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BATTERY ENERGY STORAGE FOR STAND-ALONE MICRO-SOURCE DISTRIBUTED GENERATION SYSTEMS

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ABSTRACT

Micro-source distributed generation involves application of small electrical generation sources at the load centers for providing electrical energy conveniently. It can also improve the reliability of power supply to sensitive loads by connecting alongside their main grid supply. It is considered as a viable solution to support power quality sensitive loads such as critical computing and data processing electronic equipment. This is made possible by incorporating energy storage into the system. This paper presents the energy storage needs in a distributed generation system and investigates use of lead-acid batteries to meet these demands. Batteries with a good charge acceptance and low internal resistance are suitable for this purpose. A procedure for sizing the battery, along with a case study, is presented.

KEYWORDS

Distributed generation, Micro-source, Energy storage, Lead-acid battery.

1. INTRODUCTION

In the recent past, dramatic improvements in productivity have been realized in the high technology sector as well as in traditional industries. From a point of view of the electric power supply to these industries, this has led to a concomitant increase in the number of loads that are sensitive to power quality. Some of the industries that have such large sensitive loads include semiconductor manufacturing, textile mills, paper mills and plastic injection molding. Of course, a number of smaller, but equally critical loads such as computers and electronic data processing equipment are also sensitive to power quality. Loads such as computer-based equipment are characterized by stringent supply requirements given by ITI/CBEMA curves [1].

Distributed generation involves application of small electrical generation sources at the load centers to optimally utilize resources. It can be used for providing energy stabilization, ride-through and dispatchability [2]. Micro-Source Distributed Generation (MSDG) systems consist of micro-sources like fuel cells and micro-turbines with power electronic converters to interface with the load [3]. The power electronics equipment in the MSDG system makes it possible to provide Uninterruptible Power Supply (UPS) functionality, power quality improvement and energy conversion simultaneously at a reasonable cost. In the near term, the MSDG systems are seen as the most effective technologies for provision of energy and for improving the reliability of power supply in an agile and economic fashion. However, their operational and control features need to be upgraded in order to enable them to become solutions to the sensitive load problem.

A one-line diagram of a typical MSDG system functioning in stand-alone mode of operation is shown in Fig. 1. The micro-source used in the figure is a fuel cell. A three-phase Pulse-Width Modulated (PWM) inverter converts electric power from dc to ac. An LC filter circuit attenuates the PWM switching ripples in the inverter output voltage. The filtered three-phase ac voltage is fed to several three-phase and single-phase loads through a Δ-Y transformer.

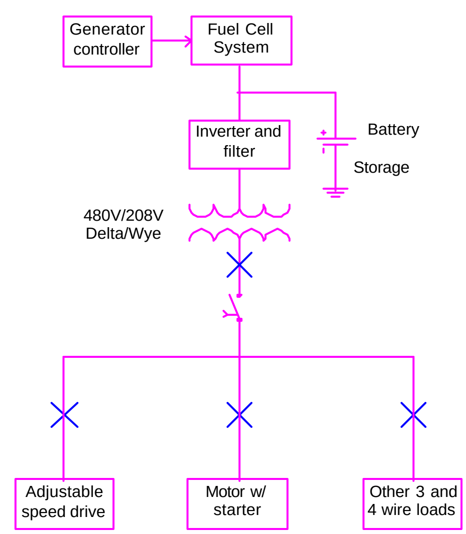

Fig. 1: Block diagram of a typical stand-alone distributed generation system connected to different classes of loads

Unlike conventional generation systems based on synchronous and induction machines, MSDG systems, which contain micro-turbines, fuel cells, etc., do not have the high inertia of a rotating mass in the energy conversion process. Furthermore, they have a slow response to step changes in load demand. As a result, under transient conditions in power demand, MSDG systems require a short-term source of energy to meet the stringent demands of premium power systems. Energy storage can be provided in an MSDG system through several means such as batteries, Super-conducting Magnetic Energy Storage (SMES), flywheel and ultra-capacitors. Among these, the technology of batteries is the most developed and is well established for a variety of applications. The other forms of energy storage are either still in the prototype stage of development or are not suitable for mass production. Since the interface between micro-source and the load/utility is typically an inverter, the dc bus forms a suitable location for fixing batteries. This paper provides considerations for sizing battery energy storage in MSDG systems.

2. ENERGY STORAGE REQUIREMENTS

It is known that an inverter without energy storage components on the dc bus is adequate to provide reactive power [4]. As mentioned earlier, a micro-source such as micro-turbine or fuel cell provides real power to the load except during transients owing to their slow response. Consequently, the energy storage in an MSDG system is mainly sized to source real power during such transient events.

Load transients occur from faults in transmission line and/or load switching. For instance, a 75 kW Honeywell™ micro-turbine takes about 35 s to respond for a 50 % change in power demand under grid-connected mode of operation [5]. On the other hand, some fuel cells require about 10 s for a 15% change in power output [6]. Furthermore, a fuel cell also has a recovery period of a few minutes to establish equilibrium before it can meet another step change in power output. The typical response that can be expected of a micro-turbine for a step change in load demand is illustrated in Fig. 2. In the figure, P_L denotes the load power demand; P_S is the response of the micro-turbine and (P_L-P_S) is the shortage in power that needs to be supplied through some means. In grid-connected mode of operation, the grid supplies this shortage in power until the micro-source responds to the transient event. However, in stand-alone mode of operation this sudden demand can be met only if additional storage is included in the MSDG system. Batteries connected to the dc bus of the inverter, provide the balance power (P_L-P_S) in this case.

Batteries, in general, are of two types – primary and secondary. Among them, a secondary (rechargeable) type is chosen if repeated discharge cycles are needed, a charging source is available, the capacity per given weight is sufficient and a lower cost averaged over the life of many cycles is needed. Thus, a rechargeable battery is suitable for use in an MSDG system. The currently available rechargeable batteries include – lead-acid, nickel cadmium (NiCd), nickel metal hydride (NiMH) and lithium (Li)-ion. NiCd and NiMH are not preferred in utility applications since they have very high self-discharge rate. Although, Li-ion has the highest energy density, it is also the most expensive. The cost/kWh of a lead-acid battery is the least among these and it can meet the power density requirements of MSDG applications. So, a lead-acid battery is considered the most suitable for MSDG applications for further study in this paper.

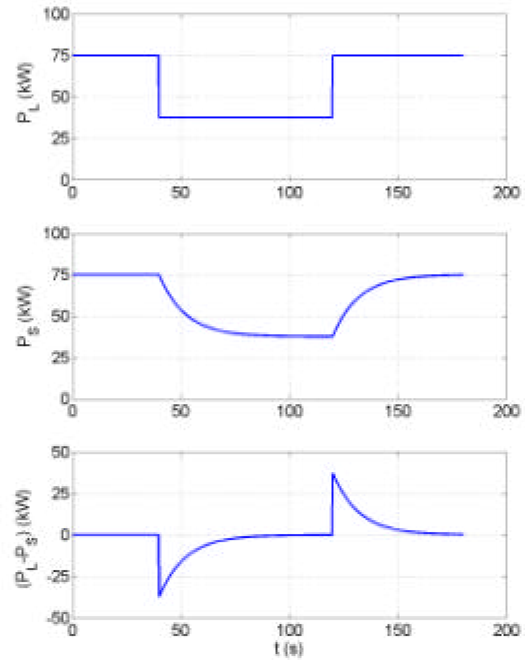

Fig. 2: Typical step response of a micro-turbine. P_L - Load power demand, P_S - Response of the micro-turbine.

3. LEAD-ACID BATTERIES

Lead-acid batteries are made for deep-cycle or starting applications. Deep-cycle batteries are used in back-up power applications where power is needed for longer durations. These batteries are typically applied in electric vehicles and UPS systems. Starting batteries are commonly used to start internal combustion engines. No power is drawn from these batteries during the normal operation of the engines. They are capable of providing large currents for a very short interval of time. For that reason, starting batteries of higher capacity are suitable for MSDG applications.

Battery sizing is dependent on the number of cells it contains, and the capacity of each cell. The cell capacity is normally measured in ampere-hours denoted here as Ah. A method of specifying charge and discharge rates of a cell is the C rate, which is defined as the current flow rate that is numerically equal to the cell rated capacity [7]. Both charge and discharge rates are normally represented as multiples of the C rate. A current that would nominally discharge the battery in 1 hour is represented as 1C. The short duration discharges typically at 3C or higher are termed as high-rate discharges. For a battery, the MSDG system is a high-rate discharge application. The maximum discharge in MSDG applications involving micro-turbines typically occurs in 100 s, and therefore discharge rate in these applications is about 36C. Battery parameters need to be derated at high discharge rates, due to increased losses in it under these conditions. For example, a battery rated on a 10 hour rate may have only 44% deliverable capacity if the discharge is conducted in 0.2 hours (i.e., 12 min.).

Most battery manufacturers' data-sheets provide tables containing dc amperes that the battery can source at different final volts per cell and for different periods of time. These tables incorporate the derating necessary for high-rate discharge application for values at lower time intervals. It may be noted that all battery ratings are for a nominal room temperature of 25°C or 77°F, and additional derating will be necessary for lower temperatures. In addition to loss of energy storage capacity, the terminal voltage of the battery is also strongly affected by the discharge rate. Fig. 3 illustrates the battery current and the corresponding terminal voltage for two sizes of cell, 'X' and 'D', at two different temperatures. In the figure, battery 'X' is rated at 3.2 Ah and 'D' at 1.8 Ah.

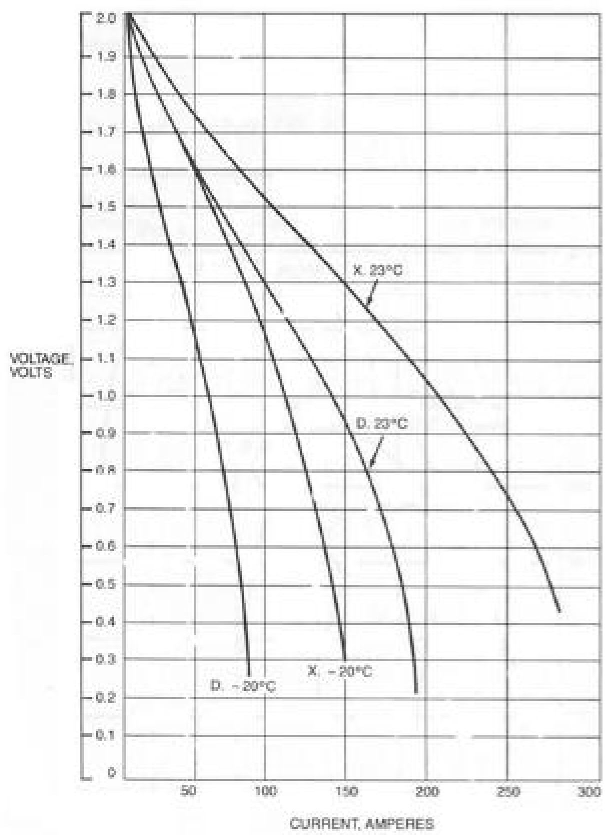

Fig. 3: Peak current and voltage per cell of a lead-acid battery for a high-rate discharge [7]

In addition to high-rate discharge, the battery is also subjected to high-rate charging in an MSDG system. This occurs when the load is suddenly removed and the micro-source continues to supply power until it is able to respond to the new power set point. The battery has to be capable of accepting this difference in power for a short duration. Thus, the battery must have high charge acceptance too.

4. BATTERY SIZING

A strategy for appropriately oversizing the battery capacity to ensure that the batteries are adequate to meet the demands of MSDG systems is presented. Commonly used battery parameters are introduced and the mathematical expressions relating the parameters are derived. The main criterion to be satisfied by the battery is to meet any change in load power demand until the micro-source responds to follow it. Provisions can also be made for including UPS function capability in the MSDG system, i.e. operation of the system for extended periods without any power delivered from the micro-source.

Design consideration of batteries for a typical MSDG system begins with characterization of the cell, which is the basic unit of a battery. Cells are specified with a nominal cell voltage (V_{cn}). It is equal to the open-circuit voltage of a cell at 100% state of charge and is the recommended float voltage of the cell. Let the cell voltage at the completion of discharge be denoted by Final Volts per Cell (FVpC). The FVpC of the battery should be selected as high as possible, at the expense of overcapacity. It may be selected within 80 – 90% range of V_{cn}.

$$FVpC = 0.8\, V_{cn} \qquad (1)$$

For a high-rate discharge application, typical FVpCs specified in the battery manufacturers' datasheets are 1.75, 1.78 and 1.81 V. The nearest value available in the data-sheets to that calculated from (1) may be selected as FVpC.

Let V_{batf} represent the terminal voltage of the battery (consisting of a series string of N_c cells) after discharge. Then, the number of cells is given by

$$N_c = \frac{V_{batf}}{FVpC} \qquad (2)$$

If N_c is not an integer, the next higher integer is chosen. For a battery connection in unregulated dc bus configuration, V_{batf} is equal to the minimum dc bus voltage of the inverter. The inverter dc bus voltage is in turn dependent on its ac voltage constraints. Likewise, in the regulated dc bus configuration, V_{batf} is decided by the dc/dc converter switching scheme.

The battery must be designed to provide power for a brief period, during a change in load demand. If the maximum change in real power demand of the load is known beforehand, it is possible to select a battery. It may be assumed that this condition occurs when switching from no-load to full-load. This has been found to be true in practical test results on Micro-Turbine Generators (MTGs) [5]. The ramping period is the highest for load change from no load condition to full load condition for a 75 kW Honeywell MTG and a 28 kW Capstone MTG. If $P_{b,max}(t)$ is the maximum power drawn from the battery in $T_{r,max}$ seconds, it is dependent on the full-load power (P_{fl}) as follows

$$P_{b,max}(t) = P_{fl} \cdot g(t) \qquad (3)$$

where g(t) is an increasing function beginning at zero and reaches a peak value of unity at a time $T_{r,max}$. The function g(t) is dependent on the type of response of the micro-source. Typically, g(t) may describe a ramp function or an exponential function.

The maximum energy storage required in the battery ($E_{b,max}$) may be determined by

$$E_{b,max} = \int_0^{T_{r,max}} P_{b,max}(t)\, dt \qquad (4)$$

The integral can be evaluated as

$$E_{b,max} = \kappa \cdot P_{fl} \cdot T_{r,max} \qquad (5)$$

where

$$\kappa = \int_0^{T_{r,max}} g(t)\, dt \qquad (6)$$

The value of κ is evaluated to be 0.5 and 0.2 when g(t) is a ramp function and an exponential function, respectively.

The full-load power (P_{fl}) can be obtained as

$$P_{fl} = \frac{kVA_{fl} \cdot pf}{\eta} \times 10^5 \qquad (7)$$

where kVA_{fl} is the full-load kVA of the inverter, pf is the power factor of the load connected to the inverter, and ? is the inverter efficiency in %.

Combining (5) and (7),

$$E_{b,max} = \frac{\kappa \cdot kVA_{fl} \cdot pf \cdot T_{r,max}}{\eta} \times 10^5 \qquad (8)$$

An expression for the ampere-hour per cell (Ah) of the battery is given by

$$Ah = \frac{E_{b,max}}{N_c \cdot FVpC \cdot 3600} \qquad (9)$$

Substituting (8) into (9),

$$Ah = \frac{\kappa \cdot kVA_{fl} \cdot pf\ T_{r,max}}{N_c \cdot FVpC \cdot \eta \cdot 3600} \times 10^5 \qquad (10)$$

The C rate of the battery is numerically equal to the Ah value obtained above. The discharge rate of the battery is specified in multiples of C rate. If d is the multiplier that determines the discharge rate of the battery, then

$$d = \frac{3600}{T_{r,max}} \qquad (11)$$

and the discharge rate of the battery may be expressed as dC.

The dc amperes drawn from each cell of the battery is the Amperes per Cell (ApC). It is obtained as

$$ApC = d \cdot Ah \qquad (12)$$

for a duration of $T_{r,max}$. It is to be noted that ApC is the average current drawn from the battery during discharge. In a high-rate discharge application, peak current would be about an order of magnitude higher than ApC.

A micro-turbine has a start-up time to reach full-load power from its cold start. For example, the start-up time for the 28 kW Capstone Micro-Turbine is approximately two minutes [8]. If it is desired to accommodate cold start of the micro-turbine, the expression for $E_{b,max}$ in (5) has to be modified to include the power drawn by the battery during start-up. The modified equation will be

$$E_{b,max}(t) = \kappa \cdot P_{fl} \cdot T_{r,max} + P_{cs} \cdot T_{cs} \qquad (13)$$

where P_{cs} is the power drawn (in watts) during cold start of the micro-turbine for a period of T_{cs} seconds. And the subsequent equations can be reformulated.

These design guidelines for sizing of batteries are presented in Fig. A1 in the form of a flow chart (refer APPENDIX).

4. CASE STUDY

A simulation model of the MSDG system along with battery storage is developed. The micro-source power supply and load power demand are modeled by mathematical functions to represent a typical micro-source and load. In order to model a micro-source, results of tests conducted by Southern California Edison on Micro-Turbine Generators (MTGs) [5] are utilized.

The specifications of the MSDG system are as follows:

Table 1: MSDG system specifications

Parameter	Value
V_{batf}	450 V
kVA_{fl}	60 kVA
pf	1.0
?	80 %
$T_{r,max}$	150 s

In this case, $\kappa = 0.2$ (Assuming an exponential response of the micro-source to a step change in power demand). UPS and cold start functionality is not included in the MSDG system. Then, the design procedure given in Section III is used to obtain the required capacity of battery storage and the required number of cells for a typical MSDG system.

From the data-sheets, cell nominal voltage is typically

$V_{cn} = 2.28$ V

Final volts per cell (FVpC) is calculated using (1) as

$FVpC = 0.8\ V_{cn} \approx 1.81$ V

Using (2), the number of cells required for the battery will be

$$N_c = \frac{V_{batf}}{FVpC} \approx 249$$

For providing a full-load demand of 100 kW, ampere-hour per cell of the battery is computed using (10) and (11) as

$$Ah = \frac{\kappa \, . \, kVA_{fl} \, . \, pf \; T_{r,max}}{N_c \, . \, FVpC \, . \, \eta \, . \, 3600} \, x \, 10^5 = 1.4$$

$$d = \frac{3600}{T_{r,max}} = 24$$

The amperes per Cell (ApC) of the battery is computed from (12) to be

$$ApC = d \, . \, Ah = 33.6 \text{ A}$$

These battery parameters are utilized in modeling a battery. Several models of lead-acid batteries are available in literature. A simplified model is used herein, whose equivalent circuit is shown in Fig. 4 [9]. This model gives a good representation of the self-discharge, storage capacity and internal resistance.

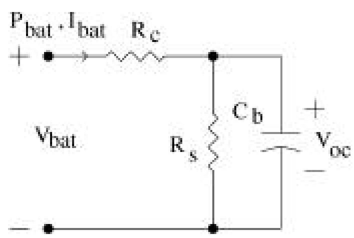

Fig. 4: Equivalent circuit of a lead-acid battery

P_{bat}, V_{bat} and I_{bat} denote the power, voltage and current of the battery. Battery open-circuit voltage (V_{oc}) is a function of the average specific gravity and temperature of the sulfuric acid electrolyte in the cell. Battery equivalent capacitance (C_b) is estimated from the maximum energy that it has to supply. The series charging/discharging resistance (R_c) is the effective internal resistance that can be obtained from the battery manufacturers' data-sheets. R_c includes the effects of the resistivity of the plate grids, the lead posts, the terminals and the interface contact resistance between these parts of the battery. The self-discharging resistance (R_s) is a function of its self-discharge characteristics. It can be obtained from the battery manufacturers' data-sheets.

The equivalent capacitance of the battery is determined as

$$C_b = \frac{2 \, . \, Ah \, . \, 3600}{V_{oc}} = 22.4 \text{ F}$$

Battery self discharging resistance (R_s) and internal resistance (R_c) are obtained from the data-sheets for N_c cells as

$R_c = 1.49\ \Omega$ (for N_c cells)

$R_s = 25\ \Omega$

The parameters of the example case study described above was simulated using MATLAB/Simulink[TM]. Fig. 5 illustrates the results from the simulation. The figure demonstrates battery response to a step change in load power demand under the following conditions – from full-load to no-load at t = 20 s and from no-load to full-load at t = 200 s. The ApC value computed above is the average current during discharge. It is observed that the peak battery current is about one order of magnitude higher than ApC. The terminal voltage (V_{bat}) waveform shows a sudden change at the instant of the high-rate charge and discharge. This is due to the internal resistance of the battery during a high-rate charge and discharge. Selecting a higher capacity battery can further reduce these voltage variations.

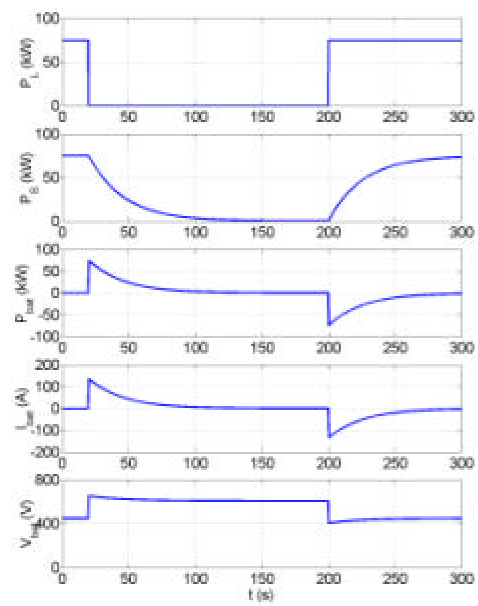

Fig. 5: Step response of a battery based MSDG system

An important assumption made in the simulation is that the values of the equivalent circuit parameters are not varying. In reality, these parameters are affected by temperature, state of charge, rate of discharge, etc. The battery models can be made more complicated to faithfully reproduce behavior that is more complex. However, for studying the general behavior of the battery from a systems viewpoint, the present models are deemed adequate.

5. CONCLUSIONS

Micro-source distributed generation (MSDG) systems are considered to be a valuable solution for providing power quality solutions to sensitive loads. The electrical energy is generated from environmentally preferred means and at a competitive cost. However, they require additional energy storage to meet abrupt changes in power demand in the stand-alone mode. The inherent delay in the response of micro-sources to fluctuations in load power demand is responsible for this requirement.

Lead-acid batteries are investigated for use as energy storage devices in the MSDG systems. The batteries are subjected to high-rate charging and discharging for a short interval of time, usually in the order 5 - 200 seconds. Thus, an MSDG system requires batteries with good charge acceptance and low internal resistance in order to maintain high power efficiency.

A procedure for sizing of batteries for MSDG application is presented. It takes into consideration the high-rate discharge effects on batteries. In addition, it ensures that the battery can provide the maximum instantaneous power required by the load. It can also be extended to other forms of MSDG systems and other types of batteries with some modifications. Simulation is conducted using MATLAB/Simulink™ software to verify the operation of the battery based MSDG system.

6. ACKNOWLEDGEMENT

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APPENDIX

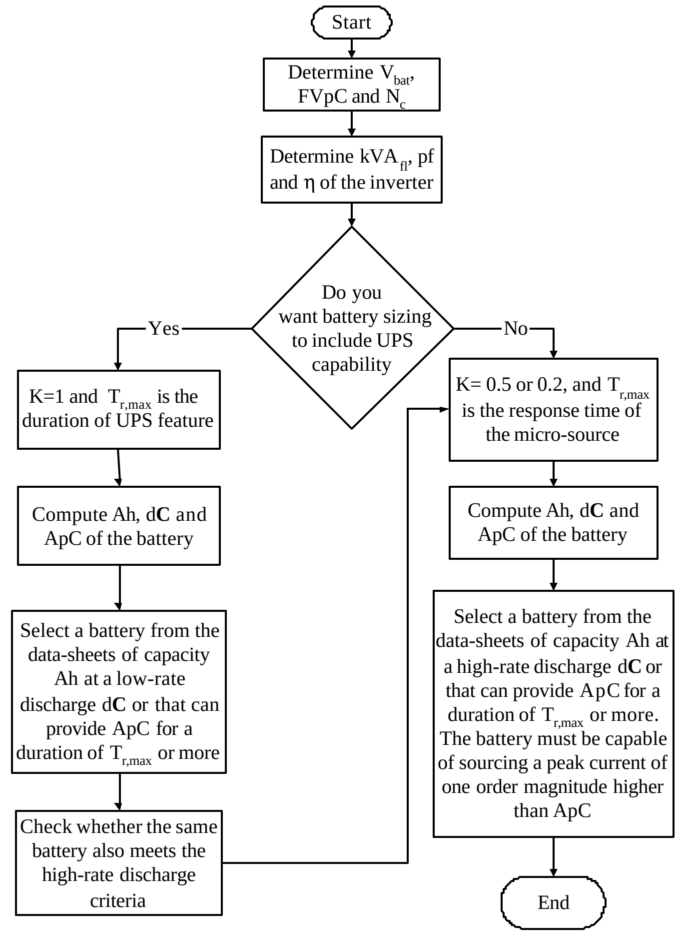

Fig. A1: Flowchart describing the battery sizing approach