GreenDataNet

D1.6 - Energy Storage and PV Architecture design

Final

Eaton Electrical, Power Quality & Electronics Division (PQED)

TABLE OF CONTENTS

REVISION SHEET

Revision Number	Date	Brief summary of changes
Rev 0.1	30/09/2014	First concept
Rev 0.2	30/10/2014	Baseline document as presented in Conference Call
Rev 0.4	19/11/2014	Concept document
Rev 0.5	19/12/2014	Final version
Rev 0.6	30/12/2014	Integration of Optimization explanation
Rev 0.7	09/01/2015	Introduction modification and Minor changes
Rev 0.8	07/03/2015	Comments added

2. INTRODUCTION

2.1 PURPOSE OF THE DOCUMENT

The aim of this document is to describe higher level requirements related to the UPS system for the urban data centre environment as targeted by the GreenDataNet project. This document describes requirements for the UPS and its interfaces for the PV energy source and EV Li-Ion battery. It also describes operational concept and use cases of the integrated UPS system in energy efficient data centre environment.

2.2 DOCUMENT OVERVIEW

This document is organized as follows. The chapter 3 provides technical and functional requirements as well as use cases. The chapter 4 introduces alternative UPS system topologies and presents the selected topology. The chapter 5 focuses on the interface between PV array and the UPS system. Interface between Nissan battery and Eaton UPS is presented in the chapter 6. The last part details the system architecture of the Demonstrator.

3. GREENDATANET UPS SYSTEM REQUIREMENTS

IT power of the Data Centre is the key parameter when specifying requirements for the UPS system. Based on definition of Urban Data Centre provided in deliverable D1.1, the GreenDataNet UPS (GDN-UPS) system for type I Data Centre shall be specified to the power range from 10 to 40 kW. Accordingly, type 2 data centre needs an UPS system rated from 20 to 250 kW IT load [19].

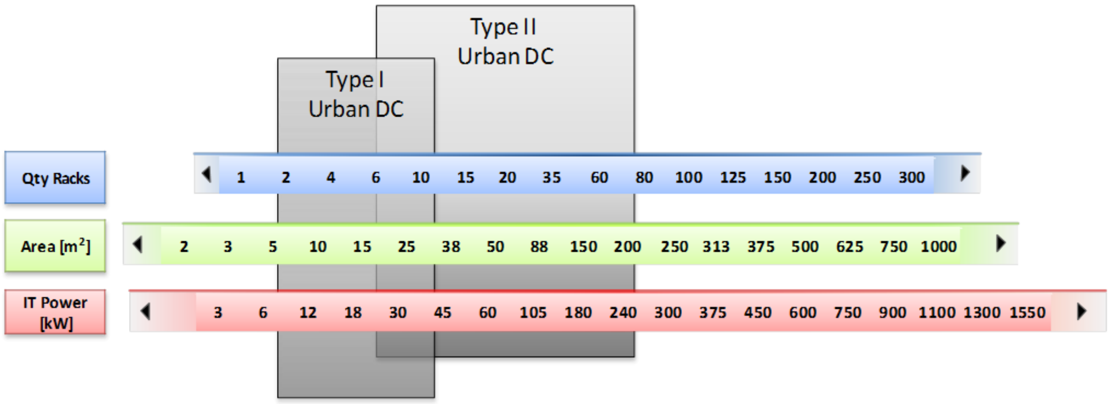


Figure 3-1 Capacity ranges of Type I and Type II Urban Data Centres (Source: ICTroom, GDN D1.1)

GreenDataNet targets to utilize up to 80% of renewable power and decrease average Power Usage Effectiveness (PUE) must be taken into account also in GDN-UPS design. Overall efficiency of the UPS system shall be as high as possible, typically up to 96% and even more, on double conversion operating mode. In GDN-UPS there shall be also an interface for PV source. It is assumed to be located in vicinity of the data centre.

Capability to store energy into Nissan Li-Ion batteries is one of the key requirements in GreenDataNet. Depending on the type of the data centre, requirement for battery back-up time varies typically between 5 to 30 minutes. There shall be a possibility to connect minimum four (4) Nissan batteries in parallel into one GDN-UPS unit. Capacity of such a battery pack is 96 kWh, enabling load peak shaving operation during load peaks.

The GDN-UPS shall be scalable system, enabling external parallel connection of the units. Mechanical dimensions and environmental specifications for the equipment shall follow the European DC Standards.

The GDN-UPS shall provide interface for communication with IT equipment and facility systems.

3.1 USE CASES

3.1.1 GRID OPERATION

In grid operation (also called as normal operating mode) the GDN-UPS supplies all power to the load from the utility mains. The PV source is disconnected if available power is too low (low irradiation) or there is a fault in PV array. Batteries are on the float charge or on the rest mode, depending on the battery state of charge. Battery charger is only turned on when the batteries need to be charged.

In normal grid operation the GDN-UPS can be in following modes:

a) Double conversion mode: the mains AC power is converted first to DC by rectifier. Then inverter derives regulated DC power from rectifier and produces regulated and filtered three-phase AC power to the load.
b) Energy Saver System mode: load is supported securely by utility power through the static switch with double conversion available on-demand with typically less than 2 ms transition time.
c) Bypass mode: the load is supported directly by utility mains through the UPS static switch.

3.1.2 STORED ENERGY MODE

On the stored energy mode (battery mode) the GDN-UPS is supplying power to the load from the battery. The UPS transfers to the stored energy mode automatically when the mains power fails or if the utility power does not confirm to specified parameters. In the grid operation the GDN-UPS can share the battery power when supplying the load if the mains utility input voltage is out of specification.

3.1.3 PV OPERATION

On the PV mode the GDN-UPS is operating independently without utility mains feed. Following use cases are supported:

a) PV is supplying power to the load, battery is on the rest mode
b) PV is charging battery, load is disconnected
c) PV is supplying power to the load and charging battery

In case the GDN-UPS is shutdown PV arrays are also disconnected.

3.1.4 LOAD SHARING

The GDN-UPS is able to share the load between utility mains, PV source and the battery. The PV source has a highest priority to provide power to the load. Following use cases are supported:

a) Utility mains and PV source are both supplying the load

b) Utility mains is lost, battery and PV source are both supplying the load
c) Utility is regaining, GDN-UPS resumes utility mains and PV power share

3.1.5 LOAD PEAK SHAVING

On the load peak shaving operation the battery energy and PV source of the GDN-UPS can be used to reduce peak demand and thus reduce the electricity cost by discharging a stored energy during load peaks.

Recharging of the battery is executed during the low demand periods, typically at night hours, but also when daytime demand is low and solar energy is available.

Commands for peak shaving operation must be provided as an external signal to the GDN-UPS signal input or through the remote monitoring interface.

This functionality was not planned in the initial description of work, but the team has considered that it would be worth to implement it as the it was not time-consuming to implement while it provides added value for the integration with the Smart Energy system that will be implemented in D3.7 – Smart Energy management system where the overall energy control is detailed .

3.1.6 BACKFEED TO UTILITY

Power back feed to utility is executed only in a case neither the load nor the battery is able to demand all the power supplied from the PV source.

Basically, power back feed to utility would enable data centre owner to support utility network in short peak demand periods by discharging stored energy and feeding solar energy to the utility network. However, even if the Rectifier and the inverter are both bi-directional, these use cases are not fully implemented to the GDN-UPS.

4. GREENDATANET UPS SYSTEM TOPOLOGY SELECTION

The power distribution architecture within a data centre affects also the integration of PV source and energy storage. Following factors shall be taken into account when selecting the most feasible solution:

a) the targeted size of the data centre
b) the critical IT load to power
c) required back-up time for the load
d) the variable energy available from the PV panels

Three alternative topologies for integration of PV source and a UPS were studied in order to find the best trade-off between total system efficiency, power density and system feasibility.

4.1 PV INTEGRATION IN DATA CENTRE POWER ARCHITECTURE

The first phase of the study involved a literature review of the state of the art of the UPS system and its environment 'Data Center' to understand the problems of photovoltaic integration and the performance of the overall system.

The PhotoVoltaic system can be integrated in different positions of the power chain of the Data Centre as described in Figure 4-1.

The first possibility would be to connect the PV panels directly at the input of the IT equipment, but by definition, the PV production is not constant, and it could not represent a reliable source to feed the IT power. Another possibility to integrate the PV power within the Datacentre is to connect PV production system in parallel with the grid which feeds the DC, via a PV inverter, which converts the DC power produced by the Solar system into an AC signal at the frequency of the grid. Therefore, Data Centre power consumption from the grid would be reduced thanks to produced PV power. This configuration is interesting especially when PV panels peak power could be higher than Datacenter power requirements, so the extra power would be re-injected into the grid.

Considering the case of GreenDataNet, where the aim is to allow Urban Data Centres (Urban DCs) to reach 80% of renewable power and decrease their average Power Usage Effectiveness (PUE), PV panels would be installed at building roof, so available surface for PV panels installation would never exceed datacentre surface.

Taking into account that:

- Average power densities range in Urban Data Centres (Urban DCs) vary between 0,5 to 2,5 kW/m^2[19].
- Maximum PV panel power density is 0.2kW/m^2 at optimal conditions of 1400W/m^2 of solar irradiation, and panel efficiency of 14%.

Consequently, PV power could never be re-injected into the grid because it could not be greater than datacentre power requirements, moreover, this power could not even be greater than IT load power requirements in a DC at PUE > 2 [20].As a result, if PV panel is integrated in parallel with the grid, conversion losses will occur in order to feed IT load as seen on Figure 4-1 Possible positions for PV power injection in the DC power infrastructure, which will reduce PV integration efficiency.

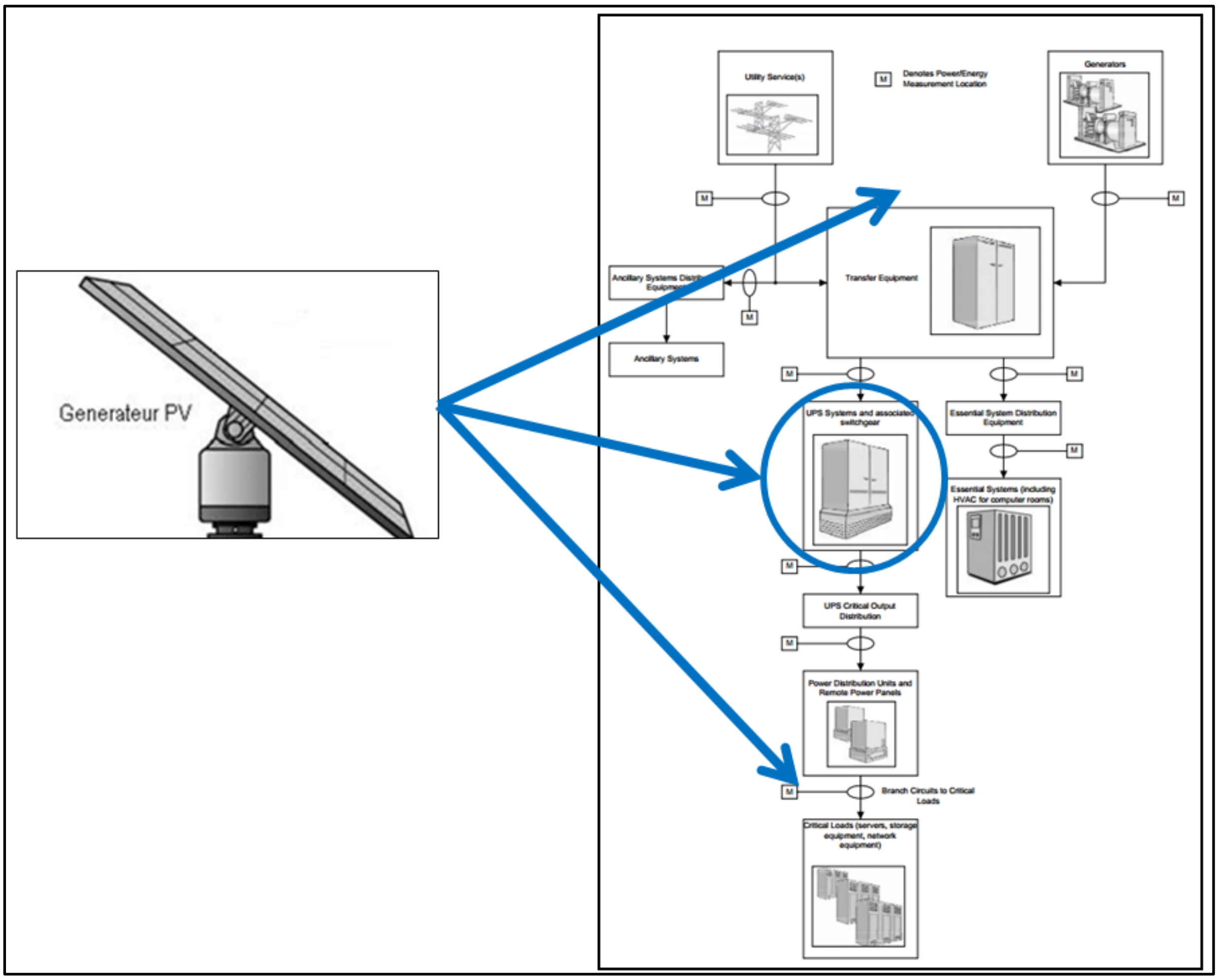


Figure 4-1 Possible positions for PV power injection in the DC power infrastructure

Taking into account the size of the targeted Data Centre which could be small to mid-size, the critical charge we have to power ‘IT Load’, and the variable available energy on photovoltaic panels, the most efficient way to take advantage of PV energy would be to connect them directly to UPS systems, so we could reduce the amount of loss due to power conversion steps.

4.2 ALTERNATIVE SYSTEM TOPOLOGIES

4.2.1 PV SOURCE WITH A GRID-CONNECTED INVERTER

A grid-connected PV inverter in the UPS input would be a simple and straight forward solution to integrate PV source to the Data Center power distribution system. However, the overall efficiency of the power system is low because of four power conversion stages from PV array to the load. In a typical grid-connected PV-inverter a DC/DC-converter and a DC/AC-converter are connected in cascade. In this topology there are additional two power conversion stages inside a UPS.

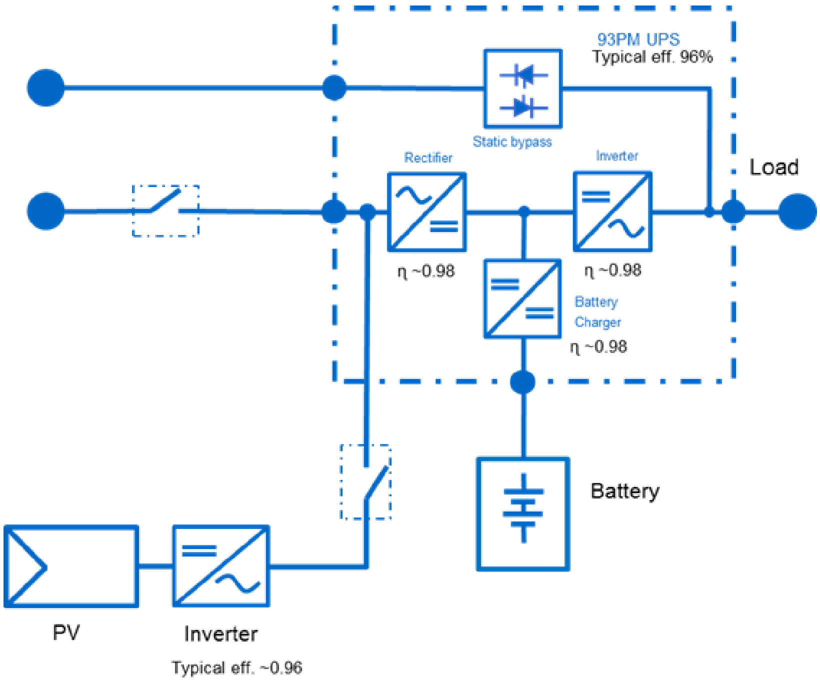


Figure 4-2 PV source with a grid connected inverter

Typical weighted efficiency for the commercial grid connected PV inverter is about 96 – 97%. Accordingly, typical efficiency in double conversion mode for premium class UPS's is around 96% [21]. For external cabling and connections about 1 % losses should be estimated. As a result, approximately 91-92% total power conversion efficiency for the PV system can be achieved with this topology.

Another disadvantage in this topology is the space occupied by separate PV inverters. Also additional cabling and connections between separate units are increasing total system losses.

4.2.2 PV SOURCE WITH A DC/DC-CONVERTER

Alternative solution to integrate PV source and a UPS is to replace inverter with the DC/DC-converter and connect it directly to the DC-bus inside the UPS device. Compared to previous topology there are two power conversions stages less in this topology, meaning higher total system efficiency. This topology also provides the possibility to integrate the PV interface into the same hardware platform with the UPS and energy storage. It will enable higher power density and smaller footprint in Data Center facility. Reduced power cabling and connections improves also total system efficiency.

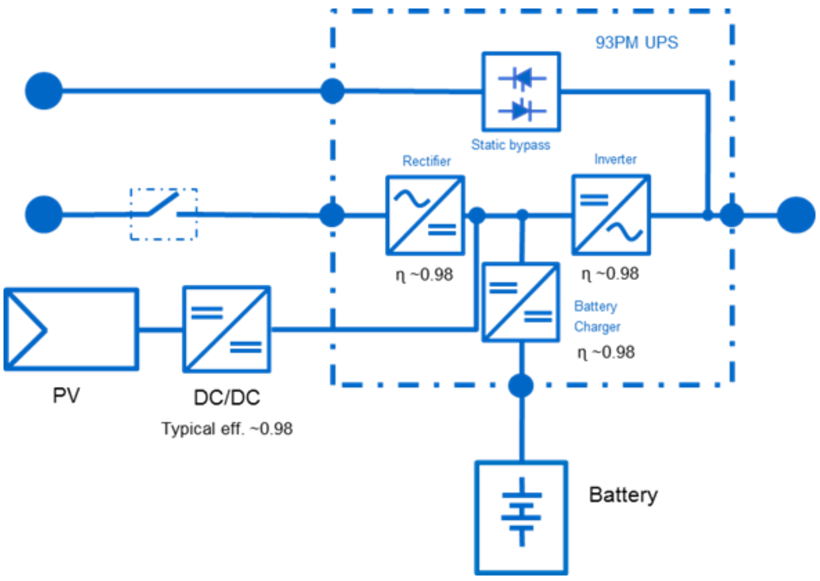


Figure 4-3 PV source with a DC-DC converter

Typical efficiency for the DC/DC converter in the PV interface can be as high as 98 – 99% [22] and it can be integrated both electrically and mechanically directly to the DC-link of the UPS. Efficiency of the DC/AC conversion inside a UPS can be higher than 98%. For external cabling and connections less than 1% losses can be estimated. As a result, approximately 96-97% total power conversion efficiency for the PV system can be achieved with this topology.

4.2.3 PV ARRAY CONNECTED DIRECTLY TO THE DC-BUS OF A UPS

The third topology alternative is to connect PV arrays directly to the DC-bus of the UPS. In this topology there is only one DC/AC power conversion stage from PV source to the load. Theoretically, highest possible total power conversion efficiency, about 97-98%, could be reached with this solution. Also integration rate and power density of the system would be highest.

However, some drawbacks are related this solution. The DC-bus voltage of the UPS is regulated and voltage level has to be kept in certain limits in order to perform its basic operation as a UPS device. In this topology PV array voltage should be specified to that same narrow voltage range.

PV panel is inherently a nonlinear current source and its output power is dependent on ambient temperature and irradiation. Based on that, there would be only few operating points and occasions when the PV source was able to generate power to the load. So, this topology alternative is not a feasible solution to be used as we are trying to maximize the HW platform efficiency.

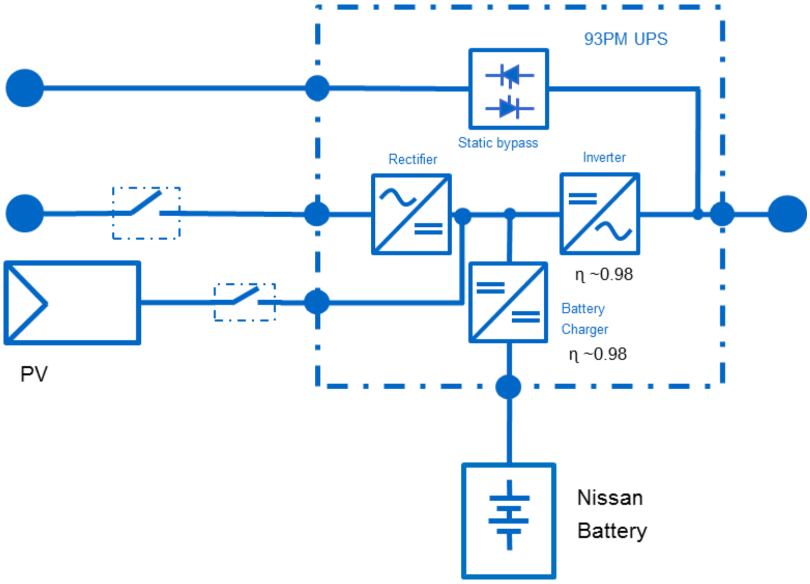


Figure 4-4 PV array directly connected to the DC bus

4.3 OVERVIEW FOR THE SELECTED TOPOLOGY

The conclusion of the topology analysis is that the most efficient and feasible method to take advantage of the PV energy is to connect it directly to the DC-bus of the UPS by using DC/DC-converter. This decreases losses due to reduced number of power conversion stages, increases power density and provides flexibility for PV array specification.

The selected system topology is presented in the figure below. It enables integration of PV source interface and energy storage capacity into one HW platform. A PV and energy storage interfaces design is discussed more detail in the following chapters.

The system topology should include the following functional blocks and sub-systems:

- Rectifier for the utility interface
- Static switch for the utility bypass operation
- Inverter for the load interface
- Battery charger for the energy storage interface
- The EV Li-Ion battery
- DC/DC converter for PV interface
- PV array

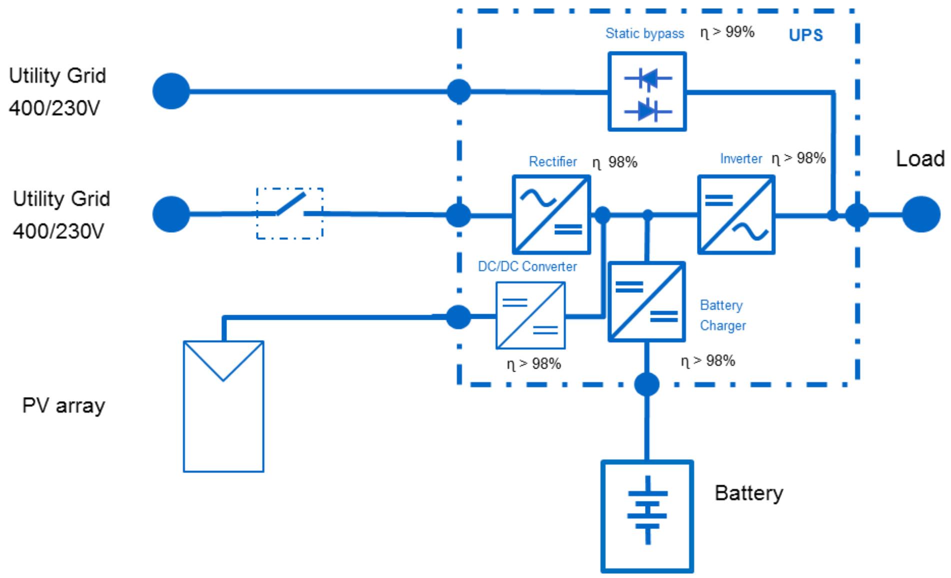


Figure 4-5 Functional blocks of the HW system

The GDN-UPS design is based on the integration of Eaton 93PM UPS family and Nissan Leaf EV batteries.

5. INTERFACE WITH PV SOURCE

The interface between a PV array and a UPS is done by means of DC/DC-converter. Following factors are specifying the interface between the PV array and the UPS:

a) Maximum allowed PV system voltage
b) DC-bus voltage of the UPS
c) DC/DC-converter topology selection
d) Grounding of the PV array system
e) PV system efficiency requirements

5.1 PV FIELD SPECIFICATIONS FOR THE PV INTEGRATION

With the wide expansion of PV installations, different arrangements of PV panels with their associated power converters have been developed to increase power production and reliability of the PV generators, Figure 5-1: PV Field Topologies. In the following chapter, most interesting system topologies will be presented, the most adapted to GDN case will be retained, then the needed power electronic converters will be studied.

5.1.1 REVIEW OF PV FIELD TOPOLOGIES

Today, the most common topology is the central inverter [1], which consists of using a single inverter as interface between the PV field and the grid. In this configuration, the number of PV panels connected in series is determined to correspond to the inverter input voltage range, then several strings are connected in parallel to meet the power constraint of the installation. The central inverter has usually a variable voltage input range, which is possible thanks to a DC-DC converter installed at the input of the inverter.

This topology is very attractive because it is inexpensive, simple to maintain and monitor. On the other hand, the use of a single MPPT for the entire field does not make the optimum field power extraction; especially when it is partially shaded.

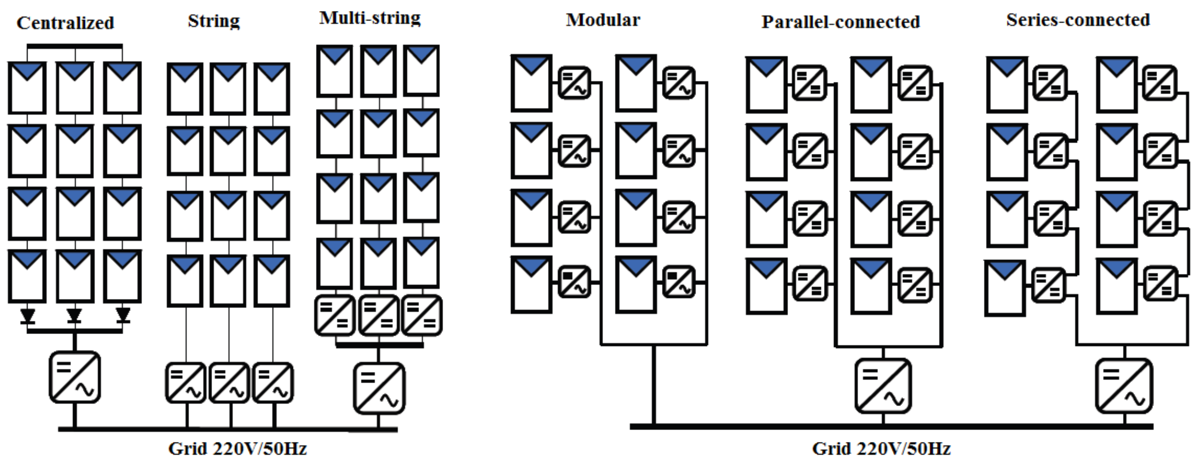


Figure 5-1: PV Field Topologies

The String Inverter configuration [2] consists in one inverter for each array of PV panels , also known as string. This has the effect of increasing the number of MPPT in the field and allows to have better continuity of service comparing to the central inverter, upon failure of the inverter, for example. However, the overall cost of the system increases and the string inverters efficiency are low when the solar energy is not enough. To increase the efficiency of inverters at low insolation, improved concept called "team" was developed. The team concept is to reduce the number of inverters that convert the power of the field by installing controlled switches between the strings at the level of the inverter. Similarly, the multi-string inverter allows a single inverter[3], while retaining the possibility of using a MPPT per string by using a DC-DC converter per string. The main interest is to reduce the cost investment comparing with the use of string inverters by making the DC to AC current conversion in a single element, the main inverter. On the other side, service continuity and scalability of this topology are reduced because this main inverter is a single point of failure.

The literature proposes also other modular systems, closer to the energy source, such as individual inverter assemblies (or Modular Inverter) parallel/series-connected DC-DC topologies [2]. The advantage of these architectures is to reduce the impact of one panel on the overall operations of the field, because they always extract the maximum energy from the PV field. In return, the increasing number of power electronics converters considerably complicates the monitoring and the maintenance of the installation.

The modular inverter allows to provide power directly to the grid. Parallel topology uses a boost converter, per PV panel/array, connected to a higher DC voltage (400 V), which is connected to an inverter. The series-connected topology also uses a DC-DC converter per PV panel/array, but they are connected in series to increase the conversion efficiency.

Finally, centralized architectures have the advantage of being simple and inexpensive while the modular structures may offer better scalability, continuity of service, and monitoring but are more expensive.

5.1.2 SELECTED TOPOLOGY FOR GDN CASE

Since the UPS already has an inverter in its structure, inverter based PV field topologies are not adapted to interface with the UPS. Therefore, selected PV field topologies for GDN case are shown in Figure 5-2: PV Field Topologies in GDN Case.

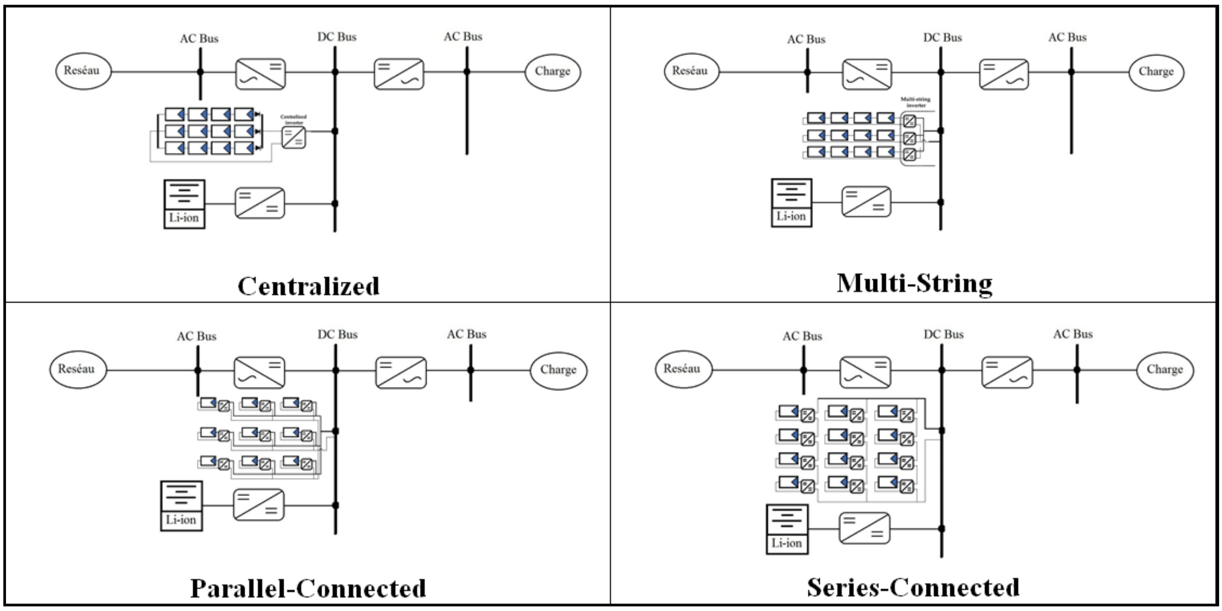


Figure 5-2: PV Field Topologies in GDN Case

The following study will focalize on these architectures to choose the most advantageous one regarding Data Centre power specifications.

5.1.3 DC-DC CONVERTERS FOR PV – UPS INTERFACE

Protection equipment used for residential and commercial PV systems is rated up to 1000 VDC, so it is important to make sure a PV array is configured so that this 1000-volt rating is not exceeded. On the other hand, the DC-bus voltage of the UPS is inherently about 720V, which determines the absolute maximum voltage for the DC/DC-converter output voltage.

A step-up converter topology could be a feasible solution for the PV arrays with maximum output voltage less than 720V. Accordingly, a step-down converter topology should be selected if PV array voltage were above 720V but less than 1000V. So, step-up converter topology provides more flexibility and scalability for PV string length and multi-string specification.

Transformer-based DC-DC topologies are interesting solutions, when a high set-up ratio is needed or when the system needs to be grounded, but since PV panel on the market have an output voltage range between 30V-100V; comparing to DC link voltage of about 720V, the maximum set-up ratio could be up-to 20; in case of modular PV field topologies which has one converter for each PV panel. In addition, security standards in Europe better define security issues, which allows to overcome galvanic isolation. Consequently, transformer-less DC-DC topologies are preferred to transformer-based ones regarding the high efficiency target.

Among the various set-up DC-DC topologies, we can distinguish the three most interesting ones Figure 5-3: Boost Based Topologies. These topologies is based on boost converter.

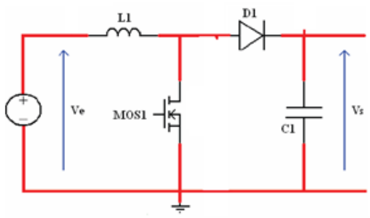
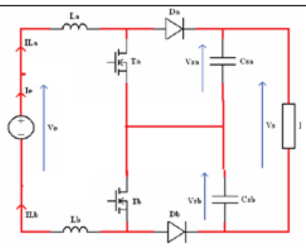
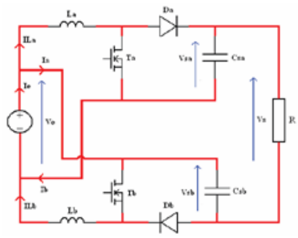
Topology	 (a) BOOST	 (b) 2 Levels BOOST	 (c) IDD Boost
Set-up Ratio	10	10	20

Figure 5-3: Boost Based Topologies

5.1.4 MPPT CONTROL

A good PV converter must be capable of obtaining the maximum power available from any PV panel. The PV converter can track the maximum power being provided by the PV panel in any condition. When the power output does not change dramatically, the converter is obtaining the maximum power from the panel. When the power reading changes significantly, the converter is tracking power according to the variation of the sunlight. In GDN-UPS design, perturb and observe (P&O) method is used for tracking maximum power point [6].

The GDN-UPS has two working modes. If the power produced by the PV array is lower than the load, the boost converter controls the PV voltage and track the maximum power point. Rest of the power to the load is supplied by the utility mains or the battery. If the PV power is higher than the load, the DC-bus voltage may increase above the acceptable level. In that case, the UPS rectifier or the battery converter must take care of the DC-bus voltage control.

5.2 OPTIMIZATION OF THE PV – UPS INTERFACE

Regarding the number of possibilities to build PV-UPS interface regarding PV field arrangements, power converter topologies, power components technologies and power requirement according to Data Centre installation, it is difficult to select the most efficient interface by using classic iterative or comparing methods. Therefore, an optimization method has been adopted in order to find the best solution which could meet our goals of increasing PV energy integration ratio and improve PUE within Data Centre. An optimization tool has been built by EATON specifically for GreenDataNet project to help designing this power interface and choosing the most powerful topology regarding power requirement, PV integration ratio and PV panels specification.

Finding optimal system design is a sensitive task, which requires good knowledge of each component and its effect on the system functionality. Optimization procedure is an iterative process in which system design performance is evaluated for any variables vector many times, so modelling precision plays a principal role in having best feasible solutions. Therefore, we chose to emulate real designing procedure, replacing simulation software by analytical models which could accept real components, basing in their datasheets or further testing information. Therefore, optimisation procedure gets up best feasible variables and components which fit predefined objectives. Multi-objective optimization is adopted regarding its capability of bringing out trade-off between several objectives, which is the case in industrial design, where the efficiency of a converter is not the only selecting factor, and where cost and power density have often an equivalent interest with respect to final design. The best efficiency can be obtained using oversized components, e.g. magnetic components, therefore the aim of this work is to optimize PV-UPS interface regarding efficiency and power density of power converter.

There are several methods to deal with multi-objectives optimization [7], among these methods, Pareto analysis, it does not give a single optimization result, but sums up the best compromises between several objectives. Furthermore, Pareto solutions analysis could indicate the effect of design variables on each objective.

The optimization procedure starts by defining desired interface specification, including Power requirement, output voltage, DC-DC Boost topology, PV integration ratio and PV panels specifications. Also quality variables limits are specified, as the maximal allowed variations of dc-link and PV panel output voltages and EMI limits, which are the constraints during the optimization, other constraints related to design components are set during the optimization in each model.

The free design variables and their limits are set, including the number of PV panel and DC-DC converters connected in series/parallel, the switching frequency, number of power MOSFETs and/or diodes connected in parallel and a database of several components based on their datasheets. Datasheet information is extracted as single values for components limits and as curve fitting functions for dynamic variables. In Figure 5-4: Optimization procedure flowchart a flowchart of the developed procedure for optimising the design variables is shown.

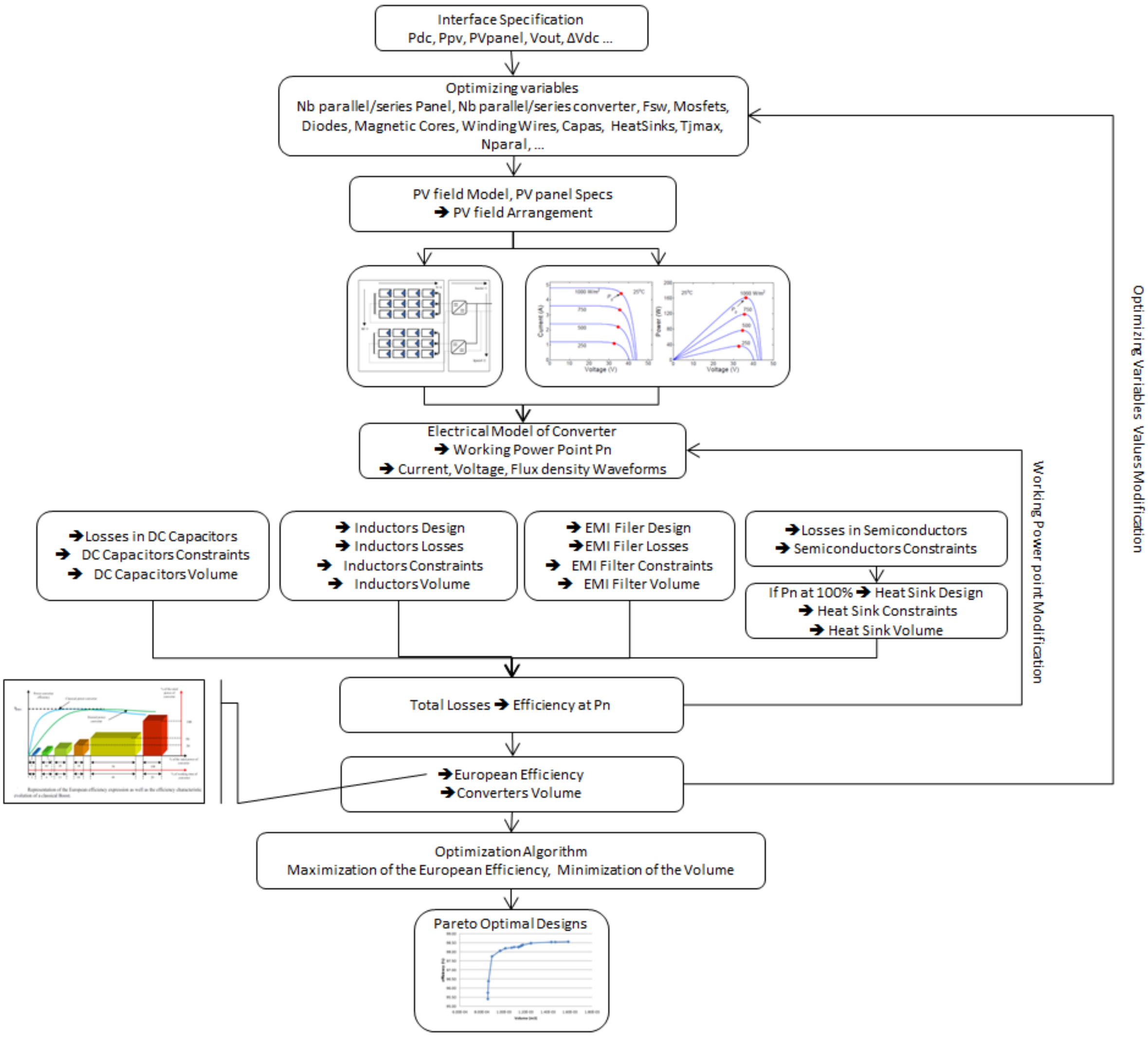


Figure 5-4: Optimization procedure flowchart

Based on interface specifications and variables free vector, PV field arrangement is determined and input/output voltage for each converter are derived, then Boost inductors value is calculated to produce desired current and voltage waveforms in each component. Waveforms are then used in components models to compute losses generate by each one, therefore, EMI filter and heat sinks are designed. Therefore, objectives can be evaluated to find Pareto front.

In the following paragraph, optimization parameters and objectives are defined, then the models of PV panel, the power converters, the semiconductors and the magnetic components as well as DC capacitor are briefly summarised.

5.2.1 OPTIMIZATION OBJECTIVES DEFINITION

The MPPT control method used to track permanently the maximum power point is important for extraction the maximum of PV array energy. But in order to transfer the maximum power to the load, converters efficiencies must be significant. The design of high efficient power converter for PV application is difficult since the PV power changes according to several parameters, such as irradiance, temperature, and meteorological conditions during the year so, PV converters don't work all the time at 100% of rated power. Therefore, classical efficiency calculation based on 100% of power rate is not adapted for PV converters [5].

Since photovoltaic generators work in average between 30% and 100% of its rated power 80% of its operating time, the European efficiency [4], Equation 5-1, is more adapted for the design of PV power converter, because it takes in account the annual statistical analysis of different conditions.

$$\eta_{euro} = 0.03\eta_5 + 0.06\eta_{10} + 0.13\eta_{20} + 0.1\eta_{30} + 0.48\eta_{50} + 0.2\eta_{100}$$

Equation 5-1

Where the index of η represents the % of the photovoltaic delivered rated power and the coefficients correspond to the statistic working time of each operation point.

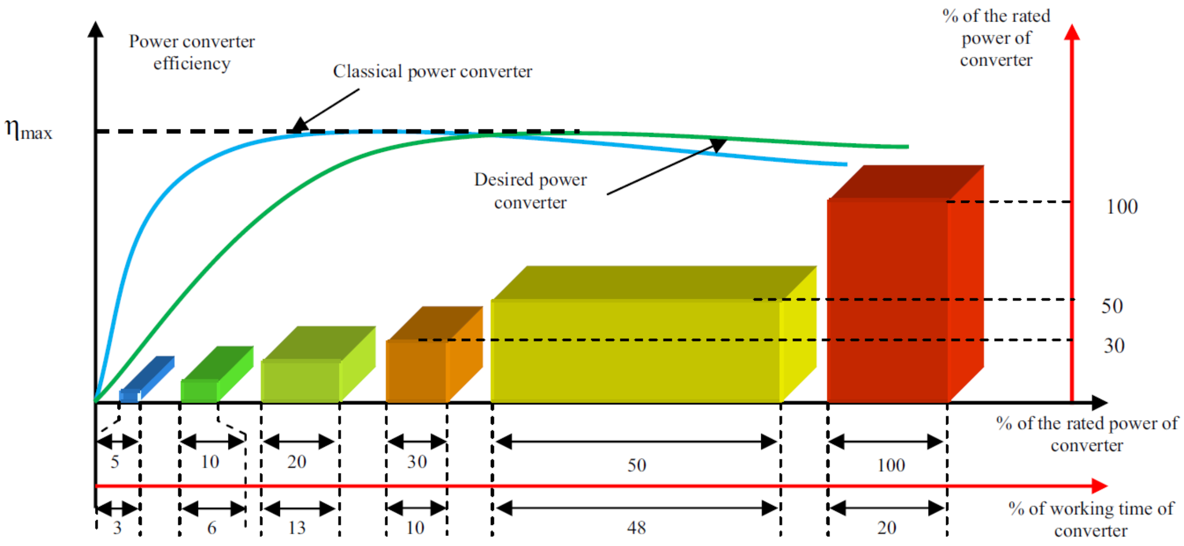


Figure 5-5: Representation of the European efficiency expression as well as the efficiency characteristic evolution of a classical Boost [5].

In order to extend IT equipment, Data Centres owner seeks to improve power density in their installation. For this reason, designing power converters must take into account this important factor by reducing the volume needed for power conversion. Consequently, power density is set as objective for optimizing PV – UPS interface, so that PV integration don't penalize the power density of the Data Centres.

5.2.2 OPTIMIZATION PARAMETERS

Optimizing result depends on optimizing parameters or system specification and the limits fixed in variable definitions, i.e. the total number of PV panels and PV panel specifications will limit the number of PV panels connected in parallel/series. Figure 5-6: PV Field variables shows the graphic relation between optimization parameters (PV panel spec & number of panels) and the optimizations variables, where

- N=number of panels connected in series in each string
- M= number of panels connected in parallel in each string
- Kserie= number of converters connected in series
- Kparal= number of converters module connected in parallel

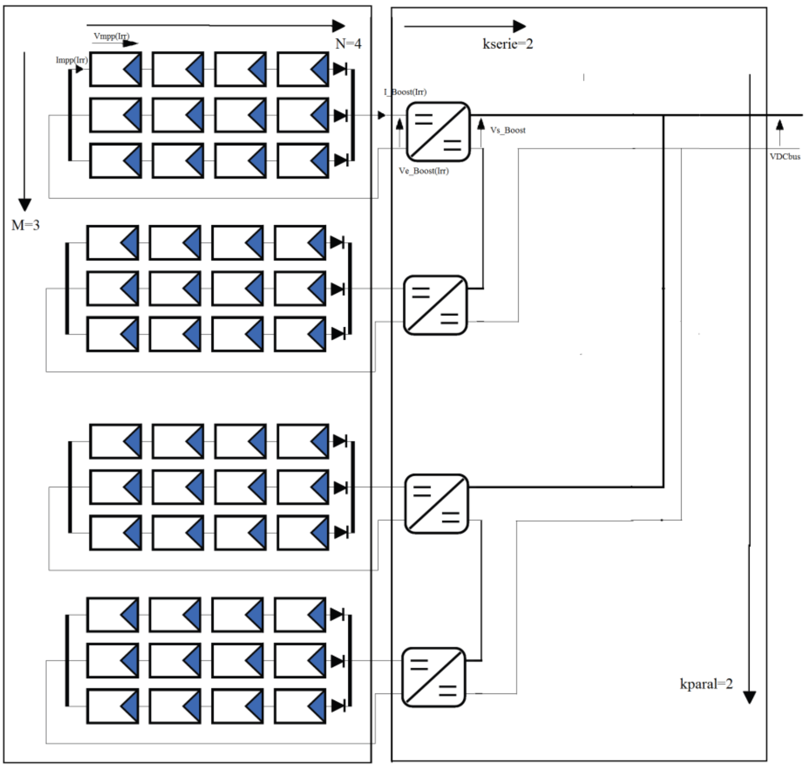


Figure 5-6: PV Field variables

Table 5-1 : Variables table shows some optimization parameters and variables and their definitions and boundaries.

Parameter/Variable	Definition	Limits
Ntot	Total number of PV panels	Fixed by Integration ration & PV panel Power

N	number of panels connected in series in each string	$1 < N < N_{max} = Ntot$
M	number of panels connected in parallel in each string	$1 < M < M_{max}=Ntot/N$
Kserie	number of converters connected in series	Function of Vpv, Vdc, N et M
Kparal	number of converters module connected in parallel	Function of Vpv, Vdc, N et M
F	Switching frequency of converter	20 kHz < F < 100 kHz
ΔI	PV panel Current ripple	10 % < ΔI < 50 %
ΔVdc	Vdc voltage ripple	5 % < ΔV < 10 %

Table 5-1 : Variables table

5.2.3 INTERFACE MODELING FOR OPTIMIZATION PROCEDURE

PV MODULES

Several models of PV cells exist and vary in complexity and accuracy [14]. The model that will be retained in this work is the one-diode model that contains five parameters as shown in Figure 5-7: One-Diode Model [16].

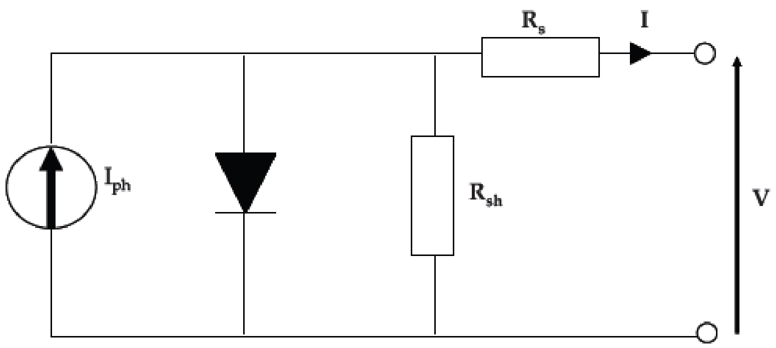


Figure 5-7: One-Diode Model [16]

The one-diode model is the most widespread model used for PV cells and PV modules due to its low complexity and good accuracy in the power generating quadrant. The PV cell model can be adapted to PV modules by modifying parameter values Iph, Io, Rs, Rsh, and Vt. The single diode model leads to a transcendental equation shown in Equation 5-2, based on PV module datasheet, this equation can be solved by numerical determination using iterative algorithms[15].

$$I = I_{ph} - I_o \cdot \left(e^{\frac{V+R_s \cdot I}{V_t}} - 1 \right) - \frac{V + R_s \cdot I}{R_{sh}}$$

Equation 5-2

A. SEMICONDUCTORS:

The structure of boost converter uses a switching cell having two semiconductors switches with anti-parallel diodes, generally a diode and a MOSFET with anti-parallel diode, beside the switching losses of the MOSFET an additional switching losses caused by forced commutation of the diode will be generated in both the diode and the MOSFET, these losses is due to the reverse recovery of the diode. So the choice of the diode will affect the total switching losses [8]. The models of the semiconductors take into account switching losses generated by the recovery of power diode within the switching cell, which allows the comparison between standard diodes and soft switching ones.

Based on the above calculated current and voltage waveforms, turn-on and turn off currents are determined, then using curve fitting functions, extracted from datasheet for dynamic variables, conducting and switching losses are computed in each switching cycle. As temperatures of semiconductors are optimizing variables, losses in semiconductors are calculated for a given temperature without any iteration.

RMS and maximum value are also computed using numerical methods then they are compared to semiconductors limits extracted from datasheet, therefore constraints on each semiconductors are evaluated.

B. HEAT-SINK:

In this version of optimization, a single source model has been used to design heat sink for each semiconductor component. As mentioned above, to avoid electro-thermal model which needs a lot of iterations, semiconductor temperature is set as an optimizing variable. Furthermore, based on models proposed by [9], natural/forced convection and radiation coefficients are calculated regarding heat sink efficiency, which depends on fins geometry. Then heat sink length is calculated to reach the given junction temperature.

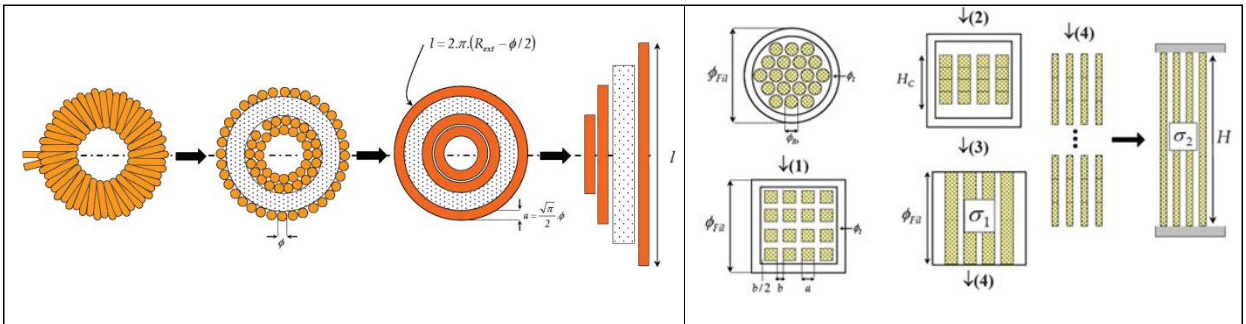
B. MAGNETIC COMPONENTS:

The design of magnetic component is a particular case in power electronic designs regarding the multiples phenomena inside, furthermore the fact that they does not exist as a single component with its own datasheet.

Design model has to deal with magnetic cores and winding wires to get a proper design. In our case for inductor design, characteristics of both magnetic core and winding wire have been taken into account, toroid cores have been chosen for their high power density ratio, and also solid wires and Litz ones have been introduced. The model starts by calculating the number of turns needed to get out the inductor value based on core information, and then it evaluates the feasibility of the design with the preselected winding wire. The next step is to estimate the losses generated within the core "Iron losses" and those generated within the wire "Winding losses".

Based on inductor current waveforms and on core datasheet, time variation of the flux density has been determined. Then the core losses can be calculated based on equations given in the datasheet [10], where coefficients are utilised for characterising the iron losses within core material in function of the rate of change of the flux density (dB/dt) and switching frequency. According to core both geometry and material, saturation of core is set as an optimizing constraint.

For winding losses, Dowell 1D model has been used to describe the inductor [11], which approximates winding layers comprising multiple turns of round wire with an equivalent rectangular conducting sheet, the current distribution change caused by this approximation is considered equivalent to a difference in conductivity. As toroid cores winding layers length are not equal Fig. 4, winding losses are calculated for each layer by devising the losses into proximity effect and skin effect losses as proposed in [12], Dowell representation is accurate for closely-packed windings [13], which gives us a design limit to be set as constraint in the optimization procedure.



a) Winding layers in toroid core

b) Transforming litz wires into conducting sheets

Fig. 4 Dowell model apply to toroid core [12]

C. DC LINK CAPACITOR:

DC capacitor and its contribution to converter power density and efficiency is not negligible, particularly in UPS system, where near-instantaneous protection of load from short power losses of the grid is claimed. The model of capacitor evaluates each capacitor and determines the number of capacitors needed to minimise voltage variation, and achieve a hold up time capability. Several constraints are set on voltage and current variations tolerance within the capacitor, then capacitor losses are calculated based on ESR value given in the datasheet.

5.2.1 OPTIMIZATION RESULTS

The optimization tool gives the specifications to build the most efficient PV-UPS Interface. Table 5-2 : Optimization Solutions Specifications contains some solutions specifications resulting from the optimization tool, the number of parallel converter connecting PV panels to DC link of the UPS ’Nb_PV_P’, the number of panels connected in series & in parallel at the input of each converter, switching frequency at which converter works to boost conversion efficiency, and power components needed to build this converter, like magnetic core & winding wire for boost inductor and Mosfet & Diode to reduce power losses within the converter.

'Eff_Europ'	'Nb_PV_S'	Nb_PV_P'	'Nb_Conv_P'	'f_sw'	'Core'	'Wire'	'Nb_Mosfet'	'Nb_Diode'
98.5	15	2	2	58000	'T400-26B'	2	1	2
98.1	15	1	4	58000	'T520-52'	2.8	1	2
97.9	15	1	4	58000	'T300-40'	1.7	1	2
97.6	15	1	4	39000	'T400-30'	1.25	1	2
97.5	10	2	3	62000	'T520-40D'	2.65	1	2
97.4	12	1	5	60000	'T650-2'	2.36	1	2
97.2	15	1	4	58000	'T400-30'	1.25	1	2

96.6	5	2	6	51000	'T520-26'	3.75	1	2
96.5	10	1	6	68000	'T520-40D'	2.5	1	2
96.0	5	2	6	51000	'T300-40'	2	1	2
95.9	15	2	2	51000	'T300-40'	2	1	2
95.7	5	2	6	60000	'T300-40'	2	1	2
95.6	15	1	4	58000	'T400-30'	1.25	1	2
95.4	6	1	10	53000	'T520-40'	2.24	1	2

Table 5-2 : Optimization Solutions Specifications

The tool was tested for a PV plant of 10kW with 60 commercial PV panels (180W/72Cells/36V), DC-DC boost topology was chosen to build the PV-UPS interface. The tool gives distributed results as a function of each objective, here European efficiency & system size are fixed as objectives, so solutions can be evaluated depending on the wanted performance. Figure 5-8 shows the different possible solutions, represented as blue stars, to build the interface between PV field and the DC link of the UPS by using 2 parallel converter, matrix of 15 series*2 parallel PV panel was connected at the input of each converter. In the same figure, red circles characterize Pareto optimal solutions, where best efficiency does not mean best power density, so a compromise between this two objectives has to be made to choose the preferred solution.

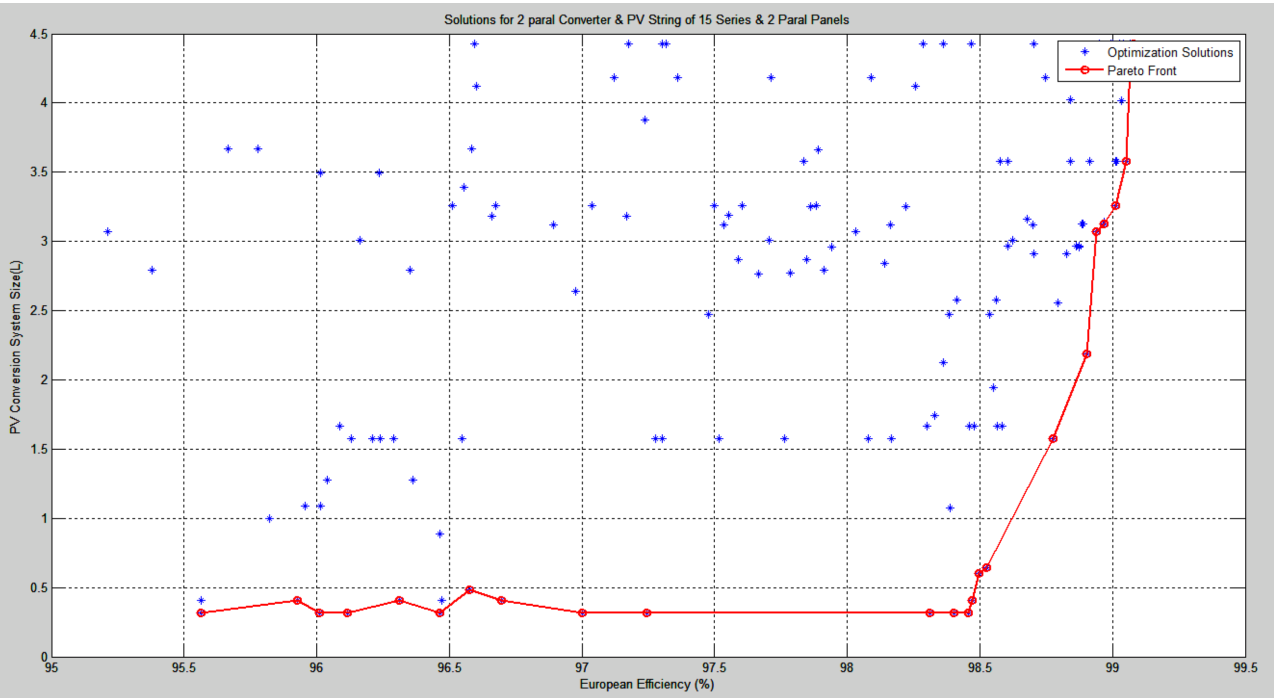


Figure 5-8: Solution for 10kW PV planet having 2 PV matrix of 15*2 Panel connected to DC-DC converter

Running the optimization for different scenarios, with different number of parallel converter and different possible connections of PV panels, as explained in paragraph “5.1.25.1.2”, gives results shown on Figure 5-9: Pareto Front for different possible connections, where a Pareto Front for each scenario was plotted. The figure indicate that Pareto Front with fewer power converters have better solutions. Also, increasing PV panels connected in series improves power conversion efficiency.

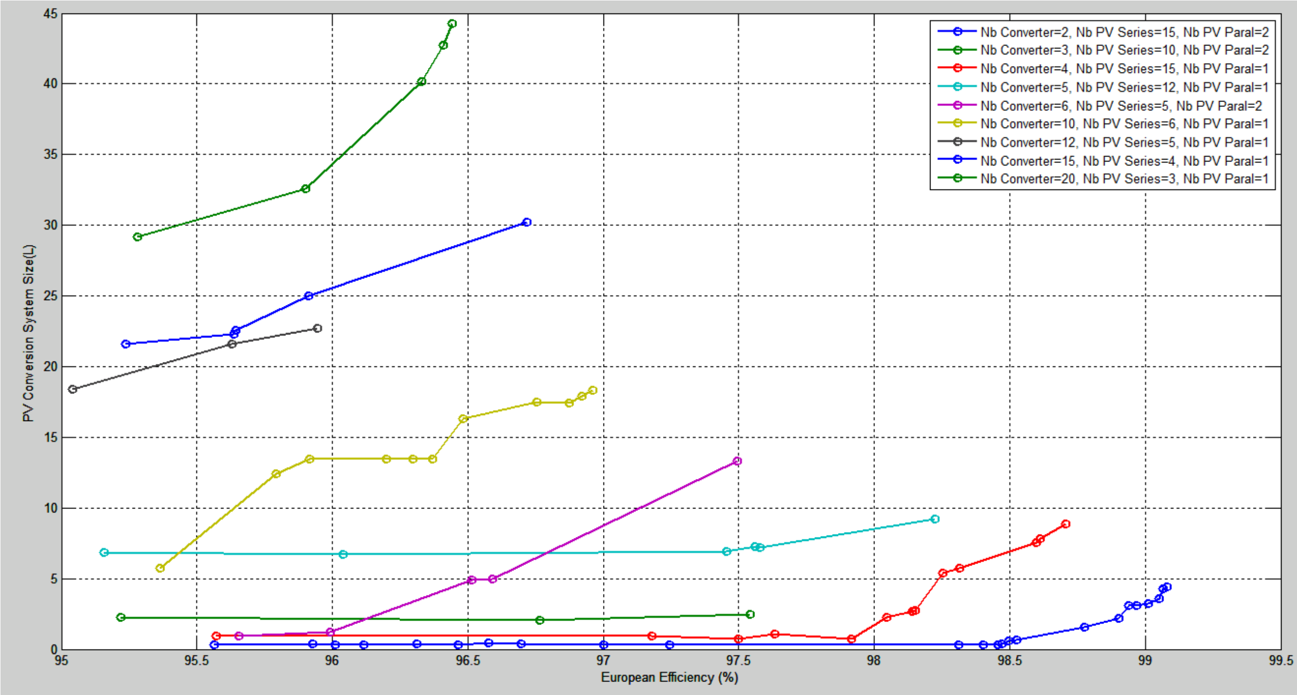


Figure 5-9: Pareto Front for different possible connections

Therefore, to build an efficient PV-UPS interface for 10kW PV plant, a 2-parallel converter system would give the best conversion efficiency with a minimum of power density .

6. INTERFACE WITH THE NISSAN BATTERIES

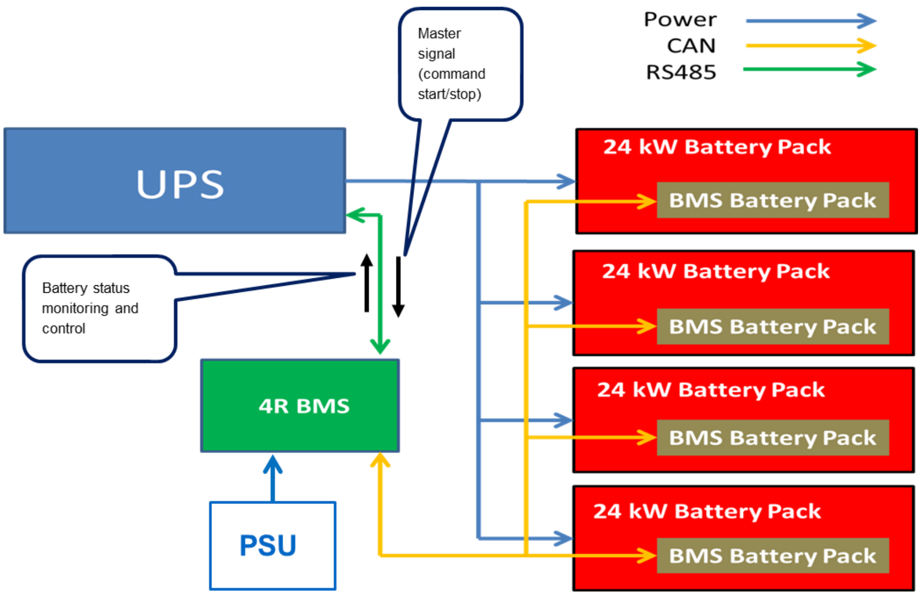
The Nissan Li-Ion battery system is originally designed for electric vehicle (EV) application, while the UPS design is optimized for stationary lead-acid batteries. Requirements for EV batteries are different compared to lead-acid technology, which is conventional e.g. in Data Center batteries. Those differences are leading to various challenges and trade-off in the interface design between Nissan battery and the Eaton UPS.

Major issues which are requiring specific attention in the battery interface design:

- Voltage matching between the battery and the rest of the system is a key issue. Specifically, because operating voltage range of Nissan battery is lower than the voltage typically used in 3-phase UPS's
- Operation and functionality of the EV battery system deviate from the conventional UPS system functionality
- Communication protocols of the Nissan battery and 93PM UPS requires coordination
- General safety issues related to Li-Ion batteries

6.1 OUTLINE OF THE BATTERY INTERFACE

Outline of the Nissan battery interface is described in picture below. It consists of up to four parallel connected battery packs, the Battery Management System (BMS), power supply and a UPS. The master controller (MCU) is physically located inside the UPS. Each battery pack includes internal high voltage relay which connect or disconnect the pack following the demand.

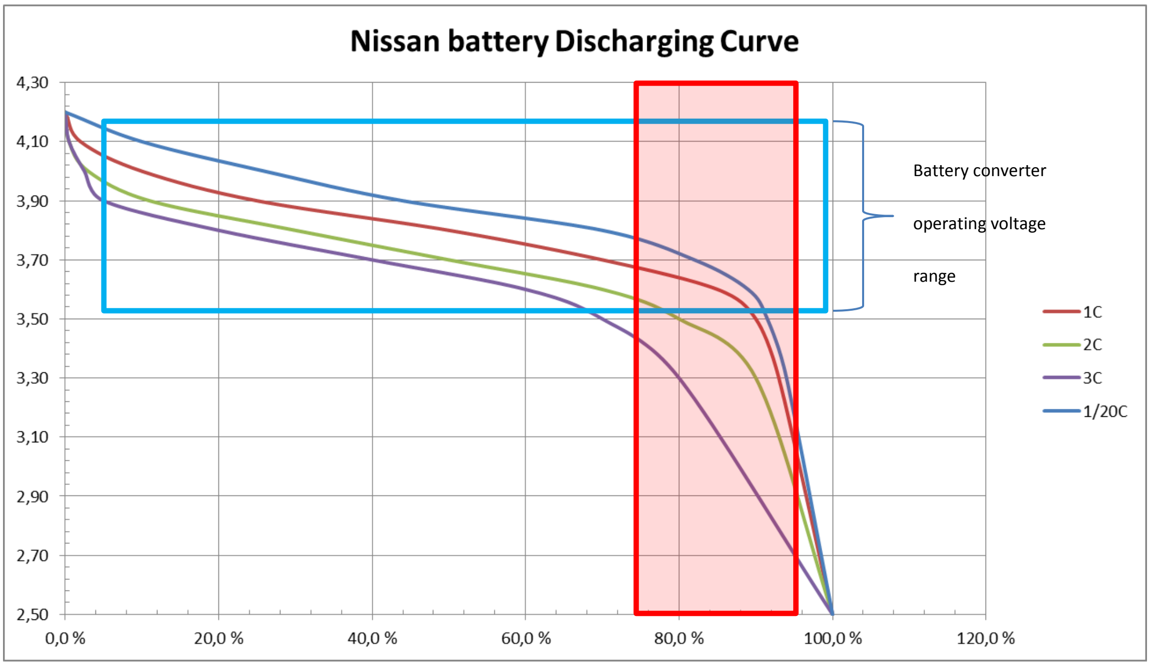


The operation principle of the system is as follows. The BMS is monitoring and controlling a state of the battery packs. Internal CAN-bus is used for communication between BMS and battery packs, while communication between MCU and BMS is based on the RS-485. The demand to transfer to the battery mode operation is initiated by the MCU. Accordingly, the MCU will send a command to the BMS when transfer back to other, e.g. grid operation, mode is acceptable. The BMS will switch ON or OFF the high voltage relays inside the battery packs according to MCU commands.

6.2 NISSAN BATTERY PACK AND 93PM BATTERY CONVERTER SPECIFICATIONS

Nissan battery pack has following technical specifications [18] :

Nominal voltage	360 V
Operating voltage range	240 – 403 V
Initial capacity for new battery (@ 0.2C discharge)	24 kWh (~66 Ah)
Estimated capacity for second-life battery	17 kWh
Max. discharge current	400 A
Max. charge current	200 A
Nominal cell voltage	3,8V
Number of cells in series	96



Specification for the battery converter of the 93PM UPS is presented in the table below. It shall be noted that the UPS is automatically limiting charge current to 16.5A, if the load is more than 40 kVA. When the load is less than 40 kVA battery charger is able to charge battery simultaneously at 29.3A current.

Charging battery	
Operating voltage range	330 – 550 V
Maximum charge current	29.3 A (when load < 40 kVA)
Charge current	16.5 A (automatically limited if load > 40 kVA)
Discharging battery	
Minimum battery voltage	336 V
Minimum cell voltage in discharge	3,50 V
Maximum continuous discharge power	50 kW

Increase of battery power and charge current capacity of 93PM UPS is possible by connecting more power modules into the system.

The operating voltage range of the battery converter and Nissan battery are overlapping in the range from 330V up to 403V so this is voltage range used for charging and discharging. Battery capacity can be utilized in that voltage range. Referring to the discharge diagram above, one can see that available capacity from the battery is dependent on the discharge rate. With high discharge rate (3C) available battery capacity is only about 70% from the nominal. That is equal to16.8 kWh from new battery and about 12 kWh from the second-life battery. However, with the slow discharge rate (1C or less) even more that 90% of the battery capacity is available. That corresponds to 21.6 kWh from new battery and about 15 kWh from second-life battery.

7. DEMONSTRATOR

A prototype of UPS integrating the PV source and the Li-Ion batteries will be implemented in order to validate the forecast performances. The architecture of the System is represented in next page This prototype will be installed in the laboratory of the CEA-INES in Chambery.

According to the results of the analysis and of the optimization tool, a DC-DC converter will be integrated to the DC bus of a 50kVA UPS in order to be able to inject the power coming from a 10kW PV field (representing an integration of 20% of renewable self-production). This DC-DC converter will be composed by 2 Boost modules of 5 kW in parallel connected to the DC bus of the UPS, this choice has been pushed in order to privilege the modularity of the PV interface. On a first step, the 20% of self-production would allow GDN project to validate the UPS modified infrastructure and measure the efficiency of the system, on a second step, further DC-DC modules can be added in order to validate the simulations results produced by CEA in D1.3 and reach a higher percentage of self-production.

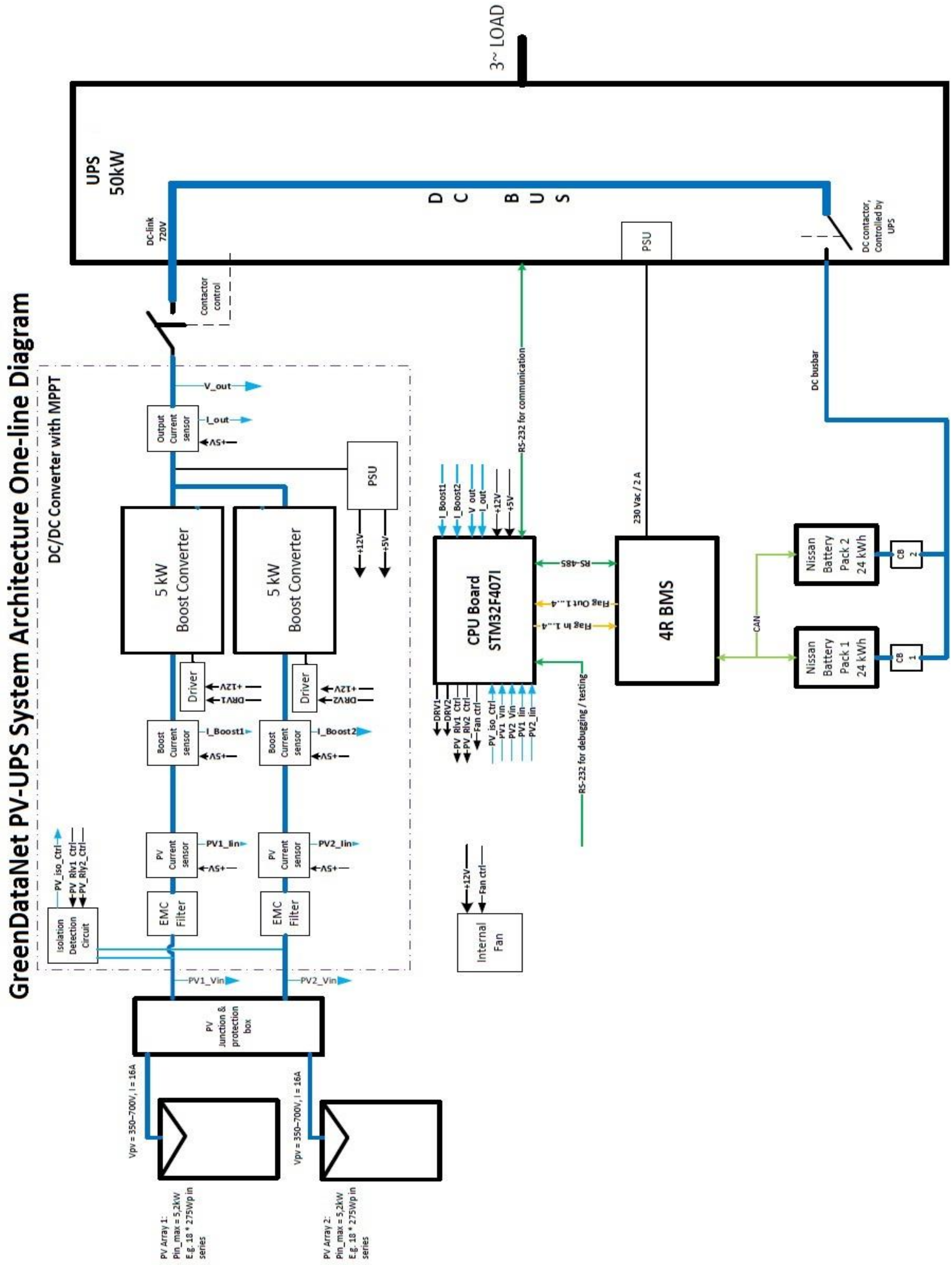
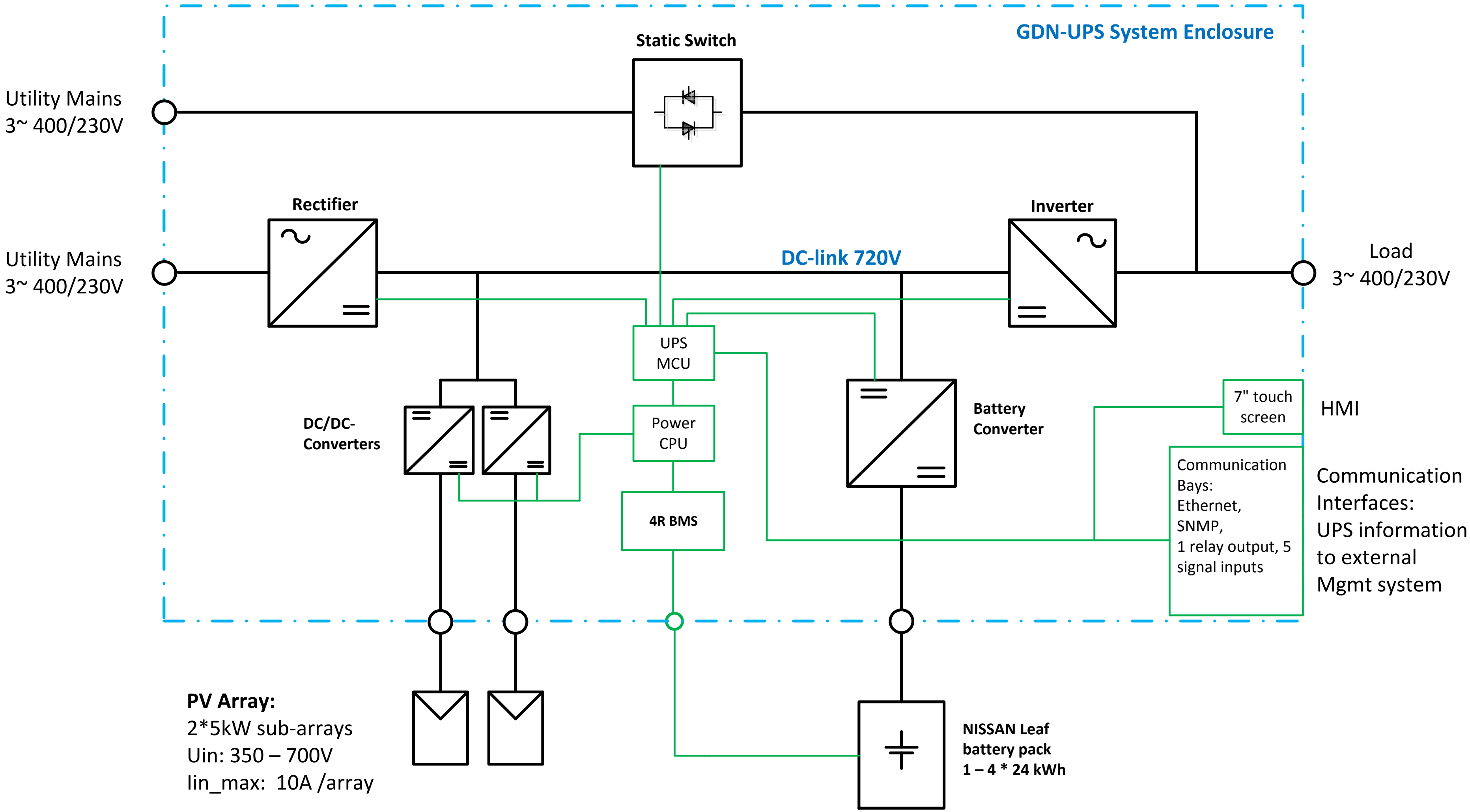


Figure 7-1 GDN Communication Architecture

Figure 7-2 GDN HW System Architecture



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