ASYNCHRONOUS INTERCONNECTION OF A MICROGRID

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ABSTRACT

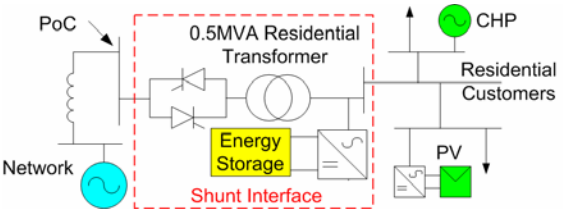
This paper shows how a back-to-back asynchronous interconnection can be used to turn part of the utility network into an advanced Smartgrid or Microgrid, which behaves like a model citizen as seen from the main network and offers uninterruptible supply functionality to its loads or microsources. Additionally energy storage can be integrated on to the DC link of the AC:DC:AC connection interface. The basic control of such a system is discussed and simulation results of its operation are presented.

INTRODUCTION

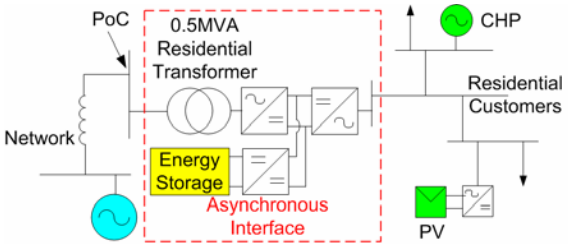
A significant 'smartgrid technology' is the so-called Microgrid, in which loads and micro-generators are bundled together, with some local storage, by intelligent control, to form a 'well-behaved' or even 'model' citizen [1]. In practice this means that the consumer network appears to the utility as a net generator or net load with well-behaved characteristics. At the same time the local storage and intelligent control, coupled with a power electronics switch connecting the Microgrid to the main network, allow the Microgrid to disconnect from the main network during network disturbances, and continue to operate autonomously, i.e. operate islanded. This, it has been argued, potentially improves power quality to the consumer.

Hitherto such Microgrids have typically taken the form of an off-line uninterruptible power supply (UPS), fig. 1a. A power electronic switch disconnects the Microgrid from the main network, and a shunt storage unit supplies the resulting short-fall in power to the loads (or absorbs excess power if the Microgrid was exporting power). The actual energy storage unit may be one or several units, and may be augmented by back-up generation and load-shedding. During islanding the Microgrid will experience a degree of disruption, until the system detects the disturbance and successfully islands. Resynchronisation requires a certain amount of care.

The concept of an inline Microgrid Connection Interface (MCI), fig. 1b has received little attention, although back-to-back voltage source HVDC has been proposed for other applications [2]. Compared with a shunt system, an inline system has the potential to almost fully decouple the main network from the local Microgrid. Resynchronisation is straightforward since the inverter connected to the main utility network need not actually disconnect. Real power flow between the two AC sides of the interconnection is merely suspended. Power quality to the Microgrid network is improved since disturbances on the main network potentially do not propagate through. The addition of a DC link also gives a ready connection point for DC energy storage and potentially a DC distribution bus. Clearly the system cost, whether it is a voltage-source interface (as here) or current-source, is increased, and system losses are an issue.



(a) Shunt Energy Storage Interface



(b) AC:DC:AC Asynchronous Interface

Figure 1 - Examples of Possible MCIs

From figure 1, clearly it can be seen that there are issues surrounding whether the Microgrid Connection Interface (MCI) is on the low-voltage (LV, 11kV) side of the connection transformer or on the consumer voltage (CV, 400V) side. This affects earthing method for the consumer voltage network, device voltage rating, fault behaviour and harmonics.

CONTROL METHOD SELECTION

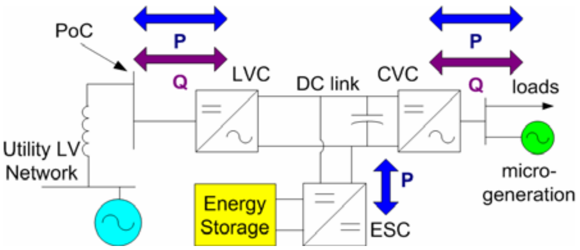


Figure 2 – Real and Reactive Power Flows in Asynchronous AC:DC:AC MCI

This paper will focus primarily on the control methodologies for the interfaces converters. For the purpose of the discussion in this paper, we designate a converter as controlling either the voltage on the DC link or as controlling another system state variable (power supplied to an ac system, or ac system voltage). The methods can then be sub-divided according to which power electronic converter acts to stabilise the DC bus.

In figure 2, the Low-Voltage Converter (LVC), an AC:DC inverter, connects the DC link to the Point of Connection to the utility network (PoC). The LVC power electronic circuit can supply or absorb real and reactive power from the utility LV network. Similarly the Consumer Voltage Converter (CVC), connects the loads and micro-generation of the consumer voltage network to the DC link. Again it can supply or absorb both real and reactive power. The Energy Storage Converter (ESC) connects the energy storage system (DC battery, DC flywheel output or similar) to the DC link. It can absorb or inject real power to the DC link.

Clearly reactive power injection through the LVC is independent of reactive power injection through the CVC, as long as the DC link voltage remains stable. However the real power flow through the LVC, CVC and ESC must balance, or else the DC link voltage will shift. Broadly speaking, operation of one of the three converters should be constrained to stabilise the DC bus.

As is summarised in table 1, the selection of which converter acts to maintain the DC link voltage, has a significant impact on the operating characteristics of the Microgrid. This is discussion applies to a Microgrid which is network connected. Under autonomous operation, the Microgrid always exchanges real power with the energy storage unit. The LVC power flow is zero in such cases.

Mode 1-ESC, with the Energy Storage Converter stabilising the DC voltage is the most desirable mode. From the utility side, the Microgrid appears as a ‘model citizen’ providing a programmable, constant flow of real and reactive power. From the Microgrid side, the interface absorbs any mismatch between local loads and micro-generation. Clearly if the sum of the two power flows (less any MCI losses) deviates significantly from zero, then the energy storage unit is rapidly charged or discharged. ‘Rapidly’ in this context assumes that dispatch commands to the Microgrid are updated in the same timeframe as to conventional generation units (fractions of an hour at best), and that energy storage is kept to a minimum to reduce cost. Consequently energy storage cannot support large mismatches between LVC and CVC real power flows.

If however mode 2 –LVC is used, then the utility is required to inject or absorb real power to balance the DC link voltage. This clearly means than the Microgrid no longer looks like a ‘model citizen’, and from a utility point of view the Microgrid potentially loses much of its system-side benefits. Significantly the ability to limit utility network power flows and avoid distribution or transmission system upgrades may be lost. Reactive power flow control may ameliorate some power flows, but the MCI proposed is a rather expensive solution to just control reactive power. In mode 2, power quality to the consumer is however safe-guarded. This may be an appropriate solution for high value consumers – in effect this is a wide-area conventional UPS.

VS	DC VS converter power flow constraint	Operation of remaining converters
1.ESC	Integral of real power limited by initial state of charge of energy storage unit	• LVC – network operator can set net P and Q. Microgrid appears as model citizen. • CVC – interface can acts as ‘slack bus’, setting Microgrid AC voltage and balancing AC Microgrid power flows.
2.LVC	Microgrid real power drawn from utility network fluctuates in response to Microgrid loads or microgeneration	• ESC – energy storage unit can be recharged or discharged. • CVC – interface can acts as ‘slack bus’, setting Microgrid AC voltage and balancing AC Microgrid power flows.
3.CVC	Load shedding, microgeneration curtailment or local storage within microgeneration units must be used to control CVC real power flow	• LVC – network operator can set net P and Q. Microgrid appears as model citizen. • ESC – energy storage unit can be recharged or discharged. Energy storage unit absorbs short-term variation in CVC power.

Table 1 – Impact of Selection of which Converter acts as DC Voltage Source (VS) i.e. DC-link Stabilisation Unit for a Network Connected Microgrid

If mode 3-CVC is used, then power flow to the utility is predictable. However since power flow to and from the Microgrid must be constrained, a combination of load management (shedding) and micro-generation curtailment must be used. Since in practice loads would switch in an out of the Microgrid, and microgeneration output will vary, this balancing is a dynamic process. Power flow from the Microgrid could only be control ‘on average’. There would be a variation which would feed through to either the utility or to the energy storage unit. Of these two options, variation of power to the energy storage unit is the more acceptable – the CVC controller could manage the average power flow, bringing it back to an acceptable value within several seconds. This assumes there are sufficient sheddable loads or controllable microgeneration units of course.

INTERFACE CONTROL

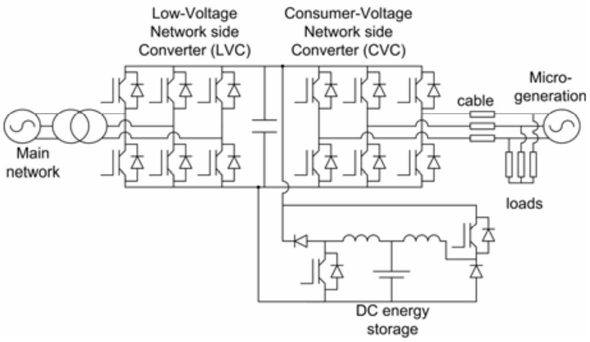


Figure 3 – Asynchronous Link with DC Energy Storage

An asynchronous Microgrid interface was modelled in PSCAD^{TM}. The inverters used were 6 switch IGBT bridges with anti-parallel diodes. For simplicity, the DC:DC converter models used to connect the 200V battery model to the DC bus were buck (step-down) and boost (step-up) converters respectively.

Low-Voltage Network Converter (LVC) Control

The main network was modelled as an infinite bus behind the connection transformer impedance. This transformer assumed to be rated at 500MVA with a 5% impedance and an X/R ratio of 15.

The LVC control was undertaken in the dq domain [3]. The dq domain was aligned so that vq=0V, and an id loop was used to control real power and an iq loop used to control reactive power. It is assumed that the utility network controller sends a dispatch signal to the MCI with nominal demand values of real and reactive power. To assist in power sharing if multiple Microgrids are connected, a droop-line based on frequency and network voltage modifies this set value [4]. Frequency and voltage were translated to current values rather than power values, since this allows the control to limit fault current contribution during a network-side sag or fault, figure 4.

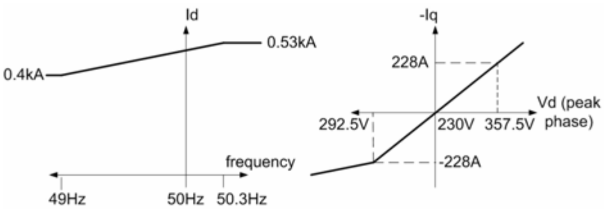


Figure 3 – CVC Current Loop Set parameters (upward axis direction implies power into CVC)

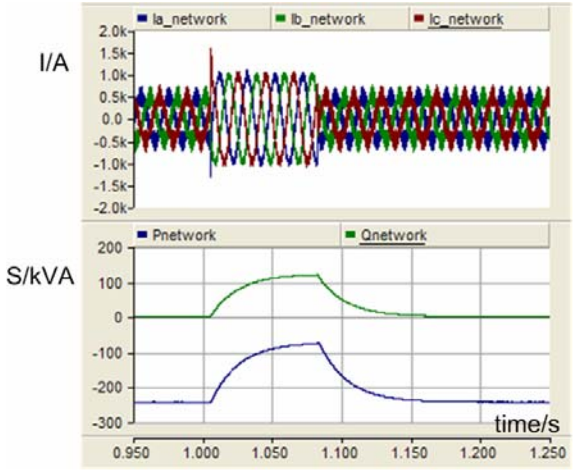


Figure 4 – CVC response to a network sag to 0.3pu retained voltage (P and Q are averaged meter values)

In this case, the dq current loops have been decoupled using set values in the decoupling terms (rather than measured values) to reduce the effect of noise. They use PI controllers with closed loop feedback and have been tuned by using a second order approximation to the step response transfer function [3], with nominal values of damping ratio and undamped natural frequency of 0.7 and 500Hz respectively. A control feed-forward term, measures the DC link voltage and adjusts the inverter PWM to decouple variations in this parameter.

As can be seen in figure 4, initially the LVC absorbs approximately 240kW from the utility and injects zero reactive power. Once the utility network experiences a sag, the amount of real power that the CVC can absorb is reduced. However the CVC starts injecting reactive power into the network to support the local voltage. Current into the network also increases, but is limited by the dq controller action. Once the utility network voltage is restored, the CVC control set-points and outputs return to their original values.

DC:DC Control

The DC:DC controllers use two nested control loops. The boost converter control is shown in figure 5. The voltage on the DC link between the two inverters (CVC and LVC) is compared with a reference. A proportional controller is used to generate a DC-link recharge current based on this DC-link voltage error. Feed-forward control subtracts the actual current into the DC link to give rapid response. A feedback control loop measured the DC:DC converter current and compares it with the reference to give an error signal into a PI control loop. Again this has been tuned using a second order approximation with a damping factor of 1 and a natural frequency of 4000 rad/s.

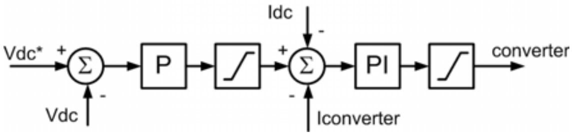


Figure 5 – Boost converter control overview

Hysteresis control (not shown in figure 5) has been added to switch off the DC:DC converters if the DC link voltage is within a tolerance band of its set value. The buck-converter control uses the same structure though positive and negative signs must be interchanged for some quantities.

Figure 6 shows the DC link and current carried by the buck and boost converters for the same period as the sag in figure 4. Before 1s, the buck converter periodically takes charge from the DC link. The utility has set the LVC to absorb enough real power to supply the net difference between the Microgrid loads and micro-generation as well as recharge the battery energy storage to the DC link.

At the onset of the sag, at 1s, the boost converter transfers a large amount of charge to the DC link to maintain the DC voltage. The DC link voltage is maintained in the range 760V to 880V for the sag duration. The disturbance on the utility network is completely isolated from the Microgrid.

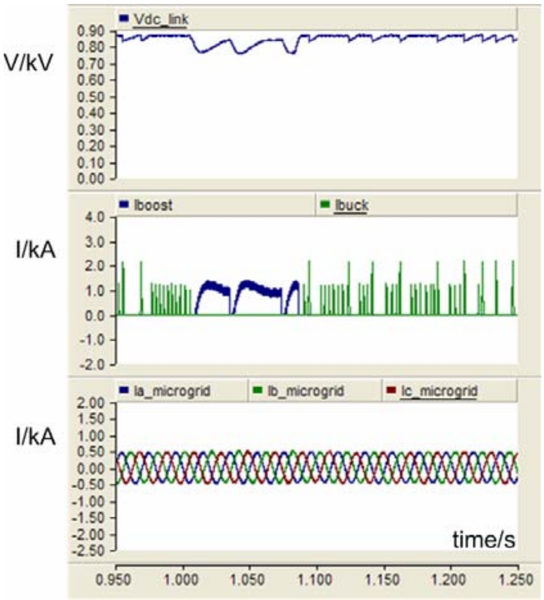


Figure 6 – DC:DC converter control in response to network sag

Consumer-Voltage Network Converter (CVC) Control

The CVC inverter control is aimed at maintaining the Microgrid voltage and frequency at a set-point. It functions as the 'grid forming' inverter, or in alternative terminology, it acts as the slack bus. Droop line control adjusts the terminal voltage according to the equations:

$$\left.\begin{array}{l}
\mathrm{Vrms} = 255\mathrm{V},\ \ \mathrm{Q} < \text{-}500\mathrm{kVAr} \\
\mathrm{Vrms} = 245 - \dfrac{10\mathrm{V}\times \mathrm{Q}}{500\mathrm{kVAr}},\ \ \text{-}500\mathrm{kVAr} < \mathrm{Q} < 0\mathrm{kVAr} \\
\mathrm{Vrms} = 245\text{-}\dfrac{5\mathrm{V}\times \mathrm{Q}}{500\mathrm{kVAr}},\ \ 0\mathrm{kVAr} < \mathrm{Q} < 500\mathrm{kVAr} \\
\mathrm{Vrms} = 240\mathrm{V},\ \ 500\mathrm{kVAr} < \mathrm{Q}
\end{array}\right\}$$

$$\left.\begin{array}{l}
\mathrm{f} = 51\mathrm{Hz},\ \ \mathrm{P} < \text{-}500\mathrm{kW} \\
\mathrm{f} = 50Hz - \dfrac{1\mathrm{Hz}\times \mathrm{P}}{500\mathrm{kW}},\ \ \text{-}500\mathrm{kW} < P < 500\mathrm{kW} \\
\mathrm{f} = 49Hz,\ \ 500\mathrm{kW} < \mathrm{P}
\end{array}\right\}$$

where a negative power indicates power absorption by the CVC inverter. The micro-generation is controlled using two closed loop PI regulators. One loop sets real power, manipulating the angle between the output voltage of the micro-generation and the Microgrid voltage. The other loop sets the reactive power by controlling the magnitude of the micro-generation output voltage. Since the power feedback is based on averaging meters rather than dq, the micro-generation response is slow.

Figure 7 shows the result of a change in micro-generation output. The micro-generation initially supplies 150kW at unity power factor. The CVC supplies the balance of apparent power to the loads. At 1s, the micro-generation set-point drops to 40kW at unity power factor. The CVC picks up the remainder of the loads, but as a result of the frequency vs. power droop control, the Microgrid frequency drops until at 1.18s, frequency-based load shedding removes one-third of the (non-critical) Microgrid loads. At 1.5s micro-generation output is increased to 150kW again, the CVC supplies less power, frequency increases and at 1.56s, the shed load is reconnected. The CVC must balance load requirements and micro-generation dynamics. The power to the network at the PoC remains constant throughout (not shown).

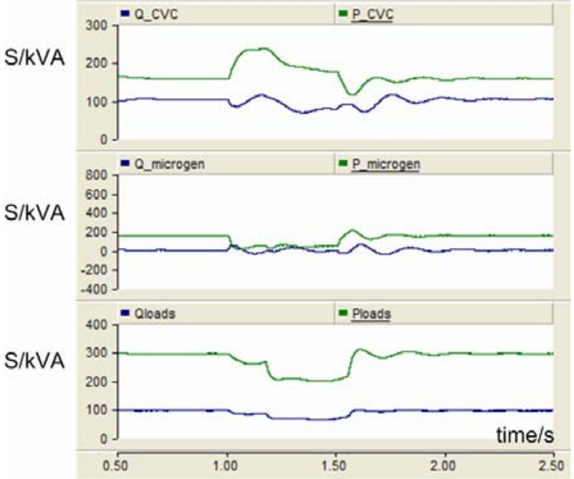


Figure 7 – Microgrid power flows during a drop in micro-generation output power (1 to 1.4s) and a consequent shedding of one-third of loads (1.18 to 1.53s).

CONCLUSIONS

This paper has shown that it is possible to use an asynchronous interface for a Microgrid, with energy storage, to both achieve improved power quality to the consumer and 'model citizen' behaviour to the utility network. The control of each power electronic block is strongly coupled and the control of the system needs careful consideration**.**

ACKNOWLEDGEMENTS

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