Dynamic behaviour of the autonomous grid of the island of Kythnos, Greece, due to large penetration of PV and wind systems

Stathis Tselepis, Aristomenis Neris
CRES, 19th km Marathonos Ave., Pikermi, Athens 19009, Greece
Tel. +30-210-6603369, fax +30-210-6603318, email: stselep@cres.gr

ABSTRACT: The purpose of the study was to evaluate the impact of a large penetration of renewable energy sources in an autonomous grid. The introduction of the considerable renewable energy units does not cause any problems, regarding the steady state operation of the grid. On the contrary, in the heavy loaded grid condition, an improvement of the general situation has been observed as seen in a previous work [1]. The situation appears different when the dynamic behavior of the RE units is considered. For this reason two main scenarios have been examined. The first one concerned the interconnection of a number of distributed photovoltaic systems and the second the interconnection of a large wind turbine. The results show the impact of the different renewable energy source grid interfaces (inverter or induction generator) on the system response and also that the system can remain stable under the examined disturbances as long as sufficient spinning reserve exists. A battery inverter can optimize the system operation since it can allow less diesel generators with a better utilization factor to operate in order to cover the load. For this reason a self commutated battery inverter was introduced in the power system model. Simulation results show that in this way frequency regulation can be improved due to the faster response of the inverter.
Keywords: Simulation, Battery Storage and Control, Autonomous Grid

1 INTRODUCTION

In the framework of the EU funded project DISPOWER, CRES in collaboration with ISET and Econnect LTD has undertaken the task to study interconnection issues of mini-grids and other renewable energy source units with the main power system of the Greek island Kythnos.
The introduction of a substantial penetration from Renewable Energy Sources in the power mix of the Greek islands grids is of great importance. This fact is justified because; island grids are autonomous and are mainly fed by diesel generators, something that increases dramatically the energy cost. Although the wind and solar potential in these areas is excellent, a number of technical issues pose a barrier. The implementation of a hybrid system with battery storage and an intelligent management system in Kythnos has been proved to be an effective solution to this problem. However, today a significant part of the renewable energy sources and other power equipment is outdated and additionally it should be worthwhile to increase further the penetration of renewable resources in the island. In this context, this work examines interconnection issues for a number of case studies involving the increase or Renewable Energy Source penetration in the grid of this island.

These interconnection issues concern the interaction with the grid. They cover the following:

- Voltage profile
- Active and reactive power flows
- Thermal (current) loading on circuit elements
- Transient stability (maintenance of synchronism)
- Voltage stability and reactive power control
- Frequency control

For the examination of the steady state situation of the actual Kythnos island grid (Figure 1), when a number of PV systems and wind turbines are connected to the island grid in various points [1], a software tool developed in the Information Division of CRES has been used for the system analysis [2]. This tool is basically a GIS application that uses an interface with PSSE® software in order to carry out load-flow analysis. The scenarios examined, concerned a significant penetration from renewable resources PV and Wind.

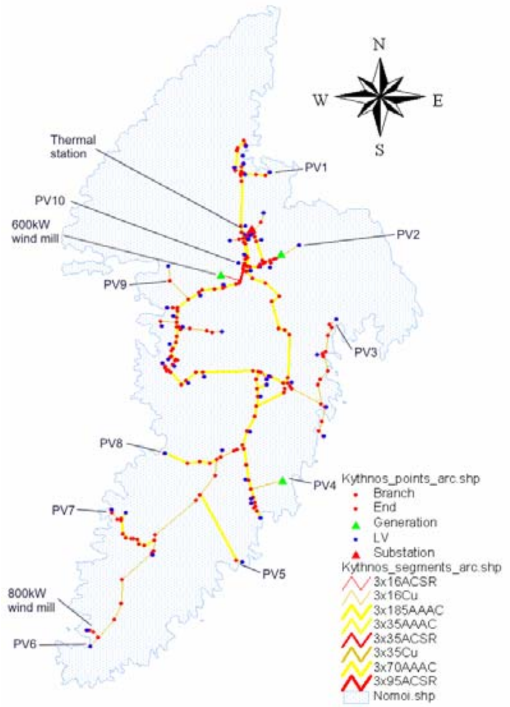

Figure 1. Kythnos medium voltage grid and the RES power sources location.

A load-flow analysis has been conducted for different levels of power injected from the photovoltaic stations [1]. When the grid is assumed to be lightly loaded, the observed voltage rise is well within the limit posed by the EN-50160 standard, which is ±10%. Considering a heavy load condition for the grid, it was observed, that the voltage at the inspected buses is below the nominal value, due to voltage drops caused by the load currents. The increment of the power injected from the photovoltaic stations, results in an improvement of the voltage profile. When a wind generator is introduced, the voltage increase in the wind generator bus is about 6%, for a lightly loaded grid, at the rated wind generator power and fully compensated reactive power. Additionally, the calculated loading of the lines is well within limits.

2 KYTHNOS POWER SYSTEM

The Kythnos island main power system is composed of five diesel-generators, producing 400kW each. These generators are equipped with electronic speed controllers and automatic load sharing devices for parallel operation with fixed frequency (isochronous mode). The renewable energy is provided by an outdated small wind-farm (5x33kW), a 500 kW Vestas wind turbine and a 100 kWp photovoltaic system. The battery bank combined with a 12-pulse converter can be used to cover the power deficit in case that a diesel or the large wind turbine is switched of unexpectedly. In the diesel-off mode it is used for frequency control. The dump load unit is interfaced with the power system with another 12-pulse converter. Its main task is to damp power peaks from the wind turbines, in order to stabilize voltage and frequency and avoid high loads on the battery inverter. The phase shifter machine is used to control grid-voltage in the diesel off mode.
All these units are connected via step-up transformers to a 15KV medium voltage overhead grid. The annual average of load served from this grid is about 600 KW, however, strong seasonal fluctuations exist, with the maximum load reaching 2000 kW in the summer.

3 EXAMINATION OF DYNAMIC ISSUES

For the examination of the grid dynamic behavior, when a significant penetration from renewable resources exists, a model of the Kythnos power system was developed in the Simulink® environment, using the Power System Blockset ® library (Figure 2). This model utilizes a simplified representation of the grid that includes only the main nodes, a model of the local power station with the diesel generators and models for the renewable resources (wind turbine and PV systems) as well as for a battery storage inverter. In order to evaluate the system dynamic behavior, two types of disturbances were examined:

- A three-phase short circuit, with different clearing times, that was applied in a specific node, away from the local power station.
- Disconnection of the wind turbine when produces maximum power. Such an incident can take place, due to the activation of the wind turbine protection system because of a high-wind condition.

Simulation results show that the power system, for the examined conditions, presents a stable behavior, as long as an adequate spinning reserve exists. Due to the high cost of the energy produced by the diesel generators it is highly desirable to achieve a reduction of this reserve without sacrificing the safety of the power system operation. In this direction two possibilities are examined in this study. The first one is related to the use of PV power electronic inverters with disturbance ride-through capability. Today these grid interfaces when a voltage disturbance takes place are disconnected quickly in order to avoid islanding situations and protect themselves. Reconnection takes place several minutes later. Disturbance ride-through capability, among other things, means that the grid interface should stay connected during the disturbance or it should be reconnected quickly after the disturbance [3]. The second option has been simulated and the results indicated that, in this way, it should be possible to operate the power system with a lower spinning reserve without a safety risk.
The second possibility is related to the use of battery inverter that will replace the spinning reserve provided by the diesel generators. Taking into account the evolution of power electronics, the replacement of the existing inverter with a shelf-commutated one based on IGBTs (Insulated Gate Bipolar Transistors) would add a number of benefits related to a more reliable behavior and the capability to assist the voltage control of the system.
The degree of renewable sources penetration and the type of the grid interface used, are the two factors defining the influence on the power system transient stability. In this study, the two interfaces considered are power electronic inverters for PV systems and asynchronous generators for wind turbines.
In the case that the grid interface is an induction generator, then during a disturbance that can cause a voltage dip the generator accelerates. Additionally, due to the induction generator characteristics, the absorbed reactive power increases. The combination of these facts can drive to an unstable behaviour of the induction generator.
In the sequel, simulation results are presented for the following cases:
a. Disconnection of distributed PV units, due to under voltage protection trip during the three phase fault. Comparison of the system frequency response, with the case where the PV inverters are quickly reconnected when the voltage recovers.
b. Disconnection of a Wind turbine due to high Wind. Comparison of the frequency response with or without battery storage.

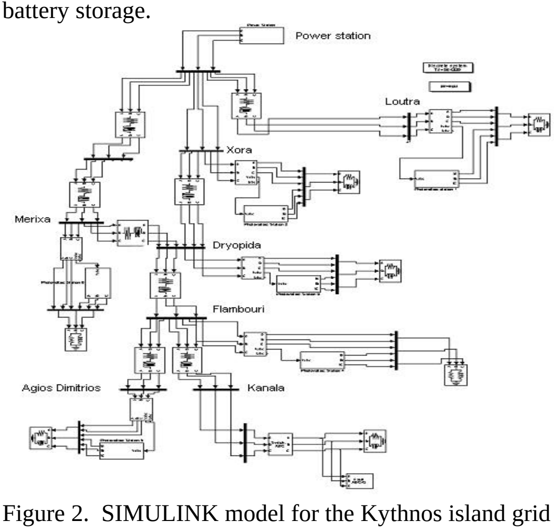

Figure 2. SIMULINK model for the Kythnos island grid (PV penetration case).

The introduction of a substantial amount of renewable energy sources demands the existence of an adequate spinning reserve. Because of this fact and taking into account the total power capacity of the diesel power station in Kythnos, a maximum PV penetration equal to

33 % was considered. For the same reason, the wind turbine nominal power was considered equal to 640kW.
The examined PV penetration levels are summarised in the following table:

Table I. Examined scenarios with PV penetration in kW.

Load in kW	1280	1400	1530	1920
Power from diesel	1280	1280	1274	1280
Power from PV	0	120	256	640
PV Power penetration	0 %	8.6%	16,7%	33%

The load power factor is considered to be equal to 0.85. In all these cases the power fed by the diesel station is almost the same. Taking into account that the nominal power of the diesel station is 2000 kW, a spinning reserve equal to 720 kW or 36% of the nominal power is available. The simulated disturbance is a three-phase fault applied at the Kanala bus that is cleared after 150msec through the action of the protection equipment. Figure 3 shows the voltage response of the grid, recorded at the power station and Figure 4 shows the frequency response of the system for the different penetration levels. Voltage is expressed in per unit values. As it can be seen, the system response is stable for all the cases. Due to the grid weakness and the nature of the applied fault, the voltage dip is severe and as a result the photovoltaic units trip due to under voltage (the under voltage protection settings considered, were 0.8 pu with a time delay of 100msec).

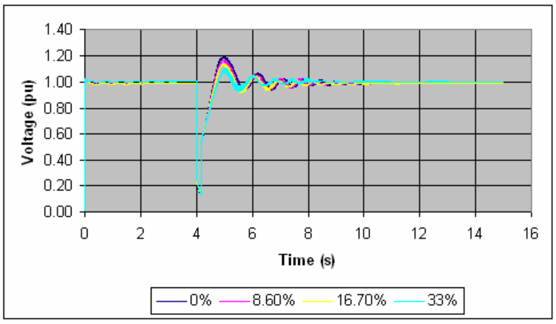

Figure 3. System voltage response for a three-phase fault.

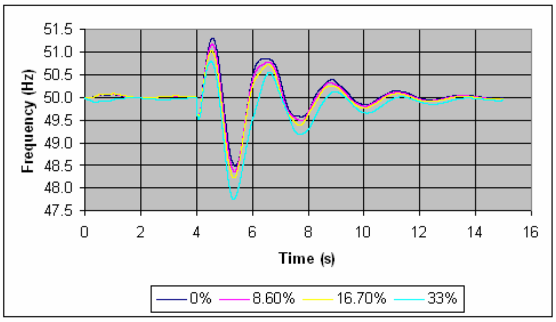

Figure 4. System frequency response for a three-phase fault.

Because of this, the diesel generators overspeed, immediately after the short circuit is reduced as the photovoltaic penetration level increases. This is explained by the fact that the disconnection of the PV units increases the load of the diesel generators. On the other hand, the opposite situation appears for the generators under speed that follows, for the same reason. The potential capability of PV inverters to reconnect immediately after voltage recovery can be considered as a form of disturbance ride through capability. As such, it could be exploited in order to achieve a stable operation of Kythnos power system, with a lower spinning reserve. In order to examine this possibility, the system response for the same disturbance, was simulated, considering the case with the biggest PV penetration (33%) and one diesel -generator less. Figures 5 and 6 depict the frequency and voltage response of the system. Both variables present a stable behaviour, since voltage recovery is fast and the reconnection of PV inverters helps to maintain the power balance. This fact shows that in order to achieve an increased PV penetration in island grids, disturbance ride through capability could be a promising solution. However it should be noted that this capability should be extended also to frequency variations tolerance, if possible, because as it can be seen from Figure 5, frequency excursions are quite large during the first period of the frequency swing (about 2Hz overshoot).

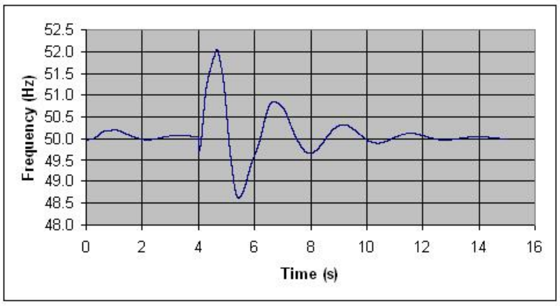

Figure 5. Frequency response with PV reconnection and reduced spinning reserve.

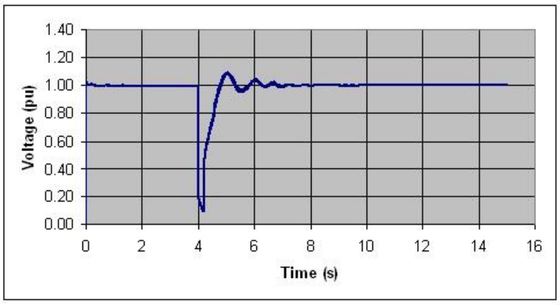

Figure 6. Voltage response with PV reconnection and reduced spinning reserve.

In autonomous power systems, with increased penetration from renewable sources, a 4-Quadrant battery inverter can be used in order to provide a number of valuable functions for the safety and quality of power system operation. These functions, among others include:

- Spinning reserve: An energy storage system with even with relatively small capacity can act as a fast reserve source for the time needed to start conventional generators, in cases where power production from renewable sources is interrupted due to some internal protection trip. It can also smooth the power step due to a sudden change in the generation from renewable sources thus giving time to the conventional generators to adapt their output.
- Energy transfer: Power from renewable sources cannot be controlled and often has a daily power

profile different from the load demand. Through a storage system the energy surplus in high generation periods can be stored and released in low generation periods.
- Frequency regulation: The response of diesel governors to changes in generator output is dynamically limited and large frequency fluctuations can be expected. Inverter interfaced storage can change its power output from +100% to -100% and vice versa, within a single cycle of the system voltage. Therefore, with a small storage, storage systems can stabilise the system frequency by instantaneously supplying the power imbalance.

In this context and in order to investigate the battery storage functionalities of spinning reserve and frequency regulation, an average model of a current controlled, shelf commutated, frequency inverter was developed and added in the Kythnos power system. The figures below depict simulation results for the wind turbine disconnection case but with a diesel-generator less (as in Figures 5 and 6) and the battery inverter model included in the system. The inverter model is equipped with a frequency controller and operates with pf=1. In Figure 7, when the wind turbine is disconnected at t=4 sec, the battery inverter power increases fast in order to compensate for the power deficit that was created. Figure 8 shows frequency response for the cases without and with battery storage. As it can be seen, when battery storage is included, the frequency deep is reduced and frequency oscillations are well damped.

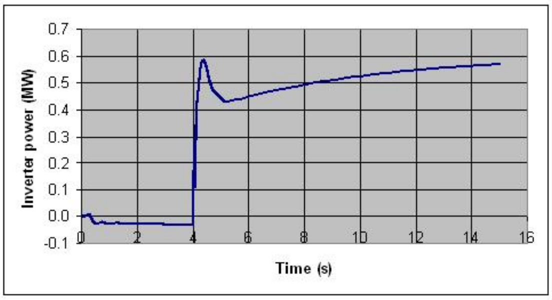

Figure 7. Battery inverter power.

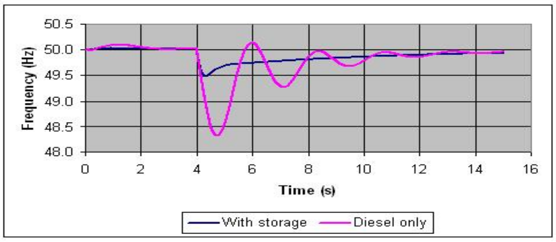

Figure 8. Frequency response for the compared cases.

4. CONCLUSIONS

In this paper, grid connection issues related to the increase of renewable sources penetration in the autonomous power system of Kythnos island have been examined. These issues covered dynamic conditions caused by abnormal events such as short circuits and loss of power sources.

Using the SIMULINK model, the frequency and voltage response of the Kythnos power system, for different PV penetration levels has been studied. Furthermore, the effect on the grid frequency was studied due to the disconnection of a wind turbine because of high wind, with or without a battery inverter, for the following disturbances:

- A three phase short-circuit away from the power station.
- Disconnection of a wind turbine operating at nominal power.

For the considered PV penetration scenarios and applied disturbance, simulation results show that the system presents a stable behavior as long as sufficient spinning reserve exists. In addition if the PV inverters are equipped with disturbance ride through capability allowing a rapid reconnection after the voltage recovery, simulation results show that this feature could be used in order to obtain a secure operation of Kythnos power system with a lower spinning reserve.

For the wind turbine disconnection, the power system presents a stable behavior provided that enough spinning reserve is available in order to cover the power deficit. For this disturbance, simulation results show that if a battery inverter is used in order to replace spinning reserve provided by the diesel generators, apart from the fuel efficiency improvement, the frequency response of the system can be improved. This fact is very important, especially for the shown case of wind turbine disconnection due to high wind, which can be a very common event.

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