The Feasibility Study of Ancillary Services Provision from Multiple Micro-Grids  
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Abstract— The integration of Distributed Generation (DG) into the distribution network has acquired unprecedented academic and governmental attention in recent years. Because of the ever-increasing energy demand, CO₂ emission and petrol shortage, development of DG based on renewable energy sources (RES) registered a considerable growth in the past decade. Having the generation sources physically close to the energy demand is another obvious promotion for the idea of DG. The sources can be solar, wind, CHP (Combined Heat and Power), fuel cells, etc. and are small in capacity. To reduce output power fluctuation, energy storage can be used in conjunction with some of these micro-sources. Inter-connected, closely located sources and loads which as an integrated system can operate in parallel with main power grid or in an intentional islanded mode form a micro-grid.

In a large physical region there can exist multiple micro-grids. Apart from participating in energy markets, an alternative way of making use of and making profit out of multiple micro-grids is to take part in the Ancillary Services (AS) market. This paper investigates the technical feasibility and difficulties of providing such services (in particular primary frequency control) as well as the potential profitability of participating in the AS markets based on a setup of multiple micro-grids.

Index Terms—Micro-grid, multi-micro-grids, ancillary services, primary frequency control, distributed generation.

1 INTRODUCTION

Attempts worldwide are being made to exploit alternative energy resources due to the upcoming fossil fuel shortage and CO₂ emission crises. These alternatives include different technologies that allow generation in small scale and some of them take advantage of renewable energy resources such as solar, wind or hydro energy. Such trend is also commonly known as Distributed Generation (DG). Having the generation units close to the consumers/load has the advantage that the transmission or distribution distances are reduced and therefore reducing transmission/distribution losses as well as preventing network congestion. Moreover, the chance of having a blackout is diminished since some of these micro-grids can work in islanded mode while disconnected from the high-voltage transmission network due to system disturbances and contingencies. Reliability is also enhanced because micro-grids consist of many small units so the chance of losing big amount of generation at a time is much reduced.

Despite the obvious benefits of micro-grids, the introduction of micro-grid or DG into the traditional distribution network system imposes new challenges of system operation. One example is the protection and control logic which was designed to deal with uni-directional current flow in distribution networks. With the integration of distributed generators, the direction of current flow is more unpredictable, which depends on the balance of local generation and consumption.

2 MICRO-GRIDS AS ENERGY AND ANCILLARY SERVICES SUPPLIES

As the name indicates, micro-grid has a small amount of total capacity. In fact, the capacity of typical micro-sources is 10-100kW. As a result, the total capacity of a micro-grid can be around 1MW. There is usually no restriction on the quantity of energy for spot or bilateral market. However, the minimum amount of reserves in UCTE (The synchronous interconnection of central European countries) for different ancillary markets is 1-2MW for primary reserves, 10-20MW for secondary reserves and tertiary reserves [1]. With a total capacity of 1MW per micro-grid, the more practical realization of supplying ancillary services would be to use multiple micro-grids for primary reserves. For example, to provide a 1MW bid, it would require 10 micro-sources of 100kW, when all of their capacity is only used for the primary reserves market. In practice, only a proportion of the capacity is used for reserves and depending on the type of technology the maximum amount of capacity reserve can vary. An example of a setup of multi-micro-grid is shown in Figure 1.

Theoretically, one could also provide secondary and tertiary reserves from more micro-sources altogether (10 fold). However, they would then be widely distributed on the network and therefore exposed to serious controllability and security issues. Therefore, in this paper, we focus on a provision of primary reserves, even though the same techniques and methodologies can be easily extended to secondary and tertiary reserves.
3 MULTIPLE MICRO-GRIDS CONTROLLABILITY

In reference [2] the authors describe the control strategies for micro-grids black start and islanded operation while in reference [3] the economic benefits of optimizing the schedule for energy and heat generation for CHP are used to justify the replacement of traditional boilers with new domestic CHP.

In this section we describe two control approaches for primary frequency control supply from multi-micro-grids. The first one is based on centralized control coordinated by the Distributed Network Operator (DNO) and the second one is based on individual micro-controller equipped at each micro-source with no real-time central coordination. In general one can also apply a combination of the two approaches.

3.1 Centralized (Coordinated) control

In reference [4] a coordinated approach is accomplished via the Micro-Grid Central Controller (MGCC). In this reference the goal is to coordinate scheduling of generations and responsive loads in order to maximize the revenues from energy market participations.

In this paper, there exists a centralized body, here the DNO, which represents an aggregated reserve from multiple micro-sources and responsive loads on the ancillary service market. DNO is also responsible for a real time provision of set points for micro-sources and responsive loads. The controller and communication infrastructure are constructed to allow optimal operation of the whole multiple micro-grid system. Real time information on a production and consumption in multiple micro-grids is collected at the central controller via fast and reliable communication system. With this implementation optimal bidding into short-term AS markets is facilitated. This requires advanced information and communication infrastructure, but can give optimal operation economically and reliably. This can be achieved when there coexist both short-term energy and short-term reserve markets. In such a market setup, the DNO gets a capacity contract from the TSO for each hour and can then decide in real-time the bids for both markets when he has better forecast supply from different resources, market prices and load. Metering at each micro-source and responsive load must be implemented for billing purposes. The concept of such a setup is illustrated in Figure 2.

Figure 2 illustrates that the central controller monitors the system frequency, real time production/consumption in micro-grid, and energy and ancillary service market information and calculates the appropriate set-points for each individual micro-source and responsive load based on the available forecast of market prices and availability of micro-sources and responsive loads. The communication system enables the exchange of the required data between the central controller and each source/load, playing a central role in such implementation.
“information models” which are standardized formats or templates for exchanging data between different equipment and devices. The information models are based on open-system language, semantics, services, protocols and architecture, all together described and standardized by IEC 61850. An extension of the standard is IEC 61850-7-420 (draft form), which deals with the specification of information models for Distributed Energy Resources (DER). Additionally, IEC 61400-25 provides a uniform communication platform for monitoring and control of wind power plants. A scenario for communication realized with different communication technologies and using IEC 61850 information models is shown in Figure 2. By means of open communication, the central controller can monitor the status of each distributed generator, can adjust the operational set-points and based on the forecasting of available power can determine the suitable participation in the energy market and/or ancillary services market.

Moreover, recent technological advances in communication and control have provided new capabilities for responsive loads to participate in primary frequency regulation. This is applicable to loads with storage and control capability (e.g. building heating/cooling, water heating, refrigeration and freezing, compressed air, water pumping, residential air-conditioning, etc.) and two-way communication with DNO. Each responsive load is equipped with monitoring equipment that telemeters load status to the DNO's central controller. This process does not require second-to-second real-time communication.

The load measurements together with a short term load forecasting (the air-conditioning load is usually highly correlated with the total system load) are used to provide an accurate assessment of available reserve from responsive load. Loads often find it impossible to make long-term curtailment commitments because there is some chance that external events will prevent them from varying power consumption when requested. Thus, only day-ahead and hour-ahead hourly markets are reserved to responsive loads.

The highest communication speed requirements are associated with a reserve activation signal that has the minimal amount of information. Monitoring the performance of individual loads is necessary to motivate future participation and is based on individual communication with a low information exchange (once within each billing cycle).

3.2 Decentralized (Uncoordinated) control

On the contrary, in the uncoordinated approach, the controller for each micro-source is tuned with a predefined droop characteristic so that it can react to system frequency changes accordingly. Such control concept is illustrated in Figure 3. This setup works well for reserve markets which have a long-term contract (days, weeks or even months) with a fixed amount of MW capacity reserved. An example with long-term reserve markets can be found in several European countries (Germany, Denmark, etc.). In many cases there co-exist energy markets that operate in much shorter-term (e.g. day-ahead or even hour-ahead markets). In such a market setup, the DNO gets a fixed capacity contract from the TSO for a certain period, e.g. one month. The DNO then decides on his own using forecast and optimization techniques to work out the optimal amount to be sub-contracted to each micro-source during this whole month. It should be noted that the coordinated control is necessary to enable the real-time primary reserve market bidding.

4 PREDICTION AND CONTROL OF RESERVE CAPACITY

4.1 Prediction of reserve capacity

One of the key elements for determining the degree of participation in either energy or ancillary services market is the prediction of reserve capacity. Although for CHPs and storage devices this might be straightforward, in case of wind turbines and PV systems this requires advanced prediction tools.

For wind turbines, the subject has been addressed in many research works [5, 6] and consequently few commercial applications are available today. Normally, the prediction algorithms use meteorological input data (wind speed and its direction) which are transformed for the local site where wind turbine is installed and then, based on the power curve of the turbine, the expected power production is calculated. For the day-ahead prediction, a Mean Absolute Error (MAE) of 10% is reported in best cases and this increases up to 15-20% for two days ahead prediction [5].

![Figure 3 Decentralized control system setup](image)
For photovoltaic systems, solar irradiance, ambient temperature and wind speed and direction have a significant contribution to the power produced by the system. Consequently, if estimates of these two parameters are available, the power production of PV systems can be predicted \[7, 8\]. Likewise, the availability of responsive loads such as heating and cooling systems has a high correlation with weather conditions. Thus, accurate weather forecasts available nowadays can facilitate a good forecast of their availability.

### 4.2 Control of output power

Another key issue for participation of DG in ancillary services market is the control of the distributed generators. Once the power production is predicted for a certain time interval, the wind turbines and PV systems should adapt their control strategies in a way that part of the available power is reserved for ancillary services market and the rest is delivered to the utility based on the agreed day ahead schedule for energy market. Due to the intense development in wind power industry, nowadays various control strategies are available for modern wind turbines \[9, 10\]:

- Maximum power extraction
- Absolute power limiter
- Gradient limitation
- Balance control
- Delta control
- Automatic frequency control

With regard to the subject discussed in this paper, the last three control strategies are interesting. Delta and balance control strategies can be used in situation of micro-grid centralized controller, which dispatches the set-points for the different distributed generators while automatic frequency control can be used in the case where no centralized controller is present and all distributed generation units do their best to control the frequency at their point of connection with the utility network.

In case of photovoltaic systems, the output power control options are limited. Nowadays, the majority of PV installations extract the available maximum power by employment of a Maximum Power Point Tracking (MPPT) controller. However, with the increasing market penetration of concentrated PV systems having sun tracking capabilities, control options similar to those of wind turbines might also become available in the future. Moreover, as discussed in section 4.1, the combination of PV systems with energy storage improve greatly the possibility of controlling the power delivered to the utility and the participation in ancillary services market.

The next section describes the mathematical formulations of the different control approaches within the microgrid and the numerical examples that follow in another section will show the benefits of the first approach over the second one.

### 5 Ancillary Service Markets Participation

In many energy markets hourly- or day-ahead market is already in practice. However, it is not the case yet for AS markets. It can be easily deduced that it is suboptimal to have a contract for any period longer than 1 hour. This will be further illustrated in the next section where numerical examples are given. In this section the mathematical formulations of a simple multi-micro-grid for the two control methodologies are stated.

The optimization formulation for coordinated real-time control approach can be stated as follows: The objective function is to maximize the net revenue of each hour, therefore:

\[
G(x) = \max \left(\text{revenue}_{\text{AS}} + \text{revenue}_{\text{EM}} - \text{productionCost}_{\text{EM}} - \text{loadAdjustmentCost}_{\text{AS}}\right)
\]

(1)

where

- \(\text{revenue}_{\text{AS}} = p^{\text{AS}} \cdot x^{\text{AS}}\) = revenue from primary reserve market,
- \(\text{revenue}_{\text{EM}} = p^{\text{EM}} \cdot x^{\text{EM}}\) = revenue from spot energy market,
- \(\text{production}_{\text{EM}} = c^{\text{P}} \cdot x^{\text{P}}\) = fuel cost to supply to energy market,
- \(\text{loadAdjustmentCost}_{\text{AS}} = c^{\text{L}} \cdot x^{\text{L}}\) = cost to reduce responsive load for the primary reserve market,
- \(p^{\text{AS}}\) = the prices of reserves for all micro-sources in $/MW,
- \(x^{\text{AS}}\) = the quantities of reserves for all micro-sources in MW,
- \(p^{\text{EM}}\) = the prices of energy for all micro-sources in $/MWh,
\(x^{EM}\) = the quantities of energy for all micro-sources in MWh,
\(c^p\) = the costs of fuel for all micro-sources in $/MWh,
\(x^p\) = the quantities of energy produced for all micro-sources in MWh,
\(c^l\) = the costs to reduce the responsive loads in $/MWh,
\(x^l\) = the quantities of energy reduced from responsive loads in MWh.

The optimization variables are \(x^{AS}, x^{EM}\) and \(x^p\). Here it is assumed that the reserves are not actually used by the system but in reality at least a certain percentage is used for frequency regulation whenever the frequency is out of the regulation dead-band. The actual usage depends on the whole interconnected system and varies from one system to another. Such a relationship can be expressed as

\[
x^l = x^{EM} + \lambda x^{AS}
\]

where \(\lambda\) is the reserve utilization factor. However, for primary reserves, it is a valid assumption that:

\[
\lambda \approx 0
\]

The reason is that frequency deviation beyond the dead band is rare and can go both ways, i.e. producing more and less fuel is insignificant (see Appendix A). Therefore, equation (2) can then be simplified to:

\[
x^l = x^{EM}
\]

The following constraint must be applied:

\[
x_{\text{min}} \leq x^{AS} + x^{EM} \leq x_{\text{max}}
\]

where \(x_{\text{min}}\) = min. capacity per hour for all micro-sources in MW

\(x_{\text{max}}\) = max. capacity per hour for all micro-sources in MW

Moreover, in order to respect the minimum reserve bidding requirement as mentioned in section 2, the following constraint has to be included:

\[
x^{AS} + x^{L} \geq x^{AS}_{\text{min}}
\]

where \(x^{AS}_{\text{min}}\) is the minimum amount of total primary reserves bid as specified by the market.

In addition, a special constraint is applied to all the CHP units to reflect the fact that due to efficiency of diesel engines it is not practical for CHP to operate under 90% of the rated power:

\[
x^{EM}_{\text{CHP}} \geq 0.9 x^{max}_{\text{CHP}}
\]

It should be noted that in this paper for concept illustration the operation of CHP is assumed to be driven by electricity production. It is however common to find that in practice electricity is a by-product from heat production.

Since reserves must be provided in both directions there is an additional constraint on the maximum of reserves provided from each micro-source:

\[
x^{AS} \leq x^{max} / 2
\]

It should be noted that quantities like \(x^{max}\) can be stochastic for micro-sources such as solar panels, wind turbines or hydro turbines since the fuel inputs can vary with weather and climate conditions. In general,

\[
x^{max} = f(y)
\]

where \(f(y)\) is a non-linear function. For example, for solar energy, \(y\) can be the solar intensity while \(y\) can be wind speed for wind energy. When \(x^{max}\) for each micro-source in each hour is given the problem can be solved using linear programming.

The optimization formulation for the non-real-time control setting approach is similar to what is shown above, however, it is a bigger problem since temporal relationship has to be represented in the model. The temporal relationship exists because of the fixed contract for reserves which lasts for longer than 1 hour. To look for the optimal amount of reserves and energy which should be sold or contracted, optimization must include the whole period for which the reserve contract lasts.

The objective function should therefore be formulated as:

\[
G(x) = \sum_j \left( \text{revenue}_j^{AS} + \text{revenue}_j^{EM} - \text{productionCost}_j^{EM} - \text{loadAdjustmentCost}_j^{AS} \right)
\]

where \(j = 1, 2, ..., T\) and \(T\) is the total number of hours of the contract.

The vectors \(p_1^{AS}, p_2^{EM}, c_1^p, c_2^l, x_1^{AS}, x_2^{EM}, x_1^p\) and \(x_2^l\) can be defined similarly as above but with additional index \(j\) to represent different values in different hours. However, for a fixed quantity contract which lasts for \(T\) hours, the following relationships hold:

\[
x_1^{AS} = x_2^{AS} = x_j^{AS}, \forall j \subset T; x_1^{L} = x_2^{L} = x_j^{L}, \forall j \subset T
\]

where:

\[
p_1^{AS} = p_2^{AS} = p_j^{AS}, \forall j \subset T; c_1^L = c_2^L = c_j^L, \forall j \subset T
\]

6 DIFFERENT SCENARIOS

In this section the different scenarios for the setup of a multi-micro-grid is presented. The flexibility and the usability of a multi-micro-grid to provide primary reserves depend on the composition of the micro-grids, i.e. the proportion of the different sources. For example, a micro-grid that has a high percentage of stochastic sources such as wind or solar has a limited level of commitment since a too high commitment/over-optimistic forecast would risk “unavailability” penalty. However, such problems can be avoided if a storage device is installed together with the stochastic micro-sources. It acts as a “smoothing” device which reduces the volatility of the output of these micro-sources.
6.1 The Addition of Storage Device

The following describes the advantages of adding storage devices to micro-sources which do not exhibit a constant output over time. They do not have constant power output because the fuel cannot be stocked and changes from time to time, which is the case for solar or wind energy. Figure 5 illustrates how the use of energy storage can flatten the output of a PV panel (solar energy).

As shown in Figure 5, for a simplified model of an energy tank, if the rate of discharge and the capacity of the energy storage device are set up correctly, constant output can be achieved. To achieve maximum constant output, the rating of the energy output of the storage device should be set so that the area of the energy output curve with the energy storage device plus the total losses is equal to that without the energy storage. Losses have to be accounted for because the charging and discharging processes have about 70-75% efficiency. With the stochastic nature of solar energy (or wind energy), one can use the expected value of the total energy in a fixed cycle together with the losses as a rating indicator. (1 day in this example).

![Image of Energy Output from PV with and without Energy Storage]

Figure 5 Energy output from PV with and without energy storage

6.2 Different Micro-grid Compositions

The availability of micro-sources based on renewable resources such as wind or solar energy exhibits a great dependency on the geographical location and the climate of the sources. For example, in northern Europe (e.g. Germany) it is more common to have a combination of CHP and wind power while in the south, e.g. Greece, wind and solar energies dominate. Such characteristics in turn affect the feasibility and profitability of ancillary services provision from the multi-micro-grids. For instance, CHP uses fuel such as diesel or gas whose costs fluctuate with the fuel markets. The profitability of bidding of CHP in the energy spot market or in the primary reserves market therefore relies on the actual prices in these markets. On the other hand, in places where there is a high proportion of wind/solar energy penetration, the feasibility of bidding in the markets is restricted by the fact that the output amount one can get is stochastic and unpredictable. Modern weather forecast technologies have become very sophisticated in recent years and the accuracy of the forecast has therefore become more reliable. However, one still cannot totally count on forecasts, especially when the forecast window is far in the future (See Section 4). Inaccurate forecast impedes profitability since a too pessimistic forecast (i.e. lower than actual) will reduce amount to be submitted for bidding while a too optimistic forecast (i.e. higher than actual) could result in “unavailability” penalty. The latter takes place only when metering and control measures are in place and implemented.

The numerical examples are simulations done in Matlab under different scenarios. The variety of the scenarios is the different composition of the micro-grids, the participation of responsive load as well as the different prices variation for the spot energy and primary reserve markets. Each of these scenarios will be simulated for both control approaches mentioned in section 3. Note that while a long-term (> 1 hour) primary reserve contract can be implemented with both approaches, the short-term/real-time contract can only be realized with the coordinated approach. Therefore, coordinated approach represents the short-term reserves market while the uncoordinated counterpart the long-term one.

6.3 Simulations and Results

Even though most of the data used in the simulations are real data, the composed cases are arbitrary since the data were obtained from different sources and markets. The CHP production costs were deducted based on the typical production costs of CHP [11] and diesel prices [12]. The primary reserves prices were from the German RWE [13] while the energy spot market prices were from EEX for the Swiss market [14].

The base case scenario has a multi-micro-grid composition of 40% CHP, 40% wind, 10% solar and 10% responsive load with total capacity of 20MW. The simulation period is one day, i.e. 24 hours. It should be noted that all the micro-sources of the same type are grouped together to facilitate analysis. In the base case, the wind is assumed to have constant output about every 4 hours with the use of an energy storage device. The short-term/real-time contract can only be realized with the coordinated approach. Therefore, coordinated approach represents the short-term reserves market while the uncoordinated counterpart the long-term one.

It should be noted that the primary reserves prices are constant during the whole duration of the day and this is because the contract for primary reserves usually sets the price and quantity for a rather long duration, up to 6 months in practice. Moreover, the price for primary reserves is very often lower than those from the energy spot market. It is because the purpose of the reserves
market is only to reserve the capacity of the plant and fuel is not consumed unless the system is in need. As mentioned in Appendix A, the reserved capacity is not used most of the time. It is noted that to have more interesting results the primary reserve prices used in simulations are doubled the original.

The base case is run for both coordinated and uncoordinated control approaches as discussed in Section 3. The results of the base case simulation for coordinated control are shown in Figure 7, Figure 8 and Figure 9. It is interesting to note that all primary reserves bidding for CHP is at the maximum allowed level (max. capacity – min. required for energy market, eqn. 7) but this does not apply to wind or solar energy. The reason is because the fuel for wind has a zero cost while that for CHP does not. Since it is assumed that the primary reserves serve as only a reserve of capacity and energy is not really produced, no fuel is used for this purpose. It is therefore much more economical to have CHP used for primary reserves bidding as there is no production cost needed. Figure 7 also shows that wind and solar also bid their maximum to the reserves market when this becomes more lucrative than bidding in the energy market (hours 2-6). Figure 8 shows CHP is bidding the minimum required energy while wind and solar sells what remains after the reserves market participation. Figure 9 shows the bids of the two responsive loads. L2, being the more expensive one, does not get any bids at all while L1 participates from hours 8-18 together with other micro-sources to make up for the minimum requirement of 1MW.

The optimal energy market bids for the base case under uncoordinated control are shown in Figure 10. The simplistic graph showing the optimal reserves bidding is not included in this paper but the results are described as follows: the only reserves participation is from CHP which is 800kWh the whole time and the remaining required primary reserves are provided by responsive load L1, i.e. 200 kWh during 24 hours. Technically the difference between this case and the coordinated one is that a single optimal quantity of primary reserves has to be found for the whole period. This is sub-optimal since it cannot adjust this quantity during whole period in order to benefit the hourly fluctuations of energy market prices as well as fuel costs.

Simulations were conducted for different scenarios for both coordinated and uncoordinated control approaches and the different scenarios are shown in below.

<table>
<thead>
<tr>
<th>Features</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHP (kW)</td>
<td>40%</td>
<td>x</td>
<td>x</td>
<td>50%</td>
</tr>
<tr>
<td>Wind (kW)</td>
<td>40%</td>
<td>80%</td>
<td>40%</td>
<td>50%</td>
</tr>
<tr>
<td>(Partial Storage)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar (Complete Storage)</td>
<td>10%</td>
<td>x</td>
<td>40%</td>
<td>x</td>
</tr>
<tr>
<td>Responsive Load x 2</td>
<td>10%</td>
<td>20%</td>
<td>20%</td>
<td>x</td>
</tr>
</tbody>
</table>

Table 1 The features of the different simulation cases (Case 1 = Base Case)
Case 2 is set up to simulate a different composition of the multi-micro-grid so that it has only wind energy and responsive loads. Case 3 has a composition of wind, solar energies and responsive load while Case 4 has only CHP and wind energy.

The results for all the cases are summarized in Figure 11. The results confirm that it is always more beneficial to have coordinated control over uncoordinated one.

Mathematically it is obvious because the uncoordinated control imposes an additional constraint on constant reserves bid throughout the whole simulation duration. The maximum benefits are observed for Case 2 and Case 3. This can be explained by the fact that in these cases there is no CHP which carries production cost from burning fuel and there exists a constraint imposing minimum energy market participation. In some hours the net profit obtained by subtracting the gain obtained from the energy market by the fuel cost is negative, i.e. a loss is resulted. This is the case during hours 3-6 (Figure 6).

7 CONCLUSIONS

In this paper, the feasibility and profitability of using multi-micro-grid to provide primary frequency regulation reserves is investigated. Two possible control approaches for DNOs are proposed. The coordinated approach requires more advanced communication infrastructure while the uncoordinated approach is simpler to implement. The coordinated control can profit the relative fluctuations and of energy, primary reserves and fuel prices more than the uncoordinated approach. Four scenarios have been set up to investigate the effects of different characteristics of the multi-micro-grid. The results of these simulations have been reported and analyzed.

8 REFERENCES


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9 BIOGRAPHIES

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10 APPENDIX

10.1 Frequency Deviation

Figure 12 shows the frequency deviation of April in 2005 of the UCTE system [15]. The frequency dead band is also marked on the diagram. Analysis (Figure 13) shows that about 67% of the time the frequency stays within the dead band, therefore reserves are only required about 33% of the time. Moreover, the histogram also shows the deviations below 49.98Hz and 50.02Hz are almost the same in magnitude (16.6% Vs 16%).

Figure 12 Frequency excursion of the UCTE system April 2005

Figure 13 Histogram showing the statistics of frequency deviation