmitting power over long distances. Tom Markvart and Ray Arnold [1] believe that micro-source power can benefit the environment due to higher energy efficiency. Because stability is an essential property of the power system, micro-grids can supply the system with sustainable energy [2], with the opportunity to extract and store green energy from renewable sources such as wind turbines or photovoltaic arrays and then use it with the main utility simultaneously [3]. Distributed energy resources will be an important element in to enable importing or exporting energy from or to a micro-grid and managing active and reactive (P&Q) power or even energy storage [3]. The energy produced by renewable sources such as photovoltaic arrays and wind turbines can have significant variability, so incorporating some type of energy storage to synchronize the peak of demanded power with the peak power of the sources [3]. Hence, budget for such projects should be considered carefully.

1.3 Micro-grid Market

Statistic shows that the world micro-grid market has been increasing and should continue to grow at least till 2020 [4]. In 2010 it reached \$4.14 billion, up from preceding year, 2009, and the market of foundational and campus micro-grids captured 45% of the aggregate market share in the same year, and North America itself posted approximately 74% of the total micro-grid market share [4]. Such numbers show the importance of

micro-grids. Reliability in power delivery is a concern [4], and micro-grids are a good alternative to provide to secure energy, and military bases are ideal places for their implementation. [5] Showed the prediction of annual micro-grid revenue from 2011-2016 with a continually increasing trend.

System Structure

As shown in Fig.1-2 our micro-grid system is not connected to the utility, and is operating in islanded mode. In the DC sub-grid we have two DC renewable sources, photovoltaic and wind, with its local load tied to two AC sources in the AC sub-grid through interfacing converter (bidirectional power flow inverter) with its local load.

Fig 1-2: Islanded micro-grid structure.

1.5 System Considerations

Usually parallel operation of DG is desirable as discussed in chapter 3. However, they must be synchronized in frequency, phase and magnitude in order to avoid circulating current. Assume the circuit in Fig.1-3, if there is difference between the two sources,

either in frequency or magnitude and phase, a circulating current i_c , defined in (1-1), flows from one source to the other causing an increasing output current [6].

$$i_c = \frac{i_1 - i_2}{2} \quad (1-1)$$

Fig 1-3 : Two parallel sources with load

Chapter 2 Structure of Micro-Sources

For AC sub-grid, ideal sources are used, while in DC sub-grid a photovoltaic array and a wind turbine are used.

Remark 1: The output power of photovoltaic arrays and wind turbines are susceptible to changes in natural phenomena such as sun light and wind speed. In this thesis we ask each micro-source to share the same amount of power, and we do not account for the variability in the power output of these sources as a function of changing environmental conditions. Therefore, we assume that wind turbine and photovoltaic array are operating with a constant power output in the time period of interest in this thesis.

Remark 2: From the control perspective, our primary focus is on regulating the output voltage from each micro-source and to be consistent with the reference voltage regardless of system dynamics. It is common in some wind turbine applications to adjust pitch angle to manage the mechanical power delivered to the rotor. However, in this project we assume constant power to the rotor from the wind and regulate generator output voltage for power sharing, assuming that the total available and demanded power are equal.

2.1 Photovoltaic Array

A photovoltaic (PV) array is composed of semiconductors devices, usually p-n junction diodes, that convert solar radiation into direct current to produce electrical power. The heart of this system is a PV cell that can be grouped together to make a PV panel or array.

The equivalent circuit of PV cell is shown in Fig.2-1, in which the current source I_{PV} connected in anti-parallel with diode I_d , in series with R_s and in parallel with R_p

Fig 2-1: Simplest equivalent circuit of PV cell.

The mathematical model of this ideal PV cell [8] is in (2-1)

$$I = I_{PV} + I_0 \left[\exp \left(\frac{qV}{akT} \right) - 1 \right] \quad (2-1)$$

where

$$I_d = I_0 \left[\exp \left(\frac{qV}{akT} \right) - 1 \right] \quad (2-2)$$

Table 2-1 lists abbreviation used in equation (2-1) and (2-2)

Symbol	Abbreviation
I_{PV}	Current generated by incident light *
I_0	The reverse saturation or leakage current of the diode
Q	The electron charge = $1.060217646 \times 10^{-19}$ C
K	The Boltzmann constant = $1.3806503 \times 10^{-23}$ J/K
T	Temperature of p-n junction in Kelvin
A	Diode constant

Table 2-1: Symbols abbreviation of equations (2-1) and (2-2).

* I_{PV} is affected by the sun light in a proportional manner.

(2-1) Is valid for a single PV cell, many cells are combined to form a PV array. Therefore, the latter can represent the I-V characteristic of a practical PV device as shown in figure 2-2 and (2-3) is valid for a PV array.

$$I = I_{PV} + I_0 \left[\exp \left(\frac{V + R_s I}{V_t a} \right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (2-3)$$

Here R_s and R_p represent the equivalent series and parallel resistances of the array respectively, V_t is the thermal constant of the array which can be represented as $V_t = \frac{N_s K T}{q}$ where N_s is the number of cells connected in series to increase current whereas N_p represents the number of cells connected in parallel to increase the output voltage [8].

Fig 2-2: Characteristics of I-V curve of practical PV array

From figure 2-2, I_{sc} is output I at short circuit, V_{oc} is the output voltage at open circuit, and MPP is the maximum power point which PV should works around it. The latter is very important to avoid wasting energy. Assume that we have a battery set to work at 12 volts, and we have a 130 watt (7.39 Amp and 17.6 volt) panel, then at 12 volts and ~ 7.4 amps , the panel can deliver 88.8 watts, hence we lost 41 watts due to the mismatch between the panel and battery [9].

2.1.1 Maximum Power Point Tracking (MPPT)

The optimal solution for the case stated above is to look at the panel output and compare it with the battery voltage, then try to determine what is the optimum power that can be produced by the panel to charge the battery, which is referred to as MMPT. In this case MPPT takes the output of our panel (17.6 volt at 7.4) and uses a power converter to step down the voltage, so the battery now gets 10.8 amps at 12 volts to yield 128 watts and the total lost power is 2 watts [9]; therefore, the efficiency = $\frac{128}{130} = 98.5\%$.

MPPT usually is an algorithm implemented digitally and there are a various methods to realize it. [12] provides a comparative study and shows the advantages and drawbacks of each algorithm. One of the most popular MPPT algorithms is Perturb and Observe (P & O), in which we perturb the power by increasing the voltage or current slightly and observe the output power. Figure 2-3 shows the power peak which is the voltage at maximum power where the perturbation has stopped. According to figure 2-3, we perturb and observe increasing power, if the power still increases then keep perturbing in the same direction. Once the power begins to decrease, we perturb, in the opposite direction, until we get to the steady state maximum power point for the load on the array. If the load changes, the MPPT will also change. Note, it is necessary to modify this algorithm in practical implementations to include a deadzone at the steady-state operating point, this will reduce chattering in the P&O algorithm [11]. Figure 2-4 illustrates the basic process.

Fig 2-3: MPPT method

Fig 2-4: P&O algorithm

2.1.2 Experimental PV Model

Fig 2-5: Photovoltaic experimental model

The PV model in figure 2-5 was developed in [8]. The number of series cells is 15, with 2 parallel strings, and 6 kW maximum power. Using MPPT as explained in section 2.1.1 the output voltage is around 26 V at the maximum power point as shown in figure 2-6.a. Figure 2-6.b shows I-V curve which confirms it. The chattering observed in Fig 2-6a is a result of the P&O algorithm without deadzone.

Fig 2-6.a: output voltage at maximum power point b : I-V curve where y-axis depicts voltage and x-axis for current.

A buck (step-down) converter has been used in order to operate the PV panel at 26.3 volts (voltage at maximum power point). The output voltage of the Buck converter (26.3 V) can be increased to 100 volts using a Boost converter to be matched with the wind turbine which has a working voltage of 100 volts to prevent circulating current as discussed in section 1.6. Chapter 3 discusses details of DC/DC converters and their control.

2.2 Wind Turbine

The wind is a useful source to produce energy. Kinetic energy is converted to mechanical energy by such a device. Wind turbines can be used to pump water or to grind grains, or

to produce electrical energy. Figure 2-7 shows the Case Western Reserve University (CWRU) on-campus wind turbine and [15] explains in detail what exactly is inside the wind turbine.

Fig 2-7 : CWRU on-campus wind turbine [18]

Power can be extracted from the wind as in (2-4) and Table 2-2 lists abbreviations used in (2-4)

$$P(t) = T(t) \omega(t) = 0.5 \rho A C_p(t) V(t)^3 \quad (2-4)$$

Where $C_p(t) = f[\gamma(t), \beta(t)] \quad (2-5)$

Symbol	Abbreviation
T	Aerodynamic torque
ω	The rotor speed
ρ	Air density
A	The rotor effective surface
V	The wind speed

C_p

Aerodynamic power coefficient

Table 2-2: Symbols used in equation (2-4).

In (2-5) $\beta(t)$ is the pitch angle, while $\gamma(t)$ is the tip speed ratio. Therefore aerodynamic design of the blades makes $C_p(t)$ a function of $\gamma(t)$ and assuming that pitch angle $\beta(t)$ is constant we have (2-6) [15]

$$\gamma(t) = \frac{R \omega_r(t)}{V(t)} \quad (2-6)$$

R is the radius of the rotor, $\omega_r(t)$ is rotor speed and $V(t)$ is wind speed.

2.2.1 Experimental Wind Turbine Model

For the purposes of our study, equation (2-4) provides the connection between wind speed and available mechanical power. SimPowerSystem is a Simulink Library that provides models for a variety of power system components and devices. Figure 2-8 shows the experimental model has been used.

Fig 2-8: Experimental Wind Turbine Model

In this model we set generator speed to be 1.2 per unit (pu) and wind speed varies from 8.5 to 10 mph and we obtain output voltage around 127 V as shown in figure 2-9

Fig 2-9: output voltage of wind turbine.

Chapter 3: Management of AC-DC (Hybrid) Micro-grids

Fig.1-3 shows that every source works in parallel with its neighbor either in AC sub-grid or DC sub-grid. In a micro-grid systems are connected in parallel to increase the current that can be delivered to a load, as well as to add redundancy to the overall system [6]. Moreover, parallel operation also facilitates proper load sharing. The latter is very important to reduce the burden on the other sources, and to do so we need to develop a proper control technique [6-7]. Droop control is a popular technique, and further explanations about this process are provided in the next subsection.

3.1 DC sub-grid droop control

In a DC power system the transfer of real (active) power is of primary concern, and active power will change proportionally with voltage at constant current. Assume that we have a simple power supply connected to a load, if the load is heavy there may be a voltage drop in the system. Consider a power supply pledge with maximum power $P_{\max}$ with maximum no load voltage V^* . Reducing (droop) in DC source voltage to V can be used to share active power amongst the DC micro-sources [2], see in Fig.3-1 and (3-1)

$$V = V^* - aP \quad (3-1)$$

Fig.3-1: DC sub-grid droop characteristics of P and V

From (3-1), “a” is the droop coefficient, the slope of the line from Fig.3-1. The steeper the slope the stronger the power sharing; however, this results in larger voltage variations and [10] suggests analyzing the system thoroughly before making such a decision.

Fig 3-2: Block diagram of DC-micro-sources control

Figure 3-2 shows the realization of (3-1), where the voltage reference value is computed from (3-1) then subtracted from the actual value and the error signal E is compensated by a Type 2 K Factor controller, the latter produces the control signal U which is converted to proper duty ratio using Pulse-Width Modulation (PWM) circuit.

3.2 AC sub-grid droop control

In contrast, in AC system we have both active and reactive power (P&Q) that requires an equation for both angular frequency ω and voltage amplitude E. Unlike DC systems, in the case of a heavy load the frequency also proportionally decreases. (3-2) and (3-3) show the droop equations for ω and E, respectively.

$$\omega = \omega^* - mP \quad (3-2)$$

$$E = E^* - nQ \quad (3-3)$$

Starred symbols indicate the reference values of ω and E at no load and n and m are the droop coefficients. Once again we should balance between the steepness of slope and power sharing. Fig.3-3 shows the droop characteristics of AC sub-grid.

Fig.3-3: Droop characteristics of AC sub-grid .

With the same technique used for the DC micro-sources, figure 3-4 shows the realization of (3-2) & (3-3). However, here we use the root-mean square (RMS) to calculate the voltages either for the reference or the actual voltage.

Figure 3-4: Block diagram of AC-micro-sources control

3.3 Interfacing Converter for Droop Control

Droop control was first introduced in [2], with the main aim of sharing the load over the grid (AC sub-grid and DC sub-grid) whereas the droop control in AC and DC sub-grids is intended to assist the sub-grids in sharing their load locally. In this configuration, the interfacing converter behaves as a load and a source for the sub-grids depending on where the power transfer needs to occur. As an example assume that the power flows from the AC to DC sub-grid, in this case the interfacing converter acts as a load for the AC sub-grid and as an additional source for DC sub-grid.

Suppose that one of the sub-grids either AC or DC has a heavy load, say 10 kW, and the maximum power that is available in the sub-grid is 8kW, then we still need 2 kW to meet the demand. Suppose that the other sub-grid has surplus power, i.e. available power is 8 kW with load demand load of 5kW. In this case there is 3 kW of excess power, but the total demanded power in entire grid (AC and DC sub-grids) is 15 KW, therefore the interfacing converter droop control, will cause AC sub-grid to reduce its produced power by 2.5 KW, while increase DC sub-grid production by 2.5 KW in order to share the same amount of power. Note, supply must always meet demand so any excess power in the AC and DC sub-grids must be stored locally, or the AC and DC sources need to be curtailed

to meet the supply = demand and equal power sharing constraints. For implementation we need to determine the ability of each sub-grid to meet its local load, if needed what power is available and can be transferred from the other sub-grid, and what the strategy is for power sharing. From sections 3.1 and 3.2 in a DC system, a drop in voltage is a sign that the system is becoming loaded, and as load is added the voltage continues dropping. Similarly, a decrease in frequency indicates a similar situation in the AC system. Figure 3-5.a shows a supply-droop and demand-droop component [2] that when merged provides a new technique as shown in figure 3-5.b where $P_{\max}$ is the maximum absolute power being transferred.

To get the final droop control of the interfacing converter as in Fig.3-5.b there are many ways to proceed. The approach we take is to normalize V_{dc} , the dc-link voltage, and f , the AC frequency, after taking their measurements locally. The final droop control consists of two droop controllers with two power values, making it difficult to use [2].

$$\text{Normalized dc-voltage} = NV_{dc} = \frac{V_{dc} - (V_{\max} + V_{\min})/2}{(V_{\max} - V_{\min})/2} \quad (3-4)$$

$$\text{Normalized ac-frequency} = NF = \frac{f - (f_{\max} + f_{\min})/2}{(f_{\max} - f_{\min})/2} \quad (3-5)$$

Where $V_{\max}$ is the maximum allowable dc-link voltage, $V_{\min}$ is the minimum allowable dc-link voltage, $f_{\max}$ is the maximum AC frequency, and $f_{\min}$ is the minimum AC frequency. Combining NV_{dc} and NF together yields a new normalized variable NI taking values between -1 and 1.

$$NI = \frac{NF - NV_{dc}}{2} \quad (3-6)$$

Positive power indicates that the power flows from DC to AC side, and (3-7) is used to compute the power.

$$P^* = \frac{-P_{max}}{2} NI \quad (3-7)$$

To control power flow among the entire grid there should be no difference between NV_{dc} and NF. A PI controller can be used to eliminate the error, as in (3-8).

$$P_{out} = P^* + (NI * PI) \quad (3-8)$$

Fig 3-5: Droop characteristics for (a) AC and DC micro-grids (b) interfacing converter

The realization of (3-4) through (3-8) is shown in figure 3-6. Where the reference power (3-8) has to be converted to current using division by AC micro-grid voltage, this is now the reference current that should be subtracted from the measured current to yield the

error signal E that is being compensated to produce the signal U signal which in turn is converted to the duty cycle ratio by the PWM circuit.

Fig 3-6 : Block diagram of interfacing converter control

3.4 Power Management Tools

Power electronics circuits are commonly used to coordinate and manage electric power. Sometimes we need to convert it from one form to another to match voltage, current frequency, and phase using semiconductor devices as switches [14]. Power electronics circuits use switches that are opened and closed in a specific period to deliver the required amount of electric power. Figure 3-7 illustrates this process by assuming that we have 9 a volt voltage source and we need to deliver only 3 volts to the resistive load, therefore the switch is open for one-third of the period T , and the average voltage v_x is equal to 3 volts.

Fig 3-7: switched circuit

Figure 3-7 shows the basic concept of electric power converters. However, depending upon the relationship between the input and output, converters can be classified into four different types [14]:

- AC input/ DC output (Rectifier)
- DC input/ AC output (Inverter)
- DC input/ DC output (DC/DC converter)
- AC input/ AC output (AC/AC converter)

In this thesis, we use all of these types. The following subsections cover in these in more detail including their functions and control.

3.4.1 DC/DC converters

This type of converter is used to convert DC voltage from one level to another. It converts DC voltage from low to high level, Boost Converter, or converts it from high to low level, Buck Converter, or makes the output voltage either higher or lower than the input voltage, Buck-Boost Converter. In this work a Buck Converter is to convert wind

turbine output voltage as shown in figure 2-10 to 100 volts, while using Boost Converter to convert PV MPP voltage as shown in figure 2-7.a to 100 volts.

Buck Converter

Figure 3-8 shows a MATLAB Buck Converter where the switch, usually a MOSFET, controls the output voltage, the diode gives a path for the inductor current in case of opened switch and is reverse biased in case of closed switch, low pass filter (LC) is added to the circuit and a resistor represents a real load.

Fig 3-8: Basic Buck Converter

Assuming this circuit works in steady state, we can determine the output voltage by determine the inductor voltage and current when the switch is closed and then when it open, as given in (3-9)

$$V_o = V_s D \quad (3-9)$$

Where V_o is the output voltage, V_s is the source voltage, and D is the duty cycle.

From (3-9) it is obvious that we can set the output voltage at a certain value using the duty cycle, and the duty ratio is the result of dividing the output voltage by the source voltage. To keep the circuit in continuous current mode the minimum value of the inductor L must be as in (3-10)

$$L_{min} = \frac{(1-D)R}{2f} \quad (3-10)$$

Where R is the load resistor and f is the switching frequency.

Output voltage can be constant without ripple by using a capacitor in figure 3-8. Equation (3-11) provides the relationship between the output voltage ripple and capacitor value.

$$C = \frac{1-D}{8L\left(\frac{\Delta V_o}{V_o}\right)f^2} \quad (3-11)$$

Where $\frac{\Delta V_o}{V_o}$ is the output voltage ripple.

Remark: In case of varying set point voltage, although (3-9) can still be used; the preferred approach is to design feedback control to make the system stable and reliable.

In our case the reference voltage comes from droop control and that means it varies with the load, therefore we must design a feedback control. The Buck Converter is a nonlinear system that makes it somewhat challenging to design the control.

DC/DC Converter Control Design

Control loop performance and stability of the converter output voltage can be decided from the open loop characteristics [14]:

- In order to get small steady-state error, the gain should be large at low frequency.
- Further, the gain should be small at the converter's switching frequency.

- Open-loop phase shift should lag by less than 180° at the crossover frequency, to provide a sufficient phase margin, usually 45° or 60° is a good choice.

Figure 3-9 shows a feedback control representation of the Buck Converter, and we can divide it to four different blocks, compensator block, PWM, switch and Filter, and Load. We use MULTISIM to model the circuits and investigate the control properties through AC analysis.

Fig 3-9: Feedback control scheme of Buck Converter

Studying the transient behavior of the converter using a switching model to provide cycle-to-cycle waveforms of voltage and current is time consuming. An efficient way to save time is to develop an Average Circuit Model to compute average values of voltages and currents during the transient, using electric transformer instead of semiconductor switches [14]. Figure 3-10 shows common Averaged Switch Model of a DC/DC converter, which can be used in simulation.

(a)

(b)

Fig 3-10: Averaged switch model in DC/DC converters (a) Buck equivalent, (c) Boost equivalent

Dynamic behavior of voltages, currents, and switching is essential to analyze the control loop. The idea is to perturb the converter with a small signal and observe its variations around the steady-state equilibrium point, as follows:

$$v_o = V_o + \tilde{v}_o$$

$$d = D + \tilde{d}$$

$$I_L = I_L + \tilde{I}_L \tag{3-12}$$

$$v_s = V_s + \tilde{v}_s$$

Where the DC term, steady-state, is depicted by capital letters and the AC term, small signal, is depicted by small letters with tilde. Once again computer software can be used to facilitate this process.

Based on dynamic behavior we can design a proper controller. The most common compensator is Type 2 or 3 Error Amplifier with compensation that compares the reference and measured voltages and converts the error between them to the duty ratio. Figure 3-11 shows a type 2 error amplifier.

Fig 3-11: type 2 error amplifier

The transfer function of this type is as in (3-13)

$$G(s) \approx \frac{s + 1/R_2 C_1}{R_1 C_2 s (s + \frac{1}{R_2 C_2})} \quad (3-13)$$

Obviously, there is one pole at the origin, pole at $\omega_p \approx \frac{1}{R_2 C_2}$ and zero at $\omega_z \approx \frac{1}{R_2 C_1}$.

A pole at the origin in (3-13) introduces -90° phase shift in the transfer function, and unfortunately -90° and the phase of the power stage transfer function at crossover

frequency $\angle G_{ps}|_{f_c}$ is less than -180° . Thus, to get specific phase margin ϕ_{PM} we have to boost the phase ϕ_{boost} at f_c by:

$$\phi_{boost} = -90 + \phi_{PM} - \angle G_{ps}|_{f_c} \quad (3-14)$$

In fact, (3-13) can be realized as in (3-15)

$$G_c(s) = \frac{K_c(1 + \frac{s}{2\pi f_z})}{s(1 + \frac{s}{2\pi f_p})} \quad (3-15)$$

Where the gain $K_c = 2\pi f_z |G_c(s)|_{f_c}$, pole at f_p equal to $\frac{f_c}{K_{boost}}$ and zero at f_z equal to $(f_c * K_{boost})$.

From the above a new factor, K_{boost} , is given in (3-16).

$$K_{boost} = \tan(45 + \frac{\phi_{boost}}{4}) \quad (3-16)$$

Design Procedure for $G_c(s)$ [16]

1. Choose the crossover frequency f_c , which should be greater than the resonance frequency of (LC) to keep loop phase angle greater than -180° at all frequencies below f_c .
2. Choose phase margin ϕ_{PM} to get the needed phase boost ϕ_{boost} as in (3-14)
3. Calculate the controller gain at f_c by assuming that the gain of the open loop is 1 or 0db as follows:

$$|G_L(s)|_{f_c} = |G_c(s)|_{f_c} \times |G_{PWM}|_{f_c} \times |G_{PS}|_{f_c} = 1 \quad (3-17)$$

Where $|G_{PWM}|_{f_c} = 0.556$, assuming PWM transfer function is $\frac{1}{V_p}$, and Saw tooth function peak is 1.8.

4. Use (3-15) and (3-16) to build the controller.

Design of the Feedback Controller of Wind Turbine Buck Converter

First, we need to determine the Buck Converter parameters such as inductor, L , capacitor, C , and resistor, R . Let's start with an arbitrary resistor value $R=10\Omega$ and switching frequency $f=100\text{kHz}$, and we know that the output of the generator is around 125 to 127 volts. Use (3-9) to compute the duty ratio D given that the desired output voltage should be 100 volt. As soon as we get D we use it in (3-10) to determine the minimum value of the inductor that keeps the current in continuous mode, therefore $L_{\min} = 21.3 \mu\text{H}$, and we can choose L to be $30 \mu\text{H}$. From (3-11) we determine the value of the capacitor C to be $18\mu\text{F}$ by assuming that the voltage ripples are not greater than 0.5 percent.

Now we use MULTISIM to model the Buck Converter and study its frequency response in order to design the controller $G_c(s)$. We use the averaged model for switch and diode for the control studying, therefore we use figure 3-10.b for Buck equivalent, and then perturb the circuit with small AC signal, say at 1 kHz, to see its behavior around a steady-state operating point as shown in figure 3-13.

Fig 3-12: Buck Converter with averaged switch & diode and small signal perturbation.

Now run AC analysis to see frequency response of G_{ps} as in figure 3-13. Figure 3-13.a is the magnitude response where we can notice the resonant frequency around 6.5 kHz, hence we can choose f_c to be greater than 6.5kHz, say 10 kHz, at this value the magnitude is 40.6062 dB, 107.23 volts. Figure 3-14.b shows the phase response with phase -158.89° at k .

(a)

(b)

Fig 3-13: Buck Converter frequency response (a) magnitude response (b) phase response

Next step choose phase margin, say 60° , to get boost phase as in (3-14) knowing that $\angle G_{ps}|_{f_c} = -158.89^\circ$, yields the required boost phase $\phi_{boost} = 128.89$.

Third step to calculate the controller gain at crossover frequency $|G_c(s)|_{f_c}$ by using (3-17), yields:

$$|G_c(s)|_{f_c} = \frac{1}{(0.556)(107.23)} = 0.0168$$

From (3-15) and (3-16) we get:

$$K_{boost} = 4.41$$

$$f_p = 44100$$

$$f_z = 2267.57$$

$$K_c = 54.28$$

Remark: The gain of $G_c(s)$ is 0.0168, so we need to adjust K_c . Therefore, we need to test our controller with small signal, as in figure 3-15.a, with the gain $K_c = 54.28$, and the new gain of the controller and adjust it with $|G_c(s)|_{f_c} = 0.0168$.

Firstly, we need to check $|G_c(s)|_{f_c}$ with the gain $K_c = 54.28$.

(a)

(b)

(c)

Figure 3-14: controller $G_c(s)$ analysis (a) controller being perturbed with small signal (b) magnitude response (c) phase response.

From figure 3-14.b the gain at $f_c = 10 \text{ KHz}$ is 0.017 dB, 1 volt. This yields:

$1 \times 0.0168 \rightarrow x=0.0168$, multiply this value by $K_c = 54.28$ to get the new corrected gain which is 0.91

In figure 3-14.c we can see boost phase clearly at the crossover frequency.

The controller is tested in closed-loop in MATLAB with the buck converter as in figure 3-10 to set the output voltage at 100 volt. Figure 3-16.a shows the output voltage of wind turbine generator, typically not regulated, while 3-16.b shows the output voltage of buck converter after being regulated.

Fig 3-15: (a) wind turbine output voltage

(b) controlled buck converter output voltage

Boost Converter

Boost Converter, sometimes called step-up converter, is shown in figure 3-17, and with the same technique and assumptions used in Buck Converter analysis we can analyze it.

Fig 3-16: Basic Boost Converter structure

For the Boost Converter we obtain:

- 1- Relationship between input and output voltage

$$V_o = \frac{V_s}{1-D} \quad (3-18)$$

- 2- Minimum inductance to keep current in continuous mode

$$L_{min} = \frac{D(1-D)^2 R}{2f} \quad (3-19)$$

- 3- Minimum capacitance to limit the output ripple voltage to certain percent

$$C \geq \frac{D}{R \left(\frac{\Delta V_o}{V_o} \right) f} \quad (3-20)$$

- 4- Since the Boost Converter is DC/DC converter, therefore controller design technique is the same as that used with the Buck Converter, except the averaged switch model should be boost equivalent as in figure 3-11.c.

Design of Feedback Controller for the Photovoltaic Boost Converter

MPP output voltage of PV is shown in figure 2-7.a , and it must be matched with the wind turbine output voltage, 100 volts, therefore we need to boost it up to 100 volts using a boost converter. With use the same procedure and steps of controller design for buck converter to deal with the boost converter.

Step 1: Determine boost converter parameters knowing that the input voltage ~26 volts is required to be at 100 volts. Therefore using (3-18) through (3-20) we get $R=32.29\Omega$, $L=25 \mu H$ and $C=45 \mu F$.

Step 2: Choose the crossover frequency.

(a)

(b)

Fig 3-17: G_{ps} frequency response of boost converter

From the above figure the resonant frequency is about 4 kHz, therefore the crossover frequency should be greater than 4kHz, say 10 kHz.

Step 3: Determine boosting phase as in (3-14).

$$\phi_{boost} = 128.26.$$

Step 4: From (3-17) determine controller gain at crossover frequency.

$$|G_c(s)|_{f_c} = 0.087$$

Step 5: From (3-15) and (3-16) get the rest of controller parameters.

$$K_{boost} = 4.35$$

$$f_p = 43500$$

$$f_z = 2298.85$$

$$K_c = 282.88$$

With the same technique we correct the gain, thus we need to check $G_c(s)$ response with

K_c

(a)

(b)

Fig 3-18: $G_c(s)$ Frequency response (a) magnitude response (b) phase response

Adjust the gain from figure 3-18.a with $|G_c(s)|_{f_c} = 0.087$, resulting in a corrected gain

$K_c = 77.065$. Once again 3-18.b is the boost phase at crossover frequency.

Next, evaluate the controller $G_c(s)$ in MATLAB to get regulated output voltage set at 100 volts. Figure 2-7.a shows photovoltaic MPP output voltage, while figure 3-19 shows regulated boost converter output voltage being set at 100 volts.

Fig 3-19: PV boost converter output voltage

DC sub-grid Coordination

Droop control discussed in section 3.1 is needed to provide load sharing between both micro-sources, by determining the appropriate reference voltage. Both micro-sources work at 100 volts, maximum, this value drops as sub-grid are loaded, so we choose it to be 80 volts at maximum power, 2kW. Therefore, we have to use buck converter to manage this variation, from 100 to 80 volts. With the same technique we design the controller.

Step 1: Determine buck converter parameters: $R=10\ \Omega$, $L=35\ \mu\text{H}$ and $C=79\ \mu\text{F}$.

Step 2: Choose the crossover frequency.

(a)

(b)

Fig 3-20: $G_{ps}(s)$ frequency response of DC sub-grid (a) magnitude response (b) phase response

From the above figure the resonant frequency is about 3 kHz, therefore the crossover frequency should be greater than 3 KHz, say 10 kHz.

Step 3: Determine boosting phase as in (3-14).

$$\phi_{boost} = 119.55^\circ$$

Step 4: From (3-17) determine controller gain at crossover frequency.

$$|G_c(s)|_{f_c} = 0.162$$

Step 5: From (3-15) and (3-16) get the rest of controller parameters.

$$K_{boost} = 3.70$$

$$f_p = 37 \text{ KHz}$$

$$f_z = 2702.70 \text{ Hz}$$

$$K_c = 118.22$$

Next, we build this controller and test it at two different reference values, say 85 and 90 volts.

(a)

(b)

(c)

Fig 3-21: Voltage level stability with load variation of buck converter (a) circuit diagram (b) transient analysis at reference point 85 volts (c) transient analysis at reference point 90 volts.

In figure 3-21.a there are two parallel resistors connected through switch to get the load to varying between 10 and 5 Ω , in order to see their effect on controller behavior. In the same figure, b and c show voltage level stability at its set point of 85 volts and 90 volts respectively even when the load is changed.

3.4.2 AC/AC Converter

AC/AC converter often called AC Voltage Controller or regulator, because it controls the average power, current and voltage, delivered to an AC load from an AC source by means of connecting and disconnecting of the source and load at specific periods of time, keeping in mind that both switches can't conduct simultaneously. Figure 3-24.a shows basic single phase AC/AC converter in which the switches, Thyristors (SCRs), connected in antiparallel, so the current can flow in either direction in the load [14]. Because this type of converter works in a switching scheme we called it phase control, therefore we can delay the firing angle by specific degrees to obtain the required output voltage as shown in figure 3-24.b. It is very important to understand the relationship between the AC input and output voltages.

(a)

Fig 3-22: (a) single phase AC voltage controller with resistive load (b) Waveforms

Assume the input voltage in figure 3-22.a is

$$V_s(\omega t) = V_m \sin \omega t \quad (3-21)$$

Output voltage will be

$$V_o(\omega t) = \begin{cases} V_m \sin \omega t & \text{for } \alpha < \omega t < \pi \text{ and } \alpha + \pi < \omega t < 2\pi \\ 0 & \text{otherwise} \end{cases} \quad (3-22)$$

Root mean square value (RMS) of the output voltage can be written as in (3-23)

$$V_{o,rms} = \frac{V_m}{\sqrt{2}} \sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}} \quad (3-23)$$

Where V_m is the peak value of the source voltage and α is the phase angle.

(3-23) is a very important equation because it provides the output voltage knowing the source voltage and phase angle.

AC sub-grid Coordination

Section 3.2 explained in detail how to design a droop control that provides the AC/AC converter with the reference voltage for each micro-sources to achieve power sharing between them, therefore assume maximum frequency to be 60 Hz which drops to 50 Hz at maximum real power, 2kW. On the other hand assume maximum amplitude to be 100 volts RMS which drops to 80 volts RMS at maximum reactive power, 500W. Resulting frequency and amplitude into (3-21) to determine RMS reference voltage. (3-23) can be implemented easily in SIMULINK to provide the converter with proper phase angle that matches the output voltage to the reference voltage, see appendix figure B.

3.4.3 Interfacing Converter

The interfacing converter should be able to transfer power between both sub-grids as needed, in other word it should acts as a rectifier in Power Factor Correction Mode PFCM, and an inverter, in Grid Connection Mode GCM. Figure 3-23 shows common single phase full-wave bridge that can work in either mode by adjusting the phase angle α .

Fig 3-23: single phase full-wave bridge

To determine the operating mode, either PFCM or GCM, (3-24) should be applied [14]

$$\begin{array}{ll} 0 < \alpha < 90^\circ \rightarrow V_o > 0 & PFCM \\ 90^\circ < \alpha < 180^\circ \rightarrow V_o < 0 & GCM \end{array} \quad (3-24)$$

Interfacing Converter Control

This type of power converter is highly nonlinear system making controller design a challenge. [13] proposed calculating duty cycle for each mode, then determine which mode is to be used based on a hysteresis band for DC voltage. To obtain the duty cycle for each mode see Figure 3 in [13].

GCM Operating Mode

From the figure, the period of the switching cycle for the positive half cycle from (n-1) to (n+2), V_{DC} is DC bus voltage, V_{AB} is the voltage of the converter, V_{ac} is AC line voltage and i_c is the converter output current. As switches turn on in segment (n, n+d), $V_{AB} = V_{DC}$ and hence:

$$V_L = V_{DC} - V_{ac}(n, n+d) = L \frac{i_{ac}(n+d) - i_{ac}(n)}{d(n) \cdot T_s} \quad (3-25)$$

Where $V_{ac}(n, n+d)$ is the average of AC line voltage, L is the inductor, d(n) duty ratio and T_s is the period of the main grid.

Next, take segment (n+d, n+1)

$$V_L = 0 - V_{ac}(n+d, n+1) = L \frac{i_{ac}(n+1) - i_{ac}(n+d)}{[1-d(n)] \cdot T_s} \quad (3-26)$$

From (3-25) and (3-26)

$$d(n) = d(n-1) + \frac{L}{T_s V_{DC}} \cdot [i_{ref}(n+1) - i_{ac}(n-1)] \quad (3-27)$$

Suppose that current set point is as the same as actual current but at the end of next cycle and substitute output current with the previous current to get

$$d(n) = 2 - d(n - 1) + \frac{L}{T_s V_{DC}} \cdot [i_{ref}(n + 1) - i_{ac}(n - 1)] - \frac{2V_{ac}(n-1)}{V_{DC}} \quad (3-28)$$

Now (3-28) is valid for negative half cycle and it is quite simple to implement it in MATLAB, or using DSP technique to implement it in a microprocessor.

PFCM Operating Mode

PFCM can be analyzed in a similar way as GCM. The difference here is to keep in mind the change of inductor voltage and output current direction. Similarly we get

$$d(n) = 2 - d(n - 1) + \frac{L}{T_s V_{DC}} \cdot [i_{ref}(n + 1) - i_{ac}(n - 1)] - \frac{2V_{ac}(n-1)}{V_{DC}} \quad (3-29)$$

Once again, (3-29) is valid for negative half cycle.

Chapter 4 System Verification and Simulation Results

Basically, assume that all micro-sources are rated equally at 2kW, and interfacing converter is rated at 4kW to transfer full power capacity of each sub-grid to another as requested. We test entire grid in four different scenarios.

Scenario 1: Light DC load vs. Heavy AC load

In this scenario DC load is assumed to be light, 1 kW, while AC load exceeds AC sub-grid power capacity, say 6.5 KW, and 7.5 KW as a total load in both sub-grids. Hence DC sub-grid still has 3 kW available, and according to (3-7) interfacing converter will transfer 2.75 kW from DC sub-grid to AC sub-grid and the latter reduces its power production by 2.75 KW. Consequently, each sub-grid produces 3.75 KW, and droop control in each sub-grid causes each micro-source to produce 1.875 KW. Figure 4-1 confirms these calculations, where (a) is AC load, (B) DC load, (c) each AC micro-sources, (d) each DC micro-sources and (e) interfacing converter. This order is valid for all scenarios.

(a)

(b)

(c)

(d)

(e)

Fig 4-1: power flow for scenario 1 (a) is AC load, (B) DC load, (c) each AC micro-sources, (d) each DC micro-sources and (e) interfacing converter.

Scenario 2: heavy DC load vs. light AC load

Assume DC load to be 5.8 kW and AC load to be 1 kW, and then in contrast the AC sub-grid has 3 kW in excess, and 2.4 kW will be transferred to DC sub-grid, and each micro-source will produce 1.7 kW. The transferred power in this scenario with negative sign to indicate that power is being transferred from AC to DC sub-grids and interfacing converter works in PFC mode.

(a)

(b)

(c)

(d)

(e)

Fig 4-2: power flow for scenario 2 (a) is AC load, (B) DC load, (c) each AC micro-sources, (d) each DC micro-sources and (e) interfacing converter.

Scenario 3: Heavy DC load vs. Heavy AC load

In this scenario assume each sub-grid works around its maximum capacity, AC load is 3.8 kW and DC load is 3.6 kW. Therefore, a small amount of power, around 0.1 kW, will be transferred from DC to AC side.

(a)

(b)

(c)

(d)

(e)

Fig 4-3: power flow for scenario 3 (a) is AC load, (B) DC load, (c) each AC micro-sources, (d) each DC micro-sources and (e) interfacing converter.

Scenario 4: Light DC load vs. light AC load

In this scenario every sub-grid has additional power, and they can only transfer small amount of power. Assume the DC load demands 2.1 kW, while AC load requests 1.9 kW, then AC sub-grid donates -0.1 kW.

(a)

(b)

(c)

(d)

(e)

Fig 4-4: power flow for scenario 4 (a) is AC load, (B) DC load, (c) each AC micro-sources, (d) each DC micro-sources and (e) interfacing converter.

Chapter 5 Conclusions and Future work

Power micro-grids are useful configurations for the power grid to improve electrical efficiency and ensure its reliability. This thesis shows the flexibility of micro-grid management, using the, Droop Demand Control technique. The new Droop Control technique proposed in [1], was applied to each sub-grid and then tested in the AC-DC grid to show proper power sharing between the sub-grids for a variety of different loading configurations.

The next step is to extend this technique to systems operating with dynamically variable supply and demand, possibly with energy storage, both in simulation and in physical laboratory hardware.

Appendix

MTLAB function of normalized NF and ND

```
function [NV,NF] = fcn(V_dc,f_grid)
%#codegen

NV=(V_dc-90)/10;
NF=(f_grid-55)/5;
```

MATLAB function of DC sub-grid droop control

```
function v_ref = fcn(p)
%#codegen

v_ref= 100-(0.005*p);
```

MATLAB function of AC sub-grid droop control

```
function v_ref = fcn(P,Q)
%#codegen
f=60-(0.0025*P);
E=100*1.414-(0.04*Q);
v_ref=E*sin(2*pi*f);
```

Wind Turbine Structure

Fig A: wind turbine MATLAB configuration

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