Applicability of droops in low voltage grids

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***Abstract*— Remote electrification with island supply systems, the increasing acceptance of the microgrids concept and the penetration of the interconnected grid with DER and 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. Despite contradicting line parameters, the applicability of this proceeding is outlined and the boundary conditions are derived.**

***Index Terms*— droops, low voltage grids, micro grids, control, distributed generation, DER, RES, VSI.**

I. INTRODUCTION

REMOTE electrification with island supply systems, the increasing acceptance of the microgrids concept [1] and the penetration of the interconnected grid with DER and 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. By this methodology a superior system architecture is enabled, 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 inductive 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 changes 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.

II. DROOP CONTROL

In expandable distributed inverter systems 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. Fig. 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
- more complex control tasks in the components.

Additional redundancy in grids can be achieved by using voltage source inverters (VSI) in parallel. 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. Fig. 2). But the configuration in Fig. 2 is difficult to handle as will be shown. The active power P and the reactive power Q of the voltage sources can be calculated as follows:

$$P_1 = \frac{U_{1,\mathrm{eff}} \cdot U_{2,\mathrm{eff}}}{\omega_\mathrm{N}(L_1 + L_2)} \sin\delta \tag{1}$$

$$Q_1 = \frac{U_{1,\mathrm{eff}}^2}{\omega_\mathrm{N}(L_1 + L_2)} - \frac{U_{1,\mathrm{eff}} \cdot U_{2,\mathrm{eff}}}{\omega_\mathrm{N}(L_1 + L_2)} \cos\delta \tag{2}$$

A phase shift δ between two voltage sources causes active power transmission. Reactive power transmission is due to the voltage difference $U_1 - U_2$. Assuming standard values for the inductance L_1 and L_2 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

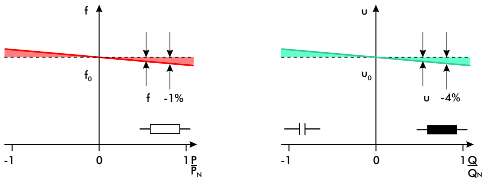


Fig. 1. Conventional droops in the interconnected grid

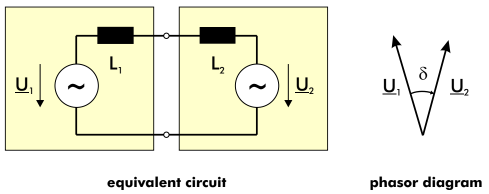


Fig. 2. Inductive coupled voltage sources

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.

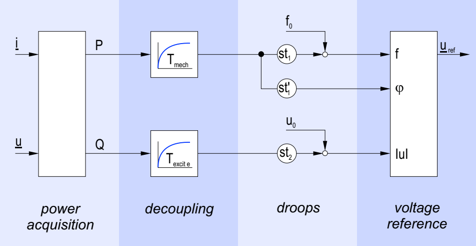


Fig. 3. Control approach *selfsync*™ by ISET e. V., Kassel, Germany [4]

Firstly this control approach, named *selfsync*™, was implemented into the battery inverter *SunnyIsland*™ for rural electrification (s. Fig. 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. 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].

III. IMPLICATIONS OF LINE PARAMETERS

A. Power transmission in the low voltage grid

Table I shows the typical line parameters R', X' and the typical rated current for the high-, medium- and low voltage lines. Assuming inductive 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 I
TYPICAL LINE PARAMETERS [8]

Type of line	R' Ω/km	X' Ω/km	I_N A	$\frac{R'}{X'}$
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

Fig. 4. Two battery inverters *SunnyIsland* ™ by SMA Regelsysteme GmbH, Kassel, Germany operating in parallel (rated power 4.2 kW, clock 16 kHz, coupling inductor 0.8 mH)

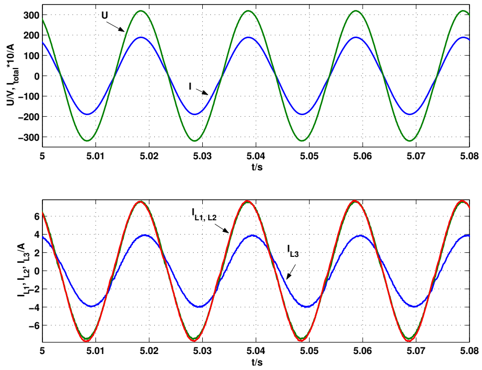


Fig. 5. 3 kW steady state operation; load sharing of three *SunnyIslands* ™ running in parallel

The active power P and the reactive power Q of resistive coupled voltage sources - here an inverter and a grid - can be calculated as follows with the notation according to Fig. 6:

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

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

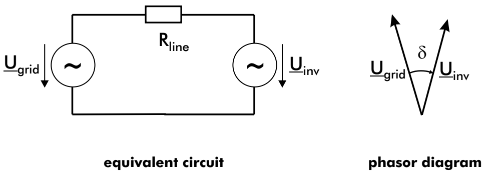


Fig. 6. Resistive coupled voltage sources

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”.

B. Comparison of droop concepts for the low voltage level

In the following the advantages and disadvantages of using conventional or inverse 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 II shows pros and cons of using these two droop concepts.

TABLE II
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 II the only advantage of using the inverse 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.

IV. 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.

A. 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. Rearranged for the inverter voltage U_{inv} with a given power P_{inv} and a grid voltage U_{grid} two solutions result from solving the quadratic equation:

$$U_{inv1,2} = \frac{U_{grid}}{2} \pm \sqrt{\frac{U_{grid}^2}{4} + P_{inv} \cdot R} \quad . \tag{5}$$

These both 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 180° 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:

$$P_{inv} = \frac{U_{inv1,2} - U_{grid}}{R} \cdot U_{inv1,2} \cdot k_{1,2} \quad . \tag{6}$$

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

$$U_{inv1,2} - U_{grid} = Q_{1,2} \cdot q_{droop} \quad , \tag{7}$$

which is a function of the angle δ:

$$Q_{1,2} \approx \delta \cdot \frac{U_{inv1,2} \cdot U_{grid}}{R} \quad . \tag{8}$$

δ results from the integral over time of the generators'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:

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

which describes a first order lag with the solution:

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

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

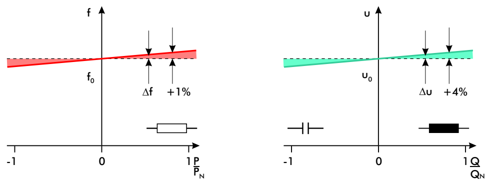
$$p_{droop} \cdot q_{droop} \cdot k_{1,2} > 0 \quad . \tag{13}$$

The four stable operating points can be derived from Eq. 13 and are summarised in Table III.

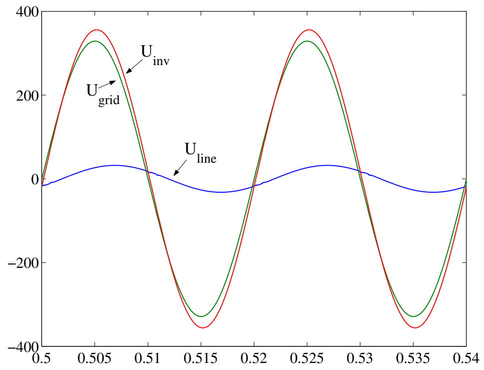
TABLE III
STABLE OPERATING POINTS OF CONVENTIONAL DROOPS IN THE LOW VOLTAGE GRID

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.



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



(b) plot of voltages @ 10 kW and 3.3 $kVar$

Fig. 7. Case 1: Inverse conventional droops

B. Simulation

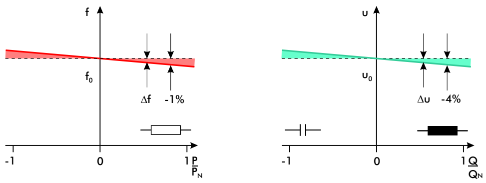
Following the plots of the inverter voltage U_{inv}, the grid voltage U_{grid} and the voltage drop across the line U_{line} are depicted for all four cases in Table III with an injected inverter power of 10 kW. They were computed with the simulation tool *SIMPLORER*™. A single phase system is modelled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

1) Case 1: Principally Case 1 (s. Fig. 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. But the droops of this case would not work with the interconnected grid or rotating generators, as they are inverse to the conventional droops.

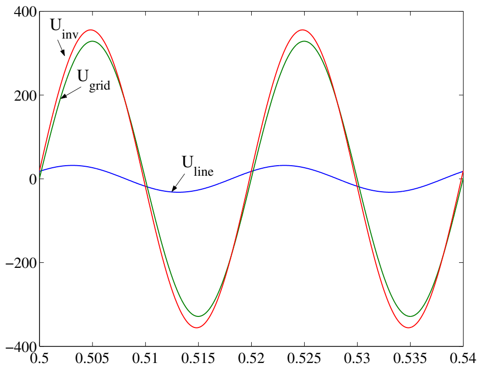
2) Case 2: Case 2 in Fig. 8 demonstrates the operability of the conventional droops in the low voltage grid. Here -3.3 $kVar$ reactive power is needed for tuning the inverter's voltage. The current (s. course of U_{line}) leads U_{grid}, thus loading the inverter capacitively in order to increase the 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 Fig. 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 Fig. 10 is almost the same as Case 3. - 72 $kVar$ is required instead of 72 $kVar$ (s. also Fig. 9).

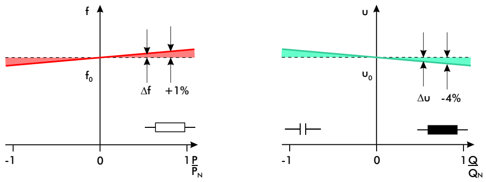


(a) droops with negative p_{droop} and q_{droop}

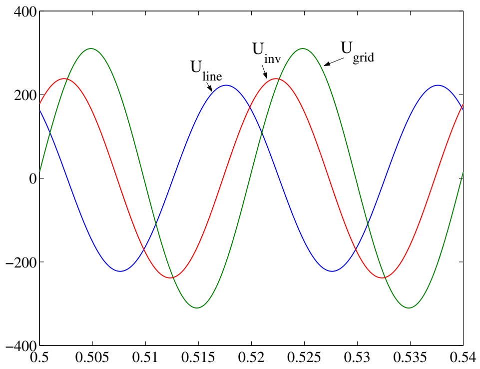


(b) plot of voltages @ 10 kW and -3.3 kVar

Fig. 8. Case 2: Conventional droops



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



(b) plot of voltages @ 10 kW and 72 kVar

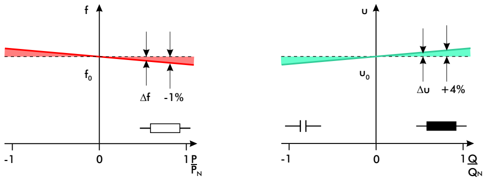
Fig. 9. Case 3: not allowed

C. Choice of droops

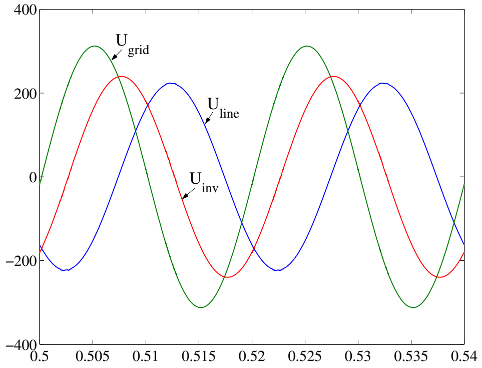
It can be concluded that the conventional droops of the interconnected grid (case 2) are the right choice for the low voltage grid. They provide a reasonable operating point and the advantages listed in Table II.

V. 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



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



(b) plot of voltages @ 10 kW and -72 kVar

Fig. 10. Case 4: not allowed

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:

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

In Fig. 11 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 Fig. 8).

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

VI. 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 concerns about grid stability and safety can be alleviated.

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.

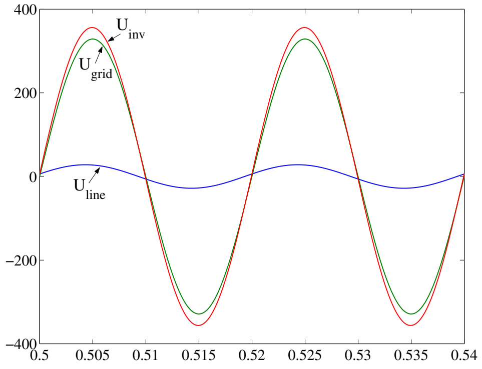


Fig. 11. Voltages @ 10 kW and ≈ 0 Var

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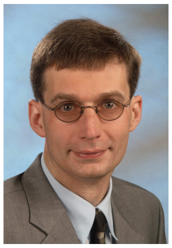

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