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Contents

1. Introduction

µGrids comprise Low Voltage distribution systems with distributed energy sources, such as micro-turbines, fuel cells, PVs, etc., together with storage devices, i.e. flywheels, energy capacitors and batteries, and controllable loads, operating as a coordinated, controlled entity.

From the Utility point of view, the application of distributed energy sources can potentially reduce the demand for distribution and transmission facilities. Clearly, distributed generation located close to loads will reduce flows in transmission and distribution networks with two important effects: loss reduction and ability to potentially substitute for network asset investments. Furthermore, the presence of generation close to demand could increase service quality received by end customers. µGrids can provide network support in times of stress by relieving congestions and aiding restoration after faults.

The characteristic differences between µGrids and simple LV grids with Distributed Generation are their ability to behave as a coordinated entity in interconnected and islanded operation.

The management of instantaneous active and reactive power balances, power flow and network voltage profiles imposes unique challenges in the context of µGrids. Traditionally, power grids are supplied by sources having rotating masses and these are regarded as essential for the inherent stability of the systems. In contrast, µGrids are dominated by inverter interfaced distributed sources that are inertia-less, but offer the possibility of a more flexible operation. A further particular problem of µGrids is the relatively high resistance of the low voltage networks. The amount of voltage drop on any RL circuit is approximately obtained by PR+QX, P and Q being the active and reactive power flow, R and X the resistance and reactance of the line. In overhead HV or MV networks, R is much lower than X, so that the injection of reactive power critically affects voltage drops. Active and reactive power effects are reasonably decoupled and this is the basis of system control as well as of several analytical techniques, like the fast decoupled load flow. On the other hand, in underground LV networks, R is much higher, it can be 3 times higher than X. This results in strong coupling of real and reactive power, and hence the control of voltage and frequency can no longer be considered separately.

µGrid transitions from interconnected to islanding mode of operation are likely to cause large mismatches between generation and loads, posing a severe frequency and voltage control problem. Storage technologies, such as batteries, ultra-capacitors and flywheels may become important components of µGrids , with the duty of providing stable operation of the network during network disturbances. Maintaining stability and power quality in the islanding mode of operation requires the development of sophisticated control strategies and needs to include both generation and demand sides.

This study is focused on the analysis of the control strategy to increase the µGrid stability. An improvement in the voltage drop and frequency drop techniques is proposed to enhance the stability of the system. The introduced control algorithm attempts to decouple the P/f and Q/V control strategy changing the behaviour of the inverter and leading the system to work as an inductive coupled system. The inverter is characterised with one fictitious inductive output impedance that yields the P/f and Q/V control algorithms to work in a more decoupled way. The proposed algorithm shares load unbalances and harmonic currents minimising these current flows among sources.

The stability analysis considers both, resistive and inductive, coupling impedances but emphasizes the resistive coupling connection, the more common in low voltage networks, and the one that provokes more stability problems.

Relevant electrical operation conditions are analysed and studied. Techniques to enhance the stability during these situations are simulated. Progressive connection of different power sources, the synchronisation process with the main grid and its later connection and the disconnection is studied from the point of view of the system stability, proposing improvements in the control strategies.

The different nature of the power sources is analysed and taken into account when designing the control strategies. Clearly, all the power sources do not behave in the same way and their individual characteristic should be considered. The control algorithm must adapt to the dynamical behaviour of the different sources such as the inherent storage capability or its power change rate, taking all the advantages of each µSource.

Finally, the unintentional islanding problem is taken into consideration. Being the system designed to improve the stability in every moment, the unintentional feeding of loads outside the grid is a real risk that must be avoided. A great variety of anti-islanding methods are analysed and particularised to the µGrid case. Alternative methods are proposed, studied and simulations are carried out to test these methods.

2. Methodology

In order to study the control strategies and compare the different responses of the algorithms a set of simulations is carried out. The program used to develop these simulations is ATP (Alternative Transient Program). This application has been chosen because the integration of different control methods in the electromagnetic simulations is easy and fast. Using the MODEL language, a wide range of control algorithms can be developed and compared.

All the systems studied are three-phase systems; the µGrids are thought to be in the size of a few hundreds of kVA, where the three-phase distribution system is the preferable to handle the power rating.

µSources are composed by an independent primary energy source, of wide variety such as micro-turbines, fuel cells, PVs, etc., and the coupling device that interconnects the energy source with the grid. The primary source may produce energy in different forms such as DC, in the case of the fuel cells and the PV cells, or in AC at variable frequency. This energy is poured into the grid by a power electronics device. In most of the cases those are IGBT converters that are very flexible and fast voltage sources, controlling their output in very short time scales, in the size of milliseconds, they can control their output voltage or current in a very flexible way, so, they may work as an independent voltage or current source. If the coupling device is supposed to be always connected to the grid the best configuration is as a current source following the main grid voltage and frequency reference, but if it is to work in an islanded mode, it should work as a voltage source to ensure the frequency and voltage levels within the island.

In order to simplify the simulations, all sources are modelled as three fully controllable and independent voltage sources. This simplification is quite acceptable, since the control flexibility of the power electronics devices is quite high and the voltage at the end of the output filter can be totally controlled by the power electronics system. The simulation has been done in the time domain and it is a full simulation off all three phases.

The connection in parallel of different voltage sources can lead to a risky situation: if the connection impedance between inverters is to low, a short circuit situation could appear. Although this anomalous connection condition could be avoided by controlling the inverter output current of the inverter, it is better to introduce a small reactance preventing any risky short circuit or high frequency currents flowing between the inverters. This reactance is assumed to be the coupling transformer leakage inductance or the inverter coupling real reactance.

Therefore, µSources are modelled as three independent voltage sources with an additional coupling reactance.

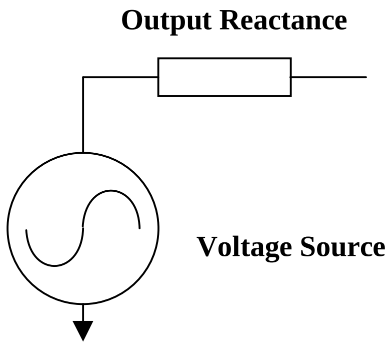

Figure 1: Equivalent model for each µSource

In addition, with this output impedance, the line impedance must be taken into consideration: in low voltage lines it is mainly resistive, but they are modelled as series connected resistances and reactances, to cope with all the possibilities.

The voltage control scheme uses the drop technique to regulate the output voltage [1]. First, the output current is measured, and applying some digital filters, the output active and reactive power is calculated. Then the drop technique is used to obtain the output voltage. This technique allows the co-ordination of the sources to be easier and requiring no communications.

The reaction time and the frequency response of the digital filters operate as the inertia of the conventional rotating mass power sources. If the response is too slow the device will react as a heavy rotor machine, with very stable output frequency. The source output response will be slow and high frequency variations of power will not affect the output frequency. On the other hand, if the time response of the digital filter is fast the device will appear as a low inertia power source, and any variation of the output power will affect the device frequency.

Therefore, the frequency of the source is highly dependent on the power fluctuations. If the power consumption changes dramatically, and both kind of the devices are feeding the µGrid, the ones with the bigger inertia, in other words slower filters, will absorb most of the power fluctuation.

3. Algorithm

A particular problem of µGrids is the relatively high resistance of low voltage networks. The voltage drop on any RL circuit is approximately obtained by PR+QX, P and Q being the active and reactive power flow, R and X the resistance and reactance of the circuit. In overhead HV or MV lines, R is much lower than X, so that the injection of reactive power critically affects voltage drops. Active and reactive power effects are reasonably decoupled and this is the basis of system control as well as of several analytical techniques, like the fast decoupled load flow. On the other hand, in underground LV networks, R is much higher, it can be up to three times higher than X. This results in strong coupling of real and reactive power. This coupling affects the drop control and leads the µGrid to a stability problem.

In order to solve the problem several techniques have been put forward. In [2], a decoupling method based on a new P and Q variable has been proposed. In [3], an additional power term is added to the angle to improve the stability. In [4], the fictitious impedance method is exposed. In this method the inductive response of the source is simulated to make the coupling among the inverters inductive.

The angle correction and the fictitious impedance methods are quite similar. In the first one, a dephase angle, proportional to the delivered power, is introduced in the output voltage. In the second one, the output voltage is modified by the introduction of a fictitious impedance, the effect of the active power flowing trough a reactance is a dephase in the output voltage. Therefore, the way the methods are implemented is different but the results are quite similar.

The proposed algorithm in this document uses the fictitious impedance method because it is easier to understand doing the similitude with the medium and high voltage system, and it is easier to size the impedance from a conceptual point of view.

3.1.1. Description

A fake impedance is introduced to change the behaviour of the coupling among inverters and to improve the stability. If the approach is based on multiplying the output current by the impedance and then add it to the output voltage, then harmonics and unbalance would affect directly the output voltage worsening output voltage shape quality.

Alternatively, if the current passing trough the reactance is balanced without harmonics then the obtained output voltage would be sinusoidal and balanced. Hence, to preserve output voltage quality it is better to filter first the output current extracting only the positive sequence current. In this way, the output voltage quality will be not affected by the fictitious reactance and it can be made as big as needed to improve the stability of the system. However, the voltage regulation is affected by impedance size.

The resulting output voltage control system is the outline in Figure 2. In summary the following steps are performed:

- Current is measured and filtered
- With the output voltage the active and reactive power are calculated
- P&Q power is filtered to smooth the response
- Drop controls are applied.
- Output impedance is simulated:
    - Inductive for the positive sequence current: This affects the main active power component
    - Resistive for the negative and zero sequence: This is intended to cope with active power fluctuations around the fundamental component

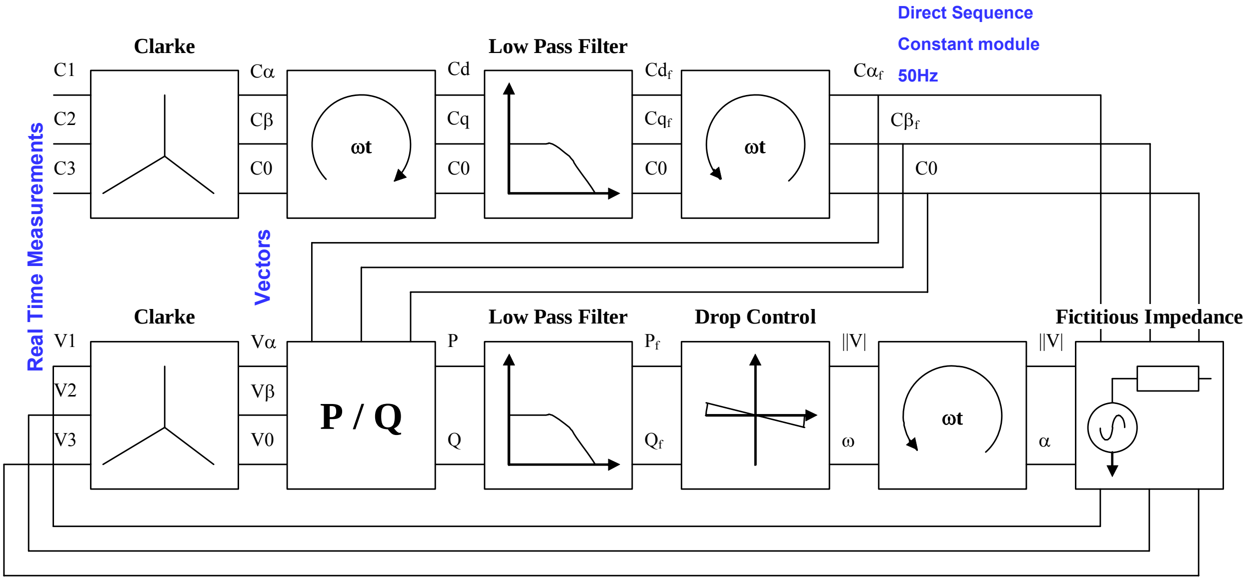

Figure 2: Output voltage control system

The algorithm internals is as follows:

1. Currents (C1, C2 and C3) are measured from the real time sampled values and voltages (V1, V2 and V3) are taken from their calculated output values.
2. Clarke transformation is applied to obtain the current in vector form (Cα, Cβ & C0) and voltage (Vα, Vβ & V0).
3. At this stage the current is affected by harmonics and unbalanced: a turning reference is used to obtain the direct, inverse and zero sequence current components (Cd, Cq & C0). After the reference is changed the positive sequence remains constant while the negative components take any disturbances above the fundamental frequency, and the cero sequence is extracted to the C0 component.
4. A low pass filter eliminates all frequencies above 100 Hz and hence the only signal remaining is the positive sequence current (Cd_f, Cq_f)
5. The previous turning reference is taken away leading to the vector representation of the fundamental component of the current ($C\alpha_f$, $C\beta_f$). If we turn again the current in the opposite direction, we obtain the present positive sequence value.
6. Active and reactive powers (P & Q) are calculated from the current and voltage in their vector form.
7. Another low pass filter is in charge of defining the control response speed pretending to be mechanical inertia. The filtered values are P_f and Q_f.
8. A drop control produces the output voltage magnitude and its frequency.
9. From voltage magnitude, frequency and time the voltage target is reconstructed.
10. Finally the fictitious impedance technique is included adding a voltage drop across the impedance to the final output voltage.

It is remarkable that the Q/V drop can be eliminated, because the effect of the reactive power flowing trough the fictitious impedance is a voltage drop, with the same slope direction as the Q/V control drop. Therefore both can be considered as complementary control strategies or, in order to simplify the control algorithm, the Q/V drop substituted by its equivalent. Choosing these impedances inversely proportional to the rated power of the inverter would automatically lead to proportional current sharing over inverters with a different rating. The simulations has been done wit devices of the same power to compare more easily the results.

3.1.2. Layout

In order to compare the response of the proposed algorithm with the conventional drop control a complete set of simulations are performed assuming islanded operation.

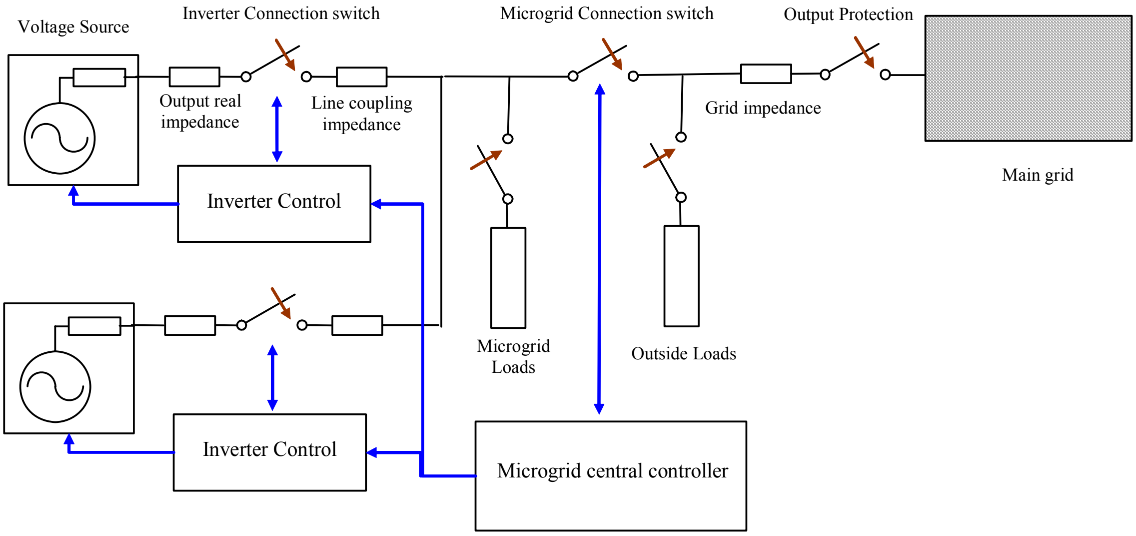

Figure 3: General simulation layout

Two inverters are coupled in parallel, each inverter is composed by three independent voltage sources, the 3-phase connection switch, the voltage real output impedance and the coupling impedance. The system composed by the two inverters is connected a set of active and reactive loads.

Inverters are sized to 10 kW with a drop control characterized by 1Hz difference between zero and maximum power output.

The value of the output inductance in use is 0.15 Ohms. Taking into account that the device nominal power is 10 kW, the output impedance, expressed in p. u., is around the 1% of the characteristic impedance. It is a rather low value, and considering that stability problems are stressed when the connection impedance is small, the source case is an unstable case, and thus obtained results can be extrapolated to other better situations.

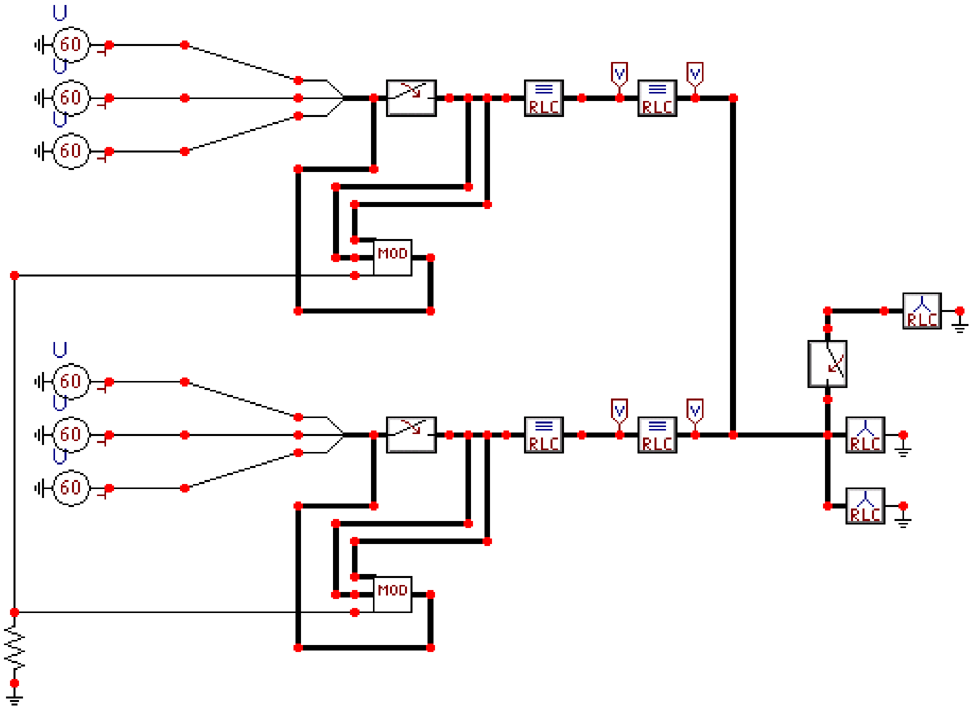

Figure 4: ATP Simulation layout

4. Results

The assessment of the improved control strategy over the conventional drop control is based on several uses cases. This uses cases have been selected to consider the most significant conditions affecting the parallel operation of inverters as well as some other specific issues.

The comparison is established at islanded operation where the self synchronisation and load sharing capabilities at parallel operation are important. In this field stability under different coupling conditions (resistive and inductive coupling) and overall performance (parallel, unbalance and harmonics) of the control system are addressed. Additionally some grid operations are considered (more inverters being connected, synchronisation, grid connection and disconnection) as well as issues about primary energy source dynamics.

The study is completed with islanding detection issues.

4.1. Islanded mode stability and performance

4.1.1. Inductive Coupling

The first study case compares both methods when the coupling between inverter is inductive. The value of the introduced inductance is between the 1% and the 5% of the characteristic impedance of the devices.

In the classic control scheme, simulations demonstrate that the stability is easier to achieve if the coupling inductance is high, around the 5% in each inverter, 0.7 Ohms and 0.8 Ohms. The line should have a small resistive component to damp the power oscillations. If to improve the frequency stability there is a reduction on the cut off frequency of the low-pass filters, then the system become more unstable. For smaller values of the inductance the system stability is difficult to reach and the cut-off frequency of the filters must be bigger, consequently frequency stability and system stability are difficult to achieve simultaneously. The line must have a resistive component to damp the oscillations.

Using the fictitious impedance method, the stability is easier to achieve in all situations but the line still has to have a small resistive component to reduce the oscillations. This resistive component is more important when the digital filter is slower.

Taking into account this behaviour and looking for improvements on the system stability, an additional term is been added to the control. The filtered current is subtracted to the measured one, and the resulting current passes trough a fictitious resistance. This resistive behaviour damps the high frequency oscillations that sometimes occurs and destabilise the system. This fictitious resistance helps at the sharing of unbalanced currents and harmonics.

With this technique, the stability is achieved for all inductive situations proved, with and without a small resistive coupling. The stability range is bigger in aspects related to the time response of the filters. Therefore, the island frequency may vary slower.

The simulation environment and the results of the simulations with the inductive coupling are described next. Initially, at 0.1 seconds, both inverters are started synchronised, at the nominal frequency, no initial power output, and with a connected load of 1800 watts and 400 VAr (inductive). In Figure 5, it is shown the behaviour of the control with a completely inductive coupling. The control starts working properly but few milliseconds later the power starts to oscillate and the system becomes unstable. If the coupling between the inverters has a small resistive component this instability disappears, as seen in Figure 6. The resistance introduced as coupling impedance has the value of 0.05 Ohms. This is a quite small resistance that every low power coupling will have. Therefore, it can be said that the system is stable without adding any resistance to the circuit.

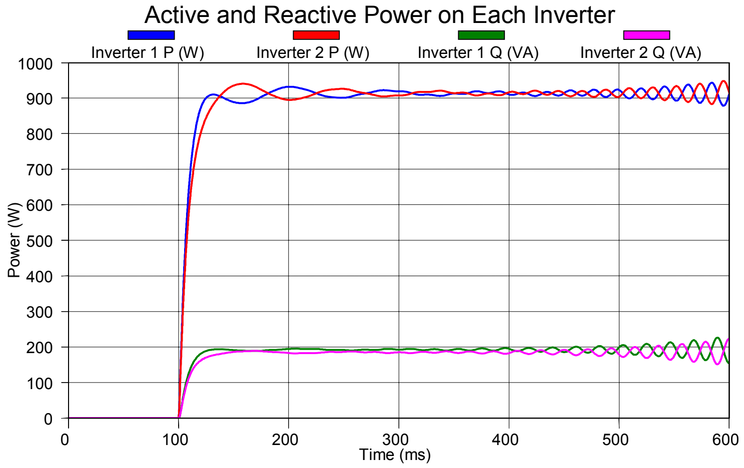

Figure 5: Output power of each inverter with totally inductive coupling and traditional drop control

Both simulations are done with a 0.7 and 0.8 ohms coupling reactances and the filters cut-off frequencies are, 20 Hz for the current cut-off frequency and 10 Hz for the power cut-off frequency. The filter is a first order filter.

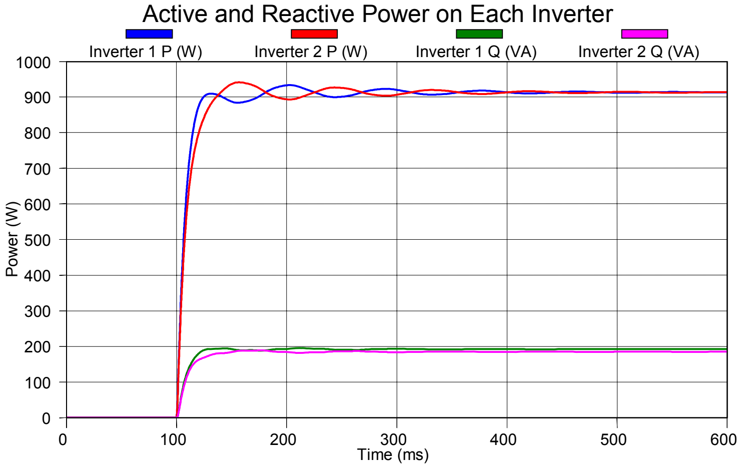

Figure 6: Output power of each inverter with inductive coupling and traditional drop control

When coupling reactance value is reduced in successive simulations the system fails to meet the stability. Therefore, the drop method seems not robust enough to connect inverters in parallel under any condition.

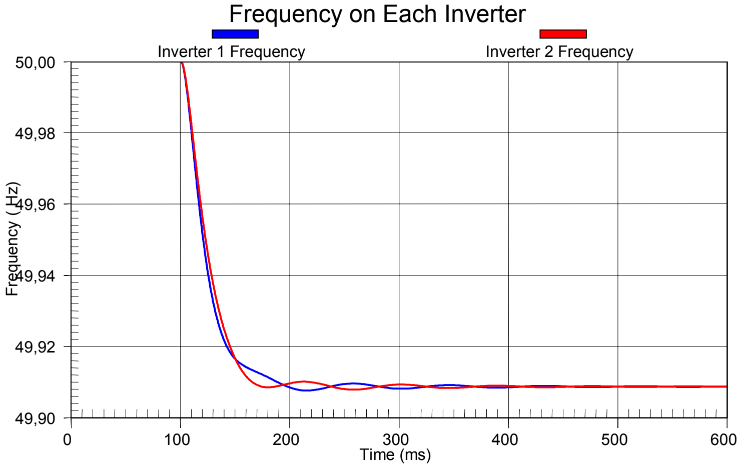

Figure 7: Output frequency of each inverter with inductive coupling and traditional drop control

In addition, in traditional drop method, the cut-off frequency of the filter has to be quite high, and this causes the frequency of the system to vary very fast reacting to load changes. In the Figure 7, output frequency of both inverters is plotted showing fast response and oscillations before reaching the steady state.

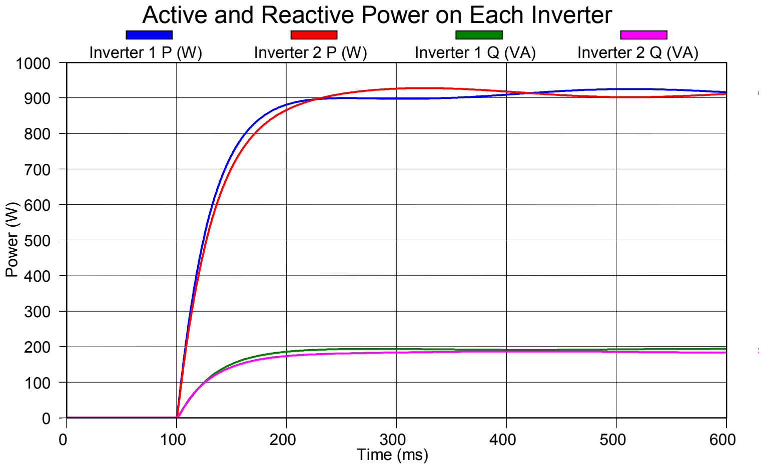

Figure 8: Output power of each inverter with inductive coupling and fictitious impedance method

With the fictitious impedance method the stability is easier to reach in all situations and it is not necessary to fine tune the control parameters to reach the stability. All simulations have been done with a 1.4 Ohms fictitious reactance and with a 0.5 Ohms fictitious resistance (only for the transient and no positive sequence current). The cut-off frequency of the current low-pass filter is set to 5 Hz and the cut-off frequency of the power low-pass filter is 1 Hz.

Simulations have been done with different coupling reactances and in all cases the system has demonstrated stable. With the fictitious impedance method the system is even stable when the coupling between inverters is purely reactive and there is no resistance to damp the oscillations.

In the Figure 8, it can be seen that the system response is slower than in the previous cases. The system takes more time to reach the stability, and the power oscillations are slower. Figure 9 illustrates the inverters frequency response; it is clear that now the system frequency is more stable and changes more gradually to the new balance point.

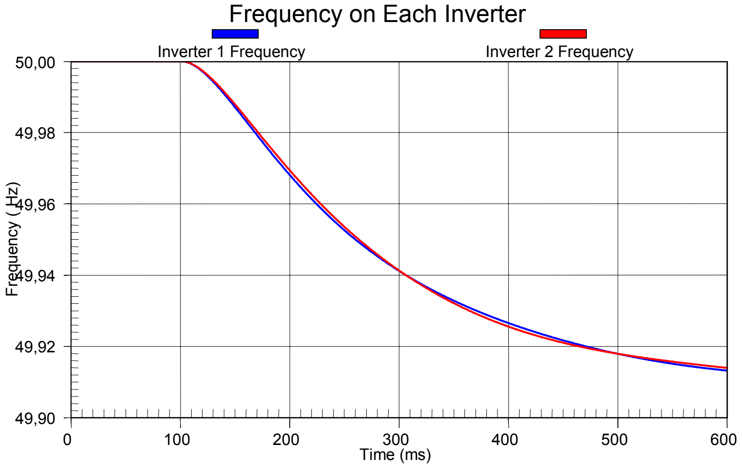

Figure 9: Output frequency of each inverter with inductive coupling and fictitious impedance method

4.1.2. Resistive Coupling

The resistive coupling is one of the biggest problems for the control of the parallel units. With the inductive coupling, the active power can be controlled varying the frequency and the reactive power can be controlled varying the voltage. With the resistive coupling this changes and the relationship are just the opposite. One can change the control method and use P/V and Q/f drops, but this new control is not suitable for the inductive coupling. However, there are methods to stabilise the system.

In the following simulations the coupling resistance is changed from 0 to 0.8 Ohms on each inverter, so the resistance varies from 0 to more than the 5% of the characteristic impedance of the devices.

When the traditional coupling is applied, Figure 10, the stability is very difficult to reach and normally the system becomes unstable due to the cross coupling of the control variables. Both inverters start sharing the power, but, with the time an oscillation starts and the system loses its stability.

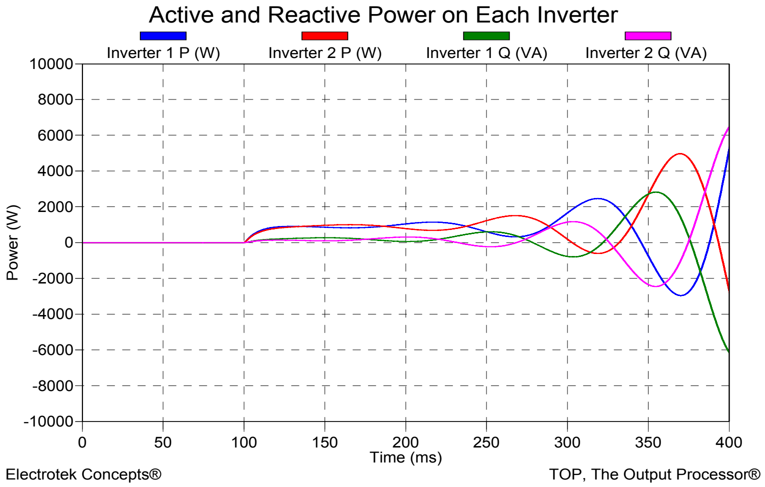

Figure 10: Output power of each inverter with resistive coupling and traditional drop control

When fictitious impedance method is in use, the stability is reached easily in almost all cases. The system is stable with no coupling impedance, only with the device output impedance. The system is more stable by large when the coupling resistance is small. In Figure 11, the behaviour of the system when the coupling resistance is of 0.1 Ohms and 0 Ohms is confirmed. Fluctuations between the output powers are quite small and the system stability is good.

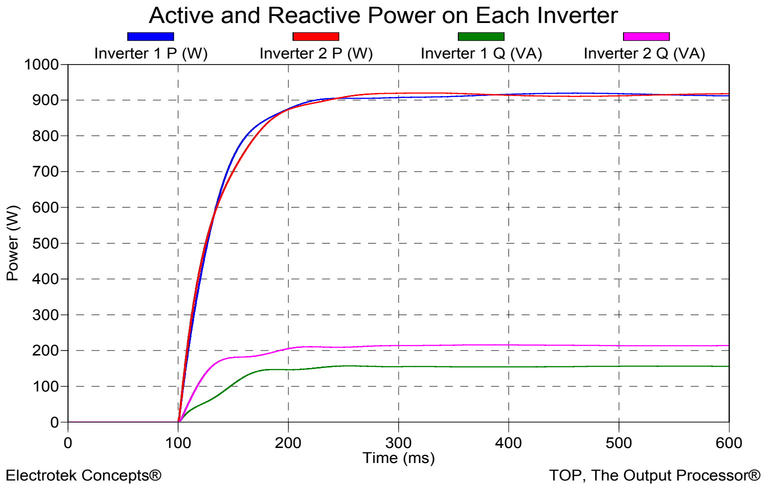

Figure 11: Output power of each inverter with resistive coupling and fictitious impedance method, with small resistance

If the coupling resistance is increased, 0.3 and 0.4 Ohms, Figure 11, the oscillations take more time to be damped, but the system is still stable.

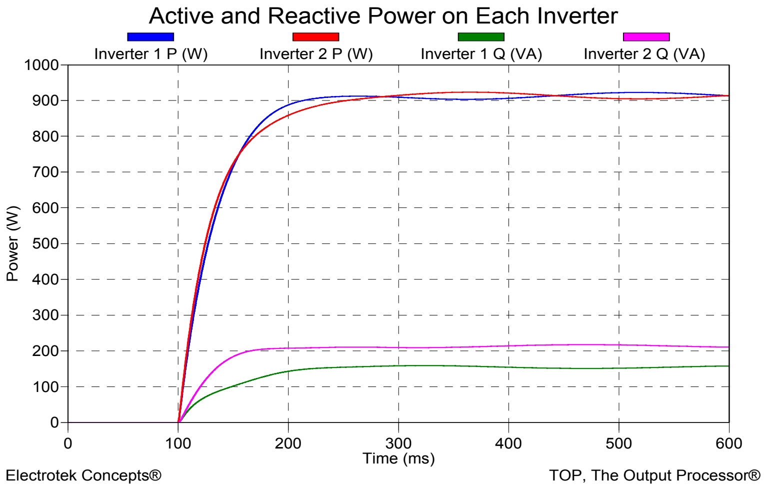

Figure 12: Output power of each inverter with resistive coupling and fictitious impedance method, with medium resistance

When the coupling resistance raises, 0.7 and 0.8 Ohms, Figure 13, the system becomes unstable. The coupling resistance is too high and the cross coupling between the controllers takes the system out of stability. There are two possibilities to solve this problem. On one hand, reduce the fictitious resistance: the system becomes stable again. With 0.2 Ohms the system is stable for all the previous cases, including all the inductive cases. It seems that if a wide range of coupling impedances is defined the system must work properly, it is not too difficult to find an inverter configuration that makes the system stable in all the cases.

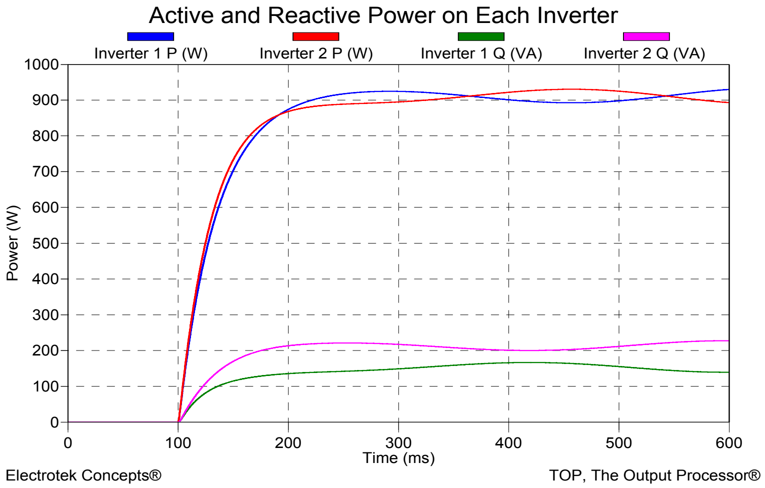

Figure 13: Output power of each inverter with resistive coupling and fictitious impedance method, with big resistance

Other possible solution is to subtract the coupling resistance to the fictitious impedance, so the system, including the coupling resistance, will behave as it has only the fictitious resistance that is defined in the device parameter set.

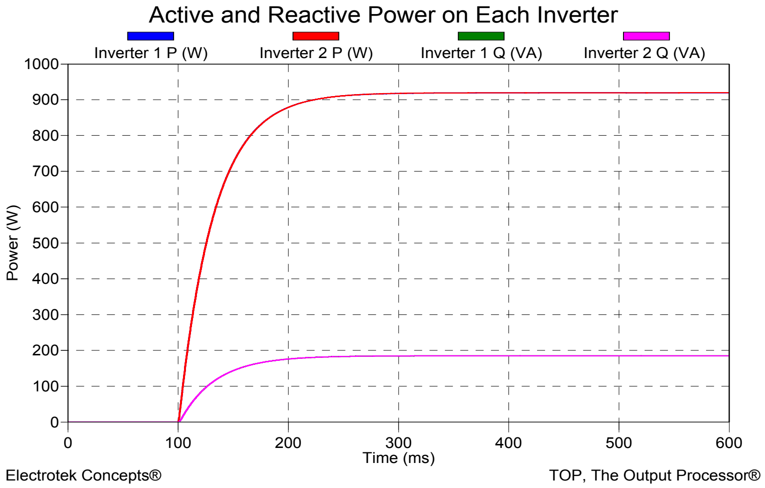

Figure 14: Output power of each inverter with resistive coupling and fictitious impedance method, with big resistance and compensated

In the Figure 14, the behaviour of the system is shown when the coupling resistance, 0.7 and 0.8 Ohms, is subtracted from the fictitious coupling impedance. This subtraction is not arithmetical, it is geometrical, so the device behaves as it had and inductive coupling and a negative resistance output. Both inverters work identically, because both have the same parameters and the same output impedances. This method is quite difficult to implement because, normally, the coupling impedance of each inverter is unknown, and in more complicated grid configurations it is not clear what its value could be.

4.1.3. Combined coupling

The system stability has been studied in the previous sections for resistive and inductive couplings, in the case of combined coupling the stability is not a bigger problem than in the previous cases. The stability of the system depends on the addition of the connection impedance between the systems; therefore, the worst case is the same as it was studied in the previous simulations.

Now, the performance of the system is addressed. The drop control is thought to share the active power among the sources and to control the grid voltage with the reactive power.

When the coupling is inductive, the reactive power flowing across the reactances provokes a voltage drop, with the V/Q drop the reactive power is generated near the consumption points and the voltage drops are minimised. On the other hand, if the coupling is resistive the active power flow provokes a drop in the coupling resistances, for that reason, with the V/Q drop the reactive power is generated near the active power consumption. The voltage drop across the resistances is not minimised, so, with resistive coupling, there is not reason to generate reactive power near the low voltage points. Now, it is better to try sharing the reactive power among the sources. Analysing all the possibilities, the worst system behaviour occurs when the coupling is resistive and the difference between the connection resistances is noticeable. In those cases the reactive power is generated mostly in the inverter with the smaller coupling resistance.

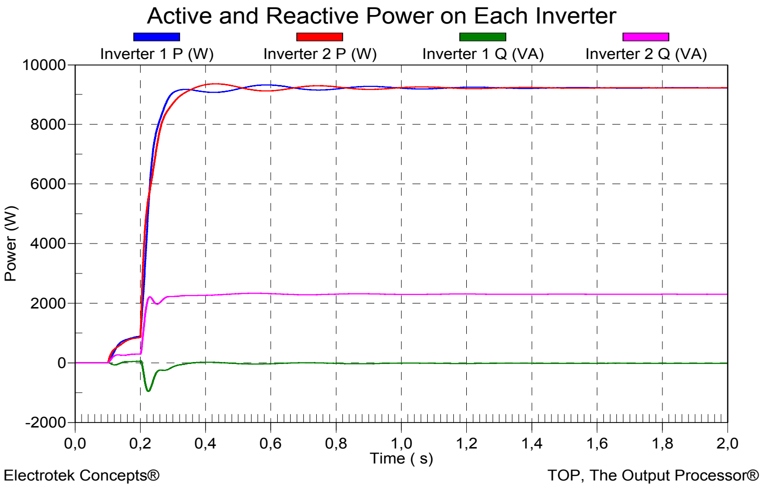

Figure 15: Output power of each inverter with very unbalanced resistive coupling and 1.4 Ohms fictitious impedance

The studied case consists on two inverters and the difference between the coupling resistances is 0.4 Ohms.

Figure 15 display the behaviour of the system when the fictitious impedance is 1.4. As it can be observed, the sharing of the active power is well achieved, but the reactive power is mainly generated by the inverter with the smaller connection resistance.

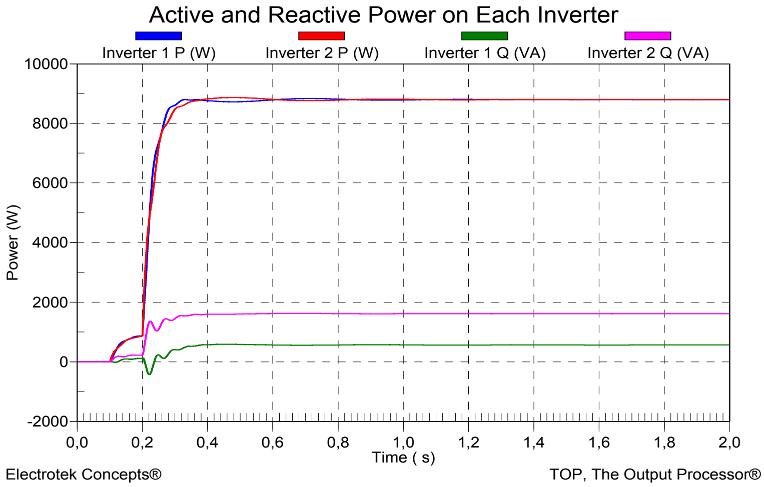

Figure 16: Output power of each inverter with very unbalanced resistive coupling and 3 Ohms fictitious impedance

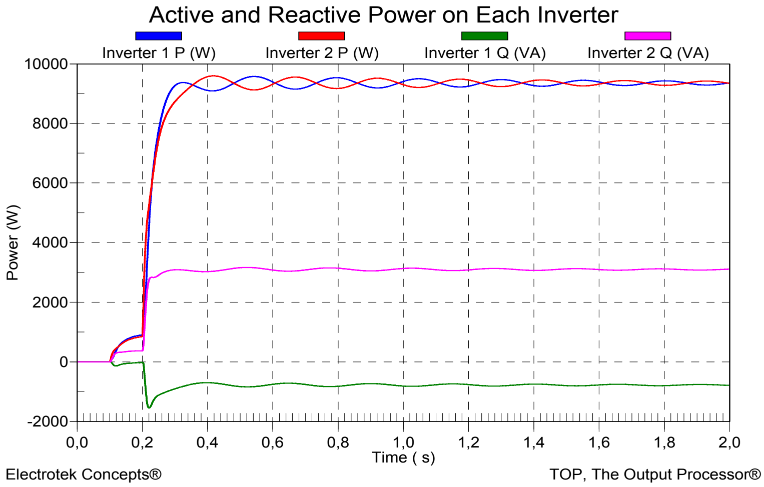

Figure 17: Output power of each inverter with very unbalanced resistive coupling and 0.8 Ohms fictitious impedance

This behaviour is only dependent on the connection impedance and the fictitious impedance, and it is not dependent on other parameters. It can be observed in Figure 16, and in Figure 17 that varying the fictitious impedance the reactive power sharing also changes.

The difference between the two reactive powers increases when the fictitious impedance decreases. The system reaches the balance when the voltage drop provoked by the active power across the extra resistance is equal to the voltage drop created by the difference of the reactive power across the fictitious impedance. Hence, this difference can be used by a central controller to estimate the coupling resistances of each inverter, or at least the difference between the inverter resistances.

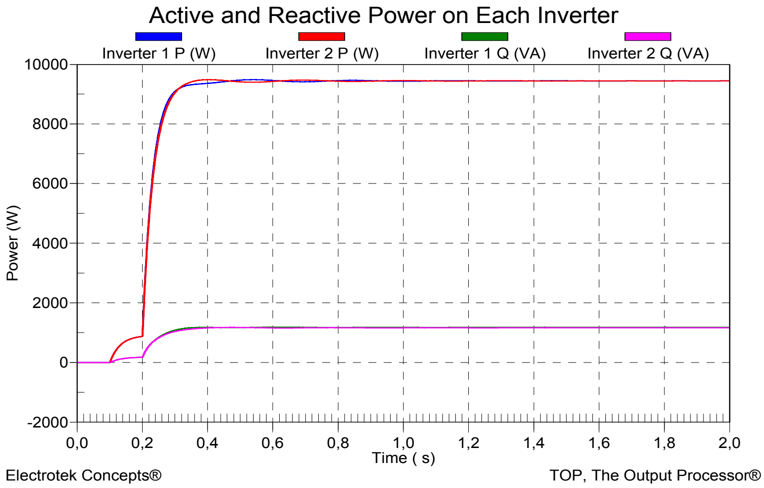

Figure 18: Output power of each inverter with very unbalanced resistive coupling and 1.4 Ohms fictitious impedance and compensated

In Figure 18, the performance of the system when the coupling resistance is compensated can be observed. Once the output resistances are compensated, the inverters behave in a very similar manner sharing both the active and the reactive power. In addition, as seen in previous sections, the system stability is improved.

4.1.4. Unbalanced Situations

As explained in 3.1.1 Description, the output currents are measured and filtered using the Clarke transformation and a rotating frame reference system. Thus, the unbalanced components of the current are extracted from the filtered currents. In Figure 19, and in Figure 20, the instantaneous and filtered values of the currents can be seen in both stationary and rotating frames.

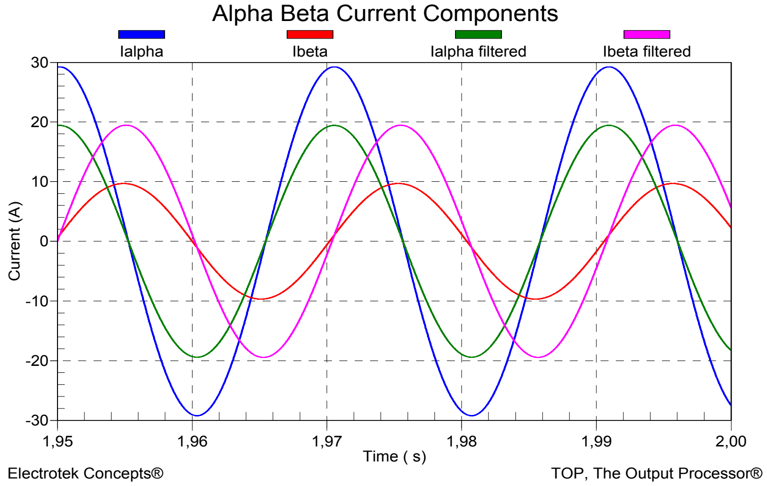

Figure 19: Alpha and Beta current components and its filtered value

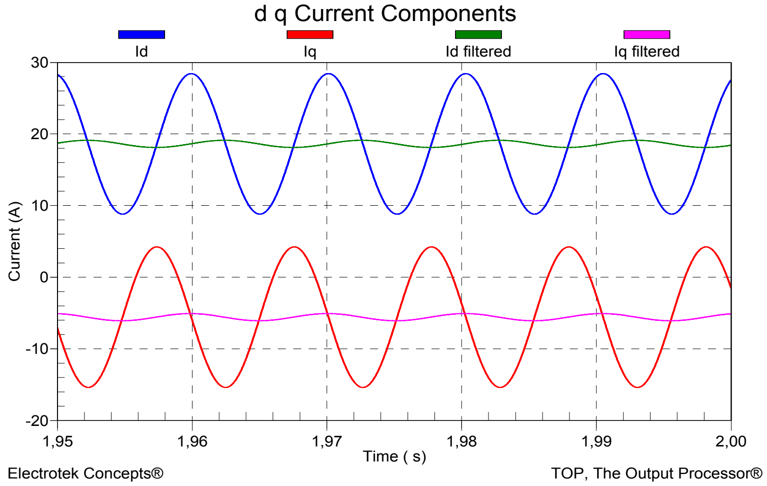

Figure 20: d and q current components and its filtered value

In the filtered values, the unbalanced components almost disappear, so the unbalanced currents have no effect when applying the fictitious impedance. All the unbalanced currents are passed throw the fictitious resistance, the addition of that signal with the real connection impedance is the parameter that has influence in the unbalance currents.

The source of the unbalance currents can be of two types, on one side, they can appear due to the unbalance load. In the other side, they can be provoked by a voltage unbalance between sources.

4.1.4.1. Unbalanced Load

When the island load is unbalanced, it is better to share the currents among the inverters. If the unbalanced currents are delivered mostly by few inverters the risk of overloading some of the inverter phases increases. The unbalanced current sharing depends on the connection impedances ratio. As said before, in the unbalanced currents sharing, the important impedance is the real connection impedance plus the fictitious resistance. The problem, here, appears when the inverter impedances are quite different. In the studied cases one inverter coupling resistance is 0.4 Ohms and the other is 0 Ohms.

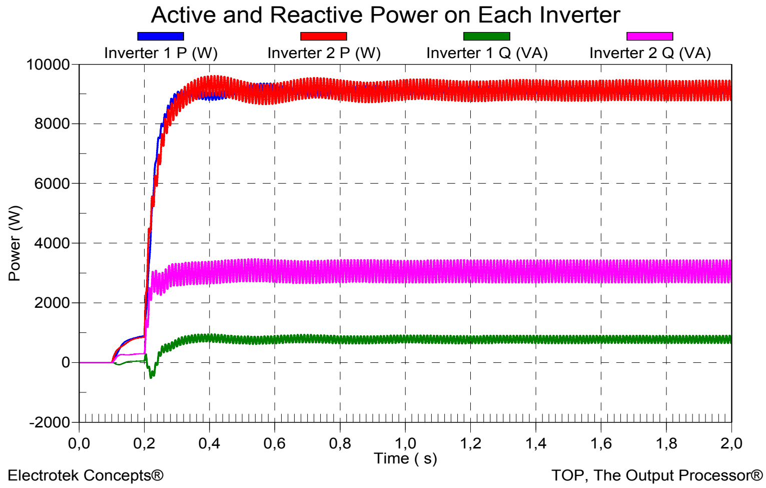

Figure 21: Output power of each inverter with unbalanced load 0.4 and 0 resistive coupling and 0.2 fictitious resistance

In the Figure 21, the behaviour of the system can be observed. As it can be seen, the active and reactive power sharing is similar to the previous studied case in the section 4.1.3 Combined coupling, the only difference is that power measurement is affected by the noise introduced by the unbalanced current. It appears to work perfectly but when one analyses the inverter currents, Figure 22, it can be seen that one of the inverter current is more unbalanced. The current from the second inverter, the one with the smaller connection resistance, is much more unbalance than in the first inverter. The phase ‘A’ current is bigger in the second inverter while phases ‘B’ and ‘C’ are smaller. This can provoke the overloading of the inverter, and in addition, the power requirements of the inverter are more fluctuant, so the storage capacitor of this inverter is more stressed.

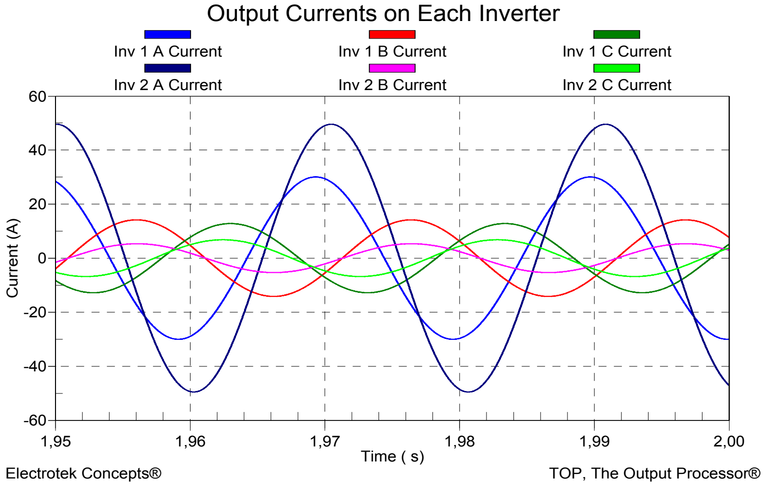

Figure 22: Output current of each inverter with unbalanced load 0.4 and 0 resistive coupling and 0.2 fictitious resistance

In the Figure 23: Output power of each inverter with unbalanced load and 0.4 and 0 resistive coupling 0.5 fictitious resistance, it can be observed the same study as in the previous case but when the fictitious resistance is increased to 0.5 Ohms.

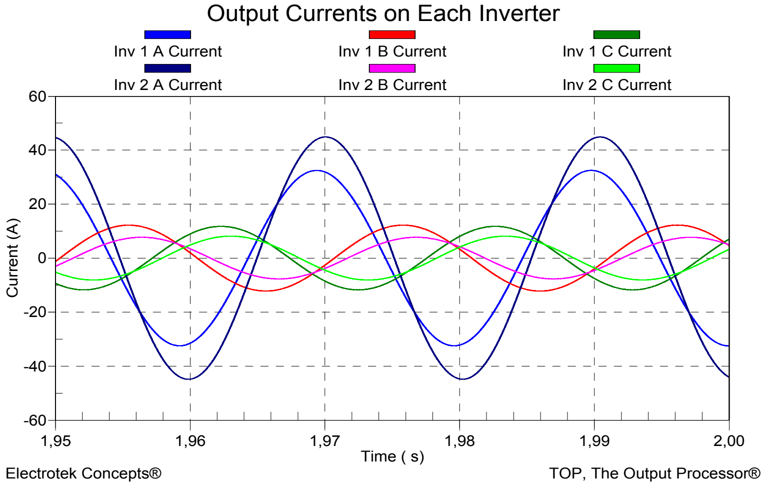

Figure 23: Output power of each inverter with unbalanced load and 0.4 and 0 resistive coupling 0.5 fictitious resistance

The current unbalance now is more similar in both inverters, but the difference already exists. The unbalance will decrease as long as the ratio of the inverters output impedances plus the fictitious resistance gets closer to one. When the fictitious impedance is increased in both inverters it takes more weight in the addition, and the output impedances are more similar, therefore the current sharing is better.

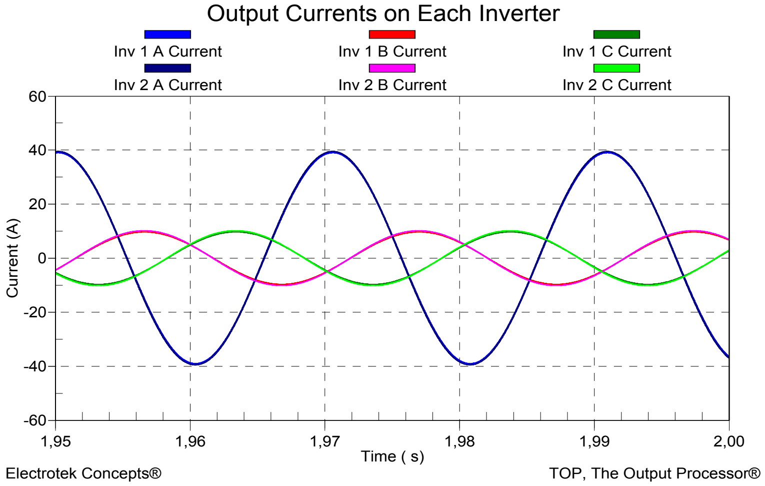

Figure 24: Output power of each inverter with unbalanced load and 0.4 and 0 resistive coupling 0.5 fictitious resistance and line compensation

To achieve the correct sharing of the currents, line impedance compensation can be done (see Figure 24: Output power of each inverter with unbalanced load and 0.4 and 0 resistive coupling 0.5 fictitious resistance and line compensation). Now the apparent output impedance of both inverters is practically the same and the optimum current sharing is achieved.

If one device is supposed to supply the majority of the unbalanced current, just because it has better storage, or because it is prepared for it, its control should be designed with a smaller fictitious resistance, and the installation should be suitable to reduce the coupling impedance. In this way, this device will supply the bigger unbalanced current share in the system.

4.1.4.2. Unbalanced Voltage

The second source of unbalanced currents in the system happens when the inverter voltages are unbalanced. If a little unbalance is created among the inverters, as the coupling impedance is very low, a not so small current will flow. The fictitious impedance has no effect to reduce this current, and now the real coupling impedance and the fictitious resistance are those having influence in the currents.

The unbalance among sources can appear because of imprecision in the inverters that make the system not perfectly balanced. This imprecision can appear due to errors in the calculus, the measurements, or because of the non perfect switching of the inverters: switching times, dead band time, voltage drops …

Now, the problem is not to improve the current sharing among the inverters, what is desirable to achieve is the reduction in the flow of unbalanced currents. This current will be smaller as the sum of the coupling impedances, fictitious and real, gets bigger.

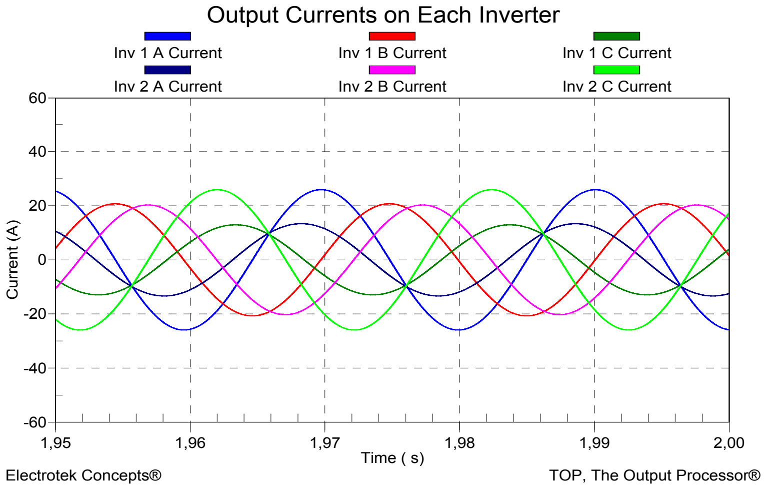

Figure 25: Currents flowing from each inverter with 0.15 fictitious resistance

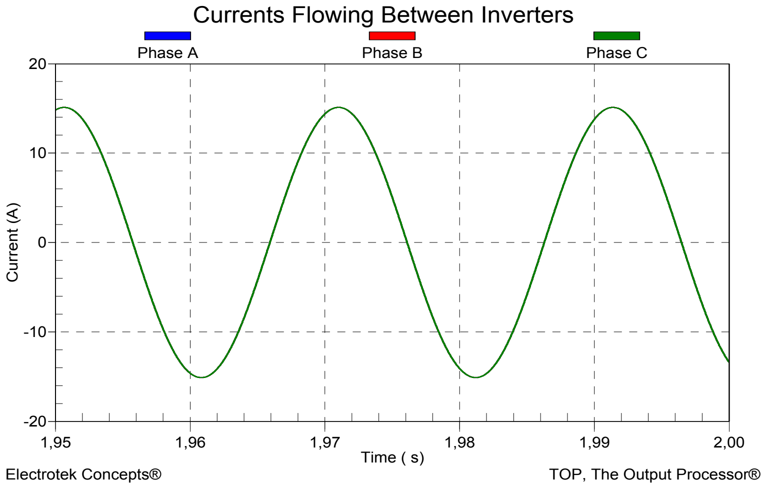

Figure 26: Currents flowing from one inverter to the other with 0.15 fictitious resistance

In the studied case a 2% cero sequence voltage has been introduced. The currents of the inverters with a 0.15 fictitious resistance and using line compensation are shown in the Figure 25. The unbalanced currents flowing from one inverter to the other are shown in the Figure 26. As indicated, when the fictitious resistance is higher the unbalanced currents are reduced. The case with a 0.5 Ohms is shown in Figure 27, and in Figure 28.

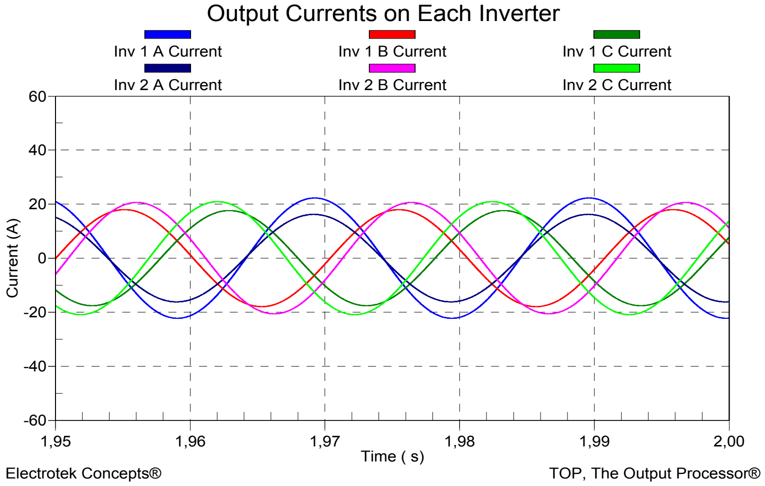

Figure 27: Currents flowing from each inverter with 0.5 fictitious resistance

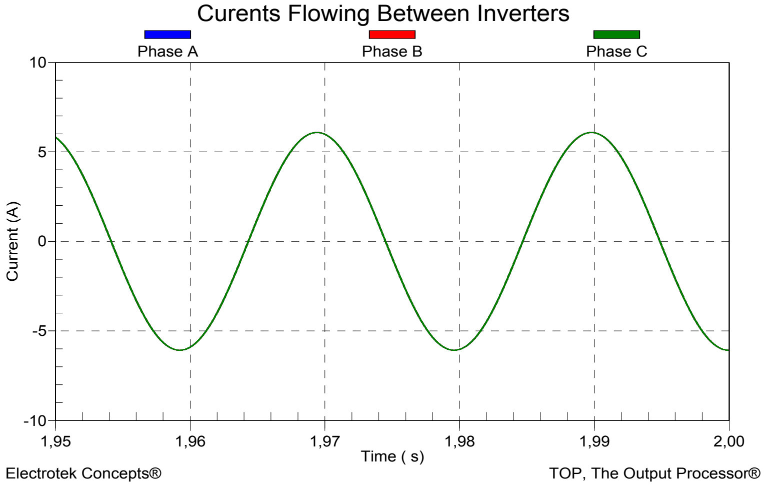

Figure 28: Currents flowing from one inverter to the other with 0.5 fictitious resistance

Using the line impedance compensation method is disadvantageous in this case because the final equivalent impedance is decreased and the current increases. Therefore, the cases without line compensation will be better than shown cases.

In both cases of unbalance, increasing the fictitious resistance is beneficial for the system, but this resistance can not be enlarged indefinitely. As seen in previous sections this affect sthe stability of the system, and, in addition, the voltage drop of the unbalanced currents across the fictitious resistance creates an unbalanced voltage in the load, affecting the quality of the electric signal. The same negative effect appears when the current contains harmonics.

4.1.5. Harmonics

In the study case regarding harmonics, the focus is on to ensure the behaviour of the system when there are non linear loads inside the Island. The results are quite similar to the previous case excepting that the fictitious resistance has less importance than before. The parameter that has influence in the sharing of harmonics currents is the ratio of equivalent coupling impedance for each harmonic. As long as the harmonic order increases, the inductive part of the coupling has more importance than the resistive one because the inductive impedance is proportional to the frequency. Therefore, the changes at the control have little influence in the behaviour of the system; the really important parameter is the real coupling inductance.

The studied case has the same source distribution than in the previous cases, but now a non controlled 3 phase rectifier is introduced as a load.

The response of the system is seen in the Figure 29: Active and reactive power with harmonic current consumption: the power and the reactive power is shared in the same manner than in the balanced and linear loads case. The figure represents the line compensated case.

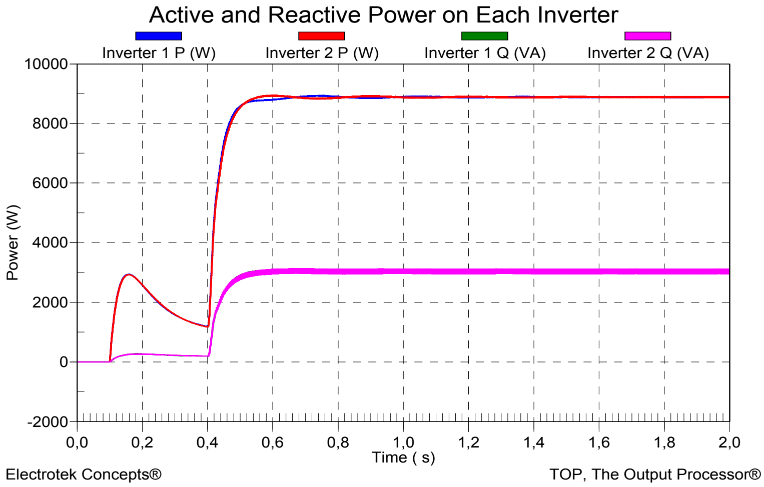

Figure 29: Active and reactive power with harmonic current consumption

The measured and filtered currents are shown in Figure 30, and in Figure 31. The filter performs better than in the unbalanced currents case because the harmonics appear with frequencies bigger than 300 Hz in the rotating frame system and the unbalanced current appeared with a 100 Hz frequency.

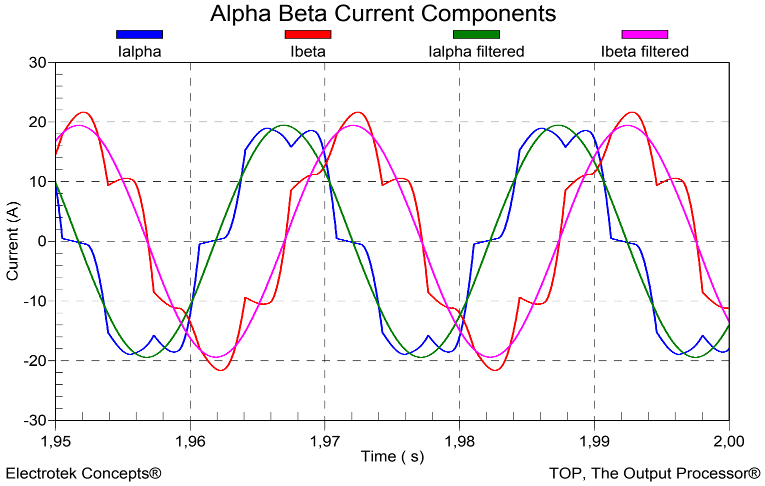

Figure 30: Rectangular current components before and after filtering

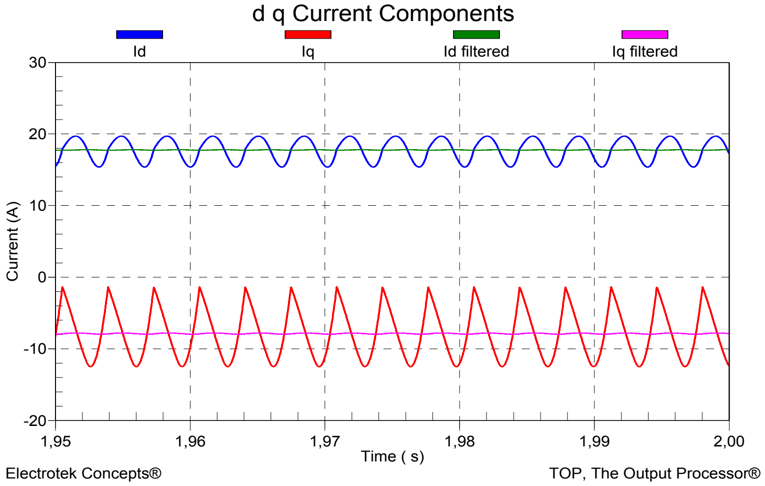

Figure 31: Rotating system current components before and after filtering

The number of studied alternative system configurations is three: in the fist one uses a small 0.15 Ohms fictitious resistance, in the second case the resistance has been increased to a 0.5 value and finally the line compensation technique has been applied to produce equal output impedances.

The Figure 32: Output harmonic currents with 0.15 Ohms fictitious resistance, and Figure 33: Output harmonic currents with 0.5 Ohms fictitious resistance, show the inverters output currents in the first two cases. Changing the fictitious impedance has small influence in the output currents. The harmonic current sharing is a little better in the second case but it is almost unnoticeable. The current differences are a consequence of harmonic and reactive power sharing difference.

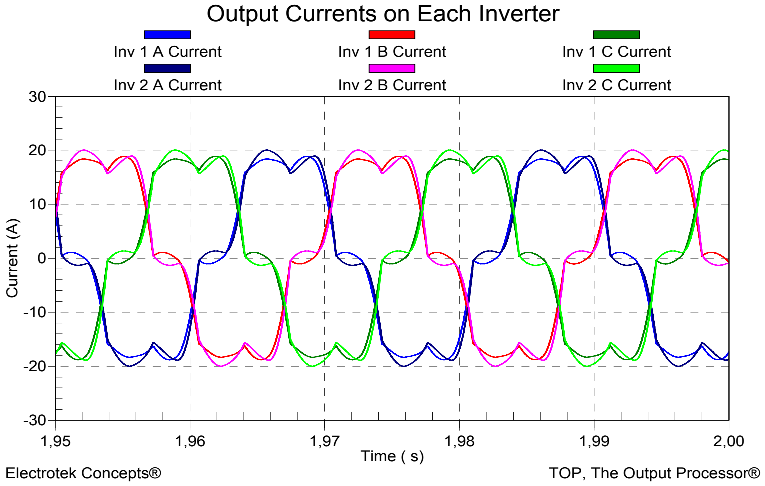

Figure 32: Output harmonic currents with 0.15 Ohms fictitious resistance

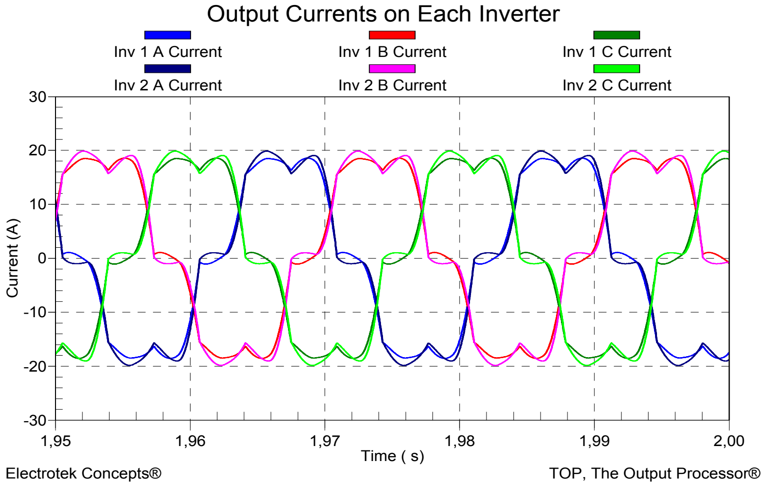

Figure 33: Output harmonic currents with 0.5 Ohms fictitious resistance

In Figure 34: Currents harmonic spectra of both inverters, the individual harmonic components are shown. The different sharing of harmonics is only representative in the low order harmonics and the difference is less important as harmonic order grows. The reason has also been mentioned; the harmonic current sharing depends on each harmonic coupling equivalent impedance. As the frequency grows the inductive part of the impedance is bigger while the resistive part remains constant, hence the impedances ratio is closer to one. This happens because both inverters are designed equal, and its coupling impedance is the same. The only difference is the line coupling impedance that can be different in each situation. With inductive coupling impedances or with a different output reactance in each inverter, the harmonic current sharing would have been worse.

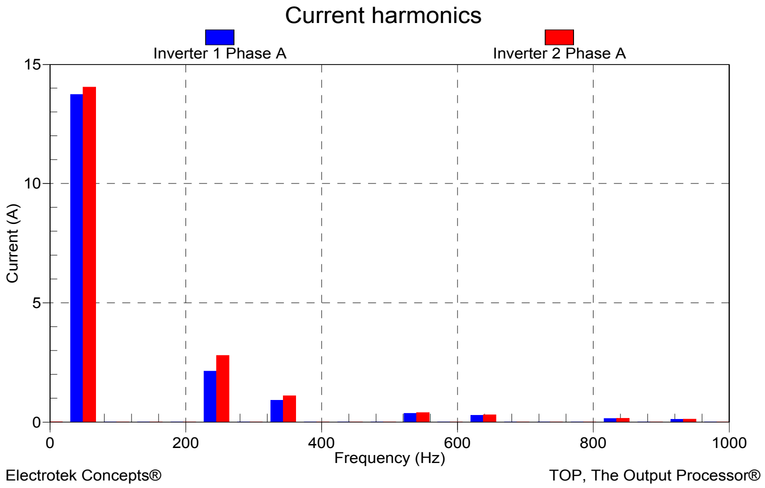

Figure 34: Currents harmonic spectra of both inverters

In the Figure 35: Output Harmonic currents with 0.5 Ohms fictitious resistance and line compensation the output currents of the inverters are shown. The currents are practically the same and the current sharing works properly.

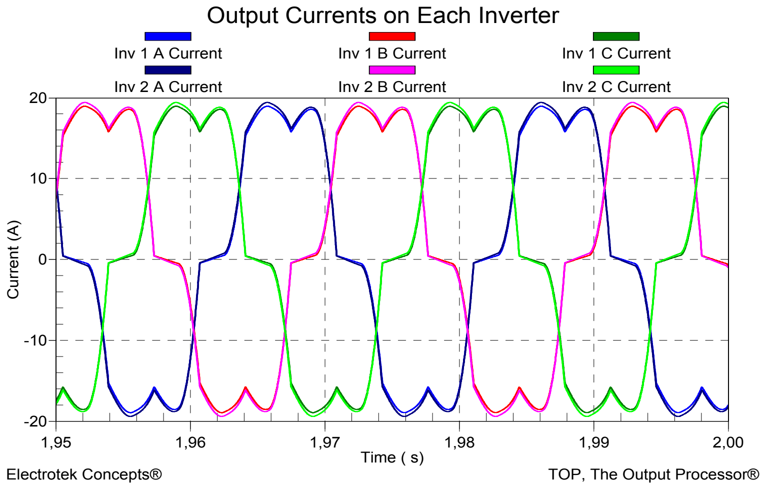

Figure 35: Output Harmonic currents with 0.5 Ohms fictitious resistance and line compensation

As a conclusion, it is important to remark that harmonic current sharing is more related to circuit element parameters than to the control parameters. If one device is not supposed to supply harmonic currents it should be provided with a higher output reactance value.

4.2. Grid Operation

Up to here, the system stability and performance in steady state has been studied, but the system must be able to adapt to changing situations. The stability and the system performance must be good in a wide range of situations. Sudden load changes, other sources connections, connection and disconnection to the main grid, should be done in a soft manner. Some control strategies must be changed or implemented in the inverters to prove these transitions possible. Load changes have been previously studied, in all those simulations a load change happened, but other grid transients have to be studied.

4.2.1. Progressive connection of µSources

In the studied cases the simulation starts with the inverters perfectly synchronised, or at least, with the same initial control values, but in the real world this is almost impossible, the inverter will have to synchronise with an existing system. When the switch of the inverter is closed, it must verify that the system it is connecting to has voltage: adapting to it or producing the voltage reference.

If the control system is able to start from a situation of no voltage, and then, each additional source is able to synchronize with the existing µGrid then those µGrid systems can later synchronise each other or even with the main grid. This sequence of events is called black-start and provides a relevant value to the overall power systems in cases of blackout.

In this study case, the simulations aim to analyse the progressive connection of different sources. At time t=0.1 s a first inverter is connected to a 2 kW load. The load initially has no voltage so the inverter creates the µGrid. Then, at time t=0.2 s, the load is increased up to 10 kW. When the system is stabilised after 2 seconds, a second inverter is connected and after another second a third one is connected to the recently created network.

All inverters are similar, but not the same, this slight difference in their parameters is included to introduce some unbalance in the system, to provoke inverter responses not being exactly the same and therefore emphasizing stability issues.

Each inverter, before connecting to the existing network voltage, synchronises its output voltage reference (magnitude and phase) and then connect to the grid. The behaviour of the system is reflected in Figure 36: Output power with sudden connection of new inverters, and in Figure 37: Output currents with sudden connection of new inverters.

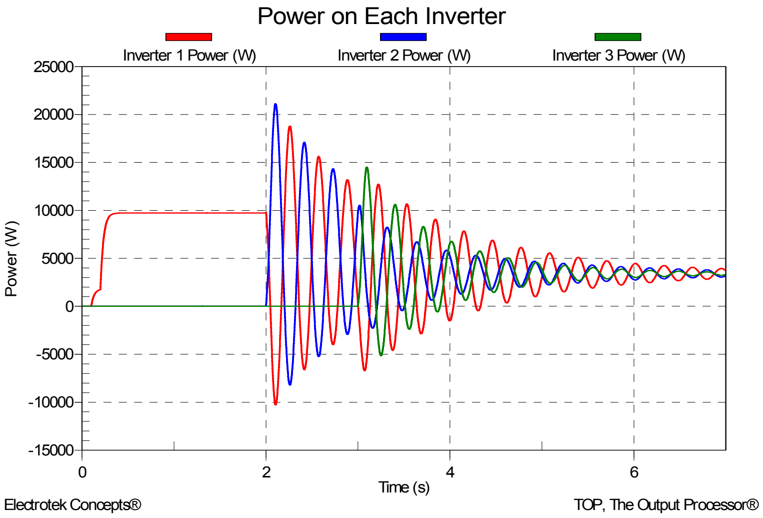

Figure 36: Output power with sudden connection of new inverters

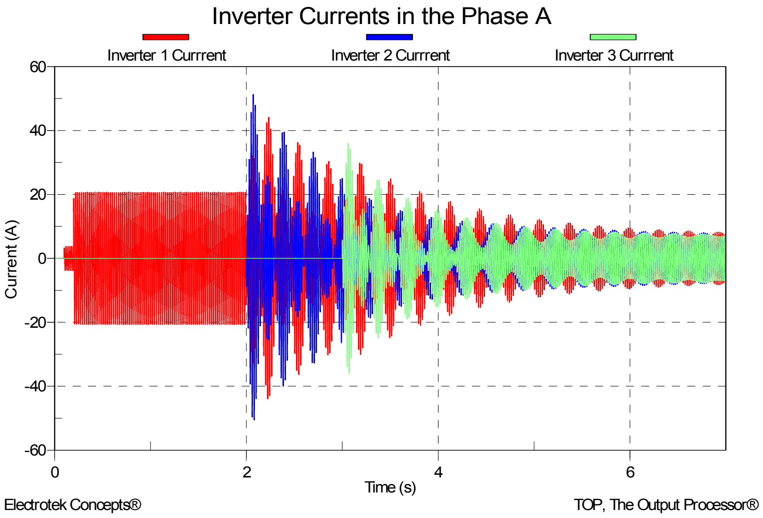

Figure 37: Output currents with sudden connection of new inverters

When a new source is connected the available power system, it starts fluctuating around the equilibrium point. The currents and powers flow from one inverter to the other until the system reaches the balance.

Several techniques have been tested to reduce the oscillatory system response. One reason causing fluctuations is that each new inverter starts with the same angle as the grid, but the frequency is imposed by the power measurement (because of the P/f drop curve). If both frequencies are not the same then the inverter frequencies fluctuates around the equilibrium point causing the currents oscillations. On the contrary, if the frequencies are the equal in the first instant them the system moves more smoothly to the steady state.

Two main alternatives can be considered to reduce this fluctuation:

- On one hand, if the frequency and the angle are the same when the new inverter connects, the oscillation is reduced, so it is interesting to adapt, during the special connection routine, the internal values of the inverter to achieve both frequencies being the same.
- On the other hand, the dynamical characteristics of the control system can be adjusted at the connection time to improve fluctuation damping.

It is also possible to act in the P/f drop to obtain the same frequency in the two inverters. Initially the power is null, so the frequency should be different from the one existing in the island. Thus, if the power is initialised to a value different from zero, the new inverter frequency could start with the island value. Other choice consists on using an offset value to the drop characteristic to match both frequencies.

The dynamical parameters of the inverters should be changed to smooth the fluctuations. There are several ways: replacing temporally the coupling fictitious impedances and resistances, substituting the cut off frequencies of current and power filters, tuning the P/f drop slope, or even swapping the digital filter transfer function.

It is worth mentioning that the only parameter set that is to be adjusted is the one belonging to the inverter being connected. The other inverter control does not know when a new inverter is connected.

All done simulations demonstrate the satisfactory, or not, progressive connection of inverters but only the techniques offering the better results are summarized.

First, to smooth the fluctuation, the power filter transfer function has been adapted. The transfer function was initially a first order low pass filter [Equation 1].

$$F(s) = \frac{1}{1 + \frac{s}{w_c}}$$

Equation 1: low pass filter

This transfer function is adjusted by the [Equation 2]. The bigger the n value is, the more similar is the transfer function to a conventional low pass filter. This new transfer function lets pass the high frequency variations of the power diminished but not delayed. It works worse as a low pass filter, the high frequency transients are not so well filtered, but the dynamical response is better.

$$F(s)=\frac{1+\frac{s}{n*w_c}}{1+\frac{s}{w_c}}$$

Equation 2: modified low pass filter

In Figure 38 and Figure 39, the damped oscillations are showed. After a small lapse of time the transfer function can be reverted back again (using n parameter term) and the system will perform normally.

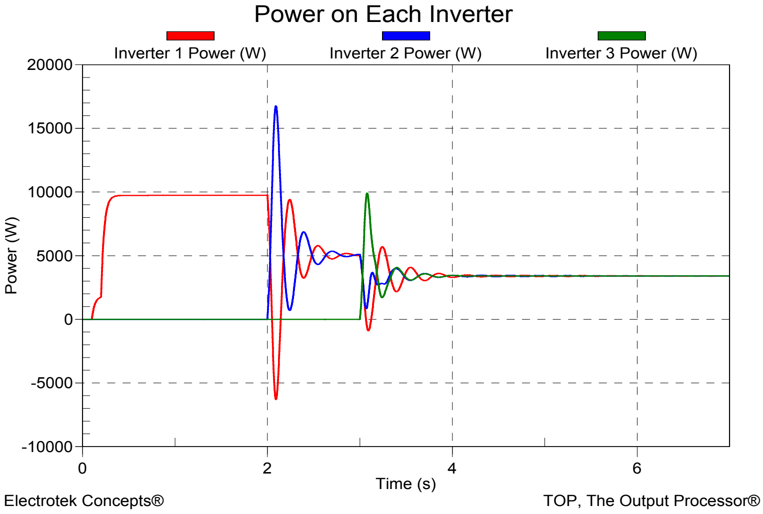

Figure 38: Output power with sudden connection of new inverters and changed power transfer function

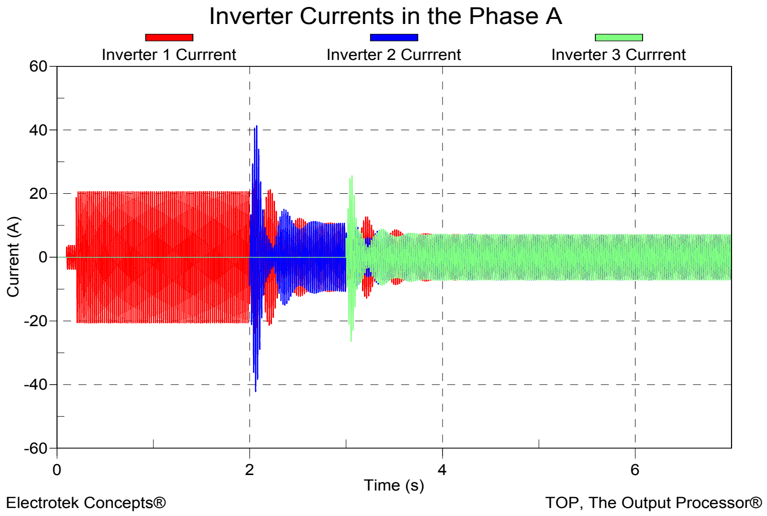

Figure 39: Output currents with sudden connection of new inverters and changed power transfer function

With this new transfer function the oscillation is reduced quickly and the current fluctuations last shorter time. This transfer function makes the new inverter frequency adapt faster to the island frequency, but on the long term the system frequency is not so stable and changes more sharply when the island has to satisfy a different power demand. Therefore it is substituted by the normal primary order form.

The technique used to achieve the two inverters frequency being equal is to add an offset to the P/f drop. Initially, and before connecting, the new inverter calculates the grid frequency and compares it with its zero power frequency. If such difference is added to the P/f drop curve when the new inverter connects, it will reach the balance with a 0 kW power output so the system should remain untouched: the connected inverters delivering all the power and the new one synchronised with the island. If, then the offset is gradually reduced to zero the system will reach the balance smoothly without fluctuations.

In the Figure 40: Output power with sudden connection of new inverters and offset technique, and the Figure 41: Output currents with sudden connection of new inverters and offset technique, the final behaviour of the system can be observed. As shown in the graphics the oscillations are reduced drastically and the connection happens in a gradual way.

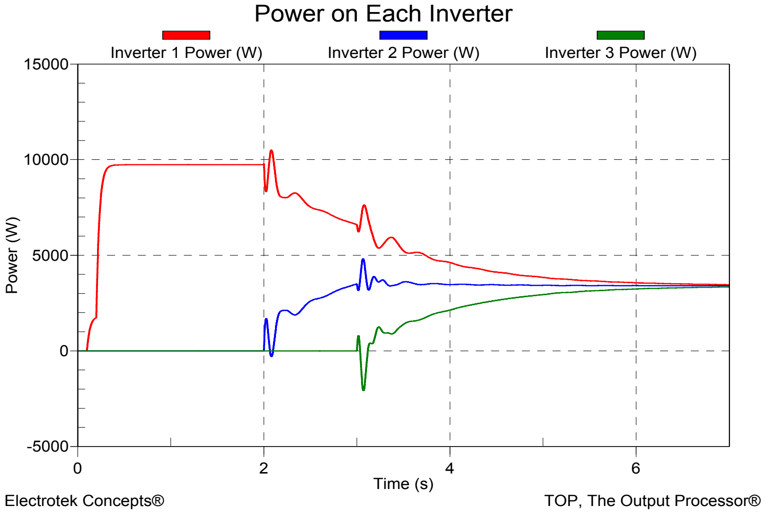

Figure 40: Output power with sudden connection of new inverters and offset technique

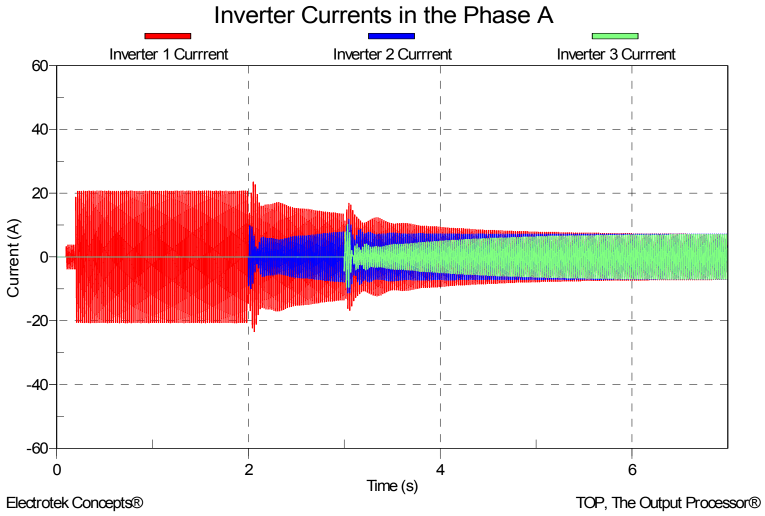

Figure 41: Output currents with sudden connection of new inverters and offset technique

4.2.2. Grid synchronization, connection & disconnection

The operations related with the main grid are the next point to study. If the island is working independently from the grid, it must synchronise the μGrid with the main grid or with another μGrid to achieve the connection. The problem is similar to the previous one, the angle and the frequency must be the same to interconnect, but the solution is more difficult because all inverter controls must be coordinated to connect with the main grid. This coordination must be done by an external controller that guides all the inverters in the synchronisation process.

Again, to vary the island frequency and to control the angle an action is required over the P/f drop curve. The chosen strategy is to communicate, from a central controller, an offset variable that will be added to the P/f drop curve to vary the equilibrium point and modify the frequency.

Two possible scenarios are possible to transfer the offset, continuous and discrete. With the continuous communication (wired signal), the synchronization process can be faster and softer while with discrete communications the offset is renew in successive periods of time.

In the conducted simulations the offset value is communicated each half a second, but in a real case the communication cadence will affect the synchronisation speed. The common sequence of events in three covered study cases is as follows: Three inverters start from zero at time t=0s, after a second (t=1s) the system reaches the steady state and the central control initiates the offset sending commands procedure. At time t=5s the system is synchronised to the main grid frequency and the breaker closes, a couple of seconds later (t=7s) the central control restores the default offset values. Finally, at time t=9s the µGrid is again disconnected from the mains.

Some relevant issues should be underlined:

- At every single instant the inverter control is operating as voltage source, therefore the power electronics control does not know whether it is operating islanded or grid connected. In this way the behaviour is always the same and when the disconnection occurs it is not necessary to detect the islanding condition to swap from current source mode to voltage source mode automatically.
- At time t=5s, when the grid breaker closes, there is some current flow through the break due to the small differences between the network voltage and the inverter control output voltage. Both voltage phases are the same but voltage magnitudes are not exactly equal and this provokes some energy flow. The central controller could be in charge of addressing this issue by means of the same communication mean used for synchronising.
- At time t=7s, when in grid connected mode, the central controller reverts the P/f drop characteristic to the default value. Taking into account that the inverter control operates as voltage source and that network frequency is 50Hz, It implies that inverter power output will be back to zero leaving room to the central controller to decide the import/export desirable balance and deliver it through new offset adjustments.

- The grid disconnection step is not a problem and the system moves smoothly to the new equilibrium point.

In the first studied case the offset is applied directly to the P/f curve. Therefore, as the power output value does not change the frequency varies in one step. The evolution of the frequency is shown in Figure 42.

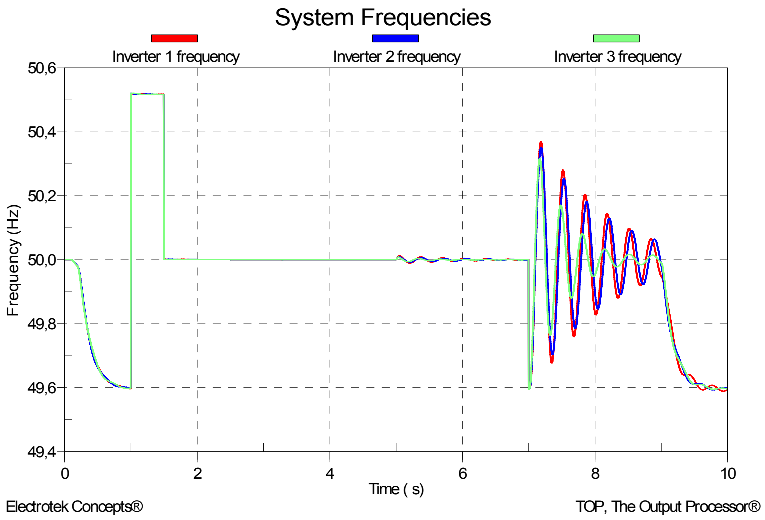

Figure 42: System frequencies in the connection process with direct offset

The systems works properly until the offset value is reset, in that moment (t=7s) a large fluctuation occurs. In the simulation all inverters change their offset value at the same time, and this is almost impossible in the reality. Therefore, it is clear that the oscillations would be important in all frequency changes.

The control system measures the difference between the island and the grid, and calculates the adjustment in island frequency to synchronize the voltages on both sides of the breaker. The voltage gap, measured in radians, can be seen in Figure 43, it is noticeable that the synchronisation is achieved in around half a second.

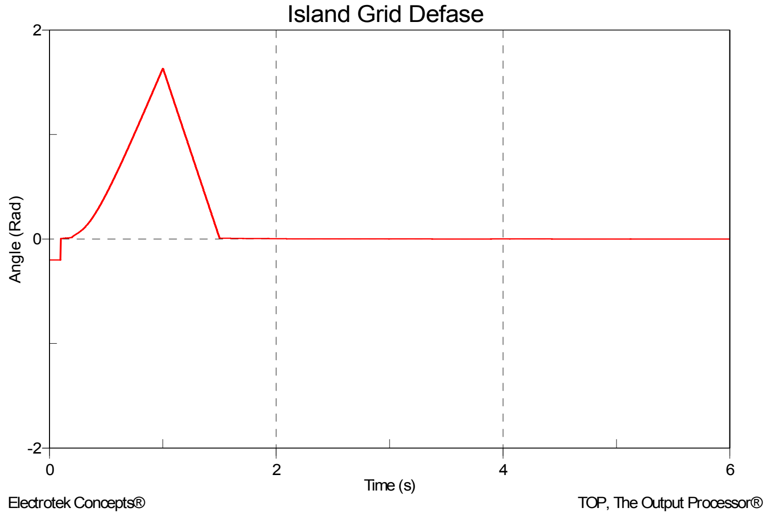

Figure 43: Dephase between the island and the grid in the connection process with direct offset

In Figure 44, the evolution of the inverter powers is shown. It can be observed that during the synchronisation process (t=1s) the inverters feed the load while they are changing their frequency; at time t=5s, the system is in grid connected mode but they keep feeding the same load. When the offset value is reset (t=7s), inverters are requested to change their output power implicitly back to zero, and then, there are some oscillations around the new equilibrium point. At the island is disconnection, again the inverters are able to provide the power for all connected loads.

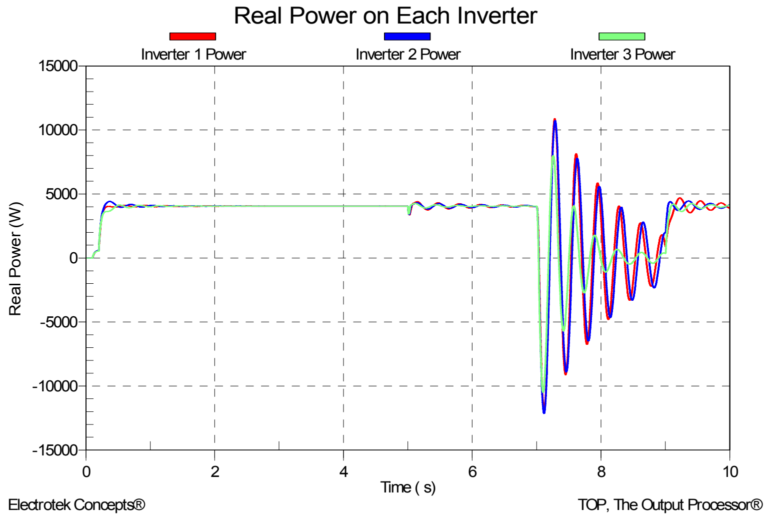

Figure 44: System active powers in the connection process with direct offset

In Figure 50, the voltage difference between the µGrid and the grid is observed. The voltage decreases with the gap until the synchronisation is obtained, having almost the same voltage in both sides of the circuit breaker.

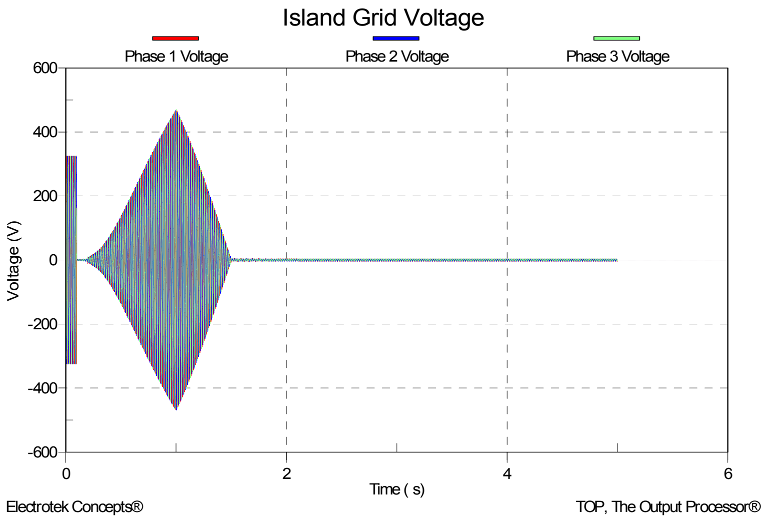

Figure 45: Island grid voltage in the connection process with direct offset

In Figure 46, the breaker currents are plotted. Between time t=5s and t=7s the system is operating in grid connected mode and the small energy flow is due to the difference between grid voltage magnitude and the inverter control output voltage (connected impedances damp this). When the offset is restored back to the default value (t=7s) there is a significant grow in the current through the breaker because the inverters are reducing their power output and system load is to be feed from the main grid. The current pattern shows that, at grid disconnection time (t=9s), the system was still in the transient state.

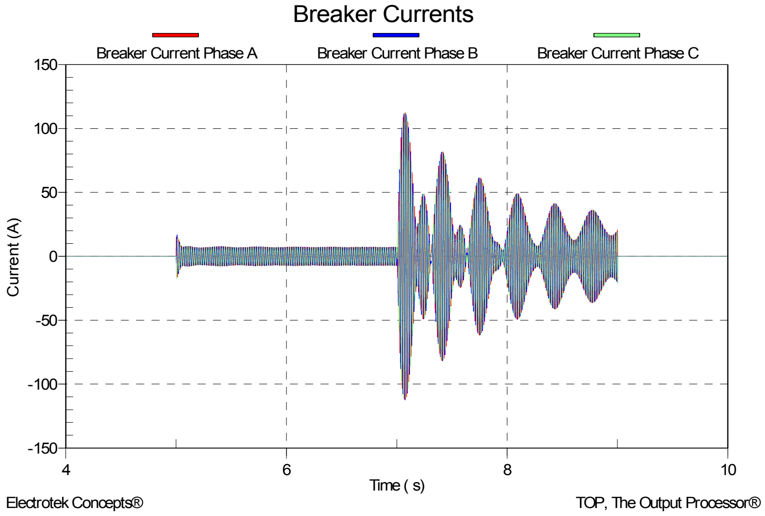

Figure 46: Currents trough the breaker in the connection process with direct offset

As said before, the frequency varies too steeply with this kind of control. To improve this, it is possible to apply the offset indirectly and gradually to the drop curve. If the inverter calculates the power that requires such a frequency shift, in other words, the amount of power that is necessary to vary in order to obtain this frequency drift, and subtracts it from the measured power value, the system will reach the desired frequency more smoothly.

The response of the system under this new control algorithm is shown in the next figures: Figure 47: System frequencies in the connection process with indirect offset, Figure 48: Dephase between the island and the grid in the connection process with indirect offset, Figure 49: System active powers in the connection process with indirect offset, Figure 50: Island grid voltage in the connection process with indirect offset, and Figure 51: Currents trough the breaker in the connection process with indirect offset.

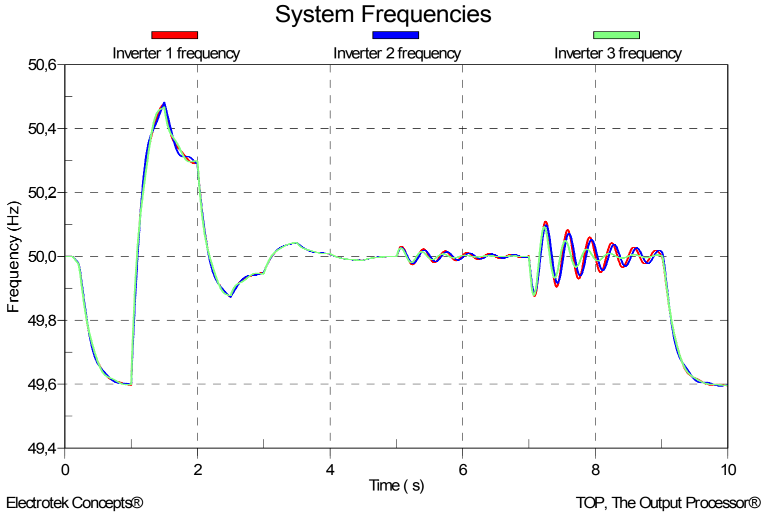

Figure 47: System frequencies in the connection process with indirect offset

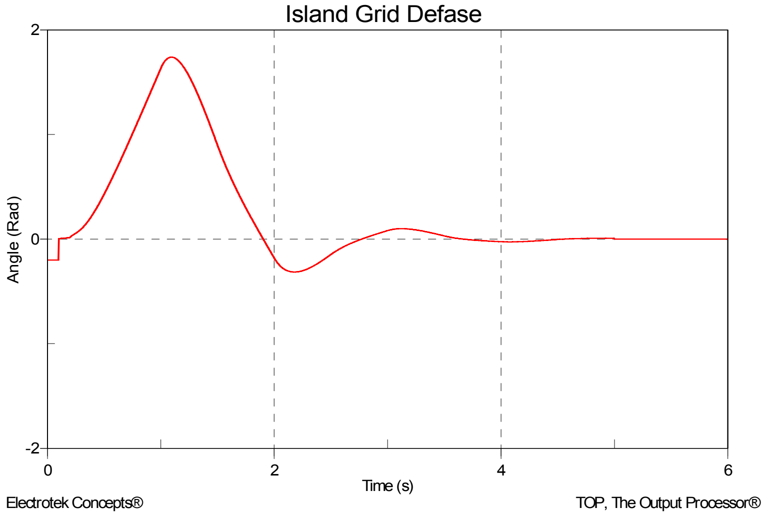

Figure 48: Dephase between the island and the grid in the connection process with indirect offset

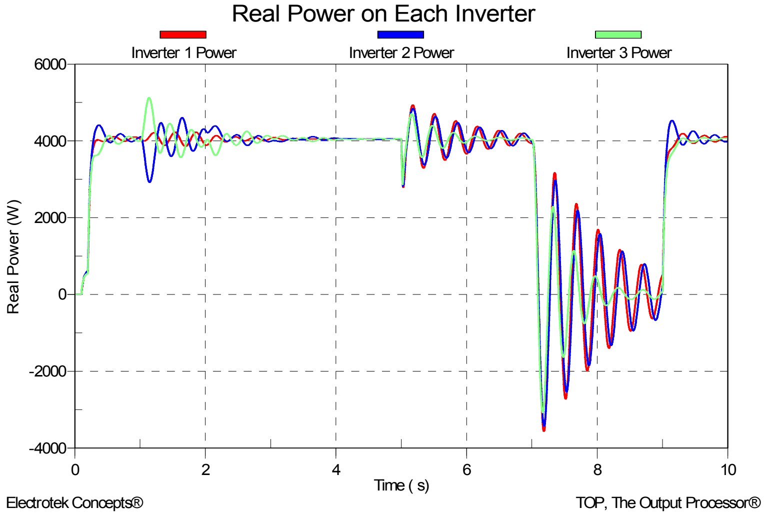

Figure 49: System active powers in the connection process with indirect offset

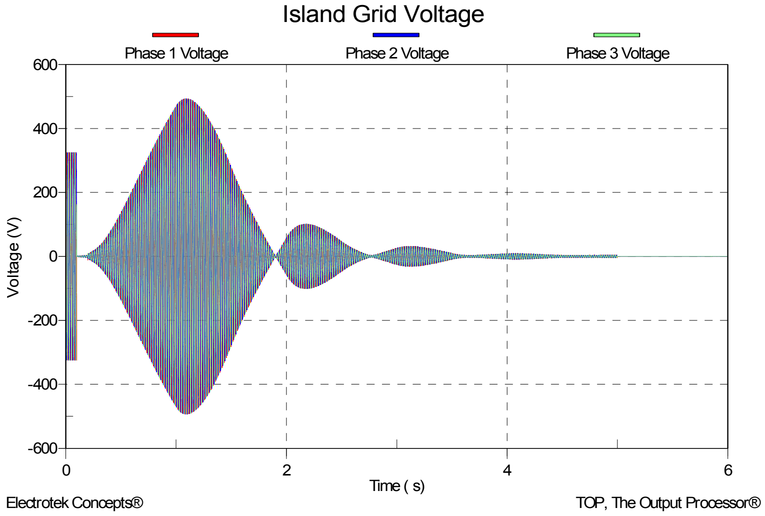

Figure 50: Island grid voltage in the connection process with indirect offset

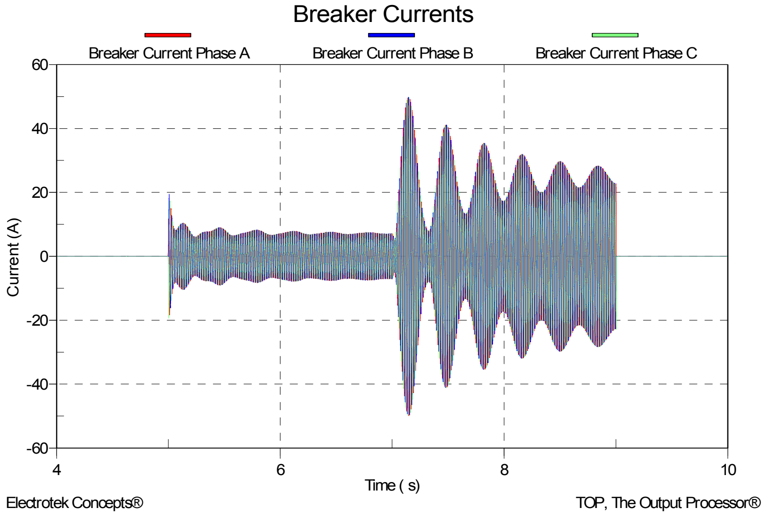

Figure 51: Currents trough the breaker in the connection process with indirect offset

The response of the system is smoother and the oscillations are smaller, but the μGrid needs more time to synchronise with the main grid. However, the fluctuations are still important and it would be interesting to reduce them.

To reduce these oscillations the same technique than in the progressive connection case is used. The power transfer function can be adapted to smooth the fluctuations. The problem is to find a suitable value of n (see Equation 2: modified low pass filter), small enough to reduce the oscillations, but big enough to filter the power and produce the frequency smaller excursions.

The final dynamic behaviour of the system is shown in: Figure 52: System frequencies in the connection process with indirect offset and modified low pass filter, Figure 53: System active powers in the connection process with indirect offset and modified low pass filter, and Figure 54: Currents trough the breaker in the connection process with indirect offset and modified low pass filter.

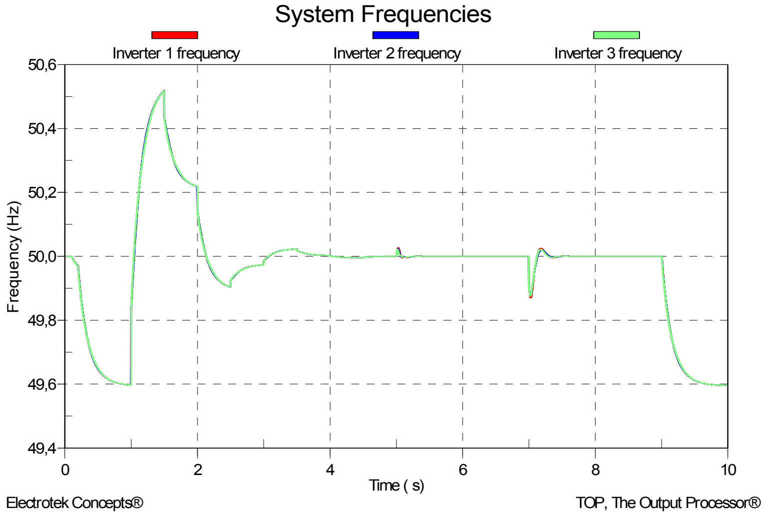

Figure 52: System frequencies in the connection process with indirect offset and modified low pass filter

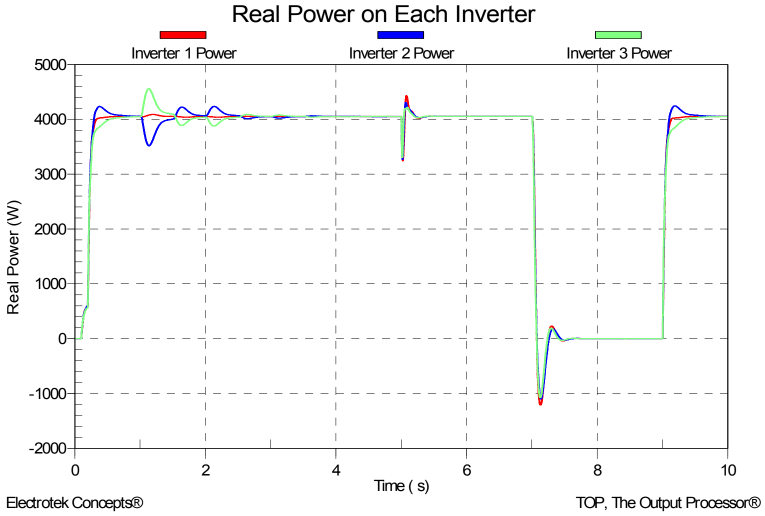

Figure 53: System active powers in the connection process with indirect offset and modified low pass filter

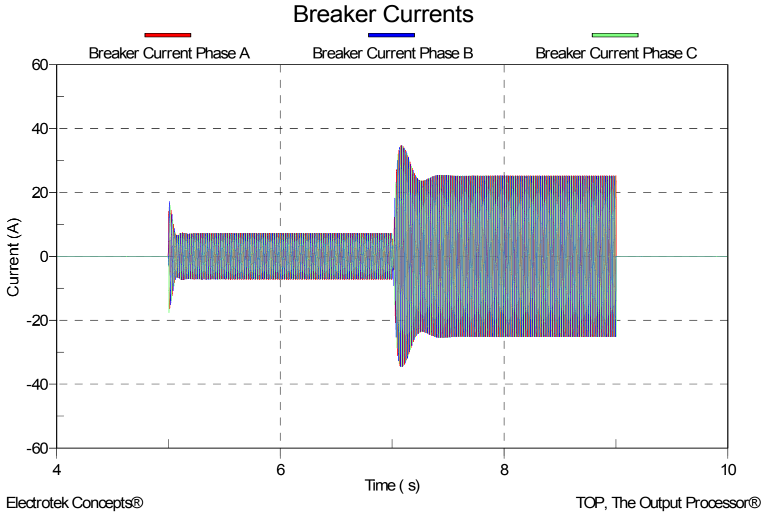

Figure 54: Currents trough the breaker in the connection process with indirect offset and modified low pass filter

The obtained system response at every event reduces frequency changes compared to the previous algorithms while power oscillations are significantly minimized both in magnitude and time. Only the synchronisation takes longer in absolute value (roughly 3,5 seconds) but, in any case, perfectly acceptable when compared to a conventional power system.

4.3. DER and storage specifications

Up to here, the analyzed cases of study have been based on the assumption that all primary power sources behave in a similar manner but in fact there are relevant differences among them in terms of primary energy source and dynamics.

The sources can be classified in different types depending on their primary energy source. Some sources are not storage capable, and if energy is not extracted at the right moment it is lost: clear examples of this type of source are renewables such as photovoltaic cells, wind generators, free flow turbines or ocean wave generators. Other sources have a primary energy that is stored and used when it is needed: examples are the diesel generators, fuel cells or conventional hydro turbines.

A second important characteristic of the micro sources is the output power change rate. Some sources are slower and take more time to change their output power (i.e. fuel cell with heavy chemical process inertia) but others change their output power without any difficulty (i.e. micro turbine).

Storage devices are another element to analyse, especially in islanded operation. Under islanded operation an incorrect design of the balance between generation and demand may lead to oversize generation devices to cope with peak load or even the intermittent nature of renewables could bring an excess of power on valley load conditions. Thus energy storage devices play an important roll to match generation and demand. As happened with the energy sources the reaction time of the energy storage can also be variable.

In brief, each kind of device should be treated in a different manner and its control must take advantage of all its inherent characteristics.

In the case of small scale non storable power sources, they can operate as a current source, providing not help to the stability of the system as if they were a mere negative load. Adding to such sources some energy storage and complicating the design would make the device more expensive and economically unfeasible.

In case of bigger scale non storable power sources, the same philosophy is not acceptable. If a given power source does not contribute to the system stability, or still worsens it, if they are an instability source because of its random and variable nature, the devices in care of the stability of the µGrid will be overloaded and the system performance would be affected.

Therefore, the bigger scale non storable sources must contribute to the system stability, for this purpose, the device should be equipped with storage capabilities. They should work as a voltage source, implementing the drop control explained in this document. In order to match the generated power with the delivered power, an internal offset value has to be added to the drop curve. This offset should be calculated to adapt both powers. The change rate of this offset will be in concordance with the device storage capability. If the storage capacity is high enough the offset can be changed slowly while the delivered power fits the generated one. A possible configuration is based on an internal DC link storage device. The power source can be attached to the DC bus by a MPPT[1] device while the DC link is connected with the µGrid by an inverter. The inverter control should maintain the DC bus voltage calculating the offset with an integral controller. As said before, the speed of this controller should be calculated taking into account the capacity of the storage device.

The storage devices should be controlled in a similar manner, they must contribute to the system stability. Now, they should add to the control drop an offset related with the state of

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[1] Maximum Power Point Tracker

charge of the storage device. In this way, the device will always be finding the medium point that allows it to inject power when the demand exceeds the generation, or absorb power in the opposite case. As in the generator case, the speed of this offset control must be related with the storage capability: the bigger the storage is, the slower the control can be.

The other question that must be taken into account in the control is the power change rate of the sources or storage devices. Not all the sources react in the same way to a change in its power setup value. To avoid the collapse of these devices, the change in the power output of the slower elements should be demanded with a smaller rate of change than in the faster devices. To control the response to sudden load changes there are alternatives based on acting on the power digital filters and on the connection impedances.

When a sudden load change occurs, devices react according to, in the very first moment, their real connection impedance, then their fictitious resistance, later their fictitious impedance, and finally, their power digital filters. The smaller the impedances are, and the slower the filter is, the faster the system response is. Therefore these parameters and elements should be adjusted to achieve the system desired response.

Assuming a system where one device is expected to react slower than other because its primary source is slower; it must be designed with bigger impedances and with a faster filter to get this response. In the simulation the first two inverters have a fast responding source and the third one is slower. The fist two inverters give stability to the system and the very slow response of their digital filters provide stability to the system frequency. If the complete system is too stable, the synchronisation and the island detection processes are slower and more difficult to obtain. Therefore, as always, the key is in finding such a value that, being stable enough, allows the change of the system frequency.

In Figure 55 and Figure 56 the dynamic response of the system facing sudden load changes is shown. The inverters initially start feeding a 2 kW load, but after three seconds, a 10kW load is connected, then, after six seconds this load is disconnected. The loads are simulated as pure resistances and reactances.

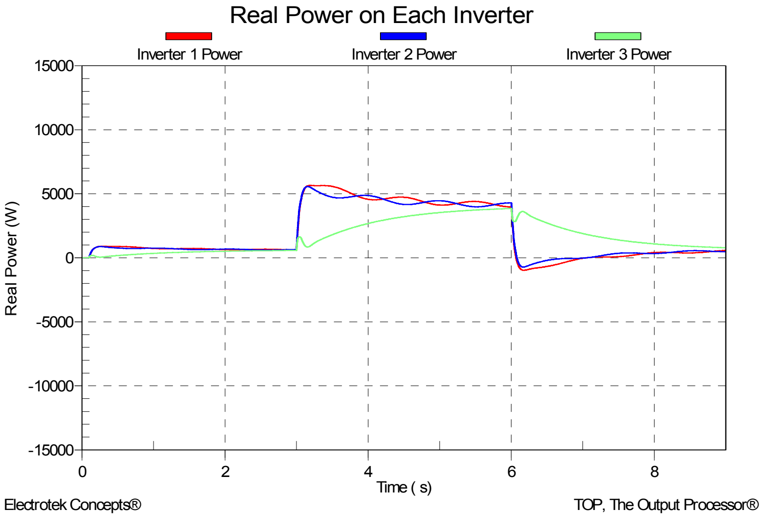

Figure 55: Devices output power with sudden load changes

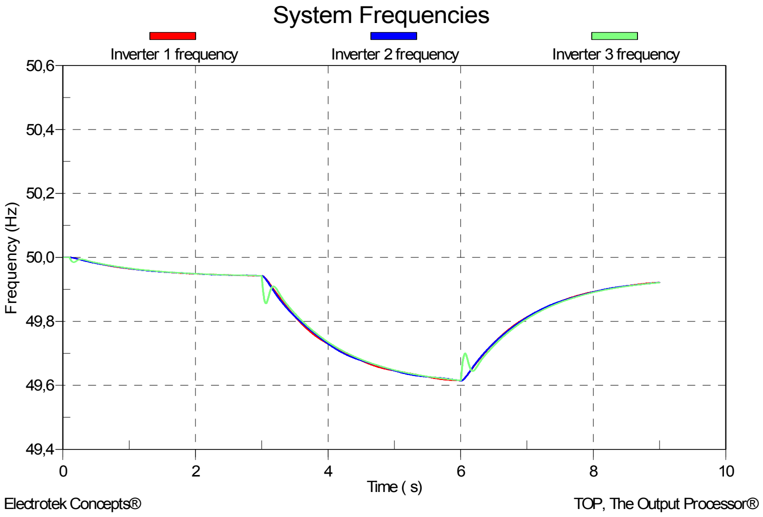

Figure 56: Devices output frequencies with sudden load changes

Observing the response of the slower device, it can be appreciated that when the load change happens, the device increases immediately its output power, then its drop control reacts faster and adapts the frequency; as a consequence the power output decreases again, and finally the three powers outputs converge slowly to the equilibrium point. The first response only depends on the devices' impedances and the second response on the digital filters. The slower filter devices absorb most of the load change while the faster filter device changes more gradually. A small storage is needed to absorb the first swing.

In Figure 57, the system stability is enhanced changing the transfer function of the low pass filter. Adding more stability to the system is supposed to worsen the response of the slower source, although it can not be detected in the simulation, and the faster sources' oscillations are damped.

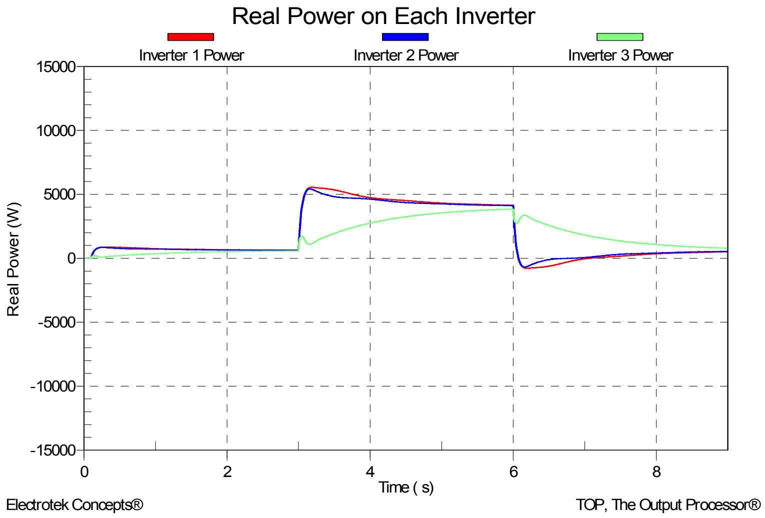

Figure 57: Devices output powers with sudden load changes and modified low pass filter

As a resume, the dynamical response of the inverters is related to the coupling impedances and to the transfer function. The inverter with smaller impedances will react in the fist instant while those with bigger impedances will take a longer time. According to the low pass filter transfer function, Equation 2: modified low pass filter, devices with a faster response must have smaller values of w_c and bigger values of n. With big n values the system fluctuations need more time to be damped. Again, the compromise between both objectives is to be found.

4.4. Islanding

The targeted objective of anti-islanding algorithms is avoiding the µGrid to energize, or feed the loads outside the µGrid, when a protection trips.

An important effort has been applied in the area of the unintentional islanding [5]. This chapter is not intended to provide an exhaustive list and detailed information about each algorithm. Instead, it is aimed to analyse the effect of these techniques on the proposed control algorithm, characterized by having the inverter control behaving as voltage source permanently.

We want the microgrid to survive after a disconnection from the external network, but we do not want it to feed the loads outside the µGrid so the island must be detected and the connection from the main grid disconnected. As it is explained later, the island detection must be implemented inside the central controller.

The main differences between this case and a traditional anti-islanding protection are the following:

- The µGrid does not have to stop operating when the islanding happens. It must continue but isolated from the grid. It is so, it is advisable to not to use, or at least, disable when disconnected, all the methods that make the island unstable.
- The µGrid is composed by different devices that are coordinated among them trough the drop control, all communications are minimised, but in some cases it would be desirable to have the device in charge of disconnecting from the main grid to spread the islanded operation.
- The µGrid devices are designed to improve the stability in case of islanding; all the methods and algorithms based on transient phenomena associated to the disconnection process have more difficulties to measure the transitions.

The islanding detection methods can be divided in four categories:

1. Local measurement of local electrical quantities (passive methods).
2. Local measurement of system characteristics (active methods).
3. De-stabilisation in case of islanding (active methods).
4. Communication of remote network status.

The majority of the methods that use local measurements of local electrical quantities will not work in the proposed algorithm, if the load outside the µGrid is small enough to be fed by the sources, their control would not notice any difference.

The methods that are based on voltage and frequency measurements to trip when those variables are out of limits will not be suitable in the majority of the cases because voltage and frequency in the µGrid is stable for a wide range of loads: unless the system becomes overloaded, the island parameters will remain within their statutory limits.

The methods that measure the rate of change of the frequency (rocof) will trip only if the net import or export balance of µGrid is high enough to produce a significant frequency excursion in the transient state. The tripping set point should be small enough to allow the detection of the anomalous situation but if it is adjusted too close to the standard frequency, false island relay detections may occur. Some characteristics of the frequency swing could be exploited to improve the algorithm: variations resulting from normal grid operation tend to produce gradual frequency changes while protection tripping causes sharper changes.

In the same way, those methods that measure a phase jump will not work because no phase jump happens; voltage harmonic component measurements is not significant, again because the inverter control system is designed to maintain a good quality of supply without harmonics; current harmonics are not meaningful, they can appear either connected or disconnected; finally, voltage unbalance methods are neither suitable.

Other methods that make use of local measurements of local characteristics, generally inject a signal to measure the line impedance. If one inverter implements this method and the others continue with their normal behaviour then the other sources will be seen as a low impedance short-circuit for the high frequency signal of the inverter. The difference between the impedance before and after the protection trip could be small enough to be unnoticed.

Some methods create a de-stabilisation in case of islanding condition but they are just against the concept of the control system; therefore, their implementation must be very careful.

The de-stabilisation can come from two sources:

- All inverters may have a de-stabilisation method to bring the island out of limits, and then, when the µGrid is disconnected from the mains this de-stabilisation algorithm must be deactivated. For the proper performance of this method, all the sources must know in every moment if the mains-µGrid connection breaker is closed. If the de-stabilisation method is too fast, the µGrid could collapse before deactivating the algorithm. It is better for the algorithm to stabilise the system out of the limits, but not to bring it to collapse.

- The de-stabilisation can come from central controller, in this case the de-stabilisation process is slower but it can be halted by the controller when the µGrid is disconnected.

Methods based in communications are, without any doubt, the best way to control the connection breaker, but a redundant method is suitable to ensure a proper behaviour when communications fail.

The central controller is the most adequate device to develop the anti-islanding protection: When the µGrid is connected to the grid, it is controlling the generation devices accordingly to their schedules. If a protection trips, the power exchanged with the main grid is the one resulting from loads outside the µGrid. This situation must be detected by the algorithm and immediately it must open the connection breaker with the mains.

An extra anti-islanding protection operation is shown in Figure 58: the controller introduces a de-stabilising term in the drop control which is proportional to the frequency deviation from the nominal value. When the µGrid is connected to the main grid this term remains constant and has no influence but, when disconnected, the frequency varies and the term grows making the system unstable.

During the simulation, the inverters start being connected to the grid working as expected, the anti-islanding algorithm works but has no effect; after four seconds a protection trips outside the grid leaving the system islanded. The active and reactive power produced in the µGrid is feeding exactly the load consumption outside the µGrid, this is the worst case and no other method would detect the island. After a few second the effect of the de-stabilisation method becomes apparent and the system frequency starts growing exponentially until the frequency is out of the limit. Finally, the central controller detects the abnormal frequency, trips the connection breaker and disables the anti-islanding protection resulting on the µGrid coming again to a normal operation with the frequency inside limits.

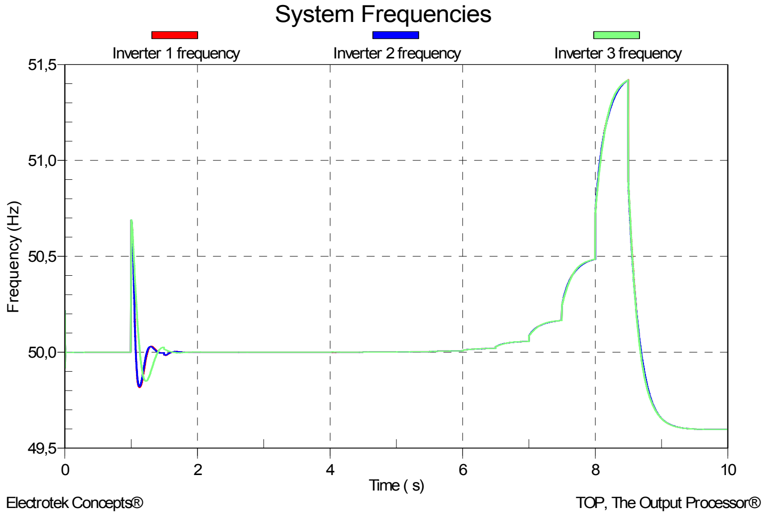

Figure 58: System frequencies with the de-stabilising method

As far as this method is based in the communications, it is slow and takes to much time to disconnect from the mains. This method can be only used as a redundant algorithm ensuring the µGrid being disconnected in case all other methods fail. The tripping time is longer than the standard normative requirements, but µGrid islanded operation detection, when communication fails, is quite difficult. Another preventive step to ensure that the island will not be created outside the µGrid is disconnecting from the grid if communications fail.

5. Conclusions

In this report, a stability analysis of the µGrid has been carried out. A control algorithm has been proposed to enhance the stability of parallel connected voltage sources. The fictitious impedance method has been studied and proved as a good alternative for the control of the voltage sources. With a limited coupling reactance and with resistive coupling wires among the sources the method has shown its worth.

The method has been tested in most kind of possible connections and the influence of its parameters has been analysed. The fictitious impedance enhances the stability in very resistive couplings. Slowing down the digital filters makes the system frequency less variable but leads to more difficult stability; in these cases the addition of the fictitious resistance improves the stability.

Regarding the performance of the control method, the active power sharing works perfectly and the power is divided proportionally to frequency drop slopes. The reactive power is generated near the low voltage consumption points. This is a good characteristic for the inductive coupled sources, because the reactive power generation helps to voltage control, but in the resistive coupled networks, the reactive power is generated near the active power consumption point, and it does not help to voltage regulation. Increasing the fictitious impedance improves the reactive power sharing, but worsens the voltage regulation. The reactive power sharing can be improved compensating the line coupling impedance; in some cases this compensation can enhance the stability. The coupling resistance can be estimated analysing the reactive power differences among sources.

When unbalanced loads are present in the µGrid, the sharing of the unbalanced improves as the fictitious resistance is increased, but at the same time the voltage unbalance grows. Every little unbalance among the sources can generate current flows. These are lessened by the real coupling impedance and the fictitious resistance.

The harmonic load case is similar but the fictitious resistance has less effect than in the previous case, because as the frequency grows, the coupling reactance takes more weight in the output impedance.

Control algorithms for the connection of new sources to the grid have been proposed. The stability of the system during the connection is improved changing the transfer function of the low pass filter and synchronising the inverter and the grid in angle and frequency, adjustments in the drop curve are made for this purpose.

The connection with the grid is done under the guidance of a central controller. Different methods has been simulated and proved. An offset in the frequency drop of each inverter is added to bring the system to the synchronisation. The filter transfer function is adapted again to improve the stability. The disconnection from the main grid is done without any difficulty.

The control algorithms are accommodated to the different types of sources. Changing the connection impedances and the parameters of the digital filters, the dynamic response of the sources can be altered. For slower response devices, the impedances must be increased and the time response of the filter shortened.

Finally, the unintentional islanding problem is analysed. The majority of the methods are proved to be inefficient, and the communications seem to be necessary for the proper anti-islanding protection. Alternative methods have been proposed, but they are slow or unreliable.

6. References

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