Control of a Three Phase Inverter Feeding an Unbalanced Load and Operating in Parallel with Other Power Sources

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Abstract

A control for a three phase inverter, acting as a voltage source, is presented. The inverter is able to work in parallel with a constant-voltage constant-frequency system, as well as with other inverters or also in standalone. There's no communication interface needed. The different power sources can share the load also under unbalanced conditions. To achieve this the frequency and the amplitude of the grid voltage can have small variations. By introducing a secondary control load sharing is even possible without frequency or amplitude deviations in steady-state. Measurements are presented to prove the good control behaviour.

Introduction

For island grids renewable energy sources become more and more attractive. For this reason the number of inverters in such grids increases. It's an aim to form grids with different power sources (such as inverters or rotating machines) with highest modularity and redundancy. For this reason all power sources should act as voltage sources. Load sharing is desired without communication interconnections between the different sources. Another application for paralleled redundant voltage sources are uninterruptible power supplies (UPS) for industry or hospitals. In the future fuel cell plants and a lot of regenerative power sources will probably feed the utility networks. Having less conventional power plants with rotating machines stability problems of the grid are expected. To overcome these problems and to fulfil the demands a control strategy for inverters is developed in this paper.

Modelling and basic control principle

A PWM voltage source inverter with LCL output filter is regarded. In Fig. 1 the single phase equivalent circuit diagram is shown. The inverter itself is a source with rectangular voltage U_{WR}. A LC-filter is used to reduce the higher harmonics and to provide a nearly sinusoidal capacitor voltage U_C. A small reactance X_N decouples the inverter from other voltage sources.

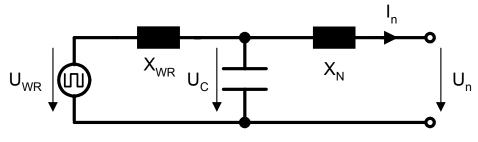

Fig. 1 Single phase equivalent circuit of the inverter output filter

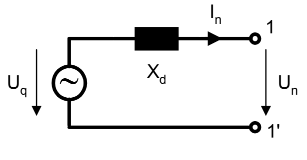

Fig. 2 Reduced equivalent circuit

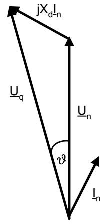

Fig. 3 Phasor diagram of the reduced circuit

It's state of the art to control the capacitor voltage of the filter with high dynamic performance. As a result an inverter can be regarded as an ideal AC-voltage source U_q with an output reactance X_d (Fig. 2). The phasor diagram of the reduced equivalent circuit in Fig. 2 is given in Fig. 3.

The power at the terminals of the circuit in Fig. 2 can be described as

$$P_n = \frac{U_n U_q}{\omega L_d} \sin \vartheta \qquad \text{active power} \qquad (1)$$

$$Q_n = \frac{U_n U_q}{\omega L_d} \cos \vartheta - \frac{U_n^2}{\omega L_d} \qquad \text{reactive power} \qquad (2)$$

with ω as the radian frequency of the grid voltage U_n. The grid voltage is assumed fixed. For a small angle ϑ, active power is determined by the angle ϑ and reactive power by the amplitude of the inverter voltage U_q.

The similarity of the circuit in Fig. 2 with the equivalent circuit diagram of a synchronous machine is obvious. Therefore the system behaviour of the synchronous machine is investigated first [1]. In a power plant the generators with turbine work relatively stiff because speed is controlled by a proportional speed governor. Out of a speed deviation it derives a signal for the turbine valve to regulate active power. A reactive power flow affects the grid voltage. Its deviation is the input signal for the proportional excitation controller. By using proportional controllers for these two tasks there are deviations of frequency and voltage which are proportional to the load. Providing active (respectively reactive) power leads to a proportional reduction of frequency (respectively voltage). The behaviour of such a controlled synchronous machine can be described by the following equations.

$$f(P) = f_0 - \frac{\Delta f}{\Delta P} \cdot P \qquad \text{with } f_0 \text{ as setpoint} \qquad (3)$$

$$U(Q) = U_0 - \frac{\Delta U}{\Delta Q} \cdot Q \qquad \text{with } U_0 \text{ as setpoint} \qquad (4)$$

This behaviour can be described by linear droops. In this way power sharing between several machines is achieved and numerous synchronous generators can work in parallel. These properties are transferred to inverters, but some significant differences must be considered. First the per unit quantity of the output reactance x_d of an inverter is nearly one order smaller. A small difference in the output voltage leads to high currents. Second there are no rotating parts with inertia, so frequency and phase angle can change very fast. Third an inverter has not the overload capability of a machine. It's clear, that a very fast control with a fast measurement method of the used variables (frequency, active & reactive power, rms-value of the grid voltage) is necessary. The principle of a fast measurement method is described in the next paragraph. A significant difference between a synchronous generator in a power plant and an inverter is, that active power can't be controlled by a steam valve or anything similar. For this reason an active power controller is implemented instead of a speed controller and for consistency a reactive power controller instead of an excitation controller. As shown in the paragraph after next the inverter behaviour is similar to the synchronous machine if the setpoint values for the two power controllers are derived from droops. An example for such droops is shown in Fig. 4. These droops were used in a test setup and are the reverse functions of (3),(4).

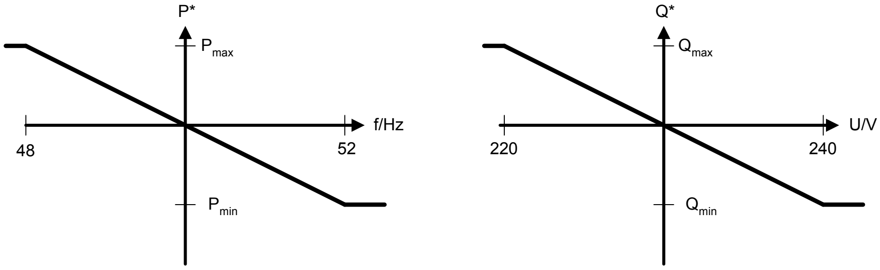

Fig. 4 P(f)-droop and Q(U)-droop

Measurement methods for frequency and for active and reactive power

If the currents and voltages of a 3-phase system are symmetrical, sinusoidal and stationary active and reactive power are not dependent on time. Currents and voltages can be described with phasors. Simple complex calculation leads to active and reactive power. In single phase systems or in unsymmetrical sinusoidal 3-phase systems the product of voltage and current will be a mean value corresponding to active power and an alternating component with double fundamental frequency [2]. Apart from simple low pass filtering or peak value detection, more detailed and faster algorithms to measure the significant values in single phase systems are presented in [3], [4]. These algorithms use low pass filtering making them slow or having a ripple content. A very fast method to measure fundamental active and reactive power, and the rms-values of the fundamentals of current and voltage can be realised by using a structure with the transfer function $G(s)=\frac{Y(s)}{W(s)}=2k\cdot\frac{s}{s^2+\omega^2}$. This structure is called "generalised integrator" (GI) (Fig. 5). The GI has a gain *k* and is adjusted for a certain frequency $\omega = 2\pi f$. If the GI is adjusted for the fundamental frequency *f* of an incoming signal *u* and if it is implemented with a feedback loop (Fig. 7) it provides a signal *y* equal to the fundamental of *u* and a fundamental signal $y_\perp$ which is lagging for 90 degrees. For better understanding the phase and the gain of the transfer functions of the GI and the GI with feedback loop is shown in Fig. 6 and Fig. 8.

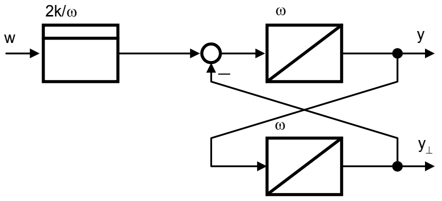

Fig. 5 "Generalised integrator" (GI)

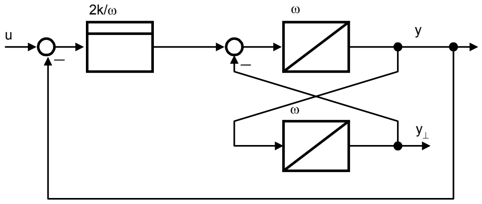

Fig. 7 GI with a feedback loop

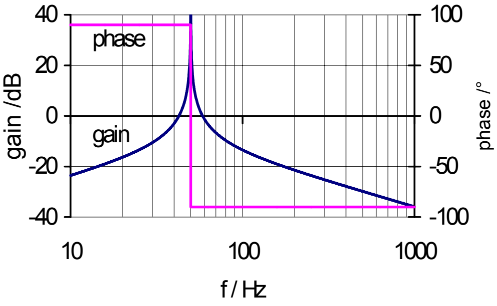

Fig. 6 Gain and phase of the GI (f = 50Hz, k = 50)

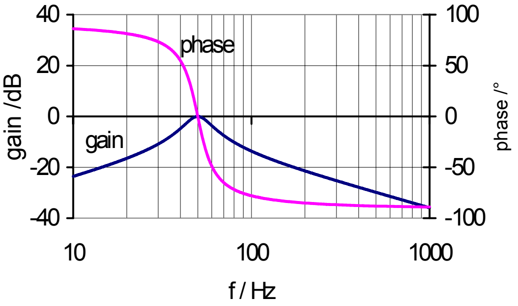

Fig. 8 Gain and phase of the GI with feedback loop (f = 50Hz, k = 50)

With the two values *y* and $y_\perp$ which are provided by the GI with feedback loop a phasor ($\underline{y} = y + jy_\perp$) for a single phase system can be defined. Complex power ($\underline{S} = \frac{1}{2}\underline{u}\cdot\underline{i}^* = P + jQ_1$) can be computed when the phasors for current and voltage are known. So active power (P) and fundamental reactive power (Q_1) can be derived. The amplitude of the fundamental of the incoming signal is the absolute value of *y*. The GI was first used for similar applications in [5] and is described in [6] and [7], too. This is a method with very high performance. $\hat{U}$, $\hat{I}$, P and Q_1 can be computed for every single phase continuously, fast and without ripple content in stationary case.

In the following the voltage system is symmetrical, the load is unbalanced and active and reactive power measurement can be done for all three phases together. An implementation of power calculation with less expenditure is to use the Park-transformation and compute active power (reactive power) as real (imaginary) part of complex power. To achieve a constant value in an unbalanced system the signals must be filtered. This is done by using the GI as a band pass (Fig. 7) to identify the 100 Hz content and to subtract it from the real (respectively imaginary) part of complex power. It's evident that at identical filtering expenditure this method is twice as fast as the computation of three single phase powers with the GI [5],[6],[7] where you have to identify 50 Hz signals.

For frequency measurement the GI can also be used. The fundamental $y = \hat{U} \cdot \sin(\omega t)$ and the 90° lagging component $y_{\perp} = \hat{U} \cdot \cos(\omega t)$ of an incoming signal can be obtained. By dividing these two parts and computing the arc tangent, ωt is obtained. By knowing the time t, frequency f is known every time of the period (except when arc tangent is infinite). No zero crossing detection is necessary and a continuous frequency signal is provided.

Parallel operation with load sharing

As shown, by changing the angle ϑ and the amplitude $\hat{U}$ of the inverter voltage, power flow at the terminals is affected (equations (1), (2)). For the proposed three phase inverter a power control as shown in Fig. 9 is implemented. The three independent single phase voltage controllers are carried out as described in [8].

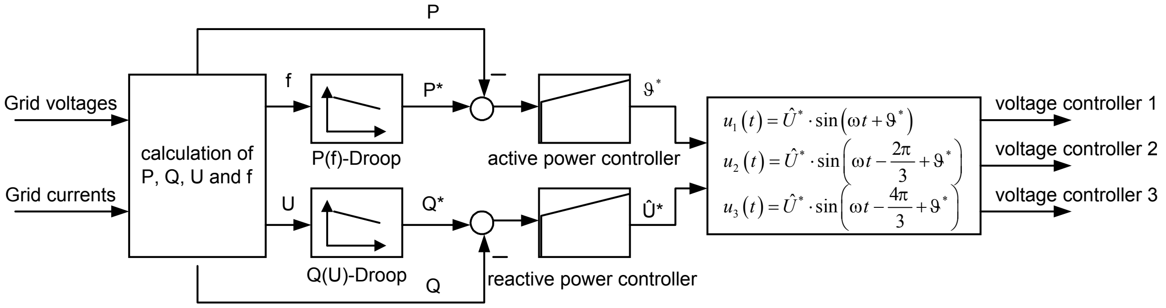

Fig. 9 Power control for the inverter

The active power controller is regarded in the following. Grid frequency is measured and the setpoint value P^* for active power is derived out of a P(f)-droop. The system deviation ΔP leads through the active power controller to an angle ϑ^*. With ϑ^* the setpoints for the three voltage controllers are derived. The active power controller has PI behaviour and is explained for three operation cases.
Case 1: Easy to understand is the operation in parallel with a constant frequency grid. If there is a system deviation of the active power, ϑ^* is decreased or increased until the active power flow (see equation (1)) corresponding to the fixed frequency is provided in the grid.
Case 2: If the inverter works in standalone, active power is determined by the load. If the setpoint value for the active power derived out of the P(f)-droop is different to the load, the angle ϑ^* is decreased or increased by the power controller **continuously**, so the grid frequency changes, and a new setpoint for the power controller is provided. The system is stable when the deviation of frequency leads to the setpoint of active power that corresponds to the power demand of the load.
Case 3: If several inverters are operating in parallel, a mix of the first two cases will happen. The angle ϑ^* is adjusted and load is given to other inverters, but also frequency is variable so that the frequency can meet a fixed load. If the droops of the inverters are identical, equal load sharing will be achieved. The measurement of the same frequency will lead to the same setpoint for the active power controller and therefore through the active power controller to the provision of same active power.

The control of reactive power is done similar by controlling the amplitude of the voltage and deriving the setpoint for the reactive power controller out of an Q(U)-droop. A disadvantage of the reactive power control is, that if there are significant line inductances between the sources, the amplitude of the voltage is measured different and therefore not the same reactive power is provided. The weight of this disadvantage depends on the grid configuration. If there is a busbar and the connection inductance of the inverters is known, the voltage at the busbar can be computed by every inverter, so load sharing can be equal. If there is no busbar and the grid is totally distributed, perhaps it would be even desirable if the reactive power sharing is not equal and depends on the local voltage condition.

A control with similar behaviour was proposed in [9]. It uses a frequency and voltage controller instead of the active and reactive power controllers and the load must be symmetrical. A control for single phase systems with droops is presented in [4]. To share reactive power an additional signal is injected in the inverter voltage. This is not useful in three phase systems because a load sharing can also be achieved between inverters and rotating machines. To do this in a simple way is to support the natural characteristics of the machines and not to implement additional control expense.

Secondary control

Up to here the sharing of active and reactive power is based on a fixed relation between f and P (respectively U and Q), implemented as a droop. To restore frequency and voltage to their nominal values the droops have to be adjusted after a load change. In the utility networks this is done equally for all power plants by communication. If there's no communication between the power sources the problem is that if one source adjusts its droop the other sources can't distinguish this from a load step. So this will lead to unbalanced load sharing, because it can't be ensured that a simple shift of the droops is done by all sources equally. To overcome this problem and to achieve frequency and voltage restoration while maintaining load sharing, a so called secondary control is implemented. For droop shifting the setpoints f_0 and U_0 (see (3)(4)) are adjusted. The shift of each droop is determined by three components. The principle of the secondary control is explained regarding the P(f)-droop.

The first component of the secondary control is the restoration of the frequency (Fig. 10). The deviation of the measured grid frequency from the nominal frequency leads through a simple integrator to the amount by which the droop is shifted. This solution was suggested in [10]. It's obvious, that for several sources working in parallel the shifting isn't done equally because of measurement mismatches. Also if the sources are connected to the island grid at a different time, equal load sharing is surely not possible, because the "histories" of the integrators are different.

For this reason the shifting of the droops is influenced by a second component, which tries to balance the load sharing at the expense of frequency restoration (Fig. 11). The balancing component tries to give power to other sources by shifting its droop. The decisive point is that this shifting is dependent on the actual power diminished by the power which should be provided at 50 Hz. For this reason more loaded sources shift their droop with greater force. When all sources provide same power and do have the same droop setpoint f_0 they shift with same force. Finally, when the frequency is at its nominal value (achieved by the frequency restoration component) the force is zero. This is so because the power controller is working and so actual power P at 50 Hz is equal to $P^*(50\text{Hz})$. Therefore the balancing control is only active if there is a frequency deviation

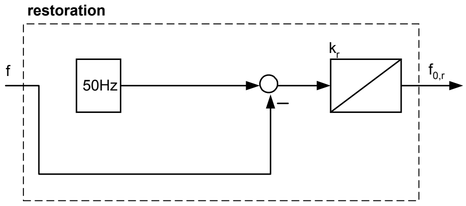

Fig. 10 Frequency restoration control

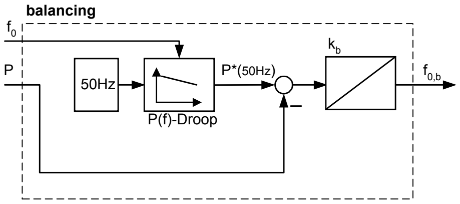

Fig. 11 Load balancing control

A tolerance band for both components is used. Small deviations of the input values are neglected. This is necessary because of small differences in frequency (respectively voltage) measurement. Despite of the tolerance bands it's possible that the load sharing becomes very slowly unsymmetrical. The resulting error in load sharing is corrected if there are load steps. The load steps will lead to frequency changes because the droops are still active. Therefore the balancing control will start working.

It is possible that there are no significant load changes or that frequency has settled before the whole difference in load sharing has gone to zero. So a stochastic disturbing component is introduced. It shifts sometimes the droop. This disturbance has the same effect as a load step. The secondary control for the voltage restoration is done in a similar way. The integration of the secondary control in the control scheme of Fig. 9 is shown in Fig. 12.

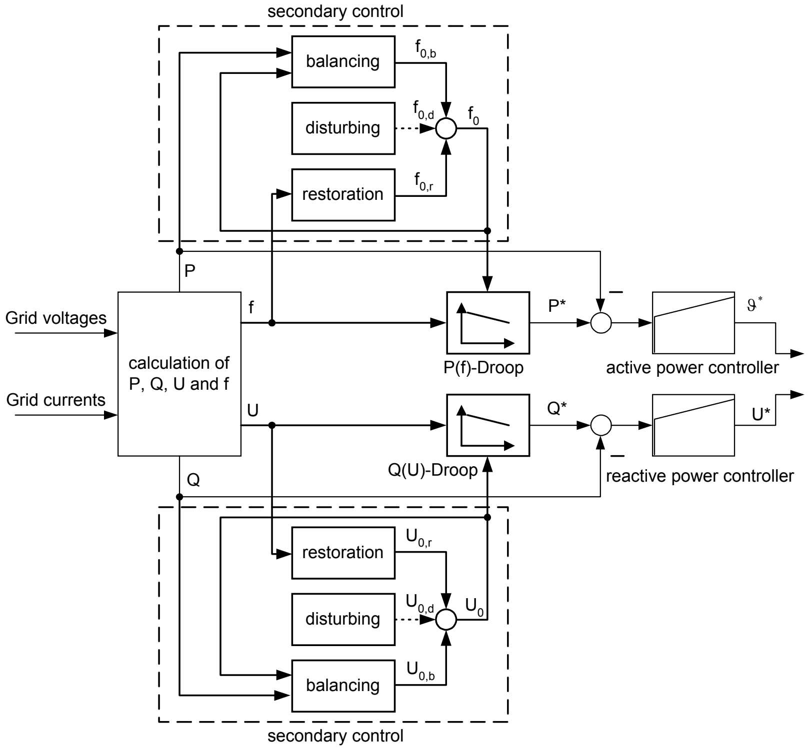

Fig. 12 Implementation of the secondary control

In stationary case the deviation from nominal values of voltage and frequency is nearly zero. This has the benefit that one can implement droops which are less stiff (meaning greater $\Delta f/\Delta P$ respectively $\Delta f/\Delta Q$). With less stiff droops the measuring of voltage and frequency can be done with less precision but anyway achieving good load sharing. It's clear that if sources with power control are connected in parallel, all or none should have a secondary control implemented if load sharing is desired.

Operation optimisation

As a third outer control loop it's possible to implement an operation optimisation for the grid forming units of the island grid. Several reasons can make it desirable to have unsymmetrical load sharing, for example if the cost of energy depends on the source and on time or if for battery inverters the charge condition of the battery is different. In these cases new setpoints for the P-f-droop can be chosen so that one inverter feeds less (or more) power to the grid than other inverters. To achieve unsymmetrical (but controlled) load sharing only the setpoint for the frequency in the balancing control (normally 50 Hz) (Fig. 11) must be adjusted. This can be done for all inverters by criterions such as the charge condition of a battery or a calculated actual energy generation price. It's clear that this energy management can only be rudimentary, but it can be done without communication.

Power sources which are not grid forming

Solar or wind power sources should deliver as much active power as is provided by wind or solar irradiation. So their control is different to that what is described up to now. These power sources do have a current control and feed an existing grid. They are not grid forming. Also single phase inverters can't be grid forming in a three phase grid. These power sources can be used to support the grid. Depending on the grid voltage they can provide reactive power also corresponding to a droop. So the stability of the grid is improved. The current controlled sources can't affect grid voltage and frequency. For supporting the grid, they need a fixed relation between reactive power and voltage. It's clear that then secondary control mustn't be activated. For feeding active power a very simple "droop" should be implemented: normally the inverters can feed as much active power as possible. Only for the frequency rising to high, active power should be reduced and finally set to zero.

Realisation and experimental results

Two inverters were built up. They are transformerless 3-phase voltage source inverters with IGBTs. The neutral point is connected, so that the three phases are independent (Fig. 13). The inverters are supplied by a DC-voltage-source U_d in the range of 700-1000 V. The DC-source is a battery bank charged from a photovoltaic array. The parameters of the AC-filter are: $L_{WR} = 12$ mH, $C = 10$ µF, $L_N = 1{,}65$ mH ($x_N = 3.3\%$). The inverters have a rated power of 10 kVA and can be overloaded by factor 1.5 for 30 seconds.

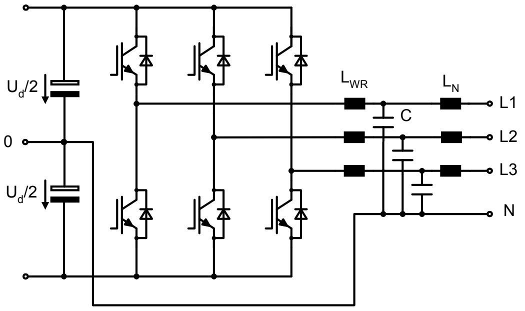

Fig. 13 Inverter topology

Measurements of three grid configurations are presented in the following to prove the main properties of the inverters and the power control. The droops shown in Fig. 4 were implemented. In all cases the load was star connected.

Configuration 1: Operation of a 10 kVA inverter in parallel with a fixed frequency grid

A unbalanced load corresponding to rated power of the inverter (L1: $\omega L = 7.84\ \Omega$, $R = 15\ \Omega$; L2 & L3: $R = 15\ \Omega$) is fed by the main grid and the inverter. If using the droops which are shown in Fig. 4, at a main grid with 50 Hz and $U = 230$ V, nearly no power is provided by the inverter. The main grid is suddenly switched off and the inverter has to provide the power for the load. Two voltages (L1 & L2) at the three phase load and the inverter currents in the corresponding phases are shown (Fig. 14). The main grid disconnection affects mostly that phase where the load current is highest. L1 is not distorted very much. In L2 it's the worst case because the resistive load was provided with maximum current when the main grid was switched off. In this case the voltage at the load is restored in the short time of about 3ms. The rms-value of the voltage in L1 is smaller because of a reactive power flow in L1 causing a voltage drop at the filter reactance. Remarkable is, that the inverter voltage is much more sinusoidal than the main grid voltage was in this measurement. In this configuration the inverter acts as an UPS which runs in parallel with the main grid. By adjusting the droops it's possible that when the grid frequency is 50 Hz the battery is charged. It's evident that more inverters with the same control can be connected to the main grid.

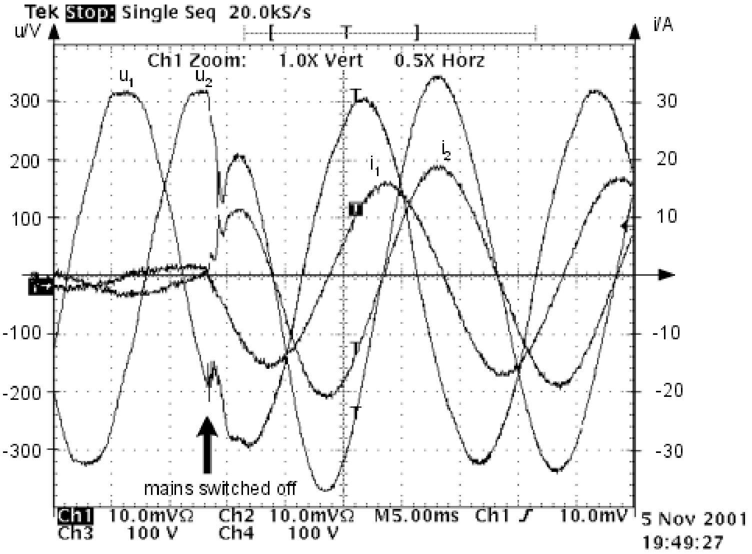

Fig. 14 Inverter used as an UPS

Configuration 2: Operation of two 10 kVA inverters in parallel

First the two inverters are running without load. Because of measurement mismatches a small reactive current is circling between the inverters. Then a load $\omega L = 3.46\ \Omega$, $R = 15\ \Omega$ in L1 is switched on. L2 and L3 are not loaded. The voltage in L1 and L2 and the two output currents of the inverters in L1 are shown in Fig. 15. The voltage in L1 settles very fast. A very good load sharing is achieved. It's obvious that in theory there's no limitation to the number of inverters which can be connected in parallel. No communication connection is needed by this method. Every inverter has the same control, no master is needed. This is the highest modularity which can be achieved and is similar to the behaviour of utility networks with numerous synchronous generators.

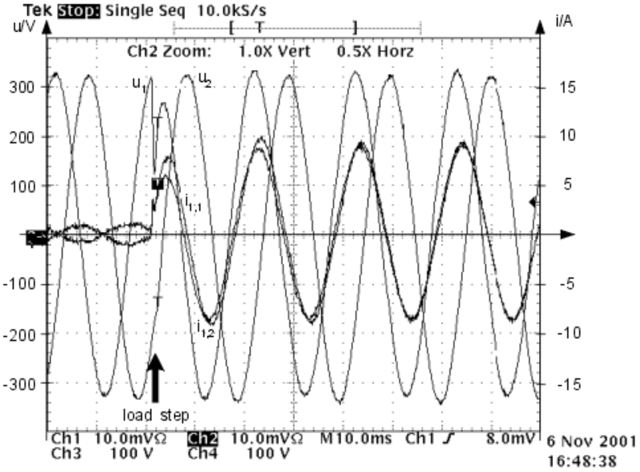

Fig. 15 Parallel operation of two inverters

Configuration 3: Operation of one 4.5 kVA inverter and one 4.5 kVA diesel generator

The diesel generator is a standard engine (Honda K-6/4). It has an inherent behaviour that with increasing load the frequency diminishes (52 Hz for no load 49 Hz for full load), this corresponds to a P(f)-droop. The voltage of the diesel generator is not very sinusoidal and contains higher harmonics. In Fig. 16 the voltage u_1 in L1 and the inverter current $i_{1,i}$ and generator current $i_{1,d}$ in L1 are shown. First the inverter and the diesel are working unloaded. The inverter charges his batteries and the diesel provides the needed power. This load sharing depends on the P(f)-droop implemented in the inverter. When the symmetrical three phase load (R1 = R2 = R3 = 18 Ω) which is nearly twice as high as the rated power of one single source is switched on, mainly the generator provides the load current because he acts more stiff than the inverter. The inverter takes on his part of the load after the speed governor of the diesel engine diminishes the speed and the grid frequency is reduced. In steady-state the load sharing is good. Despite their very different character the two 4.5 kVA power sources feed a load of 8.8 kW together!

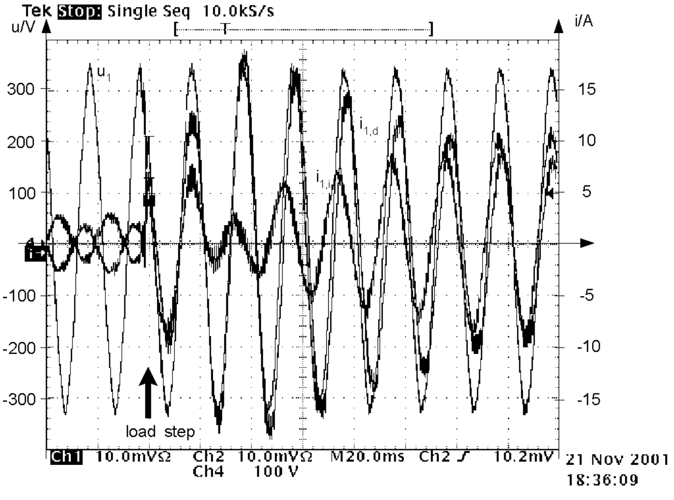

Fig. 16 Inverter in parallel with an diesel generator

Two inverters with secondary control

To prove the function of the secondary control two inverters (10 kVA rated power) were connected but at first only one was working. A load with P = 8 kW and Q = 5.5 kVAr (inductive) was fed by the first inverter. This corresponds to rated power of one inverter. Because of the restoration control frequency and voltage are near their nominal values (f_N, U_N). The second inverter is switched on and the balancing control is working. At the end load sharing not exact but surprisingly good, considering that frequency and voltage measurement can’t be used for equal load sharing anymore (Fig. 17).

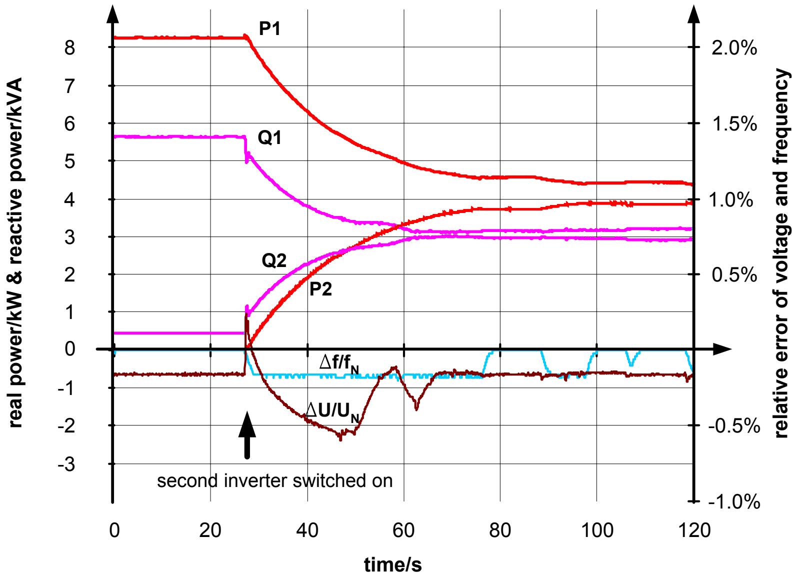

Fig. 17 Load balancing and restoration of nominal values

Conclusion

In this paper it is shown, that it is possible to connect three phase inverters which act like voltage sources in parallel. There’s no control interconnection needed. Very good load sharing is achieved by using an outer control loop with active and reactive power controller, for which the setpoint variables are derived out of droops. As a side effect with the same control the inverters can act as an “online UPS” at a fixed frequency grid. The inverters can supply unbalanced load, with good load sharing, too. With the power control using droops, the inverters have a similar behaviour as a rotating machine. It is shown, that the inverters can work in parallel with a standard diesel generator where load sharing is achieved, too. A secondary control is described which restores frequency and voltage of the grid to their nominal values without communication. Load sharing is still possible although the fixed connection of frequency and active power and voltage and reactive power is abandoned. A third control can be used for a simple energy or cost management. For current sources a grid supporting algorithm can be implemented. The methods presented in this paper allow forming modular island grids with many different power sources. The strategy to control the power flow of an inverter can also help to avoid instability in the power systems if fuel cell plants or lot of small decentralised regenerative power sources feed the utility networks.

References

1. Bergen A. R., *“Power Systems Analysis“* Prentice-Hall, Inc. Englewood Cliffs, New Jersey 1986
2. Späth H., *“Leistungbegriffe für Ein- und Mehrphasensysteme nach DIN 40110-1 und DIN 40110-2”* VDE Verlag, Berlin und Offenbach, 2000
3. Tepper S.; Dixon J.; Venegas G.; Morán L., *“A simple frequency independent method for calculating the reactive and harmonic current in a nonlinear load”*, IEEE Transactions on Industrial Electronics, Vol. 43, No 6., 1996, pp. 647-654

4. Tuladhar A.; Jin H.; Unger T.; Mauch K., *“Control of parallel inverters in distributed AC power systems with consideration of line impedance effect ”*, IEEE Transactions on Industry Applications, Vol. 36 No 1, 2000, pp. 131 -138

5. Nuß U., *“Blindleistungskompensation mit selbstgeführtem Stromrichter und kapazitivem Energiespeicher”* Dissertation at the Elektrotechnische Institut der Universität Karlsruhe, 1989

6. Hauck M., *“Wechselrichter problemlos parallel betreiben”* in Elektronik 19/2000 pp. 120-124

7. Burger B.; Engler A., *“Fast signal conditioning in single phase systems”* EPE Conference 2001

8. Burger B., *“Transformatorloses Schaltungskonzept für ein dreiphasiges Inselnetz mit Photovoltaikgenerator und Batteriespeicher”* Dissertation at the Elektrotechnische Institut der Universität Karlsruhe 1997

9. Chandorkar M.C., Divan M.D., Adapa R., *“Control of parallel connected inverters in standalone ac supply systems”* IEEE Transactions on Industry Applications, Vol. 29 No 1, 1993, pp. 136 –143

10. Chandorkar M.C., Divan M.D., Banerjee B., *“Control of distributed UPS systems”* IEEE Power Electronics Specialists Conference (PESC), Taiwan 1994, pages 197-204