UPS for demand side management

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Abstract

Using UPS for DSM has the advantage of reducing demand from the grid without the loss of functionality that arises from a power reduction to the business or industry being operated. Thus, an introduction to DSM and UPS technology is given. The balancing services and revenue streams available to demand reducers are provided and with the technical specifications of the UPS present at the University of Southampton, a simple calculation was made to determine the savings possible through using the UPS for DSM.

1. Introduction

Renewable integration and load following are issues that are becoming more problematic as the penetration of renewables increases in the UK. Forecasting, from historical patterns and predictions of consumer behaviour, allows the national grid to follow electrical demand. Historically, this has been primarily achieved by adding power to the grid, through the use of additional capacity (i.e. pumped-hydro, OCGT) and the increase of output from base-load generators (i.e. coal). This leads to the inefficient use generation facilities, 6.6% of UK capacity being used for only 1% of the time in 2008 [1]. Dynamic, second by second variations in supply and demand can be overcome through the systems inertia, a consequence of the rotating masses inherent in the large number of conventional thermal generators. Naturally, most renewable sources are stochastic in nature and therefore unable to significantly contribute to load following, while system inertia will also decrease with renewable penetration, since generators are often decoupled from the grid through power converters [2] (naturally a source such as photovoltaics has no intrinsic inertia to start with). Therefore, the integration of renewables without the need for additional capacity, often from inefficient fossil fuel powered generation, requires a method for the provision of meeting electrical demand and ensuring the stability of the electrical grid. One method put forward is that of demand side management (DSM). The aim of the study is to collate the possible services and revenue streams currently available to an energy storage system (ESS) performing DSM in the UK, and determine which of these the UPS present at the University of Southampton (UoS) could exploit.

2. Demand Side Management

DSM involves the encouragement of consumers to reduce power consumption and has gained recent attention due to the push for low carbon power sectors and the advent of smart meters. As such, analysis on the many aspects of DSM exists in the literature. [3] discusses the optimisation of a PV battery system with DSM, while [4] and [5] show how dynamic load shifting can increase the consumption of wind energy. Incentivising DSM can be carried out through altering current electricity tariffs, where the importance of dynamic tariffs, for the successful roll-out of smart meters, is discussed in [1] and along with [6] presents dynamic tariff options such as time of use and real time pricing. Time of use sets electricity tariffs for certain times of the day and so is simple but relatively inflexible. This can lead to the Rebound effect, where the creation of a second peak by consumers can limit the benefit of reducing an initial peak, which has been observed in trials where over-simplistic and inflexible time of use tariffs were employed [7] [8] [9]. Real time pricing transmits wholesale electricity costs to the consumer: more flexible and possibly fairer but a certainly more complex approach that would require greater levels of communication between provider and consumer. Alternatively, large energy users may enter contracts with system operators or retailers to reduce demand under certain conditions. Under such contracts, control of demand reduction can range from consumers bidding in to a balancing market a set amount of demand reduction at certain times of the year, to a system operator or retailer being given the authority to automatically reduce demand. The possible contracts and business models proposed for these options can therefore be seen to be particularly relevant and are reviewed in [10]. In addition, performing DSM can be achieved via 3 actions. The simplest constitutes an increase in appliance and equipment energy efficiency to provide a non time-specific demand reduction. The second encourages consumers to shift the power consumption from times of grid stress, which generally occurs between 5-6pm in the UK, to a different time. Unfortunately, this shift in demand will rely on routine changes from domestic users, while businesses and industries may not be willing to suffer the loss of functionality a load shift constitutes. Thirdly, use of an on-site generator or energy storage system (ESS) could allow a reduction of power consumption from the grid, without the loss of function.

3. UPS Background

ESS in the form of uninterruptible power supplies (UPS) are already ubiquitous in a number of service based industries. It is generally employed where power outages and or low power quality from the electricity grid cannot be tolerated, e.g. hospitals, data centres, telecommunication sites. As such, there may be a significant power capacity from a combination of the UPS present within the UK.

Grid frequency can often be used to determine the balance between supply and demand, where high grid frequency, >50Hz, implies an excess of supply and low grid frequency, <50Hz, implies an excess of power demand. In the UK, statutory frequency limits of 49.5Hz – 50.5Hz have been set, with grid frequency dropping below 49.5Hz for more than 60 seconds on only three occasions since 1990 [11], while the UK targets a loss of load expectation of 3 hours per year [12]. This suggests that significant voltage dips or power outages are irregular. As such, the battery capacities of the UPS sites present throughout the UK are unlikely to be regularly employed. It has been suggested that this often dormant capacity be used for providing services to the power network, via DSM, whilst still providing its primary UPS service. Thus, load shedding and revenue may be available through the use of an already present system.

3.1 Function

The primary function of a UPS system is generally two-fold. For so called “critical loads”, power quality is of high importance; voltage variations, harmonics and non-linear loads can have adverse effects, causing equipment damage and possible malfunction [13]. The second function requires a UPS to support loads in the event of power outages, where they can be used to allow non-critical loads to be turned off or in conjunction with on-site generators which require longer start-up times. Any downtime in telecommunication systems, IT servers and emergency systems, such as lifts, or security cameras, can result in loss of functionality and hence severe costs. As such, any perceived risk of loss of UPS functionality from its use as an energy storage system (ESS) will likely outweigh any financial gain.

3.2 Topology

Static UPS can be classified by topology, the most frequently used currently being double-conversion online and line-interactive. Under normal operation, a double conversion UPS passes power through a rectifier then inverter before supplying the load. In the event of a power outage, the rectifier drops out of the circuit and the battery capacity discharges through the inverter [14]. Compared to the other topologies, online UPS can more precisely regulate output voltage from a wider range of input voltages, control output frequency and has an effectively negligible transfer time between normal operation and use of the battery capacity [15].

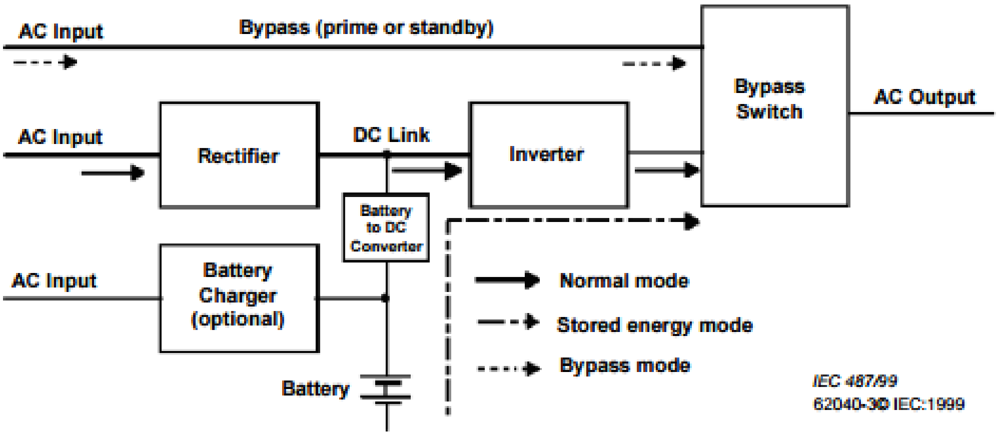

Figure 1. Topology of a double-conversion online UPS system as given by IEC 62040-3. The bypass circuit is employed in case of an extended overload from the AC input or malfunction of the battery [16].

For a line-interactive UPS in normal operation, AC power is supplied directly to the load via a series power interface, allowing voltage regulation and filtering, see fig. 2. Only in the event of a power shortage does the battery discharge through an inverter, before being re-charged through a rectifier/charger. Compared to a double-conversion system, line-interactive UPS have slightly higher efficiencies in normal mode and are generally cheaper. However, they have longer switching times and may also utilise the battery capacity more often due to lower levels of voltage and frequency regulation under normal operation [15].

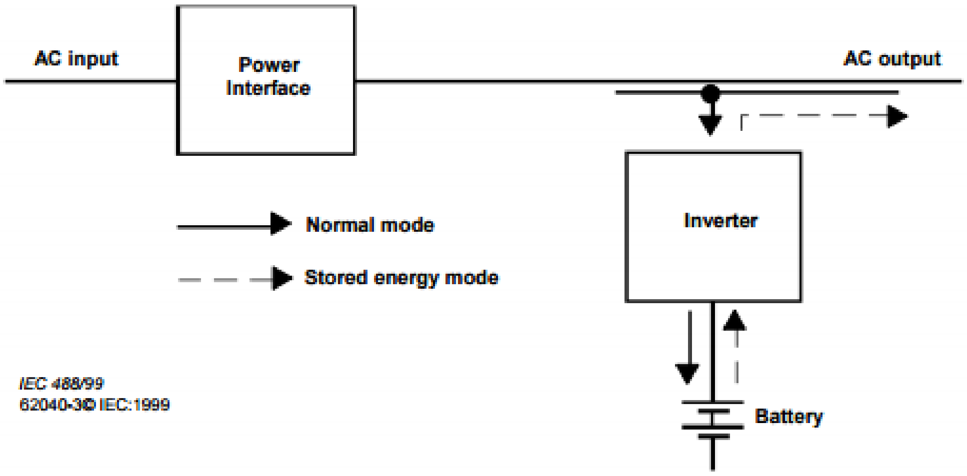

Figure 2. Topology of a line-interactive UPS system as given by IEC 62040-3. The power interface can consist of inductors, capacitors, resistors and transformers [16].

3.3 Technologies

In essence, any technology which allows a fast start-up time can be employed as a UPS. The choice of technology then comes from factors such as cost, ease of implementation, number of cycles and DoD required, energy and power capacity, maintenance needs, environmental considerations or physical size. Flywheels, supercapacitors and batteries are three technologies currently employed as UPS. The main advantage of flywheels and supercapacitors is their high cycling capability, >100,000 cycles [17] [18]. However, due to low energy densities, energy capacity is not easily scaled up and so they are primarily used for high power, short-time duration applications. Due in large part to their comparatively low capital costs, lead-acid batteries are utilised in the majority of UPS systems, where battery capacity is rarely cycled [19]. However, lead-acid UPS systems already have short lifetimes, ~5 years [20] [21], (although this is highly dependent on factors such as cycling profiles, environmental controls and the manufacturer) and were additional services and cycling to be required, degradation of the battery capacity would be rapid. Modern lithium-ion batteries are able to provide both high energy density and reasonable cycle lifetimes at high DoD. While historically expensive, the continuation of falling costs [22] may allow li-ion to be economically competitive with lead-acid batteries. With improved cycling capability, a UPS may find additional use through enabling demand side management (DSM) to exploit several revenue streams, while an aggregation of such sites will also open possibilities for the UPSs to provide a number of national grid (NG) services.

4 Added UPS Function

4.1 National Grid Services

In order to keep the grid frequency between operational limits (self-imposed by NG) of 50Hz ±0.2Hz, all large generators (≥ 100MW) are required to provide a measure of dynamic frequency response through an increase or decrease in active power output[1] [23]. Additionally, due to the nature of (non-linear) power consumption in localised, urban areas, all large generators are obliged to provide a minimum level of reactive power in order to keep stable the voltage levels in certain grid locations [24]. While these mandatory services help to keep the national grid stable on a second to second basis, additional optional services are available to generators in order to level larger, steady state frequency or power drops and are summarised in table 1.

Table 1. Balancing services procured by NG. Services are available to both conventional generators and ESS.

Service	Minimum Power	Time Requirements
FFR (firm frequency response) [25]	10MW (Dynamic)	Low frequency events (primary and secondary) and high frequency events have different time constraints.
FCDM (frequency control by demand management) [26]	3MW for (Dynamic)	Power output increase or demand decrease available for 30 minutes within 2 seconds.
STOR (short term operating reserve) [27]	3MW	Available for and within 2 hours of notice.

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[1] Primary low frequency events require an increase in active power within 10s to be sustained for an additional 20s. Secondary low frequency events require active power within 30s for an additional 30 minutes. High frequency events requires a reduction in active power within 10s to be sustained indefinitely.

Fast Reserve [28]	50MW	Output must increase at a rate of 25MW/minute and be available for 15 minutes

NG procures these services through auction, with the cheapest providers gaining a significant advantage. Payment varies from generator to generator but will account for both availability (i.e. how long and often a response provider makes available their capacity) and utilisation (i.e. the amount of energy actually required from the provider).

It is clear that the power and capacity requirements limit the opportunities for current energy storage technologies, excluding pumped hydro. Many services and revenue streams will thus be inaccessible to small sites. FCDM represents the likeliest option for ESS, although a single UPS site is unlikely to be able to provide sufficient capacity. Aggregation of a number of UPS sites is a possibility but adds complexity, both technical and economical.

4.2 Revenue Streams from DSM

Demand side balancing reserve (DSBR) is a new scheme introduced to ensure grid reliability during the winter months. As with the above balancing services, payment is via utilisation and availability to providers able to reduce demand or increase generation by 1MW for a minimum of 1 hour between the hours of 4pm-8pm from November 1st to February 28th. NG preference would be for providers capable of sustaining their reduction/output for 3 hours with the cheapest DSBR utilised first by NG [29]. Additionally, providers must not partake in other balancing services such as TRIAD avoidance (see below). As a new initiative that may be relatively short lived, DSBR is only suitable for genuine demand reducers or with existing on-site generators/ESS.

For non-domestic energy users, power demand is metered on a half-hourly (HH) timescale. For these consumers, NG charges both generators and consumers for use of the transmission network system (TNUoS). Generators will pay less the closer they are to a centre of demand while consumers will pay more for increasing the local stress on the system. For HH consumers, the demand tariff comes solely in the form of a TRIAD payment, where power consumption is measured and averaged over 3 half hour periods (between November and March) of particular national grid stress and charged on a £/kW [30]. DSM or ESS can reduce these costs by reducing the power consumption during these 3 periods. While the charge is billed retrospectively, it is possible to estimate when the periods will occur depending on factors such as weather and total NG demand with periods always ending between 5pm and 6pm since winter 1990/91.

Possibly the simplest and most widely available revenue stream, arbitrage exploits price differences between day and night electrical power. Economy 7 and peak/off-peak tariffs are available to domestic users in certain areas, while large energy users, such as a university campus, will often be on a day-night tariff. Financial gain is hence possible through storing energy through the night and using this during the day.

DNOs set a limit on the maximum apparent power capacity, known as the kVA allowance, made available to a specific site and impose a monthly standing charge, with units of £/kVA, reflecting every unit of capacity made available. With ESS, or standby generators, it is possible to lower these charges by lowering the peak power consumed by a site, hence lowering the maximum capacity required from the DNO.

5 Foreword on UoS UPS

The UoS homes 3 double on-line conversion UPS systems with data available on the power input to the UPS within the Mountbatten building. The building is home to the optoelectronic centre and school of electronic and computer science, containing numerous clean rooms and laboratories. As such, power quality and supply are highly important to the building. In addition, the data centre necessitates a UPS to ensure continuous and reliable function of the university server with a back-up generator also present. Unfortunately, available data consisted only of the power input to the UPS, with power output or data downstream of the UPS unavailable. Therefore, determining how often, and the extent to which the UPS capacity is used was not possible.

5.1 University of Southampton Load Profile

The Highfield campus load profile for a week in February can be seen in figure 3. As expected, power demand is higher during the working week with peak power consumption generally occurring between 12-4pm. Curtailing these peaks will save money through arbitrage, although TRIAD avoidance would likely require load shedding to take place between 4.30-6pm, where national electricity demand is at its highest. Carbon savings will also be achieved through arbitrage and TRIAD avoidance due to smaller portions of gas and importantly, coal, in the night time energy mix.

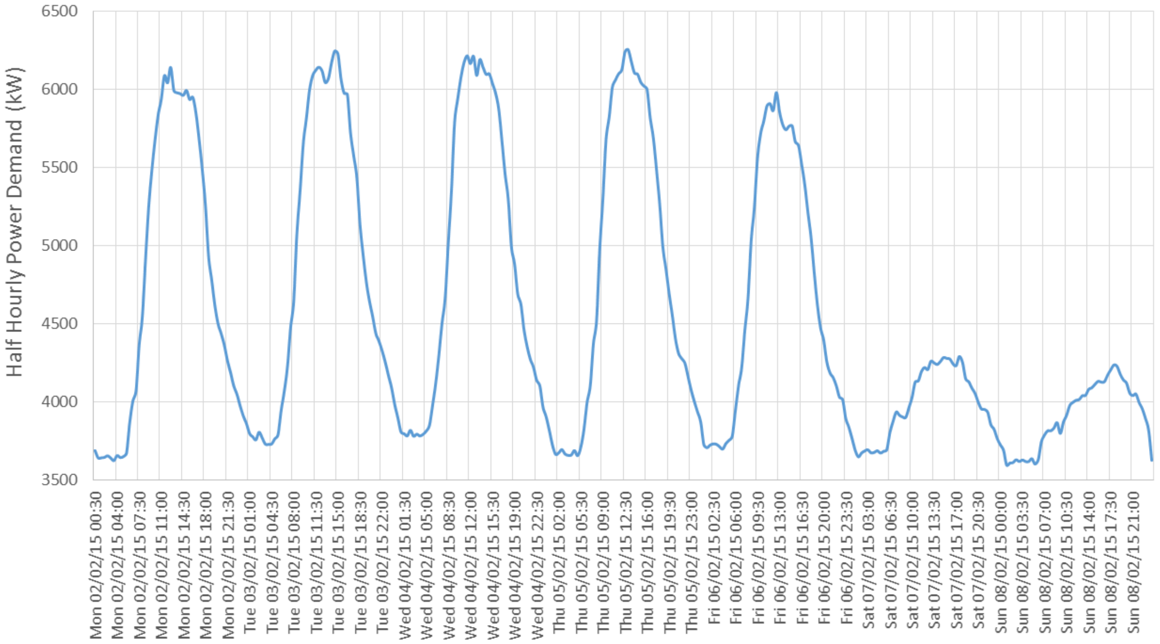

Figure 3. Half hourly power requirement of the Highfield campus during a high demand week in February 2015.

Through the replacement of lead acid with li-ion, a UPS would be capable of cycling on a daily basis, with battery manufacturer Yuasa claiming a performance of 5500 cycles at 100% DoD. The question now arises on how the capacity of the UPS is used. Three options immediately arise:

1. Extra capacity is added to the UPS battery for daily cycling ensuring that critical load can always be provided under normal UPS operation
2. The spare capacity provided to account for its natural degradation over time is used for daily cycling
3. The majority of the UPS capacity is used on a daily basis under the assumption that the capacity itself is rarely needed (times it is needed will coincide with arbitrage function anyway)

The first option does not add any value to the UPS system, since any revenue or carbon savings will effectively come from a separate ESS. Option 2 provides an advantage in that UPS functionality will not be compromised for the lifetime of the battery. Degradation of the battery capacity will take place, shortening the lifetime. Added benefits from the third option will be greater, however, use of the UPS capacity is unlikely to be popular as it interferes with its primary function. In addition, the greater DoD upon cycling will cause a greater level of capacity degradation than option 2. However, as stated in section 3.2, through use of double on-line conversion (the topology of the current UoS UPS) the chance of requiring the battery capacity is low due to its greater voltage and frequency control. Therefore, it may be possible to use a larger portion of the UPS battery capacity, although this remains speculation without a downstream UPS meter to allow an analysis on any patterns (such as time of year and time of day) in UPS battery capacity use.

5.2 Revenue Calculation

Without knowledge of how often the UoS UPS battery capacity is used, option 2 becomes the only viable scenario. Determining the capacity of the UPS was therefore done using technical specifications of the UPS systems. The cells within the UPS are 12V VRLA with a capacity of 105Ah at C_{10}. 4 parallel strings of 40 series cells results in a 480V battery with a capacity of 201.6kWh. The UPS systems themselves are rated at 360kW with a design autonomy time of 20mins and actual autonomy time of 50 minutes, i.e. time for which load can be powered. With a 20 minute autonomy time, the required capacity can be calculated as 360kW x 1/3h = 120kWh. Assuming the same capacity is required[2] implies 144kW would be supplied to the load over the course of the 50 minute actual autonomy time.

Assuming the worst case scenario that the required UPS capacity has been used immediately before cycling, Poukerts equation, eq.1 [31], can be used to estimate the remaining capacity were the battery to be discharged, for additional services, at the same rate as it was under UPS function.

$$C_n = C_r(I_r/I_n)^{pc-1} \qquad \textit{eq.1}$$

Poukert's equation is given above, where C_n = cell capacity at some discharge time n, C_r = discharge capacity at rated discharge time r, I_n = current required for cell discharge within time n, and I_r = current required for discharge within rated time r. This technique is suitable only for constant discharge currents (not the C_{10} rated current) and has shown to underestimate remaining capacity when several discharge currents are used [31]. The following therefore calculates the minimum remaining capacity. Given an actual UPS power requirement of 144kW and a voltage of 480V, the critical load draws 300A thus giving a current per string, hence cell, of I_n = 75A. An approximation of the Peukert factor, pc, was set at 1.15 [32], then given the rated capacity, $C_r = C_{10}$ = 105Ah so that I_r = 10.5A, eq. 1 is used to find the maximum capacity of each cell to be 78.2Ah when discharged at 75A, i.e. within 50mins. This gives a total UPS capacity of ~150kWh. With 120kWh needed for UPS function, around 30kWh (i.e. 20%) remains for additional services. With two such UPS facilities and another slightly smaller UPS, approximately 80kWh of spare capacity has been estimated with the current UPS sizing. Assuming the current lead-acid cells are replaced with li-ion, keeping the power and capacity requirements from the UPS identical, this 80kWh capacity can be made available for daily cycling.

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[2] The capacity discharged may actually be slightly higher since a longer discharge time will increase the batteries efficiency and hence increase the available capacity.

Performing arbitrage 365 days a year, the surplus capacity is able to save ~ £1000/year due to a price difference of 3.58p/kWh between day and night tariffs[3]. With all TRIAD periods starting at 4.30pm, 5pm or 5.30pm since 1992 (in fact over 80% of TRIAD periods started at 5pm), a conservative tactic would be to reduce power consumption by 53.3kW between 4.30-6pm during winter months, effectively ensuring a power reduction throughout the TRIAD periods and reducing payments by £2067 due to local TNUoS costs of £38.79/kW. Maximum savings/revenue of ~£3000 are available during the first year of additional cycling, with revenue subsequently decreasing with time as battery capacity degrades.

Conclusion

DSM will play an important role in future power networks, improving system reliability and enabling greater utilisation of renewables. Using UPS to provide DSM may be particularly promising as the assets already exist in numerous businesses, industries and services. However, it would not currently be possible for a single UPS site to provide any balancing services, due to the power and energy capacity required by NG. Without data on the frequency and duration with which the UPS battery capacity is called upon, it was not possible to fully determine the feasibility of using a li-ion UPS for arbitrage or TRIAD. This is a major barrier, as users will require assurance that the primary UPS function will not be compromised. Using the spare capacity from the natural oversizing of the UoS UPS provides relatively small gains but nonetheless produces cost and carbon savings. A number of issues must be addressed if a UPS is to perform additional functions. A downstream meter must be present to determine how often and to what extent the battery capacity is employed; this will allow the owner to determine whether it is possible to use the full UPS capacity during certain periods. The effect additional cycling has on the UPS/battery lifetime must be taken in to account, however, by limiting the DoD it should be possible to minimise battery degradation.

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