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Energy Storage for Balancing a Local Distribution Network Area

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1. Introduction

According to a study carried out for the formerly Department of Trade and Industry (DTI) and the British regulatory authority (OFGEM), installed micro-generation capacity in the UK could grow to as much as 8GW by 2015 (Energy Saving Trust, 2005; Ingram & Probert, 2003). This will require a new and highly decentralised approach to energy planning and policy. In addition to resolving the everyday causes of power disturbances and outages at local and regional levels, the electricity industry has to be able to restore service after major events (e.g. floods and storms). Ensuring reliability has and will continue to be a priority. The recent blackouts in UK (Blades, 2008; British Broadcasting Corporation [BBC], 2010) highlight the significant public and private interest in electricity reliability. During times of crisis caused by the rolling blackouts in California in 2001, it was found that customers are willing to pay very high prices for reliable power (Lawton et al., 2003). Backup generation ownership reveals that the owners place a high value on reliability, and therefore are willing to pay for the cost of operating backup generation to reduce the impact of an actual outage. Micro-generation can be used to sustain the distribution system during unavailability of the transmission in-feeds and brings opportunities for the improvement of security of supply to customers in major events, such as floods or storms (Kato et al., 2007; Kondo et al., 2008). Energy storage systems have been identified as a potential source to support micro-generation, to improve their carbon performance (Skarvelis-Kazakos et al., 2010) and to offset the intermittency of renewable energy micro-sources (Grau et al., 2010).

Integration of individual small scale distributed generators in the low voltage (LV) side of the grid could provide benefits for the customers, not only from an economic point of view but also as an electric supply guarantee. Supply continuity could be reached by associating a number of loads (customers) and micro-sources into different subsystems (micro-grids). Thus, a micro-grid will be able to work in parallel with the grid, with the capability to switch to off-grid mode (intentional islanded) in case of a grid emergency (Grau et al., 2009a).

Technical recommendations, such as G59/1 (Energy Network Association, 1991), G83/1 (Energy Network Association, 2008) and the standard 1547 from Institute of Electrical and Electronics Engineers (IEEE, 2003), specify that micro-generation sources must be disconnected in the case of loss of the grid. The fact that the micro-generation sources would not be controlled by the utility grid in an islanded mode, could lead to operation beyond the grid requirements. This could prove hazardous, not only for the utility equipment, but also for the personnel's health (Chowdhury et al., 2008). Embracing a reliable control strategy for the islanded mode, could be defined as the key issue in the micro-grid development and expansion. Such a strategy can maximise the micro-grid benefits, not only from the customer's point of view, but also from the utility system, since planned islanding operation may be part of the utility planning and operation strategies.

This chapter is organised in the following way: Section 2 is concerned with the technical challenges arising from intentional islanding of micro-grids that include micro-generation sources. An overview of these challenges is provided together with the possible solutions identified from the literature. A combination of an Energy Storage System (ESS) and a backup generator is proposed as a solution for intentional islanding. A micro-grid model is defined and used for steady state voltage studies using IPSA+ and PSCAD/EMTDC power systems simulation software.

Section 3 analyses the ESS requirements to balance a local area, defined as a micro-grid in this study. A methodology drawn from the literature (Abu-Sharkh et al., 2005) is used for calculating the ESS requirements. Case studies using a micro-grid model are defined.

Section 4 evaluates the combined use of a backup generator and an ESS for balancing a local area. A Java-based software tool performing sequential power flows was developed to examine the ESS and the backup generator requirements under different micro-grid load/generation conditions.

Section 5 uses the results from the previous sections to evaluate the use of ESS for electricity market participation. The MATLAB Optimisation Toolbox is used to obtain the optimal behavior of a pre-defined rated Energy Storage System, based on the requirements of a given micro-grid.

The chapter concludes with the main results and summarises the conclusions of each section.

2. Micro-grid intentional islanding

An overview of the main technical challenges regarding the grid-connected and islanded mode of micro-grids is provided. Appropriate solutions drawn from the literature are discussed. The use of energy storage and a backup generator is analysed. Part of a typical LV power distribution network is used for steady state voltage studies. Case studies are described and simulation results are analysed.

2.1 Technical challenges

When a micro-grid is to be operated at both grid-connected and islanded mode, frequency, steady state voltage, protection and earthing issues arise. These issues are discussed for each mode.

2.1.1 Frequency

2.1.1.1 Grid connected

Large centralised synchronous machines are equipped with speed governors, which are responsible for ensuring the balance of the system they belong to and hence the network frequency stability. Some micro-generation sources, are designed to operate with constant power without contributing to frequency control, therefore large penetration of such sources may lead to a less stiff system, determining the utility frequency stability (Lopes et al., 2006).

2.1.1.2 Intentional islanding

During islanded mode the micro-generation sources connected to the micro-grid may not be able to provide frequency control. The low inertia of the synchronous micro-sources together with the constant power output ones may be not sufficient for the micro-grid frequency stability without the utility support. The smaller size of the resulted micro-grid after islanding compared to the utility grids, give rise to a micro-system more sensitive to power variations, where small unbalances may be translated in big and fast frequency variations (Abu-Sharkh et al., 2006). The output of some micro-sources, such as PV and wind turbines, depends on the intermittency of their renewable resources; therefore changes in the power balance will not be only dependent on the load variation but also on the available micro-source power output.

2.1.2 Steady state voltage

2.1.2.1 Grid connected

The operation of a micro-source within the LV side of the network is associated with a rise of voltage at the point of connection (Conti et al., 2003). This can be seen as an opportunity for micro-source penetration, since a higher margin against under voltages is achieved. On the other hand, a high level of micro-source penetration could imply a violation of the upper voltage statutory limits (+ 10% in UK [Ingram & Probert, 2003]) at the point of connection (Jenkins et al., 2000). When networks are lightly loaded, voltage is more likely to violate statutory limits. That is due to the tap settings of MV/LV transformers being traditionally set to keep the voltage at the most remote customer just below the maximum limits (Jenkins et al., 2000).

2.1.2.2 Intentional islanding

In general, micro-sources operate in slave mode (i.e. they set the grid voltage as reference for their power electronics interfaces) when grid-connected. If due to the conditions prior to the intentional islanding, the micro-sources have to be disconnected, a voltage source is required to re-energise the micro-grid. Alternatively, the power electronics interface of one micro-source has to operate in master mode. This may prove a complex task when more micro-sources are added to the network, as the planning procedures of the Distribution Network Operators (DNOs) should be enhanced. Moreover the micro-grid's voltage will be dependent on the micro-sources power output, which may prove inadequate in the case of intermittent renewable micro-sources.
In high voltage electricity systems, reactive power compensation is used for the voltage control. In the low voltage side of the network, though, active power flow control will be critical to keep the voltage between statutory limits, due to the low X/R ratio. Therefore, balance inside the micro-grid may not be achieved in islanded mode, since the maximum active power flow along feeders will be limited (Zhou et al., 2007). The number of micro-sources, the penetration level and their location along the micro-grid will determine the voltage profile.

2.1.3 Protection

2.1.3.1 Grid connected

The electrical protection equipment of an electricity network is rated and operated according to the fault levels and fault clearance times of faulty currents inserted from the upstream network (Boutsika et al., 2005). When micro-sources are embedded in the

distribution network, an increase in the fault current levels is anticipated (Boutsika et al., 2005). Therefore, the rating and characteristics of electrical protection equipment may no longer be adequate to cope with the new fault current levels.
Traditional network protection schemes are based on unidirectional fault current flow. Embedded micro-sources in LV networks may reverse power flows especially when generation occurs at lightly loaded periods (Chowdhury et al., 2008).

2.1.3.2 Intentional islanding

An essential condition for the operation of micro-grids in an islanded mode is their compliance to the same safety requirements as those traditional centralised-generation operated networks (Jayawarna et al., 2005). In the case of a fault, the traditional grid rotational generators are injecting large fault currents, thus protection devices in the distribution network are mainly over-current sensing. The fault current emitted through the power electronics interfaced micro-sources inside the micro-grid, will be below the levels of traditional generators fault current (Jayawarna et al., 2005). Thus, possible faulty currents from micro-sources may not be detected by existing over-current relays.

2.1.4 Unearthed neutral

Current practices allow micro-sources to operate with their neutral earthed or not, while being synchronised to the utility system. The common practice is to earth only the neutral of the low voltage side of the MV/LV transformer (Dexters et al., 2007). The main reason for this is the degree of complexity in earth fault currents control, added by the neutral earth connection of the micro-sources (Dexters et al., 2007). When the micro-grid is intentionally islanded, an earth reference point should be provided. The lack of an earthed reference could lead to over voltages and safety problems for the personnel in case of a fault.

2.2 Solutions for intentional islanding

2.2.1 Frequency and voltage, micro-source control strategy

It is anticipated that future micro-grids will comprise a Micro-Grid Central Controller (MGCC) and dispersed micro-controllers for each micro-source and controllable load (Lopes et al., 2006). The micro-source controllers will control the power electronic interfaces (inverters) of the micro-sources. Two main strategies are currently used in inverter based control schemes: PQ inverter control, where specified P and Q values are delivered by the inverter, and Voltage Source Inverter (VSI), where voltage and frequency through P/f and Q/V droops are controlled under predetermined limits. The VSI strategy could be considered as more appropriate for islanded mode operation, since its behavior is similar to that of synchronous machines. Nevertheless, both types of inverter control strategies can coexist in an efficient way (Lopes et al., 2006). Load controllers will be mainly responsible for load shedding when the power generated inside the system cannot match the demand. Energy storage will play a key role in order to keep the frequency at the desired levels due to its bi-directional power flow capability (Ito et al., 2007).

2.2.2 Protection

In (Wu et al., 2008) a method for adjusting the settings of relays is proposed. This method can be used to modify the protection scheme during the transition from grid-connected to islanded mode. Energy storage controllers could be programmed to introduce higher fault currents to be detected by conventional protection devices. In (Jayawarna et al., 2005) a flywheel is presented as a solution for the desirable fault currents while operating in islanded mode.

2.2.3 Unearthed neutral

The earth reference of the micro-grids is usually located at the low voltage side of the MV/LV transformer. The control of a micro-source neutral connection for switching on during intentional islanding is proposed by (Dexters et al., 2007)

2.3 Energy storage and backup generator for intentional islanding operation

The connection of a backup generator and an energy storage device at the point of common coupling is proposed to replace the grid after disconnection (Fig.1) and will be similar with the spinning reserve of large generators in the conventional grid. The role of the energy storage will be: (i) to absorb any excess of energy supplied by the micro-grid; (ii) to cope with fast balance changes, and (iii) to ride-through the gap between the failure of grid power and the start-up of the generator (Grau et al., 2009b). The generator will be responsible for injecting power to the micro-grid for balancing purposes. Portable generator for backup measures offers a feasible solution when permanent deployment is not possible. The combination of energy storage, backup generator and micro-generators is anticipated to manage the micro-grid demand requirements.

The loads may be domestic loads, commercial loads or electric vehicles.

Ideal intentional islanding control strategies should achieve a smooth transition without use of load shedding. However, depending on the conditions prior to the intentional islanding, the micro-sources may need to be disconnected. In such case, the micro-grid will need to integrate black start capability in order to re-energise the system and re-start the micro-sources.

2.3.1 Micro-grid model for voltage studies

A LV micro-grid model, based on the UK generic network presented in (Ingram & Probert, 2003) is used. The model consists of a LV feeder modeled in detail, which supplies 96 residential customers, uniformly distributed among the 3-phases. Details of the whole network can be found in (Ingram & Probert, 2003; Papadopoulos et al., 2010).

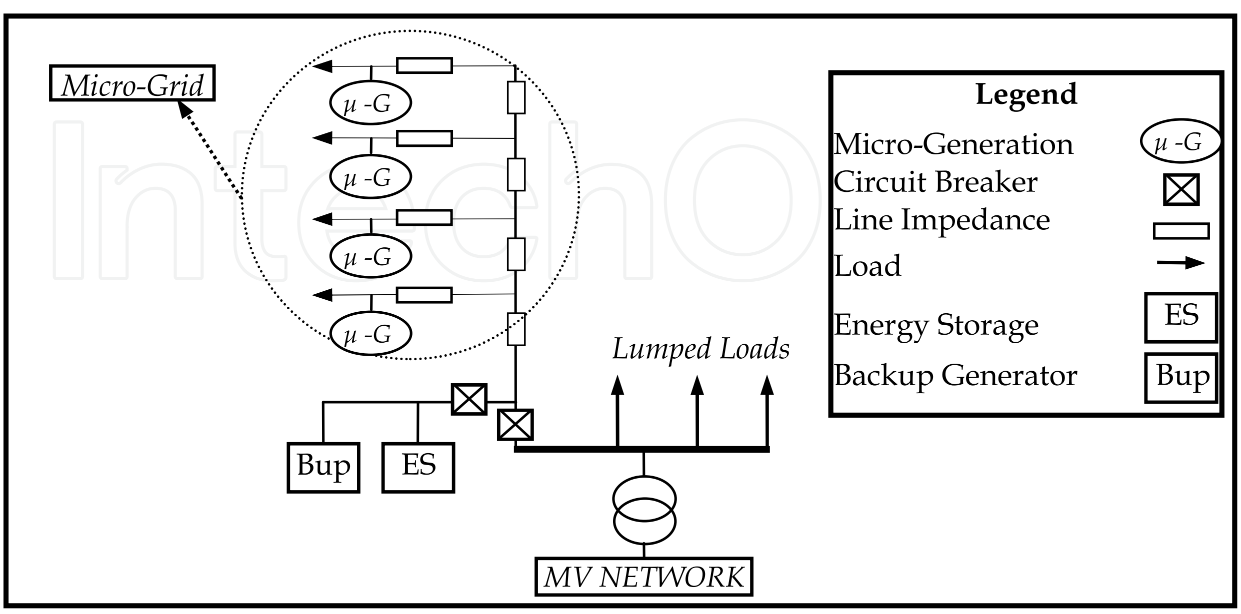

Fig. 1. Case study micro-grid

2.3.2 Case study

During islanded operation the micro-grid's demand is assumed to be covered by the power generated from the micro-sources, the backup generator and the energy storage. Simplified generation models were used to emulate the behavior of micro-generators. The domestic loads were modeled as purely resistive with typical minimum and maximum values acquired from the Electricity Association (Ingram & Probert, 2003). These are 0.16kW for a summer minimum and 1.3kW for a winter maximum residential load. An After Diversity Maximum Demand (ADMD) factor was applied per 100 customers.
Different levels of micro-generation penetration with a base scenario of 1.1kW per customer were studied. 100% penetration is equivalent to each customer having installed a micro-generator of 1.1 kW. The simulations were run for minimum and maximum loading conditions and the steady state voltage measurements recorded. The voltage set at the point of common coupling with the micro-grid was kept fixed at 1 p.u. IPSA+ and PSCAD/EMTDC micro-grid system models were used to cross-check the simulation results.

2.3.3 Simulation results

The simulation results are presented in Fig. 2 and Fig. 3, in which the measurement of each LV Segment is abbreviated with Seg, while Seg4 is the most remote segment in the micro-grid.

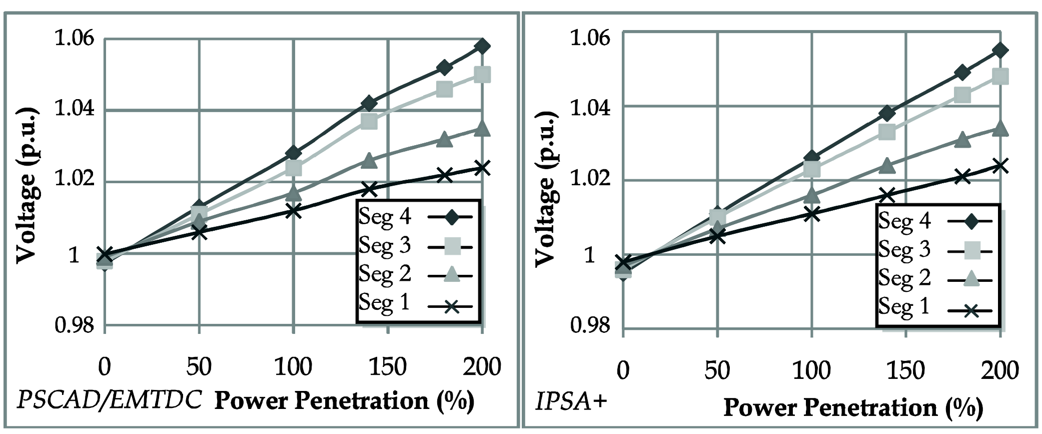

Fig. 2. Steady state voltage measurements at each LV segment during minimum load conditions

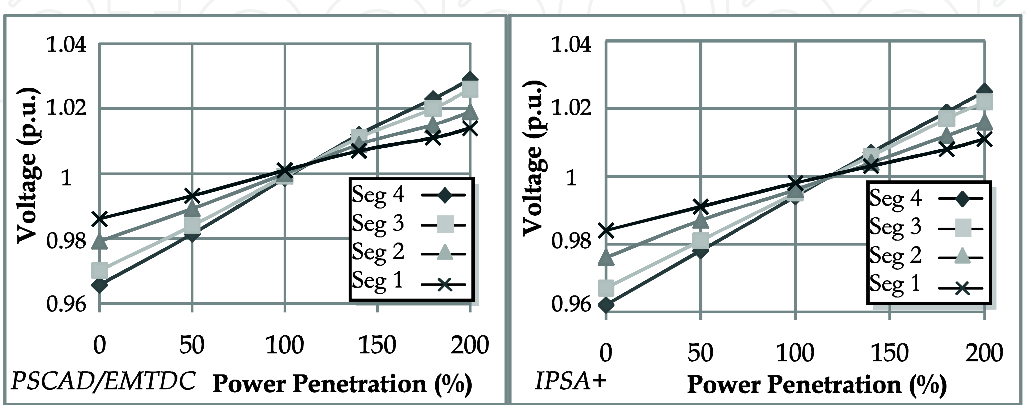

Fig. 3. Steady state voltage measurements at each LV segment during maximum load conditions

2.3.4 Discussion of the results

The results presented in Fig. 2 and Fig. 3 showed no violation of the statutory limits (1.1p.u. – 0.94p.u. in UK) for different levels of penetration. This could be a consequence of the following simulated conditions:

- Small size of the micro-grid;
- 1 p.u. constant voltage reference at the point of common coupling;
- Proximity of the reference voltage to the remotest part of the segment;
- Backup generator and energy storage capability to absorb and to inject the required power.

For maximum load scenario, it is found that until approximately 100% penetration, the power is flowing from the energy storage and backup generator to the loads. After 100% penetration, the power is flowing from the micro-sources towards the energy storage (Fig. 3).

3. Balancing a local area with energy storage

The energy storage power and capacity requirements to achieve a power balanced area are analysed. A balanced area is a part of an electricity network, self-sufficient in terms of electricity demand. To achieve self-sufficiency, the generation should always meet the demand. The methodology used to obtain the micro-generation penetration levels and the energy storage characteristics in the power balanced area is based on the work presented in (Abu-Sharkh et al., 2005). In this approach, the required combination of micro-generation sources and energy storage within a single dwelling are calculated. These requirements are then extrapolated to the number of households forming the micro-grid.

3.1 Calculation of self-sufficiency requirements

The micro-generation capacity required to satisfy the dwelling daily demand was calculated. The daily demand of the dwelling was assumed to be supplied by the micro-generators connected to it.

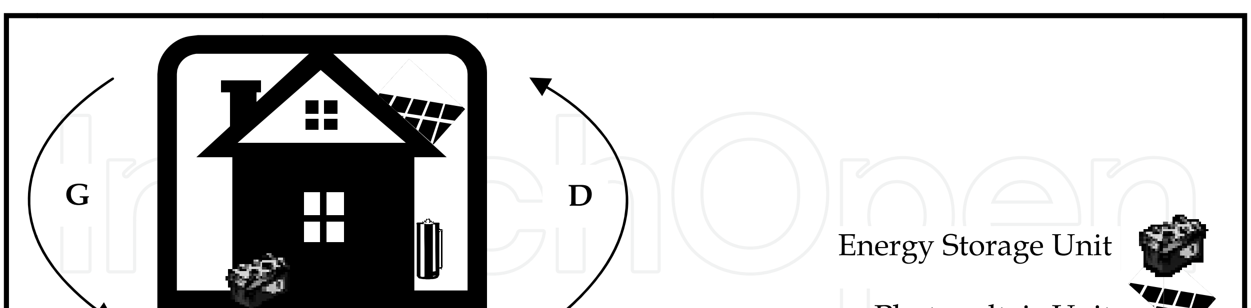

Fig. 4. Self-sufficient dwelling

Average generation and demand profiles for winter and summer seasons were used. Generation was assumed to come from PhotoVoltaics (PV) and micro-Combined Heat and Power (µ -CHP) units. The energy generated should satisfy the demand of the dwelling for both seasons (equations 1 and 2). By solving both inequalities, the penetration levels of the studied micro-sources were derived.

$$nE_{CHPwin} + mE_{PVwin} \geq E_{dwin} \quad (1)$$

$$nE_{CHPsum} + mE_{PVsum} \geq E_{dsum} \quad (2)$$

Where

E_{CHP} is the electric energy generated by the µ-CHP,
E_{PV} is the energy generated by the PV,
E_d is the energy demand,
n is the penetration levels for µ-CHP and
m the penetration levels for PV.
The sub indexs win and sum stand for winter and summer respectively.

Once the generation values were input, the characteristics of the required energy storage (maximum power and capacity requirements) were acquired. The value for a single household was then extrapolated to the number of customers forming the micro-grid.

3.2 Case study input data

Half-hourly residential load profiles where drawn from (UK Energy Research Center, 1997), and scaled to values for the specific model (from 0.16kVA to 1.3kVA per customer) provided in section 2. These profiles are deemed to be representative for the UK residential loads. Generation profiles for the PV and µ-CHP were used from (Mott McDonald, 2004) for winter and summer average days. The µ -CHP profiles were scaled to a maximum electrical power output of 1.5kWe. The data are shown in Fig. 5 and Fig. 6.

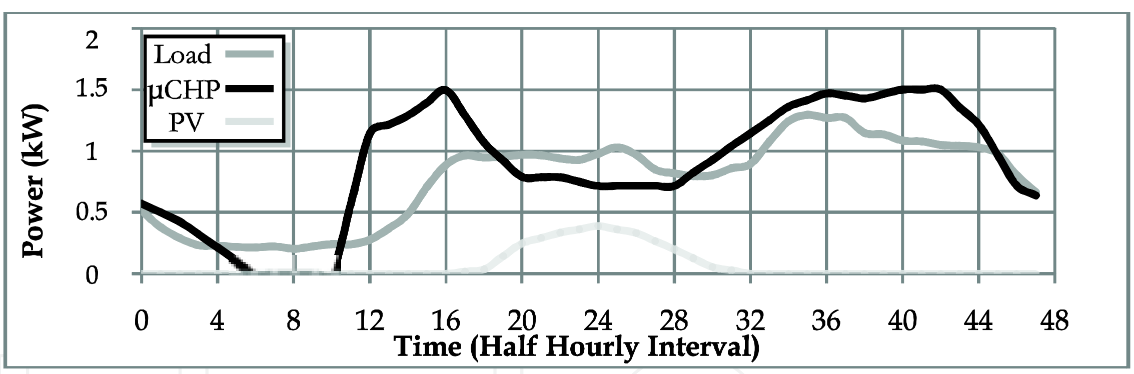

Fig. 5. Winter generation and demand profiles

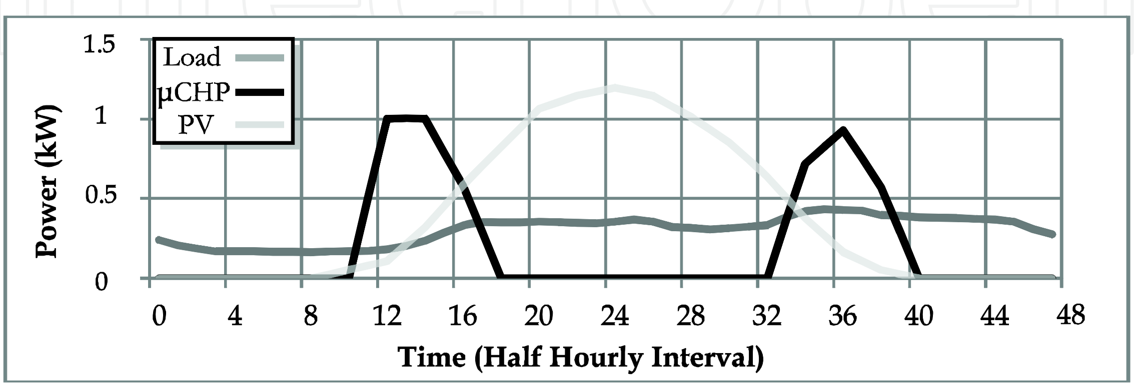

Fig. 6. Summer generation and demand profiles

3.3 Case study results

The methodology described in section 3.1 was applied and the results were extrapolated to a micro-grid consisting of 96 customers and one energy storage unit. Fig. 7 shows the graphical solutions of equation 1 and equation 2, using the data from section 3.2, which gives the micro-generation penetration levels required in each season to achieve the micro-grid balance. The intersection point indicates the optimal penetration levels required in order to achieve the balance in both seasons (Abu-Sharkh et al., 2005).

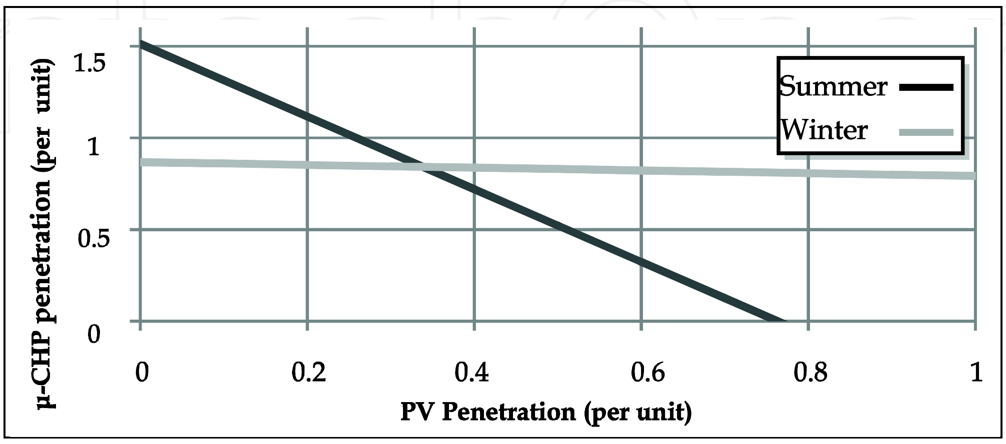

Fig. 7. Micro-generation penetration required to achieve the balance in the micro-grid

The intersection co-ordinates are m=0.34 and n=0.84, where m is the required PV penetration and n is the required µ-CHP penetration level. These penetration levels were applied to the generation profiles. By comparing the generation against the demand the energy imported from the grid and to the grid at each time interval was obtained.
The maximum energy storage capacity for each season was determined by plotting the evolution of the energy storage State of Charge (SoC), as described below. The power was assumed to be constant at each half-hourly interval; therefore the periods where the maximum energy was absorbed or injected to the grid determined the maximum power requirements.

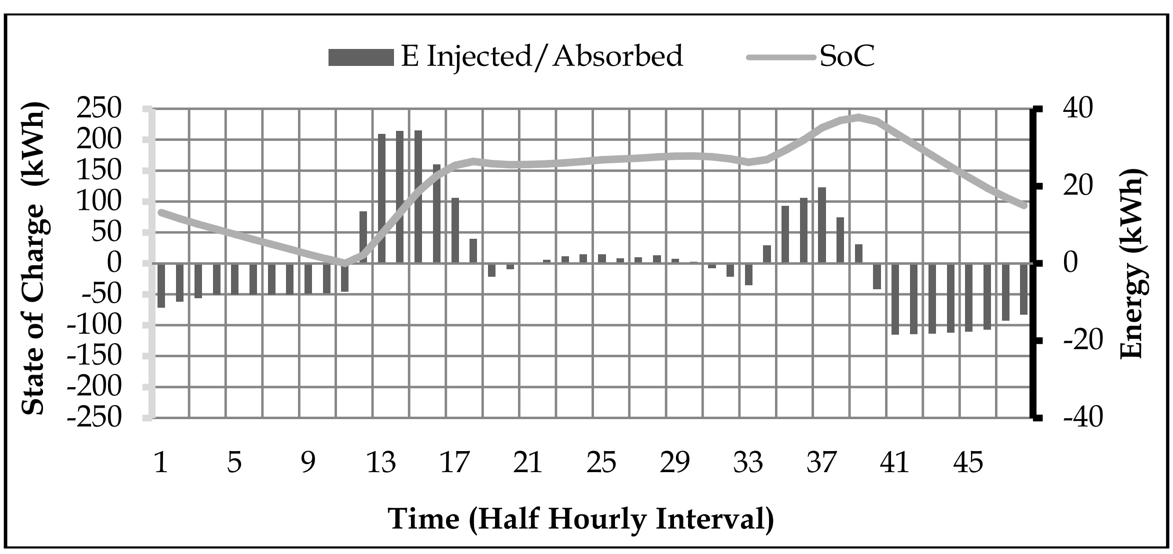

Fig. 8. Evolution of the energy storage during summer load conditions

Fig. 8 and Fig. 9 show the utilisation of the energy storage during typical summer and winter days for the optimal micro-generation penetration levels (Fig. 7). The black columns correspond to the energy injected or absorbed by the energy storage unit at each time step. The negative values represent the energy injected by the energy storage unit; conversely the positive values represent the energy absorbed by the energy storage unit. The energy injected/absorbed is presented on the figures' right axis (black). The grey line represents the evolution of the energy storage State of Charge (SoC) during the day. The SoC values are presented on the figures' left axis (grey). The maximum value of the grey line determines the capacity required by the energy storage in each season. The sizing of the energy storage in order to achieve self-sufficiency was found to be 236.27 kWh, which is the maximum value of the two seasons.

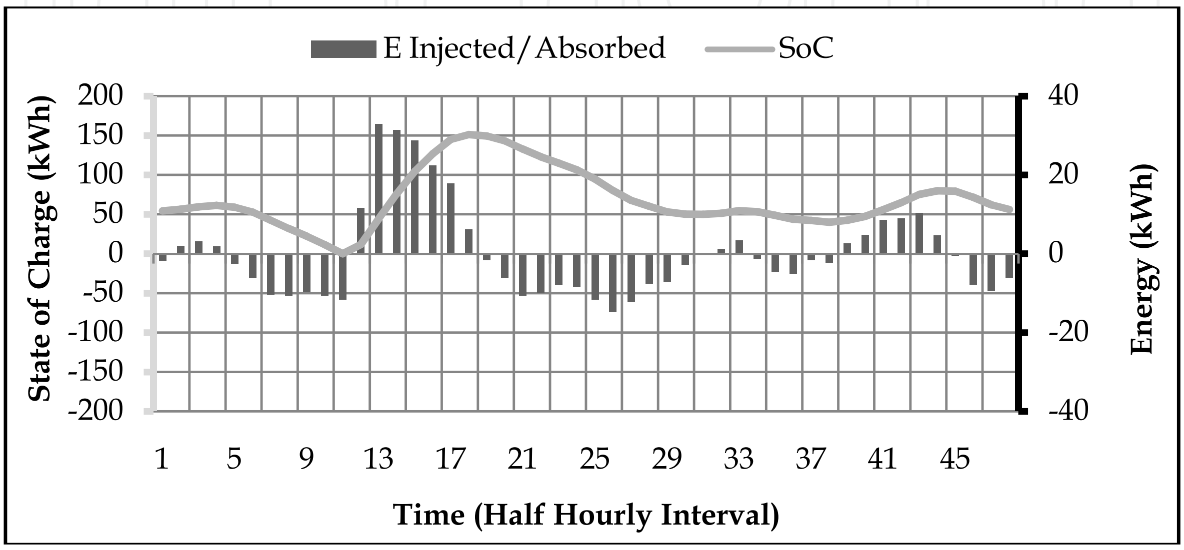

Fig. 9. Evolution of the energy storage during winter load conditions

The power and energy requirements of the energy storage system are summarised in Table 1.

Season	Maximum Power injected (kW)	Maximum Power absorbed (kW)	Capacity required (kWh)	Total Energy injected (kWh)	Total Energy absorbed (kWh)
Summer	-36.80	68.88	236.27	-251.68	251.68
Winter	-29.47	65.96	151.17	-202.55	202.55

Table 1. Energy storage requirements for summer and winter scenarios for the micro-grid

4. Balancing a local area with energy storage and backup generator

This section investigates the power rating and energy capacity requirements for the energy storage and backup generator to achieve a balanced area. Different penetration levels of PV and μ-CHP were used. The micro-grid model shown in Fig.1 was considered.
The steady state voltage changes and the system efficiency (power line losses) are evaluated for different penetration levels of micro-generation. A study case is presented, where the use of backup generator is minimised.

4.1 Methodology

The penetration levels considered for each micro-source range from 0% to 100% in steps of 10%. For each combination of micro-sources penetration level, sequential power flows were

performed at every time interval. The procedure was repeated for both summer and winter system conditions. The power line losses and the voltage steady state measurements were recorded for each time interval. The policy examined was to minimise the use of the backup generator. Once the losses were recorded, the need of a backup generator was estimated. The parameters considered were: (i) the system energy generation and demand, the (ii) energy storage efficiencies and (iii) the line losses. A round-trip efficiency of 72% was assumed for the ESS (Oudalov et al., 2007).
A backup generator was required in the case that:

$$\sum_{t=1}^{48} Egen_t - \sum_{t=1}^{48} Edem_t < 0 \tag{3}$$

Where:

$$Egen_t = \begin{cases} [(Gen_t - Dem_t) - Losses_t] * \eta ch * \eta dch, & Gen_t - Dem_t > 0 \\ 0, & Gen_t - Dem_t < 0 \end{cases}$$

$$Edem_t = \begin{cases} 0, & Gen_t - Dem_t > 0 \\ [(Dem_t - Gen_t) + Losses_t], & Gen_t - Dem_t < 0 \end{cases}$$

Where for each time step t:

Egen is the usable energy stored in the energy storage system,
Edem is the micro-grid required energy,
Gen is the energy generated by the micro-sources,
Dem is the domestic demand,
ηch is the energy storage charging efficiency and
ηdch is the energy storage discharging efficiency.

The flow chart in Fig. 10 depicts the developed algorithm. This chart shows the case where the overall system demand is higher than the generation. The calculations consider two consecutive days (i.e. 96 half hour time steps). The procedure is done for each combination of micro-sources for summer and winter season.
In time steps where the generation is higher than the demand, the energy stored in the ESS, is:

$$Ein = [(Gen_t - Dem_t) - losses_t] * \eta ch \tag{4}$$

If the demand is higher than the generation, the algorithm checks if there is energy available in the energy storage system ($SoC_t > 0$). In this case the energy supplied by the ESS is:

$$Eout = [(Dem_t - Gen_t) + Losses_t] / \eta dch \tag{5}$$

If additional energy is required than the available energy in the ESS ($SoC_{t+1} < 0$), the ESS will supply its available energy and the rest is supplied by the backup generator.
If the demand is higher than the generation and there is no energy available in the ESS, the energy is supplied by the backup generator:

$$EBup = (Dem_t - Gen_t) + Losses_t \tag{6}$$

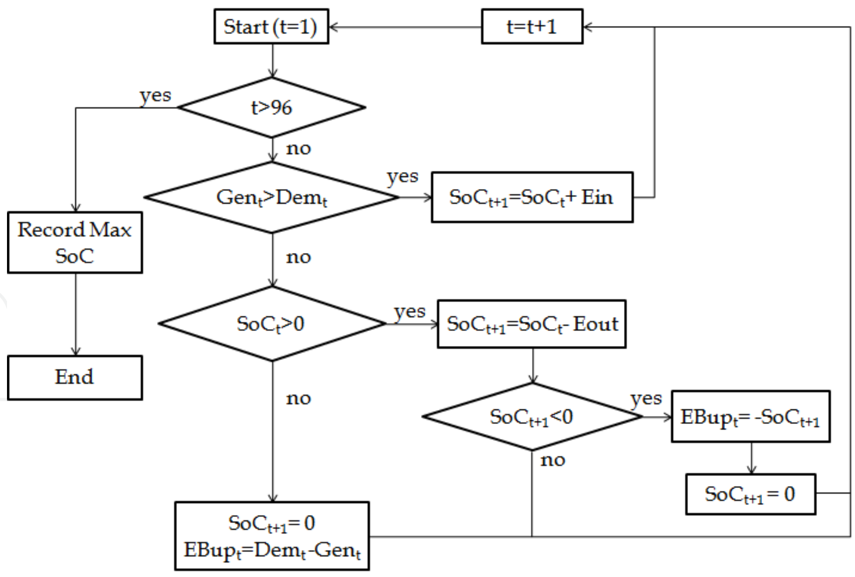

Fig. 10. Algorithm flow chart

The evolution of the energy storage system SoC was recorded; the maximum value of all the time steps determined the required capacity of the ESS. The maximum power requirements were determined by the amount of energy injected or absorbed by the ESS. The power rating of the backup generator was determined by the time step where maximum energy was generated.

4.2 Sensitivity studies

The sensitivity of the variables described in section 4.1 was examined, with respect to the energy losses and the voltage violation within the micro-grid. The capacity requirements of the ESS and the energy requirements of the backup generator were studied for various cases. The micro-generation levels were varied from 0-100% in 10% steps. The results are presented below.

4.2.1 System losses

The power line losses for all micro-generation penetration levels were recorded. Fig. 11 shows the results for both summer and winter season loading cases.

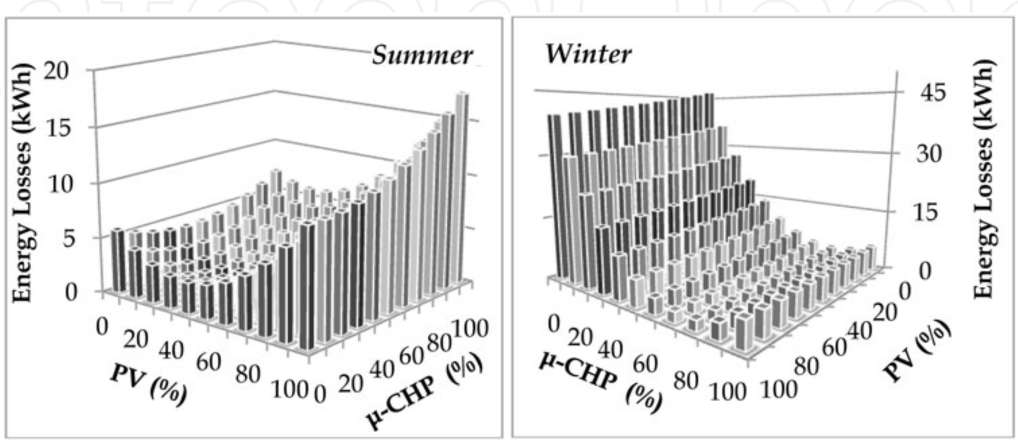

Fig. 11. Energy losses in the micro-grid

4.2.2 Steady state voltage limits violations

The voltage measurements of the remote feeder were recorded. Voltage violations were found only during summer loading conditions. Fig. 12 shows the cases when voltage violated statutory limits. Combinations of PV and μ-CHP penetration levels, marked with an "X" in Fig. 12, exceeded the voltage statutory limits.

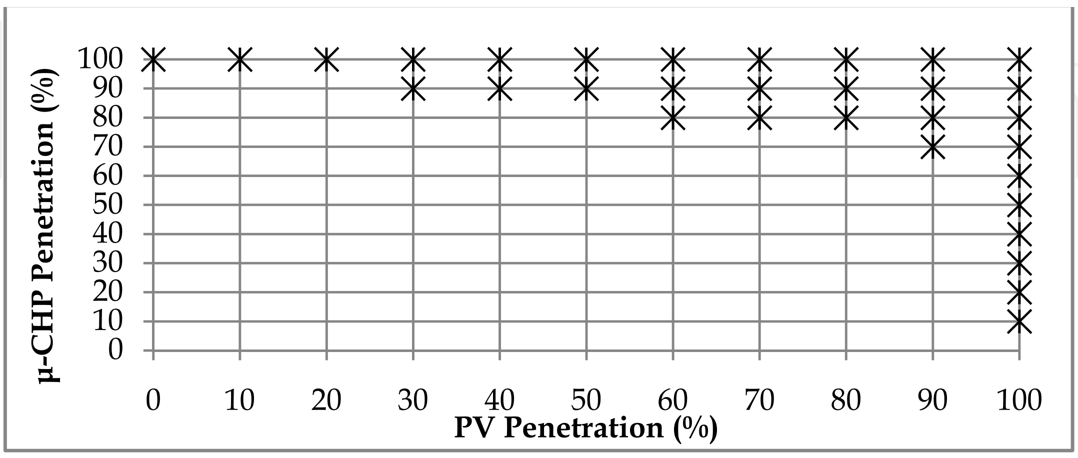

Fig. 12. Voltage statutory limits violation for summer season system loading

4.2.3 Backup generator energy requirements

Fig. 13 shows the backup generator energy requirements to achieve an energy balanced micro-grid for all studied micro-generation penetration levels. It can be observed that during the winter season, the backup generator requirements are determined by the μ-CHP penetration. In combinations where no backup generator is required, the energy balance is achieved only with the ESS.

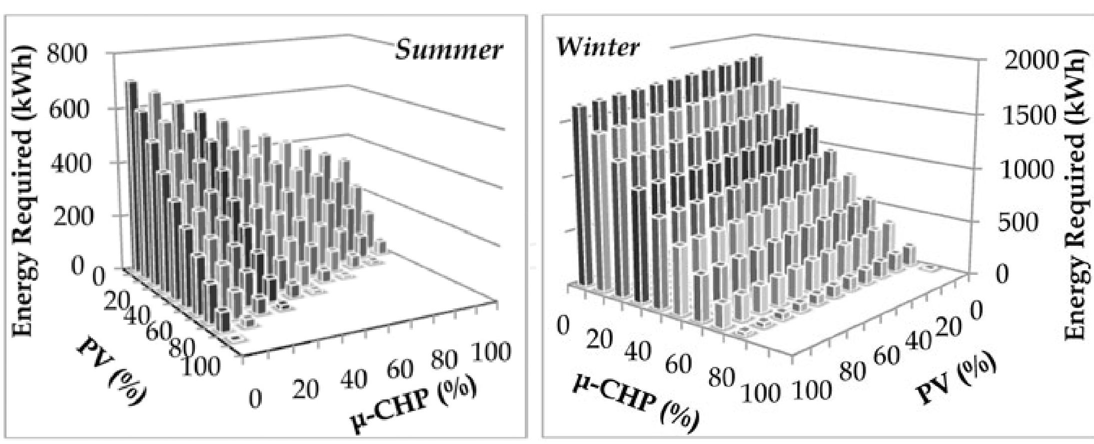

Fig. 13. Backup generator energy requirements for different penetration levels of micro-generation

4.2.4 Energy storage system capacity requirements

Fig. 14 shows the ESS capacity requirements to achieve an energy balanced micro-grid for all studied micro-generation penetration levels. It can be observed that for low micro-generation penetration levels, the energy storage capacity requirements are limited due to the reduced energy exported from the micro-generators. During summer loading conditions, for high micro-generation penetration levels, the ESS requirements are determined by the time period when no energy is generated from the micro-generators (time step 40 to time step 9 in Fig.6).

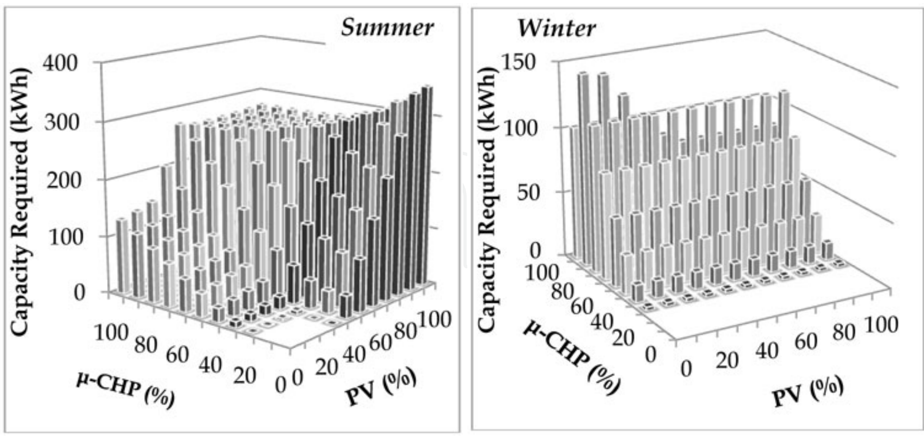

Fig. 14. ESS capacity requirements for different penetration levels of micro-generation

4.2.5 Minimum energy imported from the backup generator

The sensitivity studies of the above subsections showed that the minimum energy required from the backup generator, within voltage statutory limits, would be achieved with a μ-CHP penetration of 80% and a PV penetration of 50%. In this case, the total amount generated during summer was found to be higher than the demand. The technical ESS and backup generator requirements for this case are shown in Table 2.

<table>
<tr><td rowspan="3">Back up Generator</td><td colspan="2">Energy (kWh)</td><td colspan="2">Power (kW)</td></tr>
<tr><td>Summer</td><td>Winter</td><td>Summer</td><td>Winter</td></tr>
<tr><td>0.00</td><td>108.48</td><td>0.00</td><td>23.27</td></tr>
<tr><td rowspan="3">Energy Storage System</td><td colspan="2">Capacity (kWh)</td><td colspan="2">Power (kW)</td></tr>
<tr><td>Summer</td><td>Winter</td><td>Summer</td><td>Winter</td></tr>
<tr><td>279.64</td><td>112.74</td><td>68.59</td><td>60.35</td></tr>
</table>

Table 2. Energy storage system and backup generator's requirements

5. Energy storage market participation

The use of the energy storage device to participate in the electricity markets is presented. The minimum SoC required at every time interval to ensure energy balance in the micro-grid is obtained from Section 4. The MATLAB Optimisation Toolbox (MathWorks™, 2011) is used to obtain the optimal behavior of a pre-defined rated ESS, based on the requirements of the studied micro-grid.

5.1 Methodology

In this study, the "fmincon" tool from the MATLAB Optimisation Toolbox (MathWorks™, 2011) was used. Fmincon uses a gradient based Non-Linear Programming method. The algorithm that was used was the Interior Point algorithm. The algorithm probes the objective function variables to draw the gradient of the variables. In this way, the direction of the optimal point is estimated.

The objective function was:

$$L = \sum_{t=1}^{48} (Esell_t * Psell_t - Ebuy_t * Pbuy_t) \tag{7}$$

Where for each time step t:

Esell is the energy sold to the market,

Psell is the electricity price of the energy sold,

Ebuy is the energy bought from the market and

Pbuy is the electricity price of the energy bought.

The evolution of the energy storage SoC is constrained to the energy traded at each time period (equation 8):

$$SoC_{t+1} = SoC_t - Esell_t + Ebuy_t \tag{8}$$

The maximum energy traded is constrained by the minimum SoC requirements at every time step (equation 9). After each trading period the SoC available in the energy storage has to be at least the minimum value calculated in order to achieve an energy balance.

$$MinSoC_{t+1} \leq SoC_t - Esell_t + Ebuy_t \tag{9}$$

Where

MinSoC is the minimum State of Charge required at the specific time step

The maximum energy to be traded will be also constrained to the energy storage unit maximum capacity (equation 10) and its maximum power rating (equation 11 and 12). Since the power is assumed to be constant during each time step, the maximum power will be determined by the energy traded divided by the duration of the half an hour time step.

$$MaxSoC \geq SoC_t - Esell_t + Ebuy_t \tag{10}$$

$$Pmax \geq Esell_t / 0.5 \tag{11}$$

$$Pmax \geq Ebuy_t / 0.5 \tag{12}$$

Where

MaxSoC is the energy storage maximum capacity and

Pmax is the maximum power rating of the energy storage.

The final constraint is presented in equation 13; the aim of this constraint is to avoid selling and buying electricity at the same time step.

$$Min (Esell_t , Ebuy_t) = 0 \tag{13}$$

5.2 Case study

5.2.1 Assumptions

The micro-grid under study in this section, together with the generation and demand profiles are those presented in Section 2 and 3. The energy storage SoC requirements are the values obtained in Section 4.2.5, where an 80% μ-CHP and 50% PV penetration were considered. The energy storage unit considered has a capacity of 300kWh and a maximum power output of 100kW and is considered to be grid-connected. Average electricity prices were drawn from the literature (New Electricity Trading Arrangements, 2011), the electricity buy price (from the market) is assumed to be 10% higher than the electricity sell price (to the market) (Dimeas, 2006). The parameters considered in the optimisation algorithm are the electricity prices and the energy storage SoC requirements presented in section 4.2.5. Neither operational and maintenance costs, nor the ageing effects in the energy storage unit have been considered. It has been assumed that the energy traded is not constrained to a minimum energy amount (i.e. any amount of energy can be traded). The backup generator has not been considered in the optimisation.

5.2.2 Results

The amount of energy to be traded at different time steps, which would maximise the benefits of the energy storage unit under the given conditions, is shown in Fig. 15 for winter and in Fig. 16 for summer scenario. The grey line presents the SoC evolution of the energy storage, the black line shows the minimum SoC requirements of the energy storage at every time step. The black bars represent the amount of energy sold; the grey bars represent the amount of energy bought and the dotted black line shows the market prices (presented in the secondary axis).

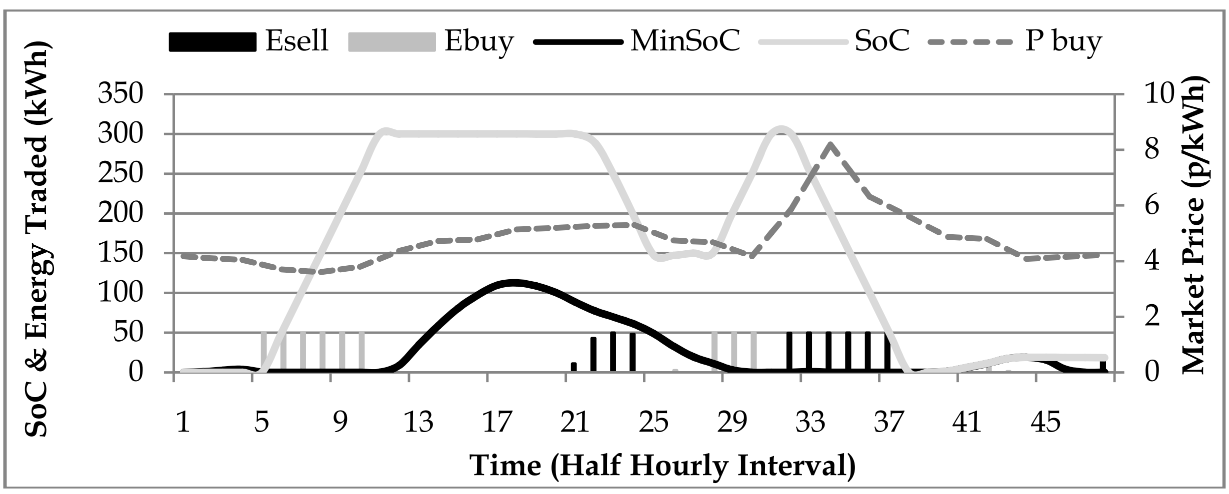

Fig. 15. Optimisation results for winter scenario

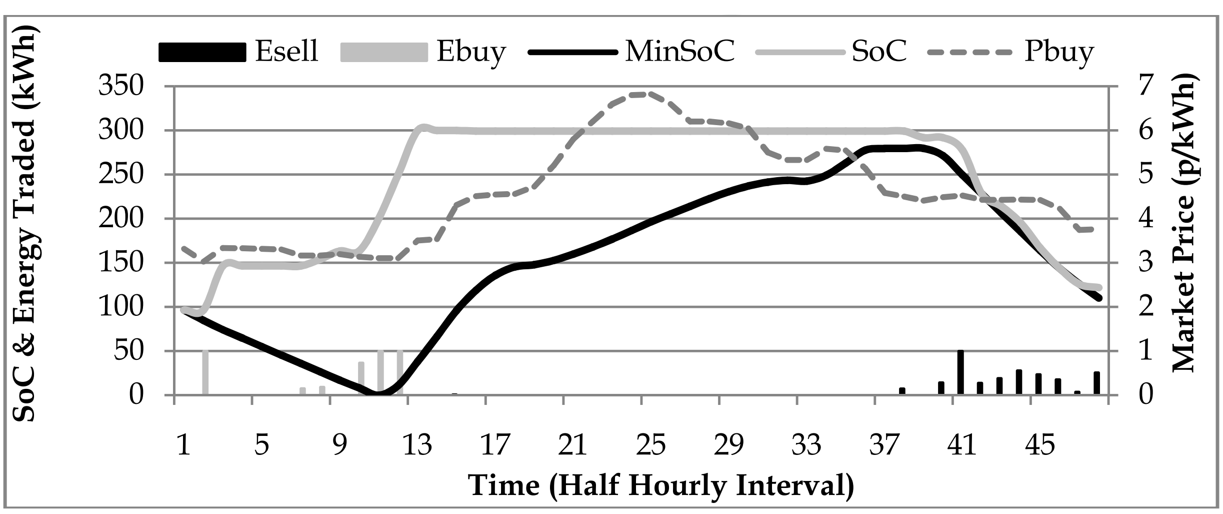

Fig. 16. Optimisation results for summer scenario

Fig. 15 and Fig. 16 show how the maximum energy that can be traded at each time step is constrained by the maximum power output of the energy storage; having a maximum power output of 100 kW, the maximum energy that can be imported or exported per time step is 50 kWh. It can be seen during summer loading conditions, that the market participation is constrained by the minimum SoC requirements. For winter loading conditions, the higher differences between the maximum energy storage capacity and the SoC requirements enables higher market participation.

6. Conclusions

Energy systems are anticipated to face changes with the increase of power generation devices embedded in the LV networks. Micro-grid is a concept developed in the last decade. It describes LV electricity networks that may deliver electricity to the customers supplied in it, either connected to the main grid or islanded in autonomous mode. The islanded mode would be feasible with the use of power generated by dispersed generation embedded in LV networks, usually at the customer premises. To ensure reliability and security of supply, the concept of intentional islanding was introduced. Intentional islanding is the forced transition to islanded mode due to a major event in the network.

The main technical issues associated with intentional islanding were addressed in Section 2. The impact of micro-generation sources on intentional islanding was analysed. Frequency, voltage, earthing and protection issues were discussed. Literature based solutions were analysed for each of the discussed impacts. A UK micro-grid electrical model was defined. The combination of an Energy Storage device with a Backup Generator for supporting islanded mode operation was proposed. This combination would assist the smooth transition between grid connected and islanded modes. Steady state voltage studies were conducted for different micro-generation penetration levels and micro-grid loading conditions. The results showed that up to 1.1 kW per customer micro-generation penetration can be safely integrated with regards to the voltage statutory limits.

To achieve energy autonomy in a micro-grid, the energy generated by micro-sources should cover the load demand. A methodology was presented in Section 3, to obtain the optimal ESS power and energy capacity within a micro-grid. The ESS would have to bring energy balance to the micro-grid, for given micro-generation penetration levels. A case study was defined based on the micro-grid model of Section 2. The combined use of a backup generator and the ESS to achieve the energy balance was investigated in Section 4. Optimal combinations were calculated for different micro-generation penetration levels and micro-grid loading conditions.

To maximise the benefits of an ESS, its participation in the electricity market was investigated in Section 5. This feature would entail the dual use of ESS for both local support and energy trading. To achieve this, a minimum State of Charge should always be available in the ESS. This minimum SoC for each time interval was obtained from Section 4. Assuming that the rest of the ESS capacity is available for market participation, an optimisation tool was used to schedule the energy storage charging and discharging.

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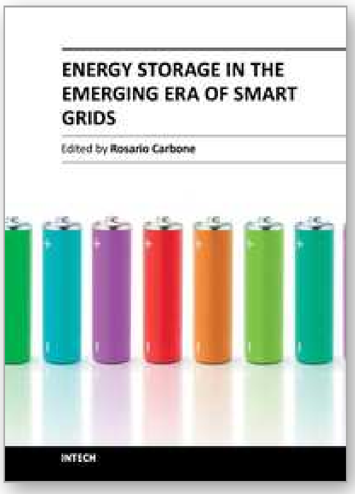

Energy Storage in the Emerging Era of Smart Grids

Edited by Prof. Rosario Carbone

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Reliable, high-efficient and cost-effective energy storage systems can undoubtedly play a crucial role for a large-scale integration on power systems of the emerging â€œdistributed generationâ€ (DG) and for enabling the starting and the consolidation of the new era of so called smart-grids. A non exhaustive list of benefits of the energy storage properly located on modern power systems with DG could be as follows: it can increase voltage control, frequency control and stability of power systems, it can reduce outages, it can allow the reduction of spinning reserves to meet peak power demands, it can reduce congestion on the transmission and distributions grids, it can release the stored energy when energy is most needed and expensive, it can improve power quality or service reliability for customers with high value processes or critical operations and so on. The main goal of the book is to give a date overview on: (I) basic and well proven energy storage systems, (II) recent advances on technologies for improving the effectiveness of energy storage devices, (III) practical applications of energy storage, in the emerging era of smart grids.

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