Impact of inverter clustering on the Small-Signal Stability of a Grid

Mauro Calabria, Walter Schumacher[1]

Abstract

In the present work, we analyse the dynamic interaction between power inverters in a low-voltage grid. The inverters are configured in a cluster providing ancillary services, namely primary control energy. The stability of the system is explored for different configurations and controller parameters, and the main factors affecting this behaviour are looked into.

1. Introduction

With ever-growing exploitation of renewable energy sources and increasing distributed generation, the operation of the power grid is shifting from a vertical system to a more horizontal one. This includes not only the generation and transmission of energy, but also the provision of the ancillary services needed to ensure reliable operation of the system with high power quality, and the participation on the deregulated energy market. However, the integration of renewable power sources into the current grid encounters some difficulties due to their fluctuability and unpredictability.

In order to compensate for these problems, different clustering algorithms are currently being developed, which attempt to balance the variations of power availability by clustering a number of power sources together. In this fashion, many small distributed generators could act as a larger equivalent source, also providing for voltage control, load following, and loss compensation.

Although this scheme delivers a promising future along with the integration of information technologies in the energy industry, there are some technical limitations that should be taken into account. One of such limitations is the stability of primary control when delivered by many distributed inverters, which has extensively been studied in the area of power electronics and microgrids but is yet to be integrated in the design of clustering algorithms.

It is the focus of this paper to analyse the variation on the dynamic behaviour of an energy grid when changing the way that control energy is generated.

2. Droop-Control and Small-Signal Stability

Since electrical energy cannot be stored in large quantities, its production has to exactly match consumption at every given time. Any deviation from the planned power balance must then be compensated with control energy within short response times to guarantee the stable functioning of the system.

[1] The authors are with the Institute of Control Engineering, Technische Universität Braunschweig, Germany
(email: m.calabria@tu-bs.de)

A distinction is made between primary, secondary, and tertiary control energy, being primary control energy the first type arriving in a matter of seconds to prevent frequency decay, and having the greatest influence on small-signal stability, i.e. the ability of the power system to maintain synchronism when subjected to small disturbances. Primary control energy is achieved by controlling the generators with a so-called droop characteristic, which can be seen in Figure 1 both for active and reactive power. Under this scheme, there is a coupling between the power being generated and consumed and the grid frequency which acts as an indicator of the power balance in the system. A grid frequency lower than nominal represents excess of demand and accordingly lack of generation, while an increment in frequency signals the opposite situation. This is used by the local droop controllers of the generators to compensate for the power imbalance, changing the amount of power produced according to the frequency deviation and hence supplying the demand.

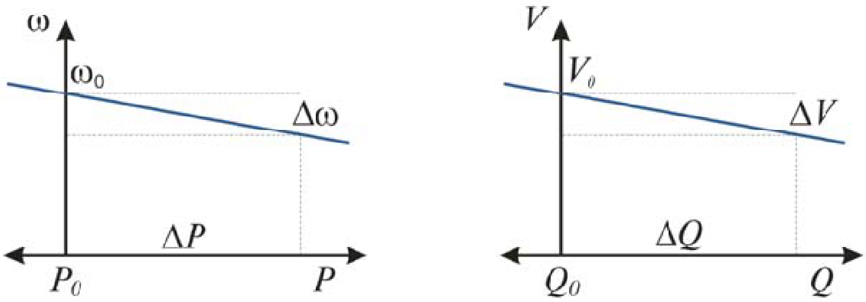

Figure 1
Droop characteristic for active and reactive power.

Since the reaction of the generators is not instantaneous given the inertia related to the large rotating masses involved, a dynamic interaction between generators arises. An example of the interaction between two large generating stations after a drop in frequency can be seen in Figure 2, which has been modelled as shown in (Kundur 1994). In this example simulation, two power generators react to a drop in frequency injecting more power according to their droop characteristic. The oscillations seen after the change in frequency are related to the mentioned dynamics and vanish within a few seconds, providing for a stable injection of primary control energy.

This coupling effect between generators has been deeply studied and accounts for inter-area oscillations and small-signal system instability. However, there exists a number of solutions to this problem, mostly comprising additional systems such as static VAR compensators and power system stabilizers (PSS) that balance the dynamic response of large power stations. In order to tune these devices and effectively stabilize the system, the location of the generating units must be well known, as well as the power lines that make up the distribution network. The compensators are configured according to these parameters and are able to keep a given system stable.

Similar is the case of microgrids, where a set of inverters is grouped forming an equivalent power station, while the energy is generated by means of smaller distributed sources. Although no rotating mass is directly involved or is hidden behind the electronics of the inverter, the small-signal dynamics of microgrids are similar to the coupled dynamics of several generators, which can in turn be interpreted as the natural interaction between coupled oscillators. In this case, the controller parameters of the power electronics of each inverter are tuned in a way that stability can be guaranteed. Different techniques have been developed in the last decade for this purpose, including active impedance matching and virtual synchronous generators, making it possible to stabilize a set of micro-generators within a given operating range.

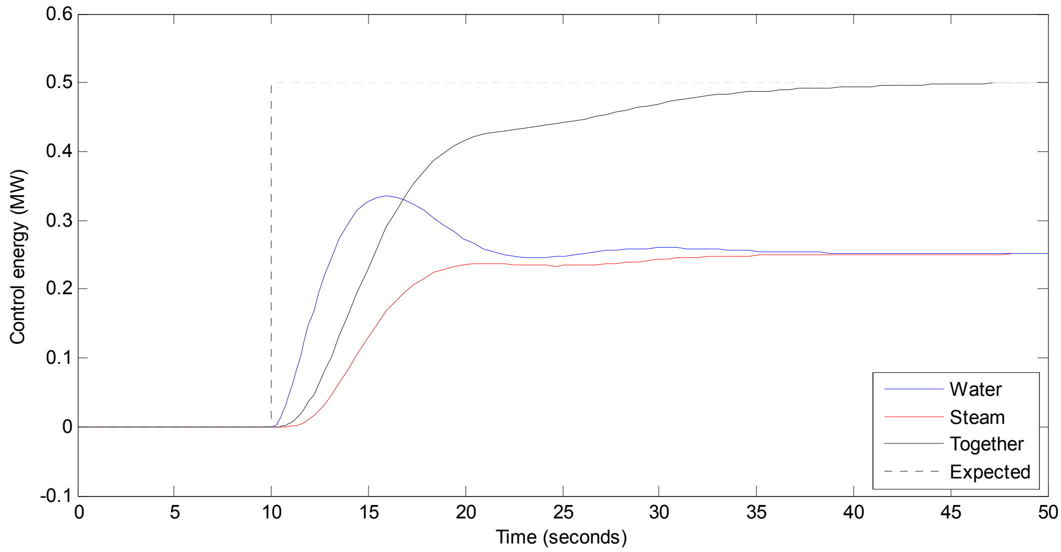

Figure 2
Simulation.

This dynamic behaviour of a given power grid depends essentially on two aspects. On the one hand, the electrical distance between generators establishes the coupling on the system. This is mostly related to the location of the generating and consuming units and the power lines that interconnect them. On the other hand, droop parameters determine the reaction of each generator to the changes on the grid. The magnitude of the droops depends on several technical and economical aspects, since control energy is marketed and generation capacity has to be reserved and guaranteed for this purpose.

Modifying these parameters influences the stability of the system. Perfectly tuned generators could also result on unstable dynamics when changing their location, or when arbitrarily modifying their droop characteristic. These variations on system parameters are intrinsic when shifting to active clustered systems as being currently discussed, where several small generating units are clustered together in order to deliver ancillary services, changing the location of the actual sources of control energy and therefore their dynamic interaction.

3 Cluster-Stability Simulation

In the following, we analyse the dynamics of different clusters in a given power grid. We have focused on a benchmark low-voltage grid consisting of one transformer and eighteen houses, which represents the scenario of future distributed generation suitably. Line and load data has been provided by a German electricity distribution operator. All of the houses are supposed to feature a programmable inverter capable of injecting control energy when so commanded. A cluster is formed selecting four of the houses on the grid as shown in Figure 3, and assigning droop parameters to each of them. The other nodes are considered passive and do not provide ancillary services.

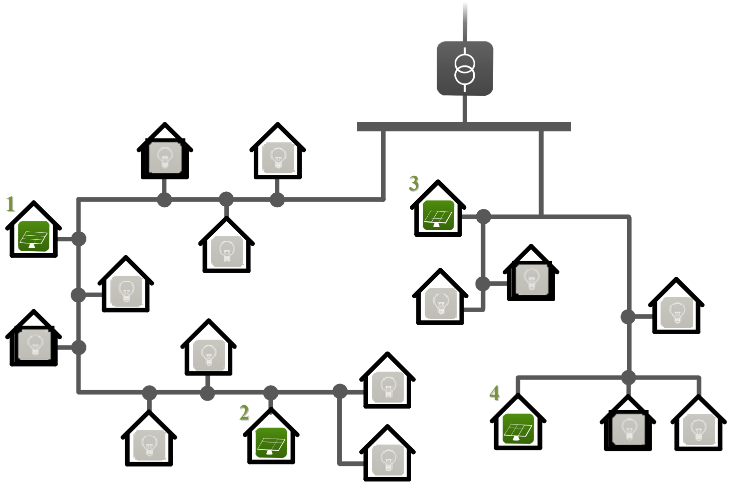

Figure 3
Example grid and selected cluster.

3.1 Grid Dynamics

The small-signal dynamics of the cluster are simulated in Matlab/Simulink. It is not the purpose of this paper to delve into the mathematics and system theory needed to derive a small-signal model of an inverter-based low voltage grid, but to show the impact of clustering on its dynamics. Details on the modelling and simulation method can be found on (Coehlo et al 2002).

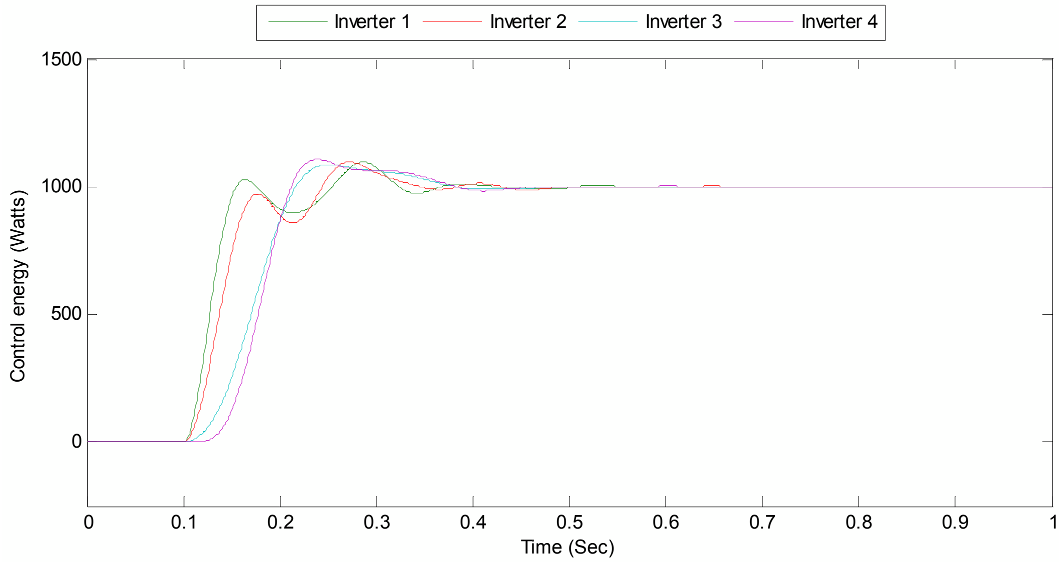

Figure 4
Small-signal simulation for the given system.

A drop on the grid frequency is simulated at the transformer node. It is expected that the inverters react to this by injecting more power into the grid, quickly achieving a new state and maintaining this value until secondary control brings the frequency back to nominal. In our simulation, the frequency drops 150 mHz at 0.1 seconds causing the inverters to react injecting control energy according to their droop parameters. Each inverter is configured to inject 100 W for every 15 mHz of frequency deviation, which is an average of the values found in the bibliography (Coehlo et al 2002, Guerrero et al 2004, Majumder et al 2009).

The dynamic response of the system is shown in Figure 4. As expected, the members of the cluster inject control energy following the drop in frequency, stabilising the system within a few hundred milliseconds. The transient behaviour is similar to the one shown in Figure 2 for the well-known case of large power generators. However, the interaction in the low-voltage grid is much quicker, given the faster dynamics of the inverters and the stronger electrical coupling between them.

3.2 Change in droop parameters

Droop parameters determine the participation of each inverter in the delivery of control energy. A bigger droop implies that more control energy has to be injected after the same frequency deviation, which translates into a greater monetary revenue. At the same time, more energy has to be reserved and guaranteed for this purpose. The selection of droop parameters is therefore formulated as part of an optimization problem, including availability, price, and reliability among others, as discussed in (Nieße et al 2012).

When a cluster markets ancillary services, the combined injection of control energy has to be guaranteed, but the individual selection of the droop parameters for each member is left for the system configuring the cluster to decide. The same combined injection could in principle be achieved by only one member of the cluster by increasing its droop fourfold and setting the other to zero, or by eight members with half the droop each. Infinite combinations could be thought of, which in turn should deliver the same combined control energy.

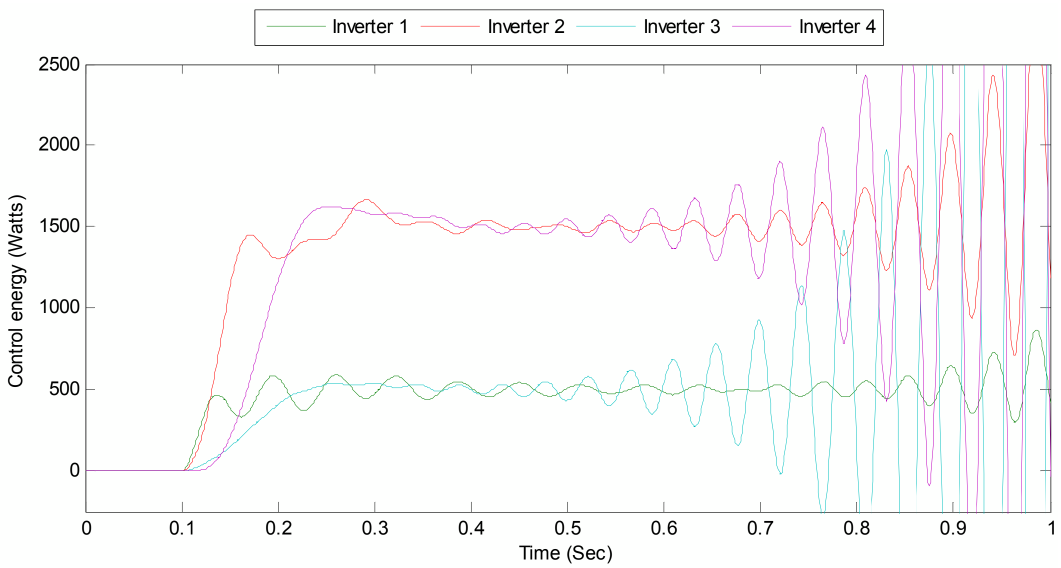

Figure 5
Small-signal simulation after changing the droop parameters.

However, droop parameters also influence the dynamics of the cluster, as discussed before. Although the added droops should in turn guarantee the desired control energy characteristic, the interaction between inverters could be unstable. To observe this, we simulate the system described before with different droop parameters. Inverters 1 and 3 inject 50% less control energy, while inverters 2 and 4 compensate this by injecting 50% more, theoretically achieving the same combined injection. Nonetheless, the simulation shows this configuration to be unstable, as seen in Figure 5. Although the sum of the droop characteristics results in the same amount of control energy, this configuration makes the inverters oscillate back and forth. These oscillations make the inverters leave their specified safe operating area, causing different protection mechanisms to put them out of service or even breaking them in the worst case.

3.3 Change in the choice of cluster members

Another decisive aspect when configuring a cluster is the choice of participating inverters, since the coupling between them also influences the stability of the system. In order to show this phenomenon, we alter the cluster and repeat the simulation. In this case, two inverters are removed and another two introduced, maintaining the same droop parameter for each inverter as in the first case. The new members are selected as shown in Figure 6. Since the inverters are now located closer to each other, the electrical coupling increases, affecting the stability of the system.

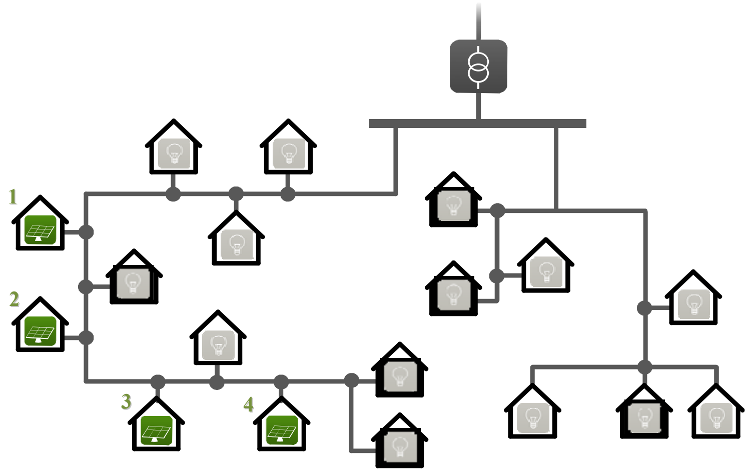

Figure 6
Modified cluster

Figure 7 shows the transient response of the system after the same drop in system frequency as before. In this case, the dynamics of the system are again unstable, even though the droop parameters were left untouched. The resulting instability renders this configuration impracticable.

6 Conclusions

We have shown that there is a dependency of the small-signal system stability with respect to the location of the cluster members and the selection of their droop parameters. The incorporation of these phenomena into the clustering algorithms is, in our opinion, a topic worthwhile of further research, since system stability is not a mere figure of merit that can be improved such as the price or the reliability of the ancillary service that a cluster provides, but a necessary condition in order for the system to function. A simplified model incorporating the necessary system theory and stability analysis could be used to derive appropriate heuristics that could be integrated in the clustering algorithms.

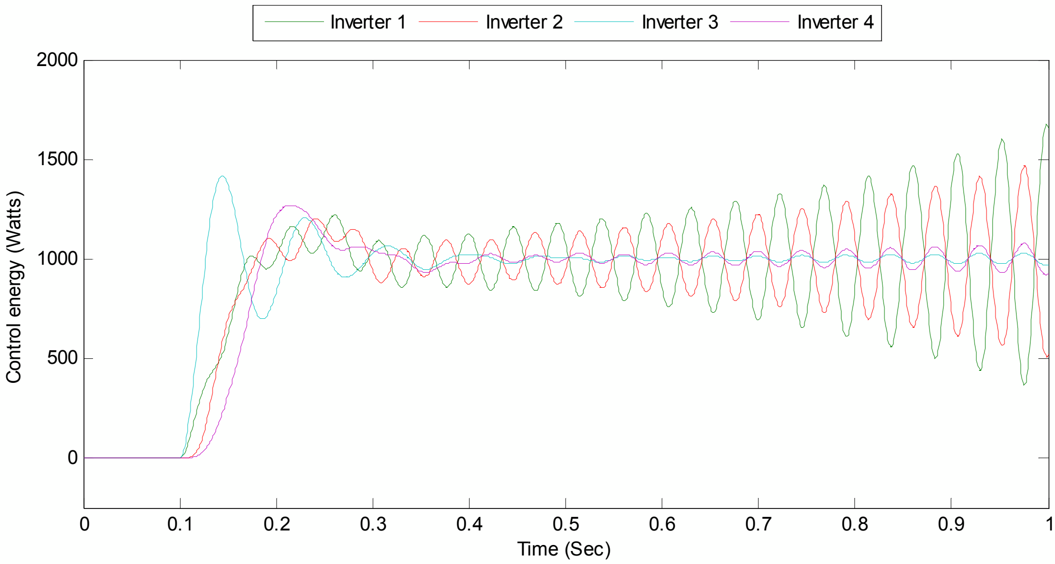

Figure 7
Small-signal simulation for the new cluster.

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