Large Scale Integration of Micro-Generation to Low Voltage Grids

Contract No: ENK-CT-2002-00610

WORK PACKAGE B

DB1:
Local Micro Source controller strategies and algorithms

February 2004

Document Information

Title:	DB1 Local Micro Source controller strategies and algorithms
Date:	25.02.2004
Deliverable:	DB1

Coordination:	Alfred **Engler**	aengler@iset.uni-kassel.de
Authors:	Alfred **Engler**	
	Oleg **Osika**	oosika@iset.uni-kassel.de
	Mikes **Barnes**	mike.barnes@umist.ac.uk
	Nick **Jenkins**	UMIST
	A. **Arulampalam**	UMIST

Access: Project Consortium
European Commission
Restricted

Status:

_	For Information
_	Draft Version
_	Final Version (internal document)
x	Submission for Approval (deliverable)
_	Final Version (deliverable, approved on._)

Contents

1. Introduction

Modern power network operators are having to respond to a number of challenges: load growth and changes in the geographical distribution of customers on the one hand; new environmental policy and the usual economic pressures of the marketplace on the other. Upgrading infrastructure to solve the former two problems is constrained by the latter two. Indeed the extension of the transmission network is now usually not possible due to an (understandable) 'Not In My Back-Yard' (NIMBY) attitude by the local community. All this and a multi-national commitment to reduce CO_2 emissions, has led to increased interest in the local connection of renewable energy generation and Combined Heat and Power (CHP) at the distribution level.

In principle this Distributed Generation (DG) can ease pressure on the transmission system capacity by supplying some of the local load. In reality there are technical limits on the degree to which Distributed Generation can be connected, especially for some intermittent forms of renewable generation and weaker areas of the distribution network. This limit principally stems from the original design philosophy of the power system. The distribution network was intended to cope with conventional loads being supplied from central generation: a hierarchical flow of power from the transmission network down. Changing the power flow causes problems since DG does not behave in the same way as a conventional load.

The Microgrid concept has been discussed as a potential means to combat problems caused by the unconventional behaviour of DG and increasing DG penetration [1]. In essence a Microgrid, Fig. 1, consists of a combination of generation sources, loads and energy storage interfaced through fast acting power electronics. This combination of units is connected to the distribution network through a single Point of Common Coupling (PCC) and appears to the

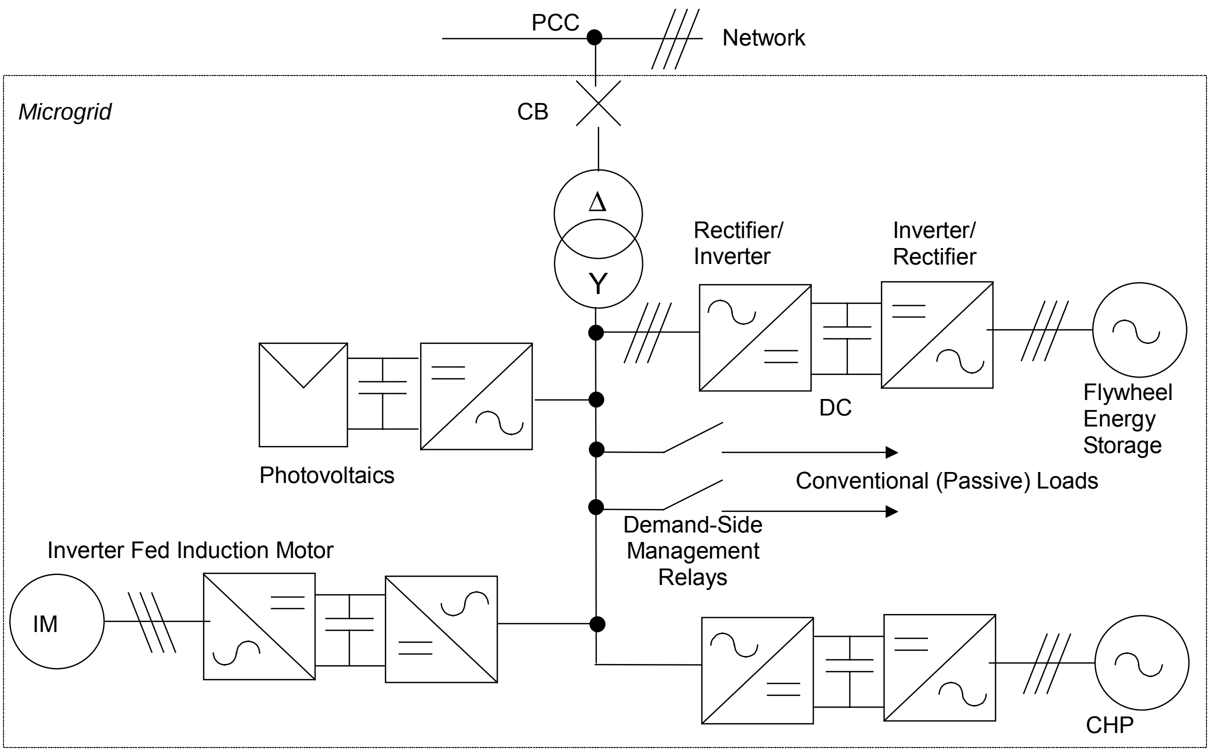

Fig. 1: Simple Example Microgrid

power network as a single unit. The aim of operating Microgrid sub-systems is to move away from considering DG as badly behaved system components, of which a limited amount can be tolerated in an area, to ‘good citizens’ [2], i.e. an aggregate of generation and load which behave as nearly ideal conventional loads. Although the concept of using Microgrids to provide ancillary services to the local network has also been discussed, present commercial incentives are probably insufficient to encourage this.

A critical feature of the Microgrid is the power electronics. ‘The majority of the microsources must be power electronic based to provide the required flexibility to ensure controlled operation as a single aggregated system’ [1]. Such as system must be capable of operating despite changes in the output of individual generators and loads. It should have ‘plug-and-play’ functionality: it should be possible to connect extra loads without reprogramming a central controller (up to a predefined limit). It should be possible that some of these are loads conventional. Likewise it must be possible to add generation capacity with minimal additional complexity. Key, immediate issues for the Microgrid are power flow balancing, voltage control and behaviour during disconnection from the point of common coupling (islanding).

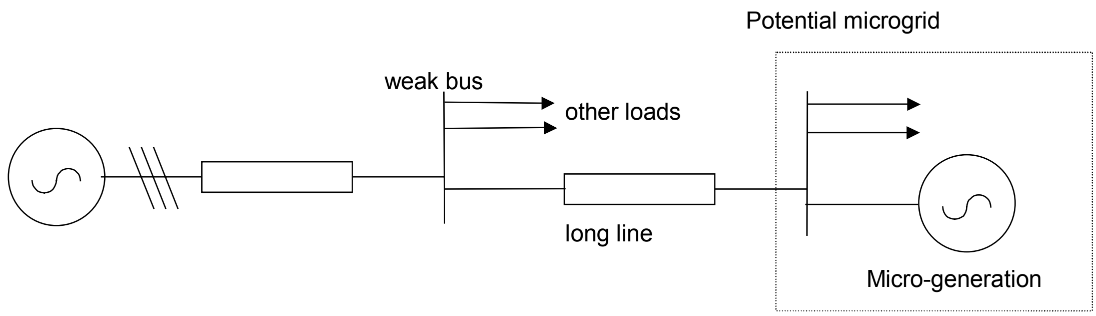

Fig. 2: Potential Microgrid: Remote Combination of Microsource(s) and Loads

The most immediate sites for application of the Microgrid concept would be existing remote systems which consist of a bundle of microsources and loads, for example Fig. 1. It could be prohibitively expensive to compensate for load growth or poor power quality, by upgrading the long supply line and the feeder to the (weak) source bus. Upgrading the local sub-system to a Microgrid could be a cheaper option. A necessary feature of such a Microgrid is that it can act as a semi-autonomous system, i.e. when the main network is not available, the Microgrid can still operate independently. This also has the potential to significantly improve the power quality of Microgrid systems by allowing them to ride through some faults. This is an advantage for sub-systems in larger installations requiring heterogeneous power quality.

To date Microgrids have been discussed as a concept [1-3]. This paper discusses how some of the key power electronics control concepts might be realised. Specific issues discussed are

- The implementation of power flow control (P and Q)
- Response to the onset of autonomous operation (islanding) and resynchronisation
- The requirement for energy storage

An assumption used in this paper is that a central controller, or ‘system optimiser’ [3] will be required to coordinate the power electronic interfaces in the Microgrids. This will be a slow acting outer control loop, the principle function of which is to determine the balance of steady-state real and reactive power flow between the Microgrid components and the

network. The central controller communicates to the individual units by a comparatively low bandwidth (and hence inexpensive) link.
Next to load flow, stability and the capability to run in grid tied and island mode the Microgrids and especially their inverters have to contribute to short circuit power and have to cope with harmonic distortion.

2. Synchronising AC-sources in micro grids

The main tasks of micro sources controllers is to allow power sharing between the different sources at different locations. As communication lines especially for long distances and control purposes are expensive and vulnerable at least fast communication should be avoided. This can be achieved by applying frequency and voltage droops. This way the local information – frequency and voltage - is used for power sharing. Normally the frequency is linked to the active power and voltage is linked to the reactive power.

Standard rotating generator systems inherently support these droops. Sometimes for improving the performance additional controllers are applied. Therefore it is possible to operate large numbers of such generators in one network. With standard inverters, characterised by fixed frequency and voltage, such an approach is not possible. A control approach providing frequency and voltage droops is required.

For explanatory purpose the self-synchronisation of rotating generators is briefly described below. It is followed by the description of frequency and voltage variable inverters applicable for micro sources. They are outlined in the model language of ATP-EMTP and some simulation results are given.

2.1. Self-synchronisation of conventional rotating generators

2.1.1. Active power control

The basic principle that lets the machines communicate without an explicit network that links them, is to allow the frequency at the inverter's terminal to change as a function of power demand. When two points in the network are operating at different frequencies there is an increase of active power delivery from the place at higher frequency to the location at lower frequency. As this happens, the two frequencies tend to drift towards a common central value until the new steady state is reached (self-synchronising torque).

2.1.2. Voltage regulation

Voltage regulation is necessary for local reliability and stability. Without local voltage control, systems with high penetrations of microsources could experience voltage and/or reactive power oscillations. Voltage control must insure that there are no large circulating reactive currents between sources. The issues are identical to those involved in control of large synchronous generators. In the power grid, the impedance between generators is usually large enough to greatly reduce the possibility of circulating currents. However, in a micro grid, which is typically radial, the problem of large circulating reactive currents is immense. With small errors in voltage set points, the circulating current can exceed the ratings of microsources. This situation requires a voltage vs. reactive current droop controller so that, as the reactive current generated by the microsource becomes more capacitive, the local voltage set point is reduced. Conversely, as the current becomes more inductive, the voltage set point is increased.

2.2. Control strategies for multiple inverters

2.2.1. Master Slave

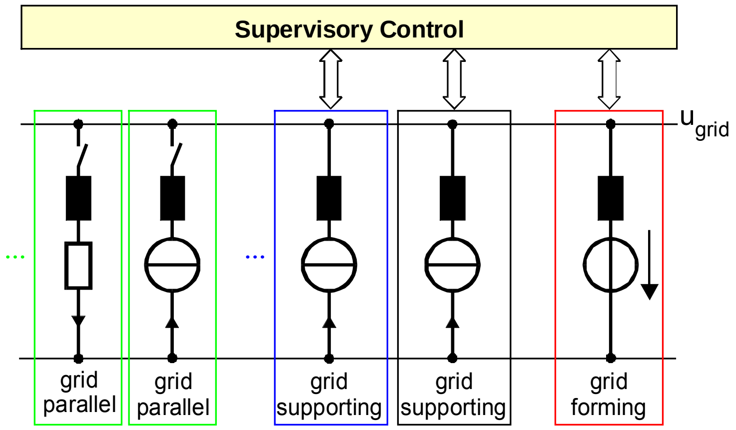

Fig. 3: Principle (classic) modular supply system consisting of one voltage source, current sources and passive loads

A system with a voltage source as master and additional controllable current sources (grid supporting units) is depicted in Fig. 3. The supervisory control is responsible for the power distribution. The features of this approach can be summarised as follows:

- simple control algorithm in components
- high expenditure for busses and their cabling
- difficult expansion of the system
- supervisory control required.

This approach is not suitable for decentralised electrification because the communication requirements are high and a supervisory control and extra cabling is even necessary for small systems.

2.2.2. Multi Master

Communication and/or extra cabling can be overcome if the inverters themselves set their instantaneous active and reactive power. In [2] a concept has been developed using reactive power/voltage and active power/frequency droops for the power control of the inverters. The droops are similar to those in utility grids. The supervisory control just provides parameter settings for each component. This way expensive control bus systems are replaced by using the grid quantities voltage and frequency for co-ordination of the components. Such approaches result in the following features:

- simple expansion of the system
- increased redundancy, as the system does not rely on a vulnerable bus system
- for optimisation a simple bus system is sufficient
- a simplified supervisory control
- more complex control tasks in the components.

Additional redundancy in micro grids can be achieved by using **v**oltage **s**ource **i**nverters (VSI) in parallel. This approach avoids the master/slave operation. In fact all VSIs form the grid.

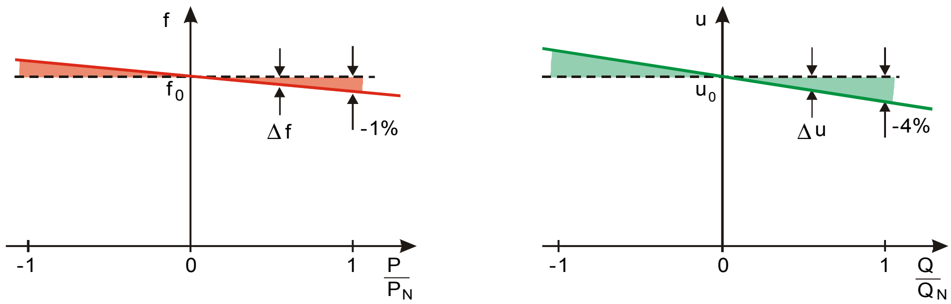

Fig. 4: Frequency and voltage droops

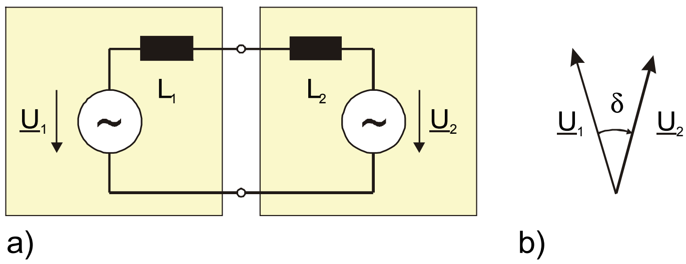

Fig. 5: Voltage sources coupled via inductors
a) equivalent circuit b) phasor diagram

The inverters are coupled via the inductances resulting from cabling and filters for the pulse suppression of the inverters (s. Fig. 5 a). But the configuration in Fig. 5 a is difficult to handle as will be shown. The active power *P* and the reactive power *Q* of voltage sources coupled with inductors can be calculated as follows:

$$P = \frac{U_1 \cdot U_2}{\omega \cdot (L_1 + L_2)} \cdot \sin(\delta)$$

and

$$Q = \frac{U_1^2}{\omega \cdot (L_1 + L_2)} - \frac{U_1 \cdot U_2}{\omega \cdot (L_1 + L_2)} \cdot \cos(\delta) \ .$$

P:	active power
Q:	reactive power
U_1, U_2:	rms-values of the voltage sources
δ:	phase shift between voltage sources
ω:	cycle frequency of the grid
$L_{1,2}$:	coupling inductances

A phase shift δ between two voltage sources causes active power transmission. Reactive power transmission is due to voltage differences U_1-U_2. Assuming standard values for the inductance L_f results in very sensitive systems, where even smallest deviations of the phase and the magnitude cause high currents between the inverters[1]. Therefore a precise control with complex algorithms is required for the parallel operation of voltage source inverters.

A precise active power dispatch is required for balancing demand and generation. Applying droops two approaches are possible: P(f) and f(P).

[1] This sensitivity is the reason why fixed frequency and voltage inverter concepts fail. There is always a voltage difference due to tolerances of the sensor, references, temperature drift and eldering (e. g. 1 - 5%) and also crystals are not equal and the angle difference is the integral of the frequency error over time!

2.2.2.1. Real power vs. frequency control

The direct control system analogy of the droop line is to measure system frequency and control real power, Fig. 6. System frequency is measured from a phase locked-loop (PLL), which operates based on three-phase terminal voltage. The system frequency is compared with a reference value (typically 50 Hz under normal operation). The frequency deviation is filtered using a low pass filter and multiplied by a gain constant to obtain droop control [3].

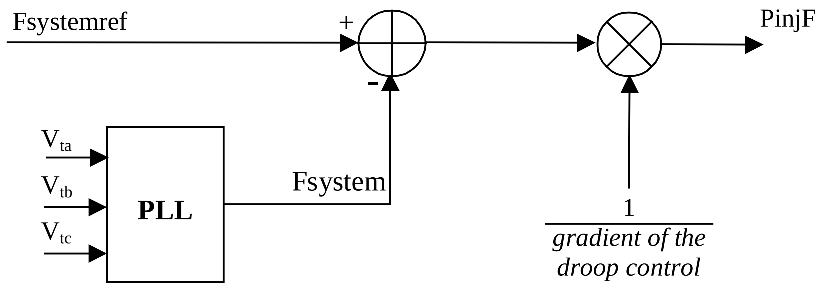

Fig. 6: Block diagram of the VSC control for frequency regulation

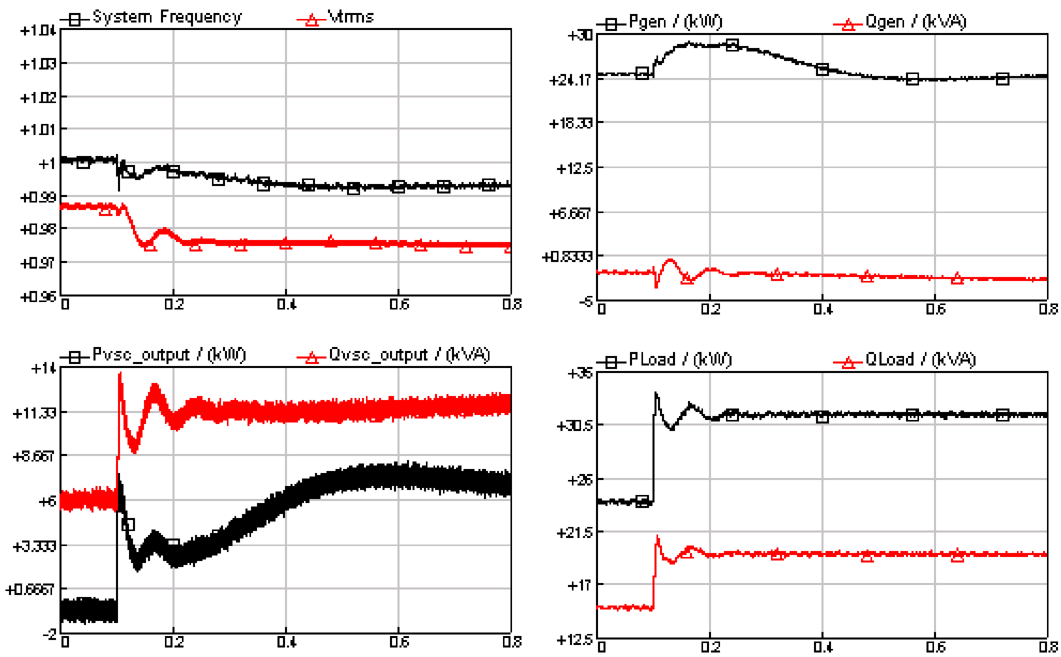

Fig. 7: Simulation results with the voltage and frequency regulation control (during island operation of the Microgrid)

Fig. 7 shows simulation results with the voltage and frequency regulation control technique, in response to an abrupt change in load when Microgrid was operated in island mode. The VSC injects active and reactive power to maintain the terminal voltage and the Microgrid system frequency within the acceptable limits.

2.2.2.2. Frequency vs. real power control

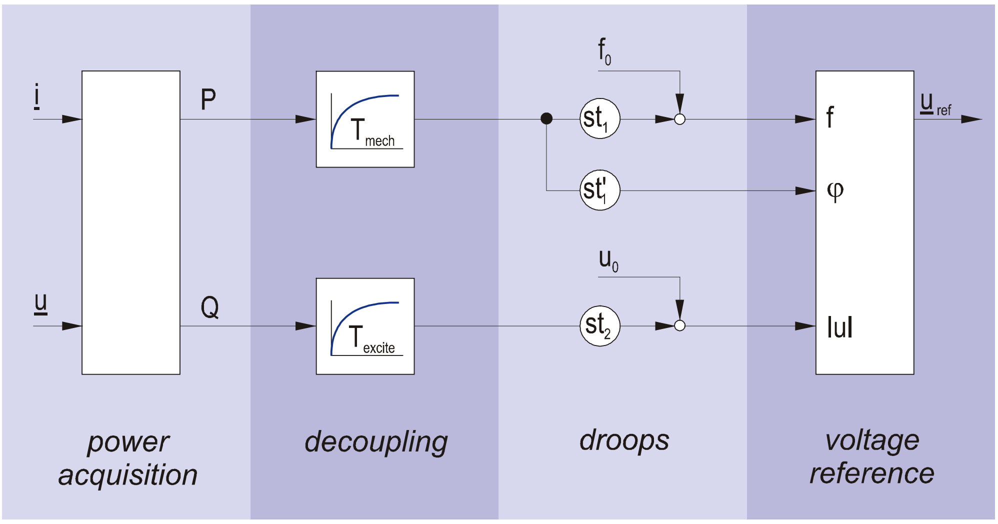

Fig. 8: control strategy based on power acquisition [5]

In a real system obtaining an accurate measurement of instantaneous frequency is not straight-forward. Measuring instantaneous real power is easier. It has therefore been proposed [5,6] that the control discussed before be reversed: the VSC output power is measured and this quantity is used to adjust its output frequency.

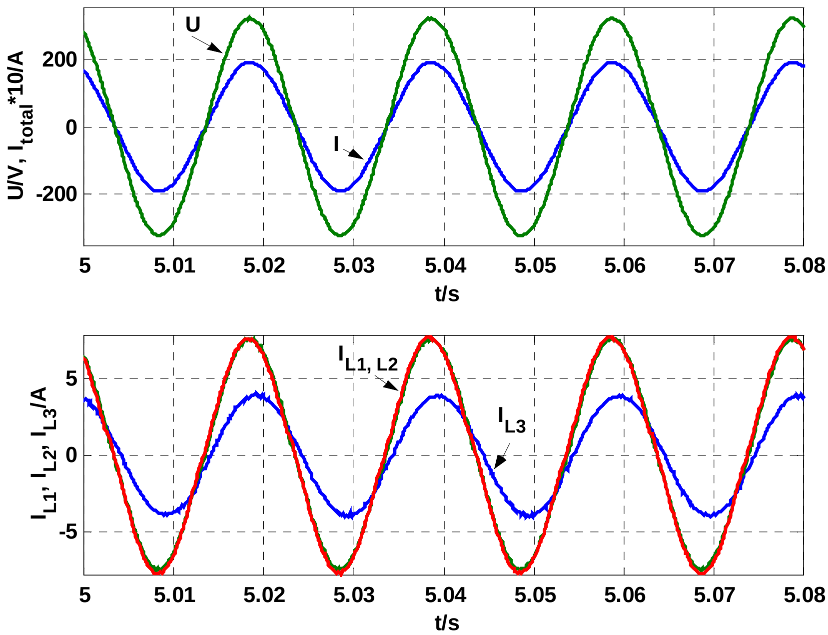

Fig. 9: Frequency vs. Power Control of a VSC

For the experiment three SMA Sunny Island™ inverters programmed with this scheme (rated power 3.3 kW, clock 16kHz, coupling inductor 0.8 mH) were connected on a single phase to an ohmic load, each via a thin (approx. 10m) low voltage cable. The frequency droop of the inverters denoted by L1, L2 in Fig. 9 was set to 1Hz/rated power. The inverter denoted with

L3 was set to 2Hz/rated power. It is evident that this method allows L3 to supply a smaller proportion of power

2.2.2.3. Microgrid Reactive Power Control

As a good approximation, most conventional power systems are mainly inductive, i.e. have a high ratio of reactance to resistance (X/R ratio). For such systems, equation (2) tells us that differences in voltage cause reactive power flows, or conversely, reactive power flows influence terminal voltage. Typically therefore reactive power is controlled by a Q vs. V droop line, Fig. 10. [3].

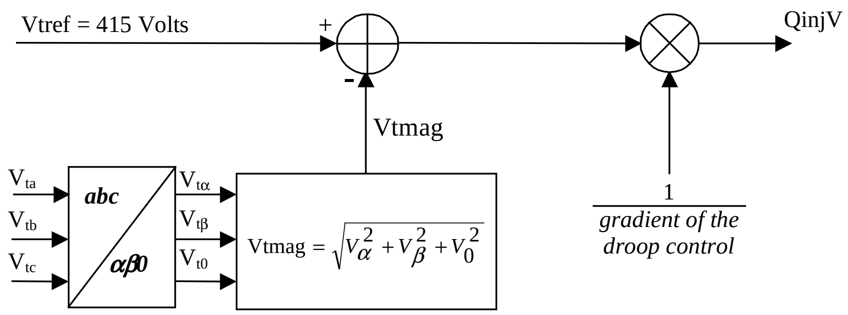

Fig. 10: Block diagram of the VSC control for voltage regulation

Fig. 10 shows the block diagram of the voltage regulation control technique. Three-phase terminal voltages (V_{ta}, V_{tb}, V_{tc}) are measured and fed as inputs to the controller. The magnitude of the terminal voltage vector (Vtmag) is calculated and compared with the set reference value (Vtref = 415 Volts). The error voltage is filtered using a low pass filter and multiplied by a gain constant to obtain droop control of the VSC. The output of the voltage regulation control block gives the reactive power (QinjV) that needs to be injected to maintain the terminal voltage according to droop set value.

Fig. 11 shows simulation results with and without the voltage regulation control technique, for an abrupt reduction in the PCC voltage at the end of the long supply feeder to which the Microgrid is connected. The Microgrid, in this case the VSC of the energy storage unit, injects reactive power to maintain the rms terminal voltage (Vtrms) within the acceptable limits.

The central controller effectively sets the droop line slope of the individual VSC interfaces to determine reactive power sharing between the units and the reactive power export/import of the Microgrid under steady-state operation. During islanded operation the net reactive power flow will be zero. The voltage in the Microgrid will then increase (if there is excess reactive power), forcing power electronic units to produce less Q or even absorb reactive power, until a new steady-state voltage is reached (net zero Q flow).

The voltage control and the impact of reactive power in the low voltage grid, which is mainly resistive, will be discussed below. Here the voltage / reactive power droops are to limit reactive power flow.

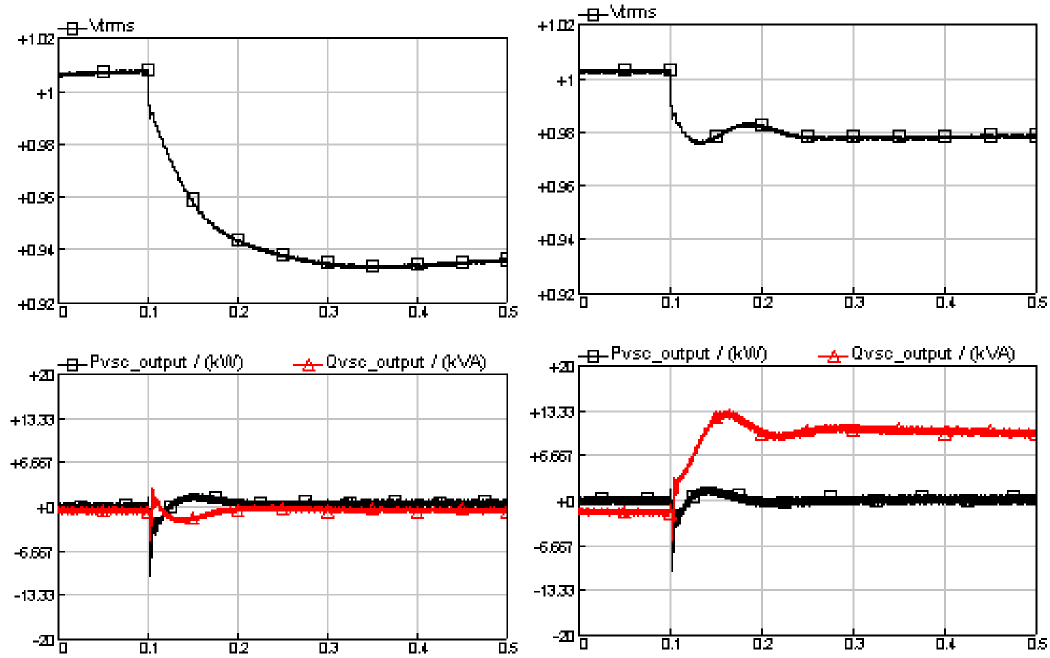

Fig. 11: Simulation results with (right) and without (left) the voltage regulation control with the Microgrid connected to main supply

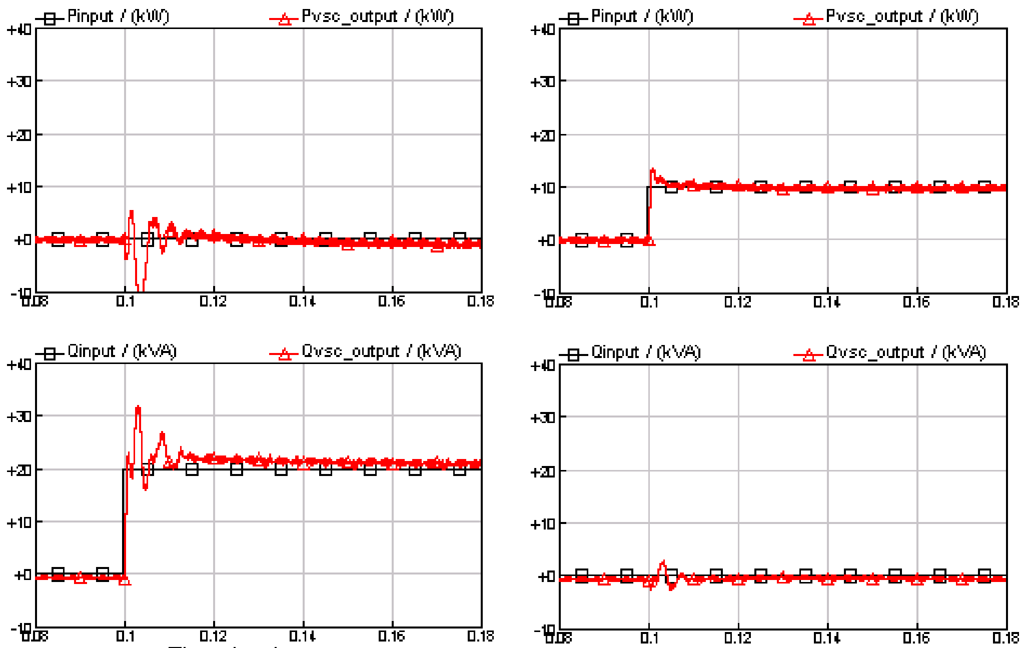

Fig. 12: Simulation results with the active and reactive power control set by central controller (all other controls are disengaged and Microgrid is connected to the main supply)

2.2.3. 'Good Citizen' Behaviour - power injection set by central controller

For the Microgrid to behave as a 'good citizen' and absorb/inject a specified amount of aggregate power the position of the droop lines of the individual VSC's must be adjusted by a central controller (s. Fig. 12). This need not be a particularly fast control loop, since even a slow telecommunications link has time-constants significantly faster than most power network sub-systems. Additional active and reactive power (Pinj, Qinj) to be injected in this case are set by the central controller for each specific VSC. The active (PinjF) and reactive (QinjV) power set by the frequency regulation and voltage regulation system controllers are also sent to this control. Alternatively the droop line settings could have been adjusted for each VSC by the central controller directly. The PLL output angle (Theta) and the reference terminal voltage magnitude (Vtref) are used to calculate the injected current from the power. In the system simulated, two limit blocks are used to limit the power injection (active power limits ± 10kW, reactive power limits ± 20kVA). These limits are important during transient period of a disturbance in the system. These simulations reveal, that Microgrids can contribute to the overall grid control and thus should be regarded as a possibility for upgrading supply systems.

2.2.4. Active power for voltage control in low voltage grids

The mainly resistive coupling in the low voltage grid would suggest to use active power for controlling the voltage. This is done e. g. with dynamic voltage restorers in order to compensate voltage sags (short term interference).

Using the active power flow for voltage control would mean to loose the possibility for economic active power dispatch. Also the compatibility with rotating generators in the low voltage grid and upwards compatibility with the main grid will be lost.

The function of voltage / reactive power droops in the low voltage grid is to limit the reactive power flow. Keeping the voltage in the allowed range should be done by a suitable layout of the low voltage lines and eventually additional distributed chokes. These will increase the reactive part of the lines.

2.2.5. Three phase implementation of control algorithm in ATP-EMTP

```
EXEC
   -----------------------------------------------------------------
   f1:=f-STP                            -- frequency droop / reference
   w1:=2*pi*f1                          -- cycle frequency
   wt:=integral(w1)                     -- reference angle(time function)
   Amp1:=Amp+STQ                        -- voltage droop / reference
   -----------------------------------------------------------------
   A:=Amp1*sin(wt+STPH)                 -- output voltage A
   B:=Amp1*sin(wt+2.09+STPH)            -- output voltage A
   C:=Amp1*sin(wt+4.18+STPH)            -- output voltage A
   -----------------------------------------------------------------
   UB1:=2/3*(sqrt(3)/2*B-sqrt(3)/2*C)   -- Clark transformation
   UA1:=2/3*(A-0.5*B-0.5*C)             -- for voltages and
   IB1:=2/3*(sqrt(3)/2*IB-sqrt(3)/2*IC) -- currents
   IA1:=2/3*(IA-0.5*IB-0.5*IC)          --
   -----------------------------------------------------------------
   P:=3*(UA1*IA1+UB1*IB1)/2             -- calculation of active power
   Q:=3*(UB1*IA1-UA1*IB1)/2             -- calculation of reactive power
   S:=sqrt(P*P+Q*Q)                     -- apparent power (just info)
   -----------------------------------------------------------------
   LAPLACE(PV/P):=(1|s0)/(1|s0+tau|s1)  -- decoupling delay (mechanical)
   LAPLACE(QV/Q):=(1|s0)/(1|s0+tau|s1)  -- decoupling delay (excitation)
   -----------------------------------------------------------------
   STP:=PV*kp                           -- frequency droop
   STQ:=QV*kq                           -- voltage droop
   STPH:=PV*kph                         -- phase correction
   -----------------------------------------------------------------
 ENDEXEC
```

Fig. 13: Executable part of ATP-EMTP models description for the frequency and voltage variable inverter

The reference voltages for the inverters are directly derived from the active and reactive power. The active power is delayed for decoupling purposes and determines the frequency via the frequency droop. A phase correction is introduced for reasons of stability. The reactive power is delayed for decoupling purposes and determines the magnitude of the voltage. The control-loop is closed via the process, i. e. the lines and loads. The resulting current is fed back. The process is not modelled in the executable depicted in Fig. 13.

2.2.5.1. Simulation of power sharing in a distributed island system

In order to assess the transient behaviour and the stability of the above outlined approach for micro grids, a simulation with three inverters coupled via a distribution system (15 kV) has been carried out. The inverters are represented by a frequency and voltage controlled three phase voltage sources and the distribution system consists of switches, overhead lines (π-blocks), transformers and the load (Fig. 14). The three inverters operate in parallel via the MV distribution system and supply the ohmic load with total power 100 kW.

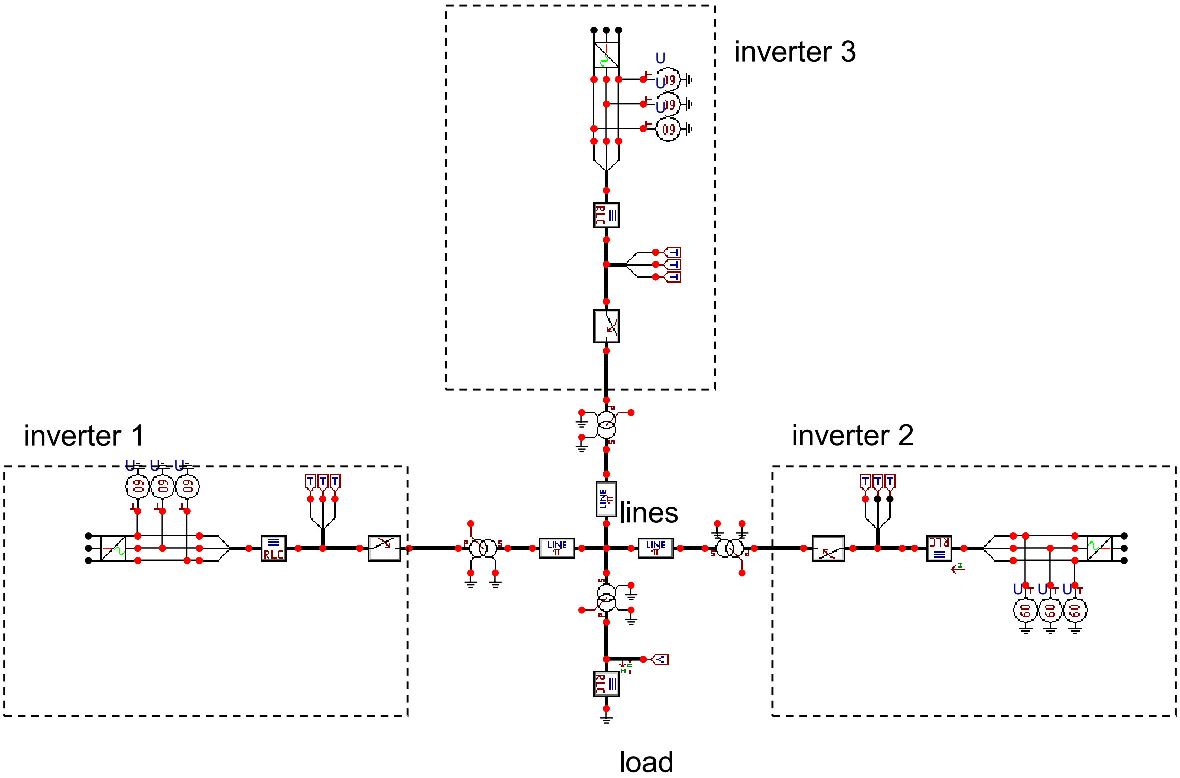

Fig. 14: Simulation of inverter dominated distribution system (ATP-EMTP)

By means of the implemented control functions, the contribution of each inverter is determined by the setting the applied droops (Fig. 4). In the case of Fig. 15 the contribution of the inverters are set to 20, 30 and 50 kW by the slope of the frequency droop of each inverter. The slope of the frequency droop can be used for taking the size of the inverter into account. The setting of the idle frequency f_0 can be used for the control of the energy flow.

The setting of the slope of the voltage droop results in a variable virtual inductance between the respective inverter and distribution systems. It should be chosen in order to ensure a stable operation. The idle voltage should be set for minimising reactive power. But certain voltage limits have to be guaranteed.

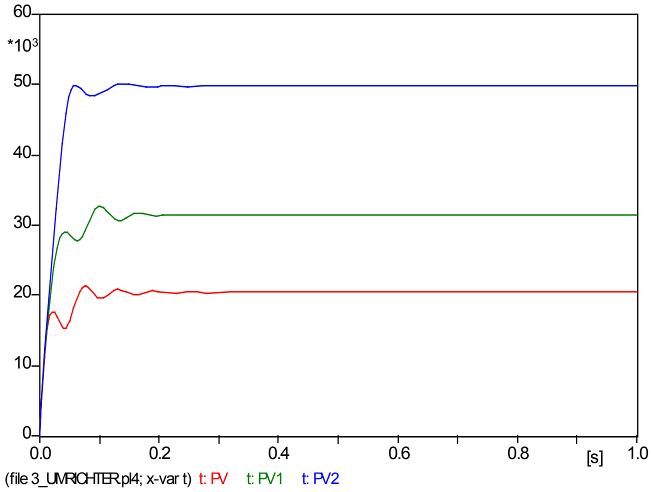

Fig. 15: Load shared between the three inverters

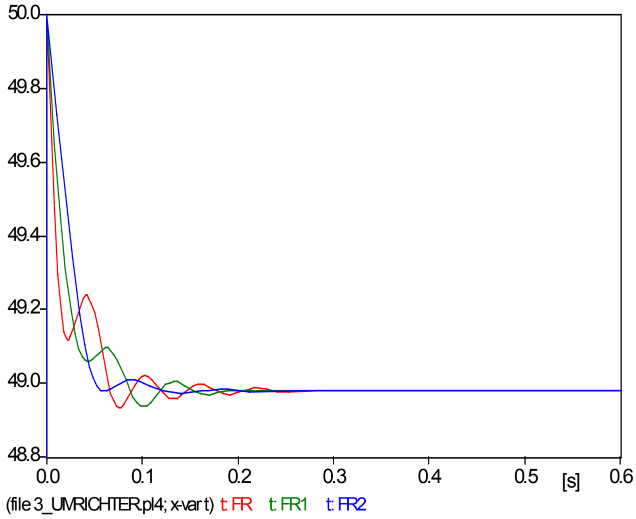

Fig. 16: Frequency change in island system

The idle frequencies of the three inverters are set to 50 Hz. Due to the loading the systems frequency decreases to 49 Hz. A supervisory control – which is normally not part of a micro source controller – could restore the frequency to 50 Hz by changing the idle frequencies of the inverters.

2.2.5.2. Application in single phase systems

The control approach in Fig. 13 is suited for 100 % unbalanced operation, *i. e. the single phase operation is included*. The stepwise unbalanced operation is shown in Fig. 17. The current of phase A is measured while after two seconds phase B and after three seconds phase C is disconnected. The droop determines the power, thus the current of phase A increases. This is not a practical example as the over current protection would stop the inverter.

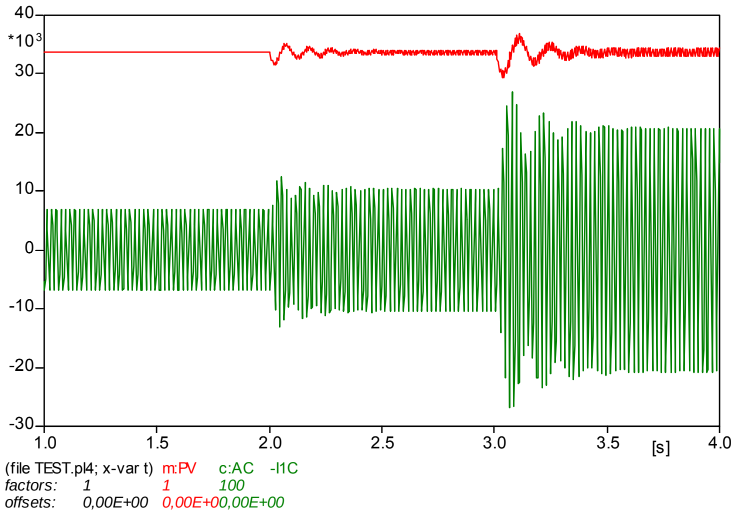

Fig. 17: Stepwise unbalanced operation of the inverter by disconnecting two phases (green: current, red: active power)

3. Stability assessment

3.1. Approach for stability assessment by means of Matlab

For the stability assessment active and reactive power flow are assumed to be decoupled. The task to be solved is to find a suitable way for the representation of the inverter dynamics, which allow an easy expansion of the systems to be investigated. With this Matlab is able to determine the stability by means of pole-zero-analysis.

The basic principle that lets the machines communicate without an explicit network that links them, is to allow the frequency at the inverter's terminal to change as a function of power demand. When two points in the network are operating at different frequencies there is an increase of active power delivery from the place at higher frequency to the location at lower frequency. As this happens, the two frequencies tend to drift towards a common central value and the new steady state is reached at a lower frequency than the system had when grid was connected. In equilibrium steady – state conditions, all the (synchronous) machines in given system have the same electrical angular speed (equal to the "synchronous" speed Ω_s), whereas their electrical angular positions differ from each other, with constant shifts depending on the load conditions of individual machines. In any dynamic condition, the mechanical balance equations of an n-machine system can generally be written in the following form [10]:

$$\frac{d\Omega_i}{dt} = \frac{1}{M_i} \cdot (P_{mi} - P_{ei})$$

$$\frac{d\delta_i}{dt} = \Omega_i - \Omega_s$$

with i=1,….,n and

Ω_i = electrical angular speed;

δ = electrical angular position, evaluated with respect to that (θ_s) of a fictitious rotor, rotating at the synchronous speed $d\theta_s/dt=\Omega_s$;
P_{mi} = mechanical driving power;
P_{ei} = active electrical power generated;
M_i = coefficient of inertia

In particular, if the solution of these equations by means of Ω_s could be derived, than it leads to the common concept of “mean frequency” of the network, which is generally used in empirical way, will get a precise definition. It will represent the “mean motion” of the set of the machines. This approach can be appllied for the inverter dominated grids.

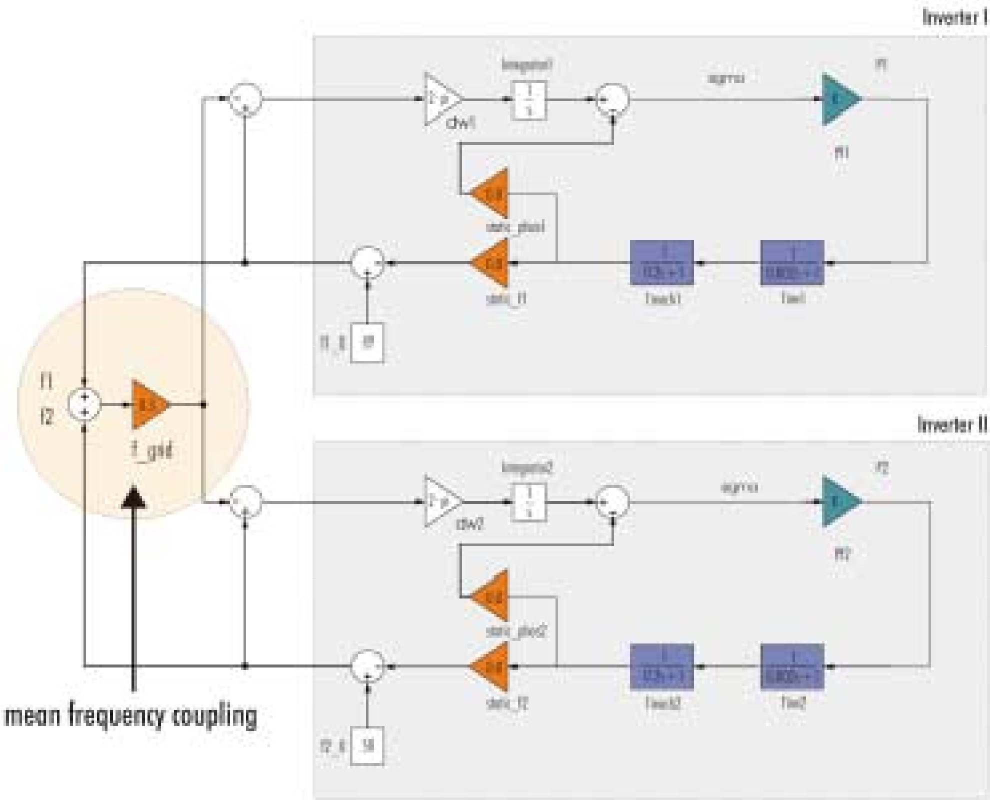

Fig. 18: Simulation of inverter dominated minigrid (MATLAB/Simulink)

In Fig. 18 a two inverter system with the control based on power acquisition (s. Fig. 8) and the “mean frequency”-coupling is depicted. This approach allows easy expansion and analysis with Matlab. This system can linearised by Matlab and its poles and zeros can be calculated.

3.1.1. Impact of coupling inductance and delays

From Fig. 19 one can see, that the coupling inductance of the inverter has a major impact on the stability. The time constants of the delays for decoupling are not neglectable, but the system is not very sensitive to varying them.

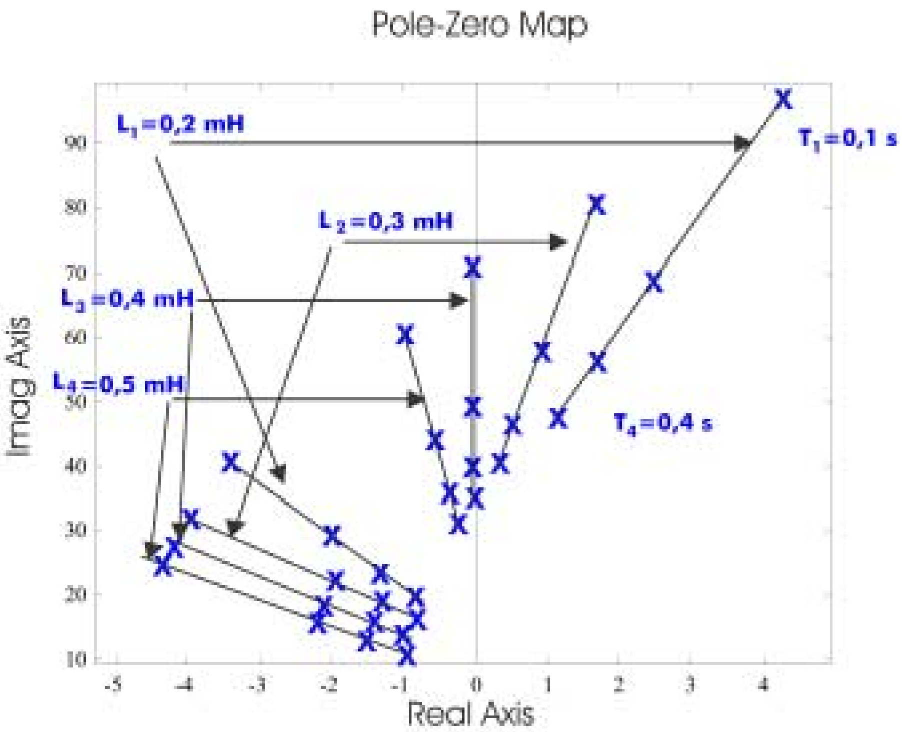

Fig. 19: Pole-zero map calculated with Matlab in order to determine the impact of the coupling inductance and the decoupling time delays

The following parameters have been used for an eight inverter system to obtain the results of Fig. 19:

- T_{mech}=[0,1…0,4] s with Δt=0,1 s
- T_{inv}=0,002 s
- L_{coup}=[0,2…0,5] mH
- k_{ph}=0 (coefficient of phase correction)
- $k_{P1}=k_{P2}=...=k_{P7}$= 1E-5 W/Hz
- k_{P8}=7E-5 W/Hz

$\left.\begin{array}{l} \\ \\ \end{array}\right\}$ Slope of the droops

3.1.2. Impact of coupling inductance and phase feed forward

Fig. 20 reveals the major impact of the phase feed forward, which is able to stabilise the system over a wide range. The use of very small coupling inductances becomes possible, which allows the construction of more cost effective inverters.

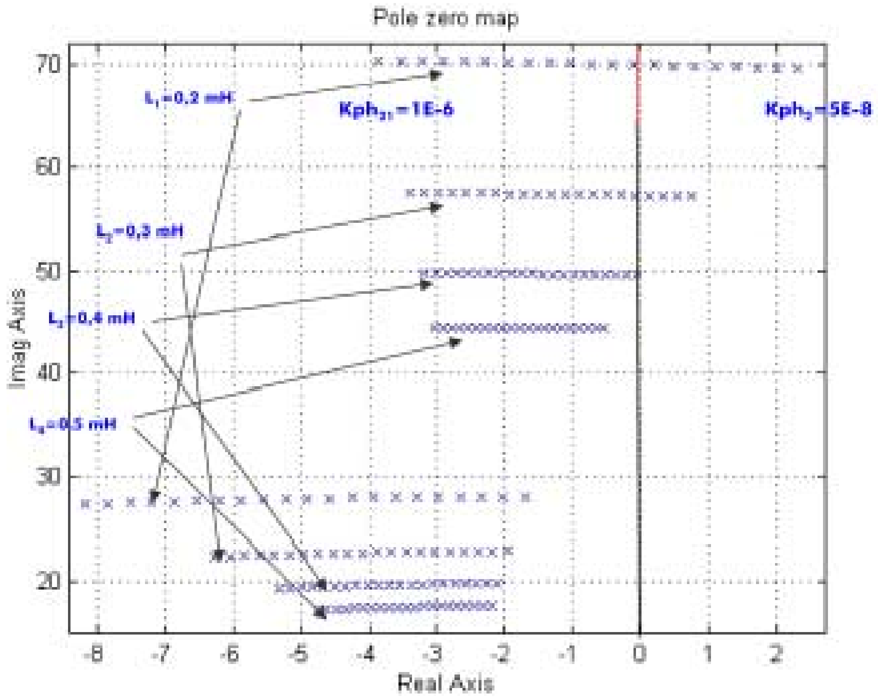

Fig. 20: Pole-zero map calculated with Matlab in order to determine the impact of the coupling inductance and the phase feed forward

The following parameters have been used for an eight inverter system to obtain the results of Fig. 20:

- k_{Ph}=[0….1E-6] W/rad with Δk_{Ph}=5E-8 W/rad
- L_{coup}=[0,2….0,5] mH
- T_{mech}=0,2 s
- T_{inv}=0,002 s
- k_{P1}= k_{P1}=k_{P2}=...=k_{P7}= 1E-5 W/Hz
- k_{P8}=7E-5 W/Hz

$\left.\begin{matrix} k_{P1} \\ k_{P8} \end{matrix}\right\}$ Slope of the droops

3.2. Impact of lines (resistive coupling)

If inverters are connected by means of transmissions lines and/or cables, the impact of resistive coupling in the low voltage network is rather high. In Fig. 21 the representation of the transmission line in the low voltage grid, where the resistive part is bigger than the reactive component, is shown.

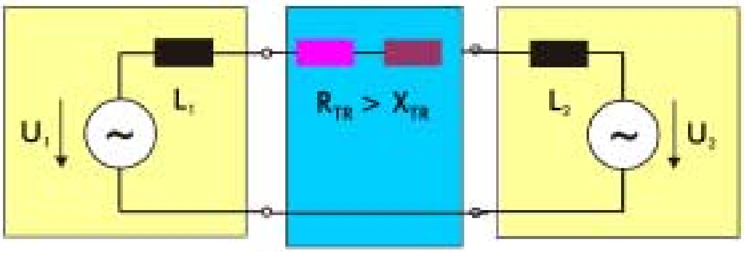

Fig. 21: Representation of transmission lines in the low voltage grid

The above outlined approach using Matlab for stability assessment is not suited for investigating the impact of resistive coupling of the low voltage grid, as this system is not decoupled by principle. Another way is to simulate this network with a time-step simulation (ATP-EMTP; Fig. 22). Here the transmission system consists of aerial lines (π-equivalent).

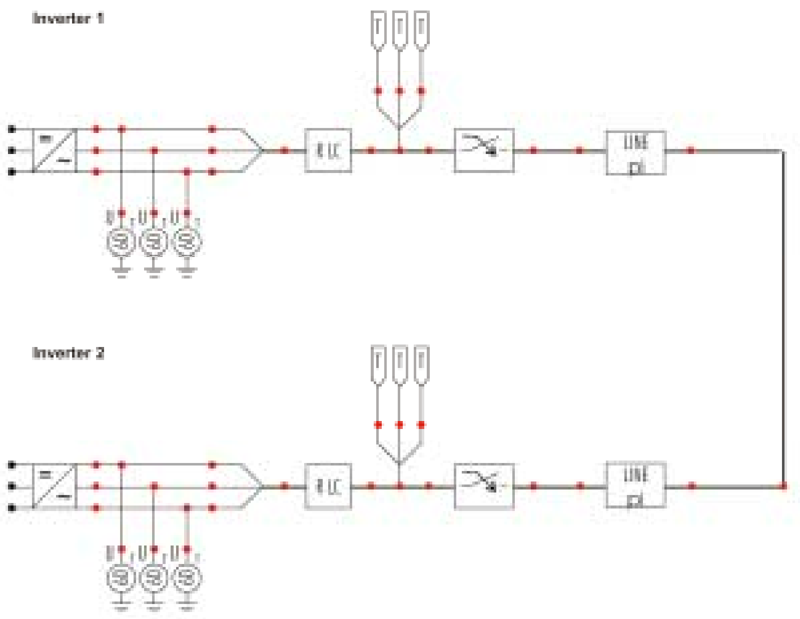

Fig. 22: Inverters connected via a low voltage line

Some statements about critical ratios between resistive and reactive (inductive coupling) components (lines and filter), and also role of phase feed forward can be derived. Firstly, if the ratio is $R<X$, than the system may be unstable due to required settings of the droop, but using the phase feed forward stabilises the system (s. Fig. 23).

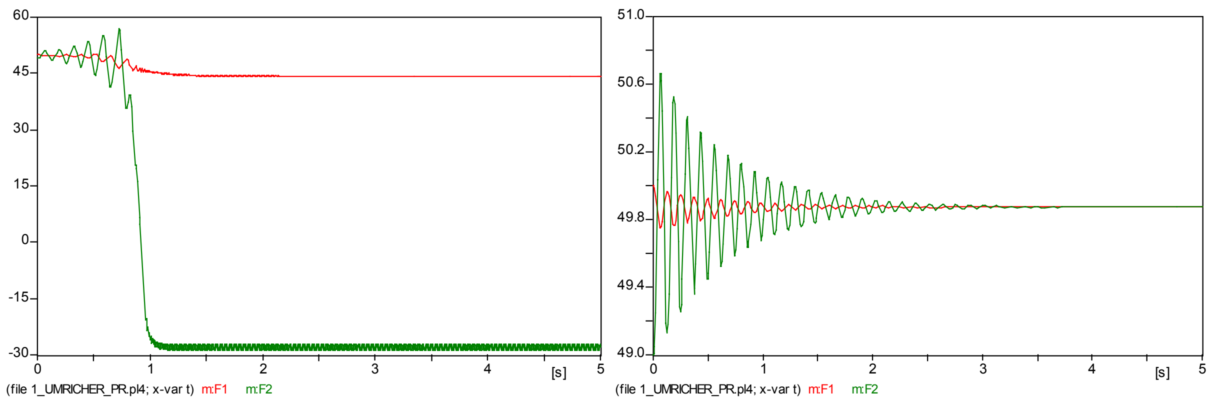

Fig. 23: Inverter frequencies with R=0,5·X : a) k_{Ph}=0 (unstable) ; b) k_{Ph}=1E-6 (stable)

With appropriate settings of the inverters a ratio of R>X is allowed for the lines. But still a critical ratio for stability exists and must be considered in order to avoid instability (s. Fig. 24).

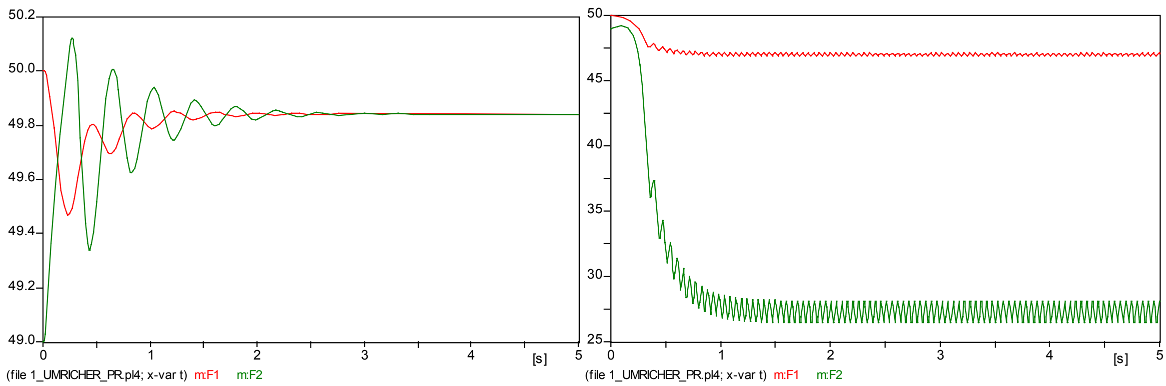

Fig. 24: Inverter frequencies with k_{Ph}=0 : a) R=3·X (stable); b) R=4·X (unstable)

3.2.1. Compensation of lines

To overcome this problem partly, the compensation of the resistive parts of the lines at least to the next point of common coupling can be implemented in the inverter control. Therefore a negative resistance has to be assumed in the voltage feed forward of the voltage controller.

3.3. Equal inverters

Using equal inverter setting results in multiple poles and zeros of the overall system's transfer function. This allows to derive a very simple design rule. If a system with two inverters is stable, one can add as many same inverters as required without inflicting problems on the system's stability.

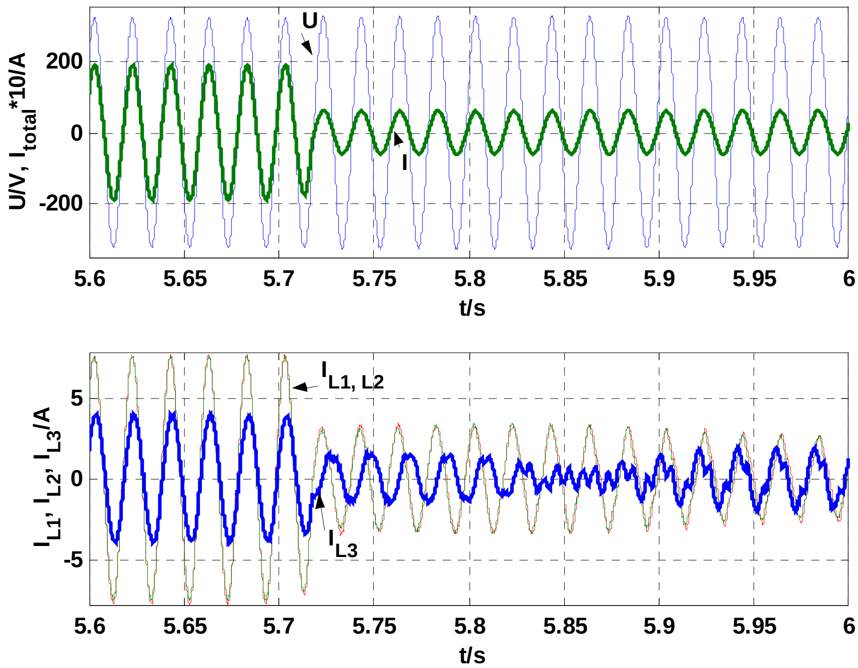

Fig. 25: Addtional dynamic processes due to different inverter setting

In this experiment (s. Fig. 25) with three SunnyIslands^{TM} the currents of the Inverter L1, L2 are equal all the time where as the current of L3 (the inverter has a different setting) is different. Due to the different settings of the inverters additional dynamic processes reveal.

4. Contribution to protection schemes and harmonic distortion

4.1. Contribution to short circuit current

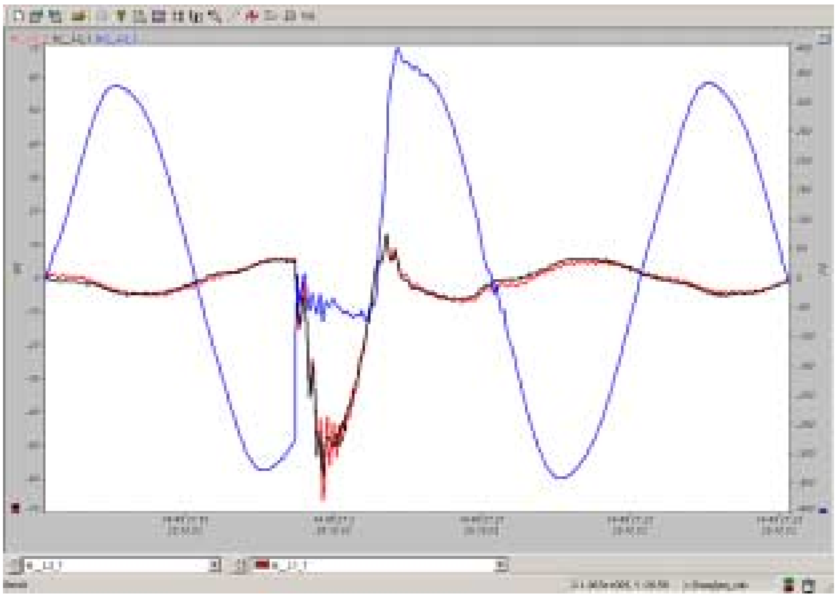

Fig. 26: Short circuit measured at the pilot plant on the Greek island Kythnos

The most convenient approach for a grid forming inverter is to control the voltage and supervise the current (leave out inner current loop control). This allows two approaches for the handling of too high currents. One is just to switch of the inverter, when too high currents occur, the other is to switch the control mode from voltage source control to current source control and inject a defined short circuit current. The second way has advantages with regard to the protection of the inverter itself, as during a short circuit unknown phenomena could occur and current injection into the inverter can be avoided. Fig. 26 depicts the triggering of a short circuit breaker applying the first method.

4.2. Contribution to harmonic distortion

By principal droops are not suited for handling distorted power, as the active and reactive power used for control, is just defined for the fundamental. Nevertheless due to the precise synchronisation resulting from using droops and in case of equal inverters even precise distribution of the distorted power is possible.

Within the experiment of Fig. 27 two fast load steps occur. As inverter one and two have the same settings they even share the fast transients perfectly.

Here no distribution system was assumed. If there is a distribution system, this of course would affect the flow of distorted power.

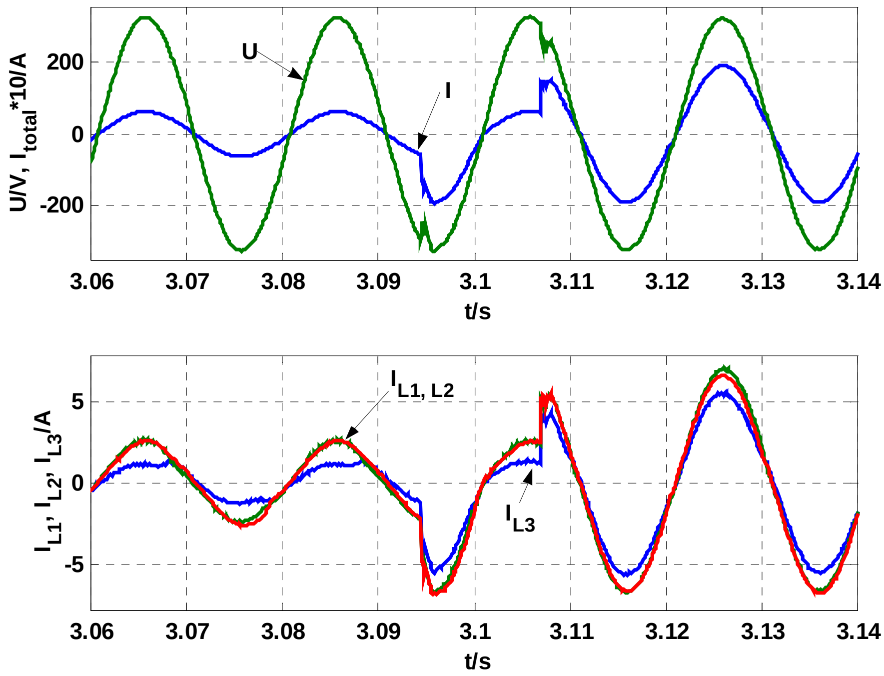

Fig. 27: Frequency vs. Power Control of a VSC, contribution to THD

5. Conclusion

In this paper solutions for micro sources controllers are outlined. The main idea is to down-scale the approach of the conventional supply system down to the low voltage level by means of droops and featuring inverters. A lot of advantages result even the parameters of low voltage lines obviously contradict the us of conventional droops. Promising results of simulations and experiments are presented.

Especially for the control of active power two concepts (P(f) and f(P)) were compared. They provide similar results but the implementation effort is different.

Major items were tackled:

- island mode of the Microgrid
- grid tied mode of the Microgrid
- stability of the Microgrid
- characteristics of low voltage grid
- short circuit capabilities of the control
- THD capabilities of the control

It can be concluded that inverter based generation in Microgrids can support all the functions required by the superior grid. Due to the droops the Microgrids become upward compatible and do not require much expensive communication. The combination of the outlined micro source controller and Microgrid central controllers Microgrids can add value to the main grid.

6. References

[1] R Lasseter, A Akhil, C Marnay, J Stephens, J Dagle, R Guttromson, AS Meliopoulos, R Yinger and J Eto, “White Paper on Integration of Distributed Energy Resources – The CERTS MicroGridConcept”, Office of Power Technologies of the US Department of Energy, Contract DE-AC03-76SF00098, April 2002.

[2] B Lasseter, “Microgrids Distributed Power Generation”, 2001 IEEE Power Engineering Society Winter Meeting Conference Proceedings, Columbus, Ohio, vol. 1, pp. 146-9.

[3] RH Lasseter, “MicroGrids”, 2002 IEEE Power Engineering Society Winter Meeting Conference Proceedings, New York, NY, vol. 1, pp. 305-8.

[4] H Tyll and K Bergmann, “Use of Static VAR Compensators (SVCs) in High Voltage Systems”, SRBE-KBVE Studiedag, 22 March 1990, Brussels

[5] Engler, A.: *Vorrichtung zum gleichberechtigten Parallelbetrieb von ein- oder drei-phasigen Spannungsquellen,*
German patent Nr. 101 40 783.1, 21.08.2001
European patent: 02 018 526.26
US patent: 10/222,310
Japanese patent: 2002-240991

[6] A. Engler, C. Hardt, P. Strauß and M. Vandenbergh, “Parallel Operation of Generators for Stand-Alone Single Phase Hybrid System*”,* EPVSEC Conference, Munich, October 2001

[7] P. Piagi, R. H. Lasseter: *Industrial Applications of MicroGrids*, CERT, University of Wisconsin-Madison, October 2001

[8] Engler, A.: *Regelung von Batteriestromrichtern in modularen und erweiterbaren Inselnetzen*, publisher Verlag Dissertation.de, Berlin, 05/2002, ISBN 3-89825-439-9

[9] Burger, B. und Engler, A.: *Verfahren und Vorrichtung zur Bestimmung charakteristischer Grössen aus einem zeitlich periodischen Signal*,
German patent Nr. 199 49 997.7, 15.10.1999

[10] Fabio Saccomanno: *Electric power systems – analysis and control*, IEEE Press, Piscataway, ISBN 0-471-23439-7, 2003