Large Scale Integration of
Micro-Generation to Low Voltage Grids

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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

Nikos **Hatziargyriou** nh@power.ece.ntua.gr

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Contents

1. Introduction

The droop control for microgrids, introduced in DB1 “Local Micro Source controller strategies and algorithms”, has been technically assessed and the required functions for the operation of microgrids have been proven and already evaluated to a certain extend. This deliverable “Evaluation of the local controller strategies” focuses to the:

- Applicability of the droop concept on low voltage level
- Compatibility with rotating generators
- Scalability.

For better understanding of the report, a brief summary of the droop control concept out of DB1 is included.

2. Applicability of droops in low voltage grids

2.1. Motivation

Remote electrification with island supply systems, the increasing acceptance of the microgrids concept [1] and the penetration of the interconnected grid with distributed energy resources (DER) and renewable energy resources (RES) require the application of inverters and the development of new control algorithms.

One promising approach is the implementation of conventional f/U-droops into the respective inverters, thus down scaling the conventional grid control concept to the low voltage grid. This methodology makes superior system architecture possible, providing redundancy, enabling expandable distributed systems and avoiding vast communication expense. With the development of the control algorithm *selfsync*™ the operability of droops in inverters has been proven.

Being based on conventional droops this control concept can be derived from inductively-coupled voltage sources. A voltage source combined with an inductance represents a high voltage line with a stiff grid or a synchronous machine (generator). Here the reactive power is related with the voltage and the active power with the phase shift or respectively with the frequency. This change with the low voltage line and its resistive character, where reactive power is related with the phase shift and active power with the voltage. Nevertheless, the droop concept is still operable due to its "indirect operation", which will be outlined below.

2.2. Droop control

In expandable distributed inverter systems and in distribution systems with grid-tied inverters communication and/or extra cabling can be overcome if the inverters themselves set their instantaneous active and reactive power. In [2], [3] 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 (s.
Figure 2-1). The supervisory control just provides parameter settings for each component, which comprise the idle frequency, the idle voltage, the slopes of the droops and basic commands. This way, expensive control bus systems are replaced by using the grid quantities voltage and frequency for the co-ordination of the components. Such approach results 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 but
- more complex control tasks in the components.

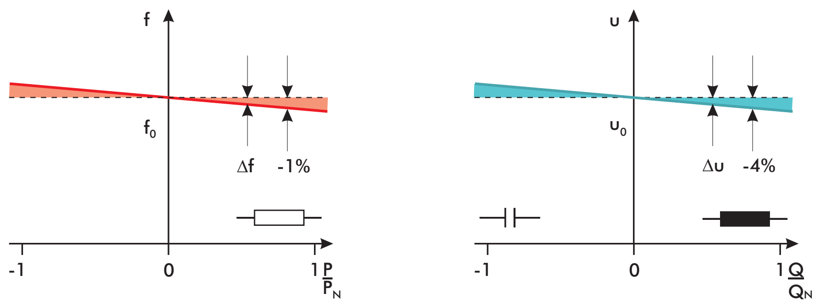


Figure 2-1: Conventional droops in the interconnected grid

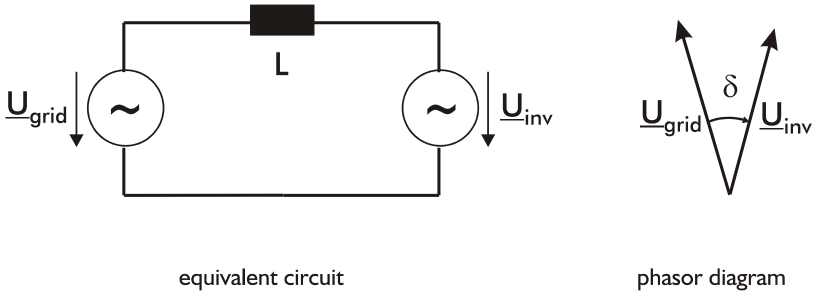


Figure 2-2: Inductively-coupled voltage sources

Exclusively using voltage source inverters (VSI) in parallel or even using VSIs for grid connection can achieve additional redundancy in power supply systems. This approach avoids the master/slave operation. In fact, all VSIs form the grid. The inverters are coupled via the inductances resulting from their filters for the pulse suppression and of decoupling chokes (s. Figure 2-2). But the configuration in Figure 2-2 is difficult to handle as will be shown.

The active power P_{inv} and the reactive power Q_{inv} of the voltage sources – here representing a grid-connected inverter - can be calculated as follows:

$$P_{inv} = \frac{U_{inv} \cdot U_{grid}}{\omega_N L} \sin\delta \tag{1}$$

$$Q_{inv} = \frac{U_{inv}^2}{\omega_N L} - \frac{U_{inv} \cdot U_{grid}}{\omega_N L} \cos\delta \tag{2}$$

A phase shift δ between two voltage sources causes active power transmission. Reactive power transmission is due to the voltage difference U_{inv} - U_{grid}. Assuming standard values for the inductance L results in very sensitive systems, where even smallest deviations of the phase and the magnitude cause high currents between the inverters. This sensitivity is the reason why fixed frequency and fixed voltage controlled inverters can't operate in parallel. There is always a voltage difference due to tolerances of the sensors, references, temperature drift and ageing (e. g. 1 – 5 %) and also crystals are not equal. The frequency errors of the crystals are integrated over the time, resulting in hazardous angle differences (s.Eq. 1).

The obvious method for implementing frequency droops is to use *P* as a function of *f.* But 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 [2] a control with *f* to be a function of *P*: the VSI output power is measured and this quantity is used to adjust its output frequency.

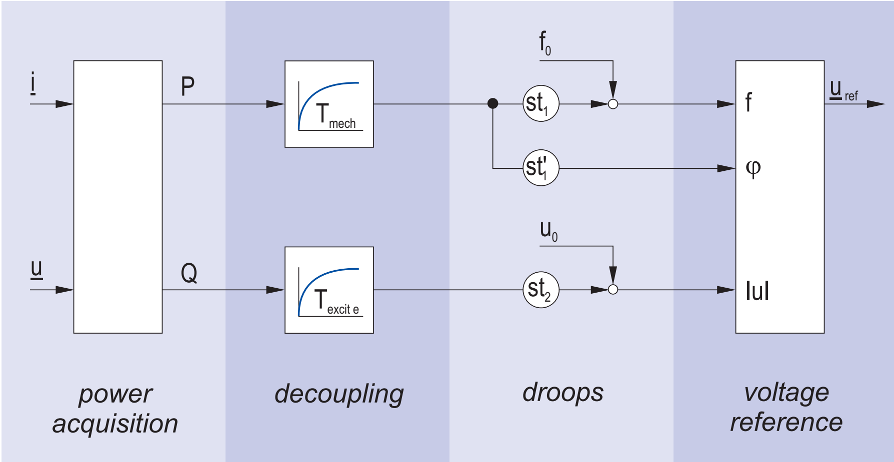


Figure 2-3: Control approach *selfsync*™ by ISET e.V., Kassel, Germany [4]

Firstly this control approach (s. Figure 2-3), named *selfsync*™, was implemented into the battery inverter *SunnyIsland*™ for rural electrification (s. Figure 2-4). For an experiment [5] three of these inverters programmed with this scheme were connected on a single phase to an ohmic load, each via a thin low voltage cable. The frequency droop of the inverters denoted by L_1, L_2 in Fig. 2.5 was set to 1 Hz/rated power. The inverter denoted with L_3 was set to 2 Hz/rated power. It is evident that this method allows L_3 to supply a smaller proportion of power. The load sharing corresponds to the settings. L_1, L_2 are equal, L_3 half of it. Noticeable is the phase shift of L_3 to L_1, L_2 which is due to the different loading of the cables, causing a slight voltage difference between the inverters, which results in reactive power flow.

The compatibility of *selfsync*™ with rotating generators has been shown in [6] and the compatibility with the grid in [7].

Figure 2-4: Two battery inverters *SunnyIsland*™ by SMA Technologie AG, Niestetal, Germany operating in parallel (rated power 4.2 kW, clock 16 kHz, coupling inductor 0.8 mH)

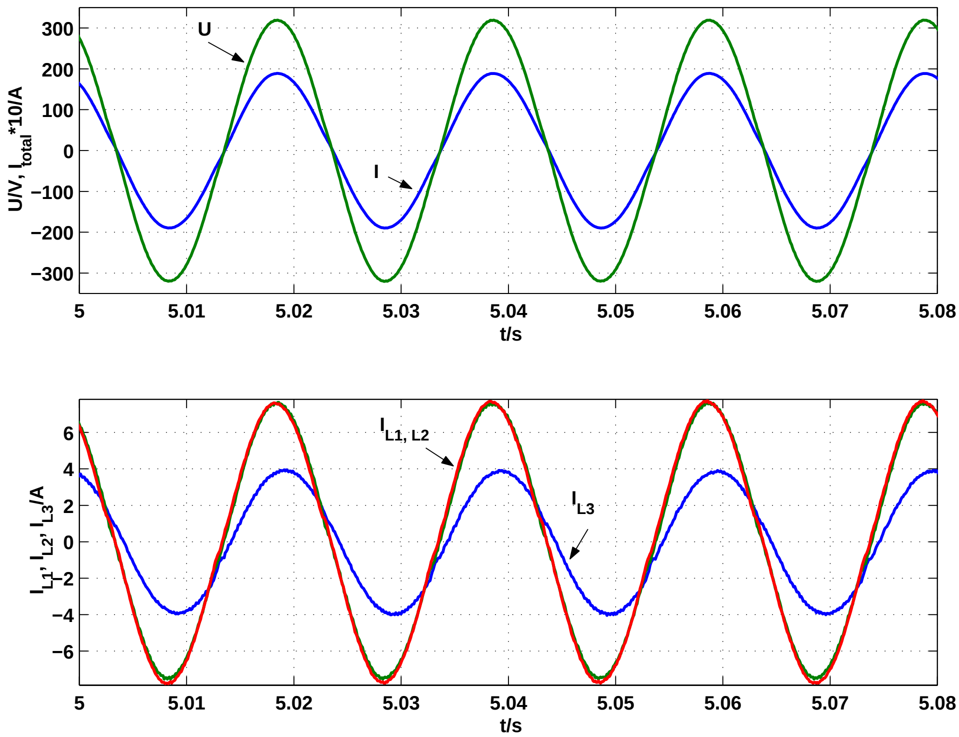


Figure 2-5: *3 kW* steady state operation; load sharing of three *SunnyIsland™* running in parallel

2.3. Implications of line parameters

2.3.1. Power transmission in the low voltage grid

Table 1 shows the typical line parameters *R′*, *X′* and the typical rated current for the high-, medium- and low voltage lines. Assuming inductively-coupled voltages sources for representing the droop controlled inverters and the distribution system would be only correct for the high voltage level. A medium voltage line has mixed parameters and the low voltage line is even predominantly resistive.

Table 1: Typical Line Parameters [8]

Type of line	*R’* *Ω/km*	*X’* *Ω/km*	I_N *A*	$\frac{R^1}{X^1}$
low voltage line	0.642	0.083	142	7.7
medium voltage line	0.161	0.190	396	0.85
High voltage line	0.06	0.191	580	0.31

The active power P_{inv} and the reactive power Q_{inv} of resistively-coupled voltage sources - here an inverter and a grid – can be calculated as follows with the notation according to Figure 2-1:

$$Q_{inv} = \frac{U_{inv} \cdot U_{grid}}{R_{line}} \sin\delta \tag{3}$$

$$P_{inv} = \frac{U_{inv}^2}{R_{line}} - \frac{U_{inv} \cdot U_{grid}}{R_{line}} \cos\delta . \tag{4}$$

Eq. 4 reveals that the active power flow and the voltage is linked in the low voltage grid. A phase difference between the voltage sources causes reactive power flow (s. Eq. 3). This fact suggests to use active power/voltage and reactive power/frequency droops - hereinafter called “opposite droops” - in the low voltage grid, instead of reactive power/voltage and active power/frequency droops - hereinafter called “conventional droops”.

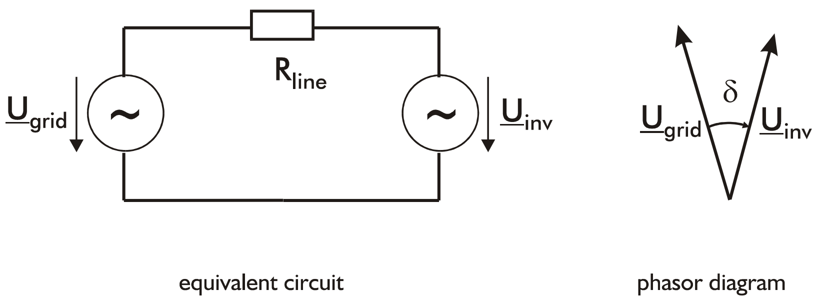


Figure 2-6: Resistively-coupled voltage sources

2.3.2. Comparison of droop concepts for the low voltage level

In the following the advantages and disadvantages of using conventional or opposite droops on the low voltage level are discussed. The boundary conditions for applying conventional droops in low voltage grids will be outlined afterwards. In the low voltage grid the voltage profile is linked with the active power distribution. Reactive power is not suited for voltage control. From a system's view the voltage control and the active power dispatch are the major control issues. Table 2 shows pros and cons of using these two droop concepts.

Table 2: Comparison of Droop Concepts for the Low Voltage Level

	Conventional droop	*Opposite droop*
Compatible with HV-level	Yes	No
Compatible with generators	Yes	No
Direct voltage control	No	Yes
Active power dispatch	Yes	No

As one can see from the Table 2 the only advantage of using the opposite droops is the direct voltage control. But if one would control the voltage this way, no power dispatch would be possible. Each load would be fully supplied by the nearest generator. As this generally is not possible, voltage deviations would remain in the grid. Using conventional droops results in connectivity to the high voltage level, allows power sharing also with rotating generators and a precise power dispatch. The voltage deviations within the grid depend on the grid layout, which is today's standard.

2.4. Indirect operation of droops

Basically, the conventional droop is operable in the low voltage grid due to the generator's voltage variability by means of exchanging reactive power. The reactive power of each generator is tuned the way that the resulting voltage profile satisfies the desired active power distribution. In the low voltage grid the reactive power is a function of the phase angle (s. Eq. 3). This is adjusted with the active power / frequency -droop. The control sense of the entire loop has to be consistent. Four stable operating points result, two of which make sense, depending on the slopes of the droops.

2.4.1. Stable operating points

In order to derive the operating points of conventional droops in the low voltage grid the power transfer equation Eq. 4 is assessed for stability in a simplified manner. At a reasonable operating point δ is rather small, thus $\cos(\delta)$ becomes almost 1 and can be omitted. Rearranging Eq. 4 for the inverter voltage U_{inv} with a given power P_{inv} and a given grid voltage U_{grid} results in two solutions of the quadratic equation:

$$U_{inv1,2} = \frac{U_{grid}}{2} \pm \sqrt{\frac{U_{grid}^2}{4} + P_{inv} \cdot R} \; . \qquad (5)$$

Both solutions have to be taken into account for describing the process. U_{inv1} is a voltage close to the grid voltage and U_{inv2} is a slightly negative voltage. This implies a 180º phase shift. Therefore in Eq. 6 the factor k is introduced with $k_1=1$ for the first solution and $k_2=-1$ for the negative solution. The factor k is an approximation of the cos-function in Eq. 4:

$$P_{inv} = \frac{U_{inv1,2} - U_{grid}}{R} \cdot U_{inv1,2} \cdot k_{1,2} \; . \qquad (6)$$

The inverter power P_{inv} is adjusted by changing the inverter voltage U_{inv} with the reactive power:

$$U_{inv1,2} - U_{grid} = Q_{inv1,2} \cdot q_{droop} \; , \qquad (7)$$

which is a function of the angle δ:

$$Q_{inv1,2} \approx \delta \cdot \frac{U_{inv1,2} \cdot U_{grid}}{R} \quad . \tag{8}$$

δ results from the integral over time of the generator's frequency difference to the grid:

$$\delta = \int \Delta f dt \tag{9}$$

$$\Delta f = (P_{set} - P_{inv}) \cdot p_{droop} \tag{10}$$

The integral character of this process ensures the above-mentioned precise power distribution. Merging Eq. 6 to 10 and solving for P_{inv} results in:

$$P_{inv} = \int P_{set} - P_{inv} dt \cdot \underbrace{\frac{p_{droop} \cdot q_{droop} \cdot k_{1,2} \cdot U_{grid} \cdot U_{inv1,2}^2}{R^2}}_{=C} , \tag{11}$$

which describes a first order lag with the solution:

$$P_{inv} = P_{set}(1 - e^{-C \cdot t}). \tag{12}$$

The simplicity of this solution is mainly due to regarding U_{inv} as time-invariant and the neglect of the power acquisition's dynamic. Eq. 12 only becomes stable if the constant C is positive, which requires

$$p_{droop} \cdot q_{droop} \cdot k_{1,2} > 0 \quad , \tag{13}$$

with p_{droop} and q_{droop} as the respective droop-factors. The four stable operating points can be derived from Eq. 13 and are summarised in Table 3.

Table 3: Stable Operating Points of Conventional Droops
in the Low Voltage Grid

case	*description*	p_{droop}	q_{droop}	*K*	*comment*
1	inverse conv.	pos.	pos.	1	allowed
2	Conv.	neg.	neg.	1	allowed
3		pos.	neg.	-1	not allowed
4		neg.	pos.	-1	not allowed

Case 1 and 2 (the inverse conventional and the conventional droop) are characterised by the same sign of both droop factors. This requires *k* to be 1, which results in an inverter voltage which is near the grid voltage (s. Eq. 5). Only little reactive power is needed to tune the voltage, whereas in case 3 and 4 huge reactive power is needed. Even worse, the inverter power and a huge amount of grid power is dissipated in the line. Therefore, case 3 and 4 is not allowed.

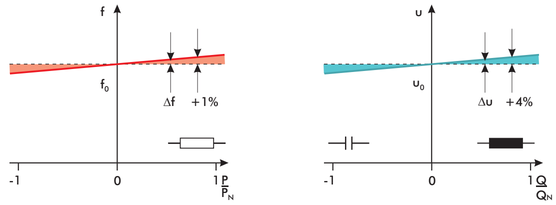
2.4.2. Simulation

Following the plots of the inverter voltage U_{inv}, the grid voltage U_{grid} and the voltage drop across the line U_{line} are depicted for all four cases in Table 4.1 with an injected inverter power of 10 kW. They were computed with the simulation tool *SIMPLORER*™. A single phase system is modelled assuming a line resistance of 0.5 Ω. This corresponds to about 1 km line length.

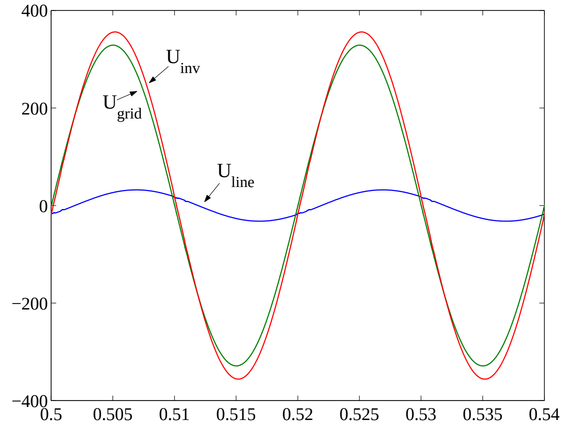
1) *Case 1:* Principally Case 1 (s. Figure 2-7) operates satisfactorily. 3.3 kVar reactive power is needed for tuning the inverter's voltage. The current (s. course of U_{line}) lags the grid voltage U_{grid}. Thus, the inverter is loaded inductively and according to the reactive power / voltage-droop its voltage is increased. However, the droops of this case would not work with the interconnected grid or rotating generators, as they are inverse to the conventional droops.
2) *Case 2:* Case 2 in Figure 2-8 demonstrates the operability of the conventional droops in the low voltage grid. Here 3.3 kVar reactive power is needed for tuning the inverter's voltage. The current (s. course of U_{line}) leads U_{grid}, thus loading the inverter capacitively in order to increase the voltage. According to the active power / frequency-droop and the setting of the idle frequency exactly 10.0 kW is fed into the grid.
3) *Case 3:* In Figure 2-9 the operation at a stable but not allowed operating point is depicted. It is characterised by huge currents. The inverter also injects exactly 10 kW but 72 kVar reactive power would be needed. The corresponding currents would cause a huge voltage drop across the line with losses, which are bigger than the injected active power of the inverter itself.
4) *Case 4:* Case 4 in Figure 2-10 is almost the same as Case 3. – 72 kVar is required instead of 72 kVar (s. also Figure 2-10).

2.4.3. Choice of droops

It can be concluded that the conventional droops of the interconnected grid (case 2) are the right choice for the low voltage grid. They provide a reasonable operating point and the advantages listed in Table 2.

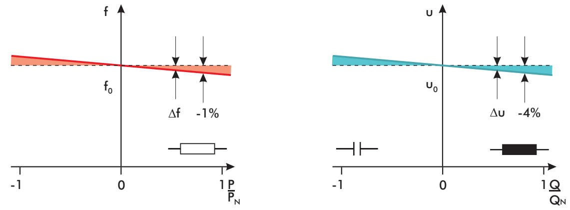


(a) droops with positive p_{droop} and q_{droop}

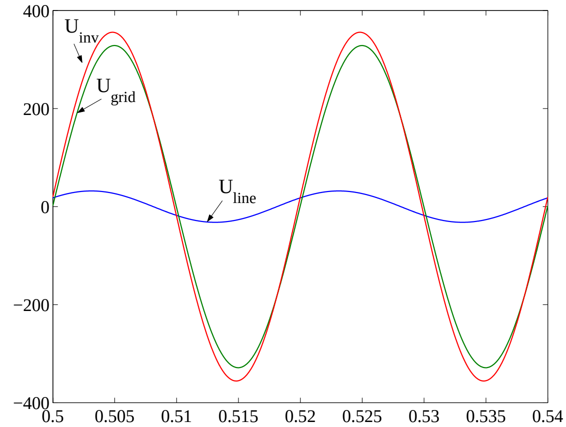


(b) voltages @ 10 kW and 3.3 kVar

Figure 2-7
Case 1: Inverse conventional droops

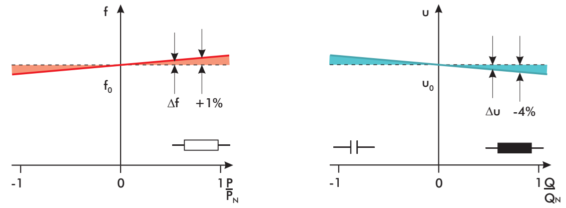


(a) droops with negative p_{droop} and q_{droop}

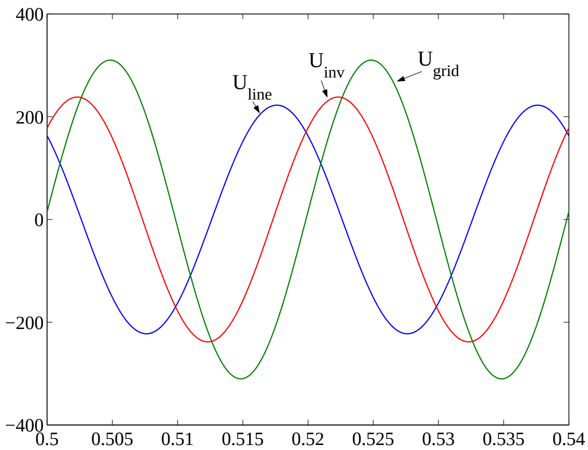


(b) voltages @ 10 kW and -3.3 kVar

Figure 2-8
Case 2: Conventional droops

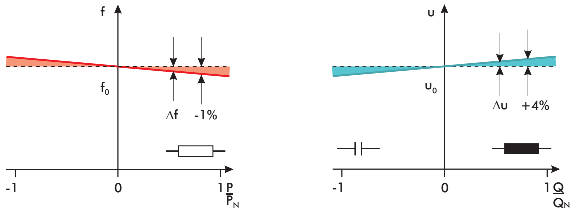


(a) positive p_{droop} and negative q_{droop}

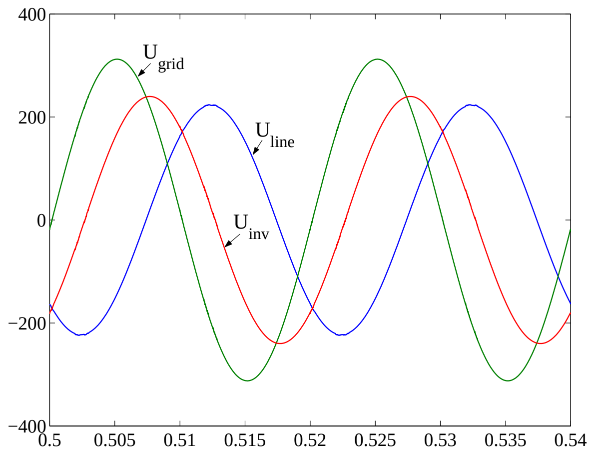


(b) voltages @ 10 kW and 72 kVar

Figure 2-9
Case 3: not allowed



(a) negative p_{droop} and positive q_{droop}



(b) voltages @ 10 kW and -72 kVar

Figure 2-10
Case 4: not allowed

2.5. Compensation for Lines

With regard to losses and inverter utilisation, the necessity of reactive power for tuning the voltage of inverters in the low voltage grid is undesirable. Nevertheless, in order to reduce the required reactive power a partial compensation for the lines can be performed. Therefore, the inverter voltage is corrected by a term calculated of the actual inverter current multiplied by the resistivity of the line to be compensated for:

$$u'_{inv}(t) = u_{inv}(t) + i_{inv}(t) \cdot R_{line} \quad . \tag{14}$$

In Fig. 5.1 resulting voltages with approximately total compensation are depicted. 10 kW is injected requiring almost no reactive power. Accordingly, there is almost no phase shift between the inverter- and grid voltage (compare with Figure 2-8).

One should be careful with line compensation as overcompensation becomes unstable. An approach could be the compensation of 90 % - unknown resistively and sensor errors - of the line up to the next node. As lower currents circulate in the grid, problems concerning voltages are reduced.

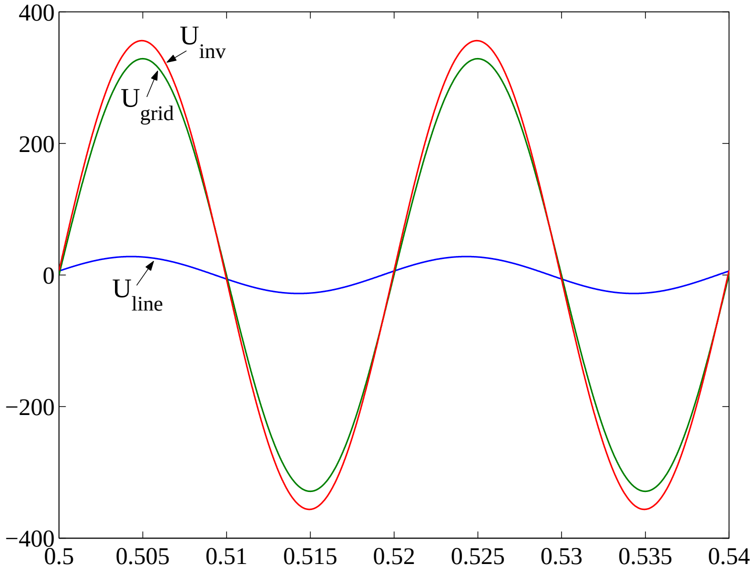


Figure 2-11: Voltages @ 10 kW and ≈ 0 Var

3. System's design

3.1. Combining Inverters of different power classes

Normally, islanded microgrids operation has to cope with load steps in the range of the installed power. Due to the applied droops, all inverters – namely voltage sources – are synchronised well. In case of transients (switching of loads or generators), droops do not take effect, but due to their synchronisation and in case of same inverter impedances the inverters tend to equally contribute to the load step, independent of their nominal power. Droops just affect the system in steady state, i. e. for the fundamental, and ensure the required power distribution.

In order to avoid overloading of the small inverters in case of transients, measures have to be taken. Three parameters of the inverter are suited for it:

- the time delay for active power (T_{mech}),
- the phase feed forward K_p and
- the coupling inductance.

As a rule of thumb, following relation can be used:

$$\frac{K_{p2}}{K_{p1}} \approx \frac{P_2}{P_1} \approx \frac{T_{mech1}}{T_{mech2}} \quad . \tag{15}$$

The coupling inductances of inverters must be chosen according to their short-circuit voltage (5 -10 %).

Figure 3-1 and Figure 3-2 give an example of the transient power distribution between inverters of different power classes (10 and 100 kW). Due to the right setting of the inverter parameters and coupling inductor the transient currents of the small inverter is limited and the transient contribution of each inverter corresponds to its rated power.

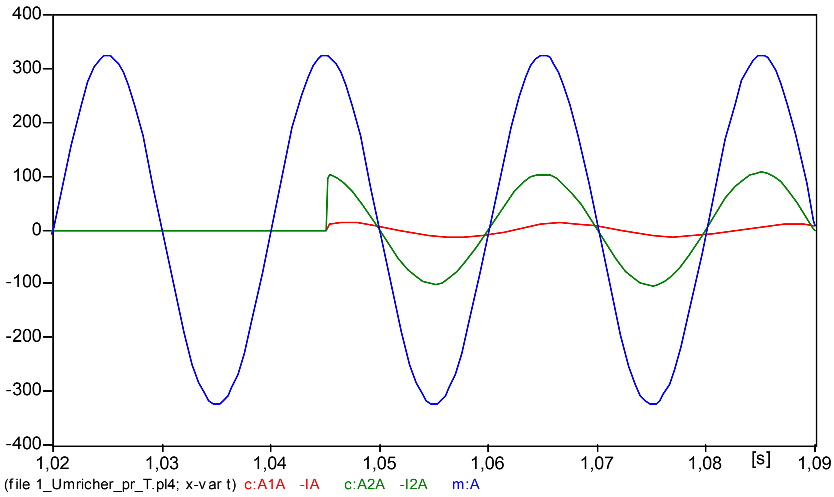


Figure 3-1: Output currents of inverters due to ohmic load step P_{load}≈55 kW

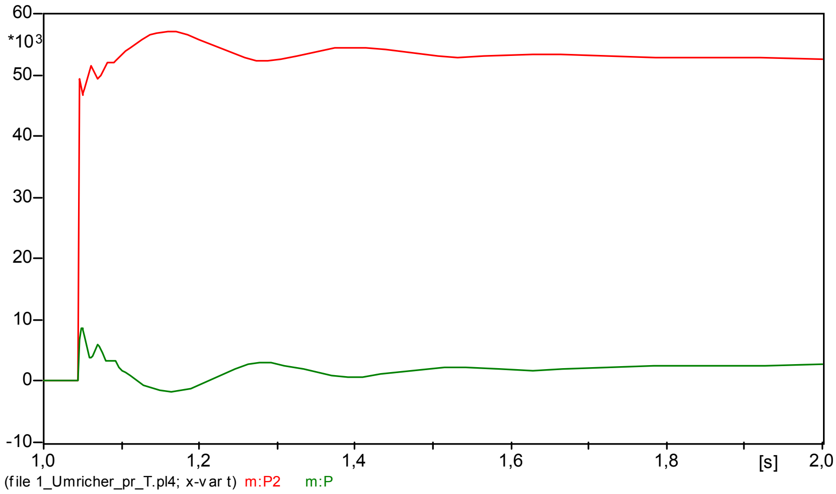


Figure 3-2: Active power output of the inverters due to ohmic load step P_{load}≈55 kW

Especially Figure 3-2 reveals the importance of the damping of the whole supply system. As one can see, in the beginning the swinging of the big inverter determines the power of the small inverter. In the end (at t = 2s) the droops apply and the power is shared according to the settings.

3.2. Operation of inverters with rotating generators

In order to assess the performance of the introduced microgrids local controller strategies in combination with rotating generators, e. g. diesel gensets or wind energy converters, an ATP-EMTP simulation has been performed.

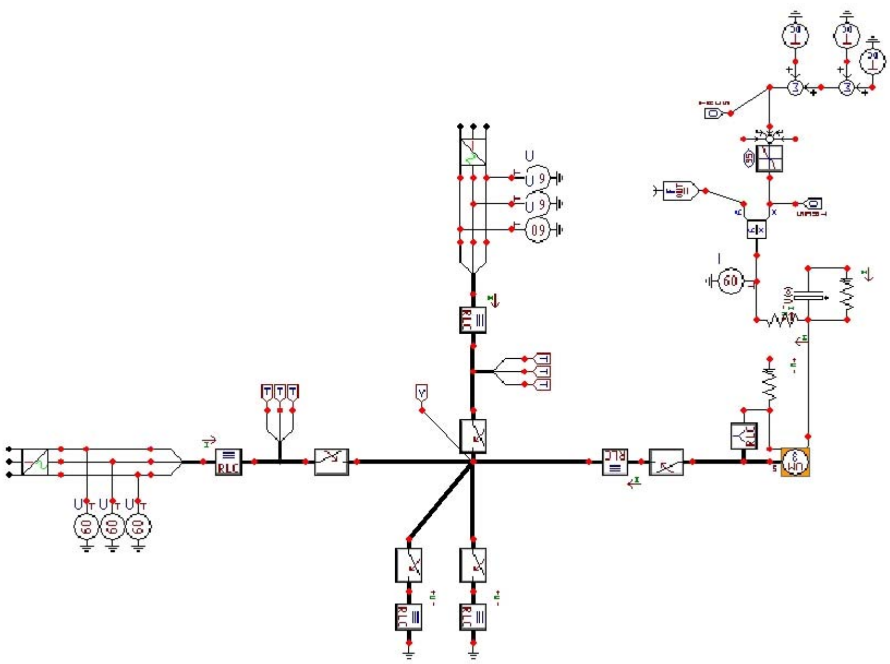


Figure 3-3: ATP-EMTP simulation of an inverter-dominated grid with a rotating generator (generic WEC-model)

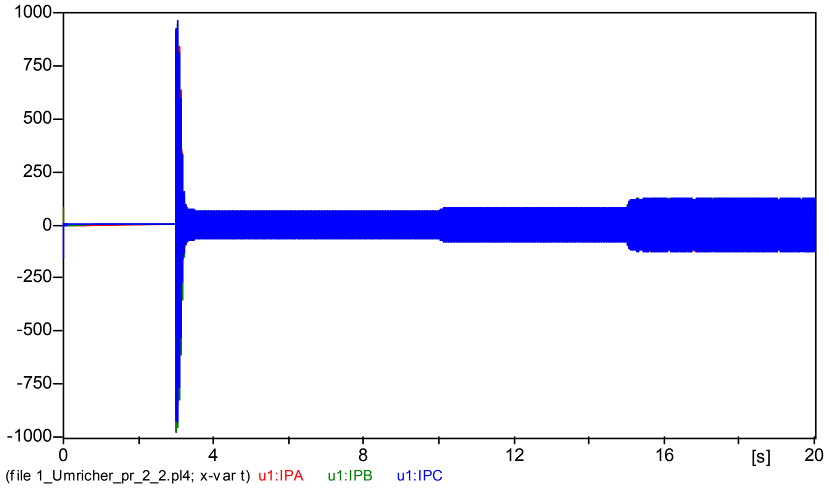


Figure 3-4: Output currents of the WEC-simulator with changing wind profile

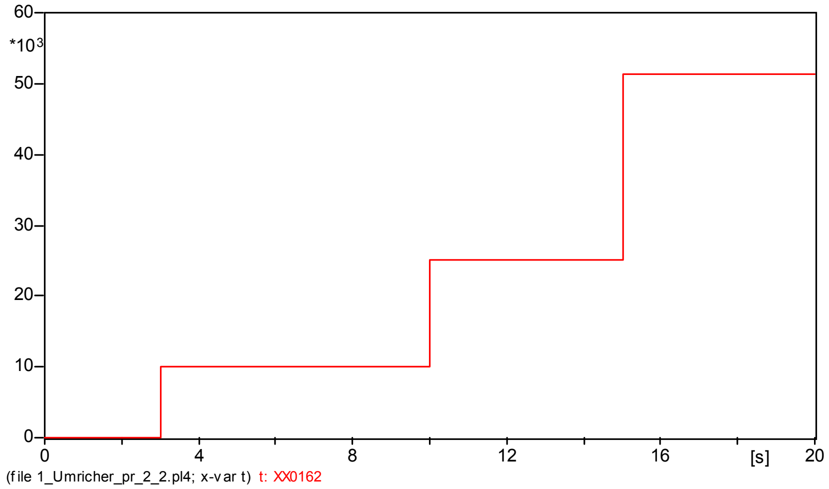


Figure 3-5: Input power of WEC due to artificial wind profile

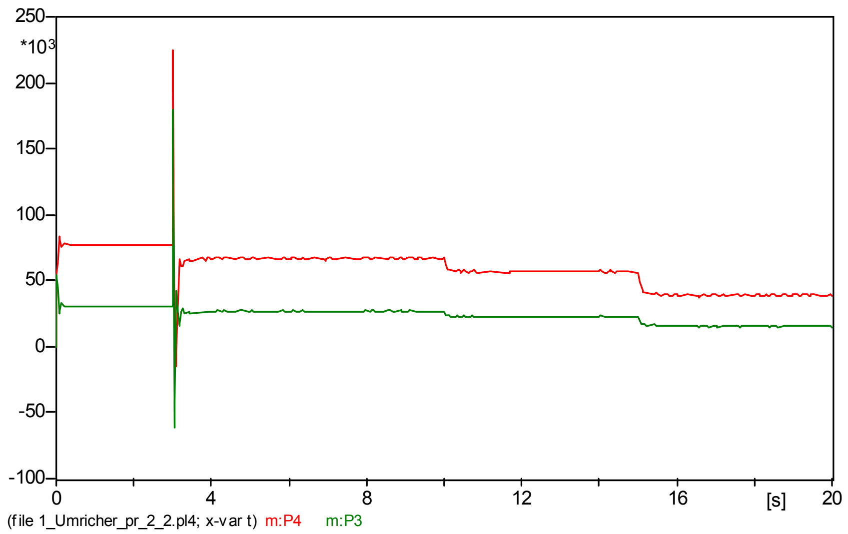


Figure 3-6: Active power contribution (consumption) of the inverters

A system consisting of two droop-controlled inverters is connected to a generic wind energy converter with an asynchronous generator. In principal, the droop control and an asynchronous generator are compatible due to the generator's slip, which has the same behaviour of a frequency droop and the excitation character of the generator representing the voltage droop.

At t = 3 s the WEC connects to the line of the inverter dominated grid. Immediately all loads are supplied by the WEC and the power difference P_{load}-P_{WEC} is shared between inverters according to their droop settings (s. Figure 3-4, Figure 3-5 and Figure 3-6).

The frequency of the system changes as a result of the power fluctuation.

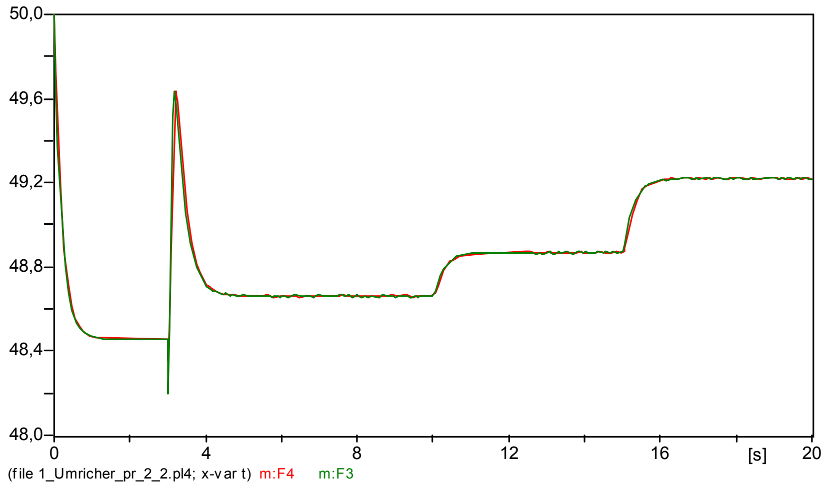


Figure 3-7: Frequency change due to the fluctuation of the wind velocity

3.3. General design rules

A broad applicability of control strategies strongly depends on robust and simple parameterisation. Therefore Table 4 has been elaborated, providing a “universal parameter set”. This is suitable for different power classes and varying numbers of inverters in parallel or even in the grid parallel operation. For all configurations an adaptation of the parameters was not necessary during the simulations and also during the laboratory tests. One setting enables stable operation of multi-inverter grids.

The voltage droop has been chosen according to conventional power systems, by assuming a similar short-circuit voltage. The frequency droop is derived from typical frequency variations of small diesel gensets. Theoretically, the slope of the frequency droop can be very small. The time delay settings for the inverters with different nominal power must be optimised in order to avoid overloading of the inverters.

Table 4: Universal parameter set

Parameter	Symbol	Range	Comments
Slope of the frequency droop	K_p	$\frac{0,1\ Hz \div 1\ Hz}{P_{nom}}$	
Slope of the voltage droop	K_Q	$\frac{5\%\ U_{nom} \div 10\%\ U_{nom}}{Q_{nom}}$	
Phase feed forward (phase correction)	K_{ph}	$\frac{0,005\ rad \div 0,05\ rad}{P_{nom}}$ * $\frac{0,05\ rad \div 5\ rad}{P_{nom}}$ **	* for inductive coupling ** for resistive coupling
Inductive coupling	L_{coup}	$U_k\%=5\% \div 10\%$ of U_{nom}	$U_k = \frac{P_{nom}}{U_{nom}} \cdot \omega \cdot L_{coup}$
Time-delay for the frequency control loop	T_{mech}	0,2 s ÷ 2 s	The setting of the T_{mech} depends on the P_{nom}. The most powerful one gets the biggest time delay.
Time delay for the voltage control loop	T_{exc}	0,2 s ÷ 1 s	.

3.4. Self-excitation

If a power system is operated with a conventional voltage droop, i. e. voltage dependence on reactive power, boundary conditions concerning the capacitive load have to be considered. Too high capacitive load might lead to the well-known “self-excitation” phenomenon.

The common stability criterion is:

$$\frac{1}{\omega \cdot C_{Load}} > \omega \cdot L_{vir} \quad (16)$$

where C_{Load} is the maximum capacitance of the load and L_{vir} is a "virtual" inductance, which describes the sum of the effect of the voltage droop and the coupling inductance. The "virtual" inductance can be calculated as a differential inductivity:

$$(\omega \cdot L_{vir}) = \frac{\Delta U}{\Delta I_{REACTIVE}} \ . \quad (17)$$

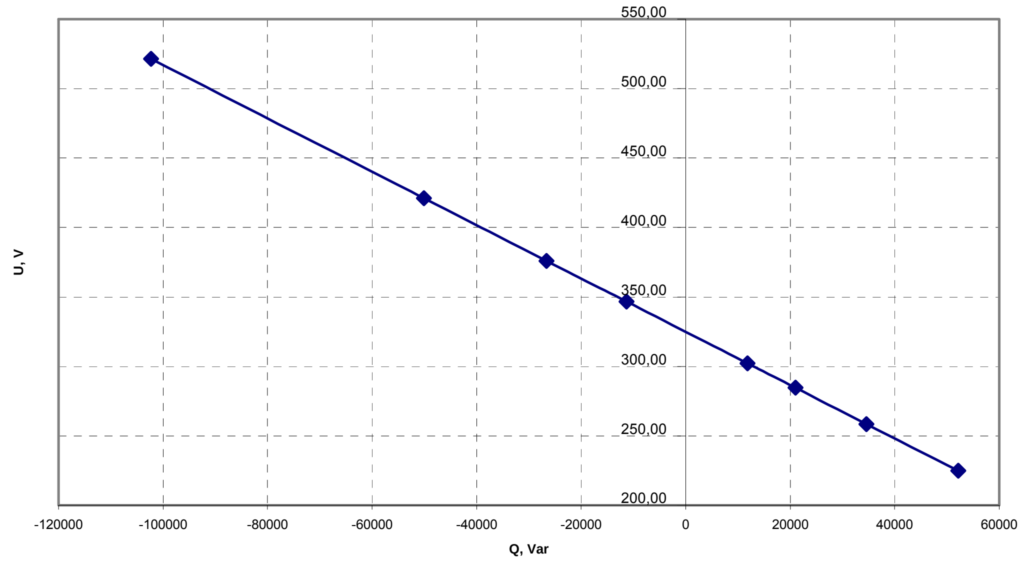


Figure 3-8: Voltage droop: k_Q=0,00192 V/Var and R=0,1 Ohm

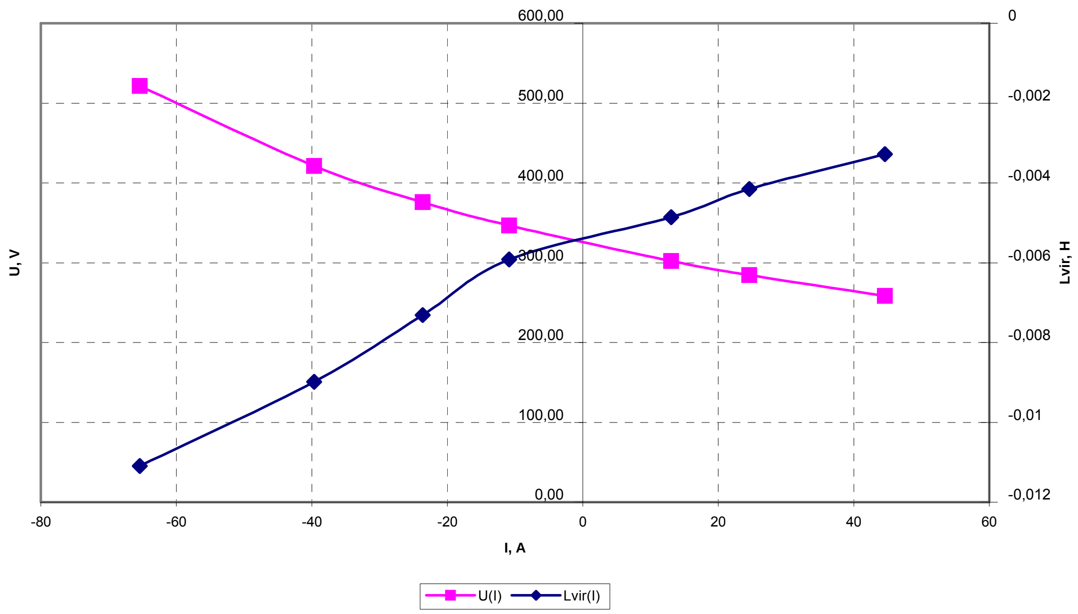


Figure 3-9: U(I) and L_{vir}(I) characteristics

The linear voltage droop in Figure 3-8 results in a non-linear U($I_{REACTIVE}$)-function in Figure 3-9. The differentiation of the U($I_{REACTIVE}$)-function results in a current dependant differential "virtual" inductance, i. e. in a dynamic stability area.

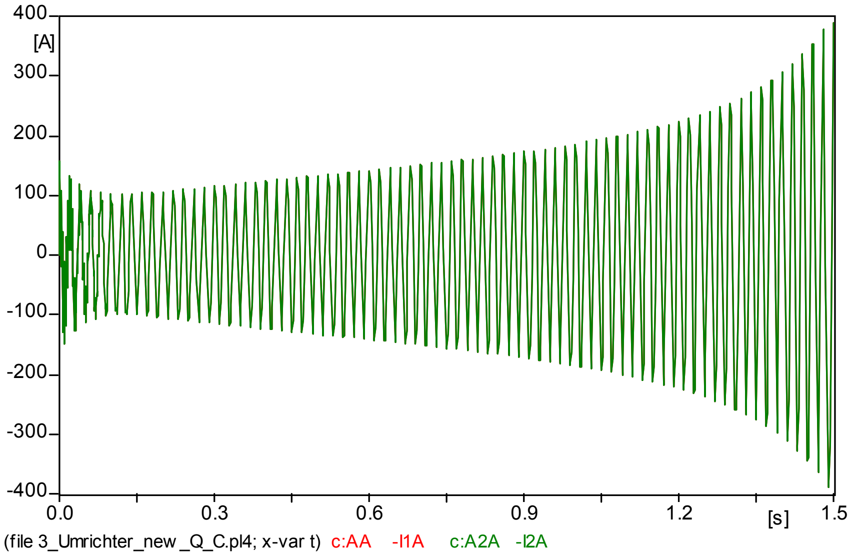


Figure 3-10: Output current of inverter in case of "self-excitation"

If the condition in equation (16) is not fulfilled, the excitation currents start to increase (s. Figure 3-10). The presence of a resistance helps to reduce the probability of "self-excitation", but stability limits must be still taken into account.

The effect of a resistance can be described by following circle equation:

$$(x_C - \frac{x_{coup}}{2})^2 + R^2 = (\frac{x_{coup}}{2})^2 \quad (18)$$

where $X_C = 1 / \omega C_{Load}$ and $X_{coup} = \omega L_{VIR}$.

The inner of circle in Figure 3-11 (grey) represents the dangerous self-excitation zone characterised by a small X_C, i. e. big C_{Load}.

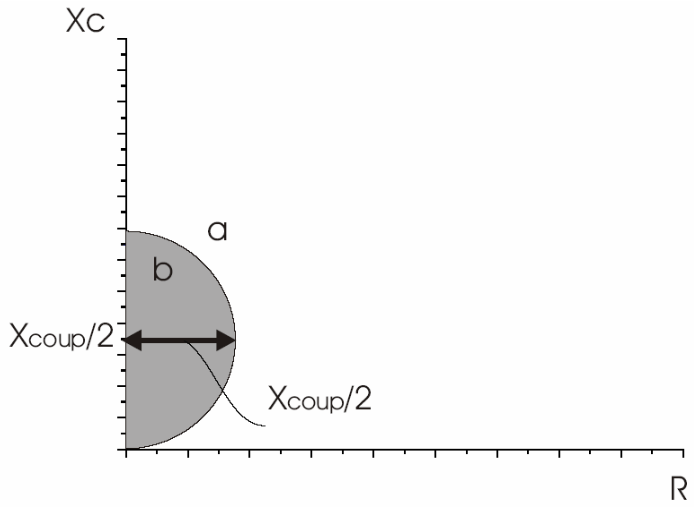


Figure 3-11: Boundary curve for the “self-excitation”: a stability zone; b “self-excitation zone”.

4. Conclusion

It has been shown that the droops, used in the interconnected grid, can be used effectively on the low voltage level due to their “indirect operation”. So far, this effect has not been reported about. The only boundary condition is the same sign for the frequency as well as for the voltage droop factors. As a consequence of this outcome the control strategy of the conventional grid can be down scaled to the low voltage level without any restrictions. This coherence will support the introduction of DER and RES on the low voltage level and alleviates concerns about grid stability and safety.

Still the question of voltage control remains open, which should be supported by the grid layout. However, in order to improve the situation the partial compensation of lines has been successfully demonstrated by means of simulation.

Further results of the evaluation are:

- The combination of inverters of different power classes is possible. Suitable parameter settings avoid overloading of the small inverters.
- As rotating machines are characterised by inherent droops, the combination with the proposed droop-control is possible.
- Broadly applicable parameter sets for the inverter control can be derived.
- “Self-excitation” might be problem (as in conventional power systems).

With these results one can conclude, that the proposed droop-control fulfils all requirements for designing microgrids of different sizes and with different generators. The parameters for enabling a stable operation of the microgrids are easily to derive and need not to be adapted for different operation situations.

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