The scientific proposal

1. State-of-the-art and Objectives

In the early days of electrification the alternating current (AC) transformer decided the historic “battle of currents” [1], which made AC the preferred technology for transmission and distribution until today. In an AC system, transformers simultaneously provide galvanic isolation and voltage adaptation, while being extremely simple, robust, passive and uncontrollable devices made out of copper and iron. Undoubtedly, their role in the electrification of the world for over more than a century is immeasurable.

The AC transformer operating principles use the Faraday Law of electromagnetic induction and the fact that varying (AC) excitation voltage of transformer’s primary winding causes a varying magnetic flux within a transformer core, which in turn induces a varying voltage (electromotive force) in the secondary winding. In contrast to present AC power systems where low frequency transformers (e.g. 50Hz) are sufficient for AC-AC conversion, this will not be the case in the future energy systems where increased presence of direct current (DC) grids is expected. As the AC transformer operating principles rely on the presence of a variable magnetic flux within a magnetic core, it cannot be operated with DC voltages directly. However, power electronics switching devices can be used to provide high frequency time varying voltages for magnetic devices. These conversion principles are not knew and are widely deployed and used in the low voltage applications concerning switched mode power supplies.

MVDC power distribution networks may be connected to the existing AC or DC power systems of different voltage level. As most of these technologies for AC-DC or DC-AC conversion are already available, they are out of scope of this project proposal (Fig.1). We are predominantly interested into a high power DC-DC type of conversion and achieving a simple, reliable and efficient conversion configuration that will enable seamless energy routing in DC systems. Similar to the role of AC transformer in AC systems, we aim to develop, power electronics based *DC Transformer* that has all good properties of AC transformer (*simplicity, reliability, efficiency*), but also features that go well beyond those found in AC systems (*compactness, intelligence, protection and fault mode operation*). The EMPOWER project proposal is not about converter development, but about groundbreaking work establishing novel design paradigm in DC systems, merging conversion and protection functions inside the single device, and thus effectively solving two large problems at once. A solution we propose has not been considered or demonstrated so far, and is radically different from the current conversion research trends.

Questions to be addressed in the project, originate from power electronics dominated power grids developments where power electronic technologies offer fully controllable power flows. Considering such a large control effort already present in majority of supply and load converters, leads to several paradigms that we will address: i) What kind of properties are really required at the interconnection points between different MVDC voltage levels? ii) How can the power flows be left uncontrolled while guaranteeing the power balance in MVDC power distribution network? iii) How we can achieve *DC Transformers* behaving similarly to AC transformers: simple, efficient and reliable? iv) How we can benefit from controllability of power electronics devices, and integrate protection functions inside the *DC Transformer*, to achieve functionalities of a DC breaker – another missing component for DC power distribution systems?

The EMPOWER project will resolve these questions and develop a *DC Transformer*, with unique operating principles, allowing for seamless and protected energy exchange in MVDC power distribution networks.

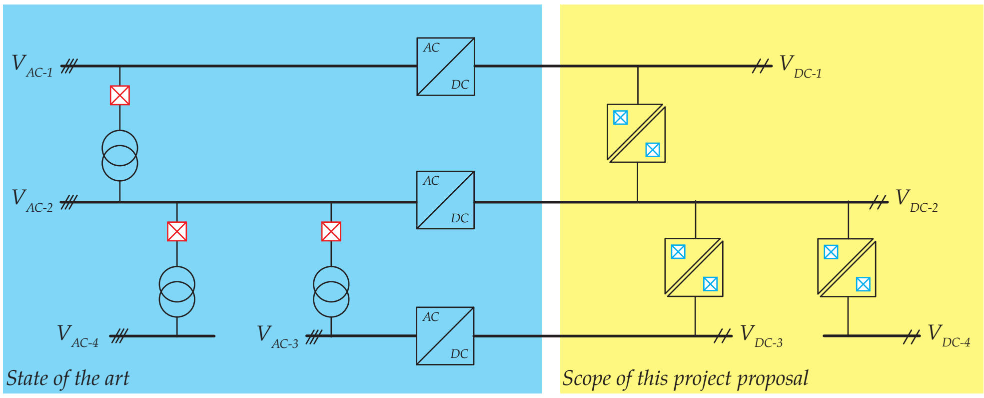


Fig. 1: *State-of-the-art AC power system with multiple voltage levels interfaced with AC transformers and protected by circuit breakers, and future MVDC power distribution networks enabled by DC Transformers.*

State-of-the-art: MVDC Applications

There are several applications where MVDC power collection and distribution grids are serious contenders to the existing AC systems or promising new solution. While, each application may have completely different drivers behind, in almost all the cases, lack of suitable conversion and protection technologies are the reasons for absence of practical realization [1].

Wind energy systems, and in particular those off-shore are considering MVDC systems as way to collect energy generation of individual wind-turbines prior to interfacing complete wind park to the shore. Considering that wind generators are almost exclusively AC electrical machines, direct AC-DC or cascaded AC-DC + DC-DC conversion is required to reach MVDC voltage levels [2]. While multiple advantages have been recognized (lower cost, increased availability, system expandability, smaller footprint, reduced filtering effort), a number of challenges still remain (protection, no standardized DC voltage level, no suitable converters), resulting in no large-scale MVDC distribution systems in use [3]. Similar consideration can be found in large photovoltaic (PV) applications [4].

Marine all electric ship initiatives are looking into complete replacement of existing MVAC distribution system with MVDC distribution. Main motivations are often summarized as increased fuel efficiency due to elimination of need to synchronize multiple generators to fixed frequency of MVAC grid, space savings due to removal of bulky low frequency transformers, easier integration of energy storage systems, etc [5,6]. The future shipboard systems will have many of the same characteristics and requirements as on-shore micro-grids, as specified in recently released normative [7], even though there is a large technology gap to be overcome [8]. Big data centers with computing servers can be seen as large DC loads, and DC distribution is seen as way to improve overall efficiency, eliminating AC-DC conversion from the energy path. As installed power of data centers is steadily increasing, MVDC power distribution networks are seen as entry point to these installations [9].

Fig.2 illustrates a possible scenario where MVDC distribution is used to connect different groups of loads to the existing AC system. MVDC to MVAC connection can be established easily considering commercially available technologies, such as those based on the modular multilevel converter (MMC). However, conversion from MVDC to other DC voltage levels is an open question nowadays, as the technology does not exist and its roles and operating principles are unclear. New type of installations, such as: electric vehicle charging stations, energy storage systems, photovoltaic energy generation, to name a few, raises the questions on the power flows in the future energy systems and who and how controls it.

In 2015, CIGRE has launched working group "MVDC Grid Feasibility Study", looking into various aspects associated with deployment of these power distribution networks as addition or replacement to existing power systems (PI of this proposal is an active member of this working group). Considering an increased penetration of power electronics technologies into power systems, all future energy scenarios demand improvements or development of enabling power conversion technologies. Rather than being specific on a particular application, the EMPOWER project relies on a holistic approach, proposing a paradigm shift for future power distribution networks.

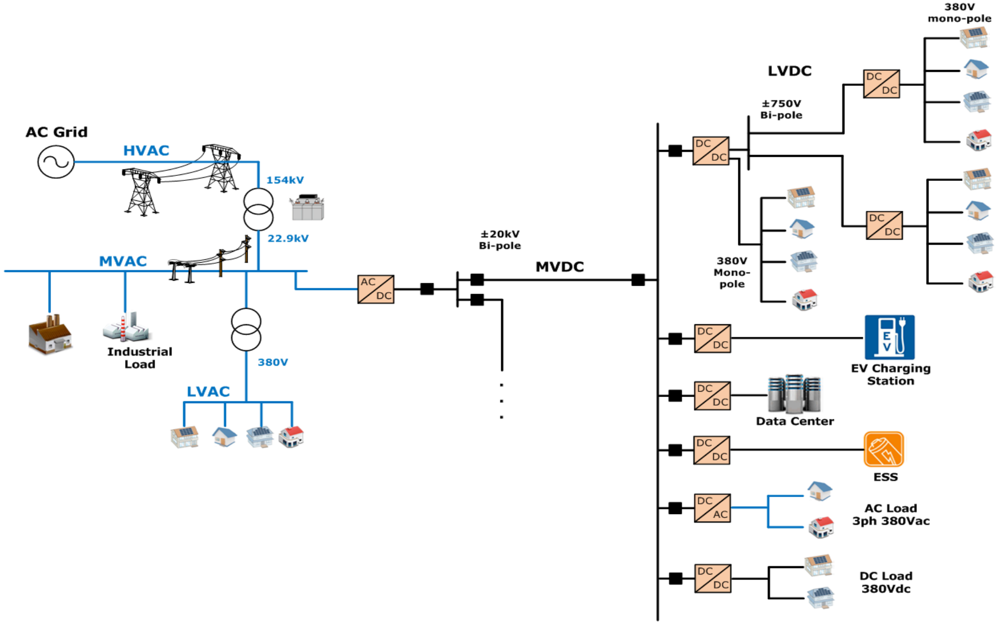


Fig.2: *An illustrative example of the MVDC electrical distribution interfaced to the existing AC grids, emerging DC grids and different kinds of already existing sources and loads.*

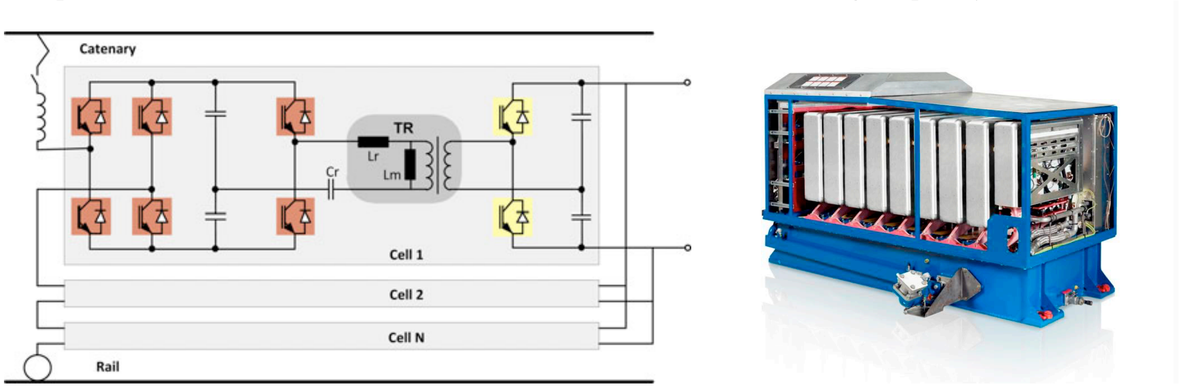
State-of-the-art: MV Conversion and Protection Technology

There are several high power medium voltage conversion areas that are already well developed; largely thanks to standardized AC voltage levels and well understood application requirements (e.g. STATCOM and FACTS devices, medium voltage drives [10]). On the other hand, smart grid applications have increased interest into so-called power electronic transformer (PET) or solid-state transformer (SST) for AC-AC or AC-DC type of conversion [11,12]. These concepts utilize high number of semiconductors in combination with multiple medium frequency transformers (MFTs) operated at frequencies in the range of several or tens of kHz. The majority of relevant literature can be classified into either three-phase PET smart-grid applications [13–25], or single-phase PET for traction on-board applications [28-41].

Three-phase PET early concepts can be traced back to the 1960s and 1970s [13], but so far the work has stayed more on the academic level, with several laboratory-scale prototypes realized based on different topologies and various control schemes [14-25]. The shift towards smart-grid concepts for the distribution system has brought PET concepts into the spotlight again [22], and has been strongly supported by developments related to high-voltage SiC-based semiconductors [19,23]. So far, no medium-voltage high-power PET pilot installation was reported by any of the key industrial players on the market. One obstacle is the fact that the majority of utility applications ask for very high efficiencies of each element in the direct path of the energy flow [21]. Distribution medium voltage line-frequency transformers were designed and optimized over the years for fairly high efficiencies (>98%), something not easy to achieve with a power-electronic equivalent solution that includes galvanic isolation. Nevertheless, large European projects with similar objectives: (UNIFLEX) has been already conducted [26], ERC CoG project HEART is ongoing [27] as well as industrial ANGLE-DC project.

Single-phase PET applications are related to traction AC grids that in Europe are 15kV, 16.7Hz or 25kV, 50Hz. Traction on-board applications are the ones where proliferation of PETs is expected to happen in the near future [28]. While early works can be traced back to thyristor-based solutions [29,30], with the introduction of insulated gate bipolar transistors (IGBTs), they became the primary choice of various research groups [31-35], resulting in developments of several full-scale PET prototypes [34], [36-41]. The most prominent example is a 1.2MVA power electronic traction transformer (PETT) for 15kV, 16.7Hz railway grid, developed by ABB, commissioned and successfully tested on a locomotive [36-41]. It featured multiple MFTs with ratings of 150kW, operated at switching frequency of 1.8kHz with IGBTs devices (Fig.3), and exceeding efficiency of the state-of-the-art traction chains by 2-4%, depending on the operating point. The PI of this project proposal has been actively involved into this R&D project during its execution, as seen in the list of references and resume.

Increased interest into the PET-like conversion technologies has been well supported by the activities in the area of semiconductor devices. High voltage Si-based IGBT devices are considered by many authors [42-48], in hard-switched or resonant converters [35,42-44] utilizing 3.3kV IGBTs [35], standard and modified 6.5kV IGBTs (irradiated in order to reduce carrier lifetime) in [42,43]. Similarly, standard 6.5kV IGBTs were analyzed in relation to soft switching applications [44-46], while optimization by means of anode engineering was presented in [47], achieving significant reduction of switching losses, an important factor for high switching frequencies. Lifetime control optimization (irradiation), applied to a 3.3kV IGBT, has been presented in [48] in order to reduce the turn-off losses and reverse recovery losses. Different applications of 6.5kV IGBTs are presented in [49,50], where a soft commutated AC-DC converter using non-dissipative snubber circuits has been considered to increase the switching frequency.



a) b)

Fig. 3: *a) Topology of a Power Electronic Traction Transformer (PETT) for 15kV, 16.7Hz traction applications featuring double stage conversion (AC-DC + DC-DC) with IGBT devices; b) 1.2MVA PETT prototype from where modular structure can be clearly identified [41].*

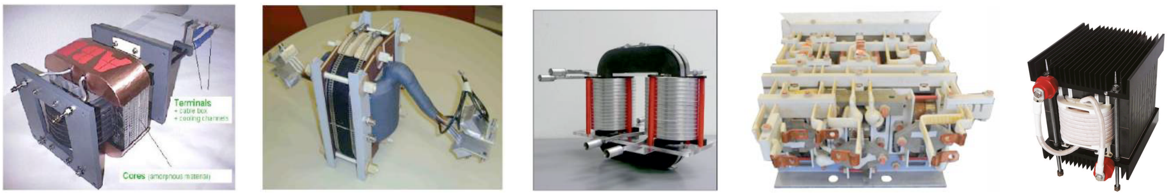
a) b) c)

Fig. 4: *a) Cross section of an asymmetric GCT; b) 91mm GCT wafer; c) IGCT with Gate Unit [58].*

Semiconductor devices based on SiC are another mean to increase the switching frequency in high power, medium-frequency applications, and thus SiC diodes were analyzed in [51], while the custom developed 10kV SiC MOSFET module has been presented in [23]. Results obtained with 10kV SiC MOSFET [52] and 15kV SiC IGBT [53-55] have demonstrated potentials of these technologies. When it comes to high-power high-current applications, IGCT (Fig.4) has established itself as device of choice. IGCT is a monolithic gate-controller turn-off semiconductor device which turns off like a transistor, but conducts like a thyristor, thus having very low conduction losses [56]. It has very high surge current capabilities and possible switching frequency is up to 1kHz. As an example, a half-bridge inverter realized with 4500V, 2100A IGCTs, has ratings of almost 1.5MVA using just two devices, and industrial converters are easily reaching power densities of 3.5MVA/m3 [57]. Recent advancements in IGCT technology have been mainly focused on increase of power density through lower losses and ability to operate at higher temperatures (IGCT HPT at 140^{o}C), maximization of controllable turn-off current capabilities (IGCT SOA area), integration of reverse conducting diode (RC-IGCT), and blocking voltage increase up to 10kV [58]. While, some research activities were reported on the use of IGCTs in resonant mode with Dual Active Bridge (DAB) topology [59, 60], this is a greatly overlooked research area. A drawback often associated with IGCT is a complex and power demanding gate unit (≈50W compared to ≈10W for IGBT), which to turn-off IGCT must provide high gate current (few kA) to commutate complete collector current. Significant improvements in performance are possible through resonant mode of operation, which we will explore.

Thanks to the semiconductors, increase of the operating frequency has direct impact on the size reduction of a transformer found inside these converter structures. Yet, while semiconductor devices are having discrete ratings (blocking voltages and current ratings), ratings of the medium frequency transformers are not bound and can be freely chosen and optimized (operating frequency, power). This has been another area of increased research activities [61-63]. Various designs have been proposed and laboratory prototypes developed using different core materials, such as silicon steel [34], nanocrystalline [36-41], ferrites [32,61,62] or iron amorphous in combination with different insulation materials (air, oil, epoxy). Each of these technological choices has an impact of the final result of optimization, making it hard to compare different realization. This can be seen from several examples illustrated in Fig.5, where examples d) and e) represent those where PI of this project proposal was directly involved.

Regarding high power medium voltage dc-dc conversion, some research has been provided in the past years [64-66]. Unfortunately, these, application-oriented solution do not address problem at large. High power DAB based DC-DC converter has been proposed and analysed in [64], providing full active power control and considering IGCT type of devices. Combination of MMC and MFT has been proposed in [65], enabling variable voltage ratio between two terminals, enabled by intelligent and active control. Slightly different approach has been proposed in [66], where non-isolated high gain DC-DC converter has been proposed using thyristor devices. All these proposals are radically different topologically, and are based on active power flow control; a feature we believe is not needed for a *DC Transformer*.



a) b) c) d) e)

Fig. 5: *MFT prototypes reported in literature: a) [61], b) [32], c) [43], d) [41], e) [63].*

Finally, protection coordination in MVDC power distribution networks in an open research question. Lack of natural zero current crossing and generally low resistance and virtually zero reactance associated with DC cables, require very fast action of the protection equipment and fault current clearing within 1-2 ms [67]. Use of voltage source converters (VSCs) as interface between AC and DC grids, leads to uncontrolled fault currents as soon as IGBT devices are blocked, while DC bus capacitance impacts the peak fault current value [68]. Nevertheless, for lower voltages use of AC breakers on the AC side is possible approach to protect the system. Modular multilevel converter (MMC) and its implementation with full-bridge cells, allows for fault current limitations on the DC side, thanks to ability to reverse the voltage of the cell, yet it is costly solution [69]. Except for traction MVDC applications (up to 3kV), affordable DC breaker is not yet commercially available technology. Generally, three concepts are mostly considered: i) mechanical DC circuit breaker with auxiliary circuits to produce resonant swing and create zero current crossing; ii) solid-state DC circuit breaker based on semiconductor devices (characterized with high cost and high losses in operation) and iii) hybrid DC circuit breaker, being a combination of mechanical and semiconductor part, offering in perspective the best performances as standalone device [67]. Rather than relying on the external device, we aim to utilize presence of galvanic isolation and fast switching semiconductors, and integrate protection and fault limiting functions as core features of *DC Transformer*.

The EMPOWER Objectives

The aim of the EMPOWER project is to solve the problem of DC power transformation and protection, to enable the future MVDC power distribution networks. To achieve that goal, we will develop a *DC Transformer*, a missing enabling technology, integrating conversion, isolation and protection functions into a single device. Considering state-of-the-art, various technologies are missing or are not having sufficient performances. We propose novel paradigm for MVDC power distribution networks, their interface and energy management. Our *DC Transformer* will be semiconductor based with galvanic isolation by means of MFTs, it will dramatically increase the reliability, efficiency and flexibility of high power systems.

To achieve project goals we will follow an integrated research approach based upon three closely interlinked research strands, addressing the different challenges and serving the common objective:

➢ **DC Transformer as Conversion Device**:

This is the primary function we aim to achieve in a highly flexible manner achieving: bidirectional, isolated, modular and scalable platform for high-power DC-DC conversion at medium voltage level. Strings of high voltage semiconductor based switching cells and high frequency transformers will be jointly optimized for demanding medium voltage high power operation. While the resonance is something to be avoided in AC systems, resonant power conversion allow for partial or complete removal of the control effort. We will demonstrate that *DC Transformer* can be simple and not actively controlled device (without closed loop control loops), yet with intelligence providing advance protection features, thanks to the availability of fast acting and controllable semiconductors.

➢ **DC Transformer as a Protection Device**:

Secondary function we aim to integrate into *DC Transformer* is related to fault limiting and protection, thanks to its semiconductor base and possibility to realize intelligent fast fault detection and reaction schemes. Rather than relying on separate discrete device, we will develop and integrate fault-limiting functionalities directly into the structure of a *DC Transformer*. Otherwise seen as passive DC-DC conversion device, the *DC Transformer* will become active protection device when required. This novel design paradigm will be tested through simulations, but also experimentally verified on the prototype device.

➢ **MVDC Power Distribution Networks**:

Devised conversion principles will be tested and tuned considering large-scale MVDC power distribution networks, through simulations (both off-line and in real-time using Hardware-in-the-Loop (HIL) systems. Focusing only on the DC-DC interfaces, we will propose and demonstrate optimal network layouts, energy management schemes, control schemes and protection coordination in systems with large number of *DC Transformers*. Operating regions guaranteeing dynamic stability assessment will be systematically derived allowing for predictable system behavior, especially for systems involving multiple nodes, sources or loads.

These research strands constitute the main backbone of the EMPOWER project, closely considering system level implications on the conversion and protection technologies, and vice versa. Successful resolution of these research questions will enable novel, efficient and reliable future energy systems.

2. Methodology

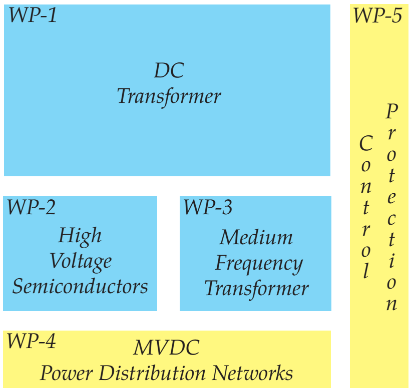


Fig. 6: *EMPOWER work-packages*

In the initial phase of project development, in-depth literature review and identification of the state-of-the-art in the fields of interest will be conducted. The initial study will help defining technical requirements and specifications (to be used only as guidelines) as well as performance metrics that will be used for quantitative assessment of project findings and results. Nevertheless, technical objectives may be put in place for the purpose of experimental demonstration of project results. Based on the real world applications, one could imagine technical objective for the optimization and demonstration to be defined as: 1MW rated bidirectional *DC Transformer* interfacing 40kV to 5kV voltage levels and having efficiency above 98%. Topologically there are many possibilities to realize conversion structure for these ratings, and high conversion efficiency together with ability to integrate protection features represent key research challenges from where research tasks are derived.

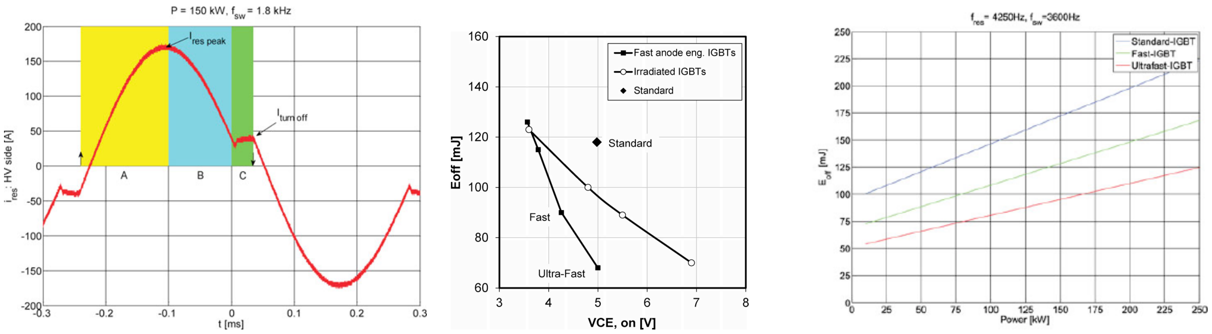
Based on set of target specifications, semiconductor devices of interest will be sourced, specified, customized (technology curve optimization) and fabricated through industrial contacts that are already established (e.g. ABB Semiconductors). Similarly, magnetic materials of interest and suitable insulation materials will be sourced, characterized and compared before their full integration into designs. Blocking voltages of present semiconductors are much lower than anticipated MVDC working voltages requiring series connection of multiple devices or conversion sub-stages. This is linked to modeling of dielectric stresses and insulation coordination strategies, which represent significant challenge of a project that will be addressed through the activities related to novel high voltage medium frequency transformer structures.

To achieve the goals of the project, we will use readily available tools for modeling and simulation of power semiconductor devices (TCAD), power electronic circuits (MATLAB, PLECS) and electromagnetic simulations (COMSOL, ANSYS). Novel multi-physics models, design tools and characterization setups will be developed, to support optimal designs considering multivariable optimization. For the large-scale simulations of MVDC power distribution networks with multiple *DC Transformers*, we aim to use a Real-Time Hardware-in-the-Loop (RT-HIL) system. This piece of equipment is currently unavailable at the Power Electronics Laboratory and is added into budget as additional request. To experimentally verify theoretical developments and resulting designs, experimental laboratory setups will be built, and integrated in the medium voltage research facility of the Power Electronics Laboratory. Existing laboratory infrastructure is already prepared for these research activities, and includes equipment such as: high voltage supplies (20kV, 5A), high current supplies (20V, 2250A), 90kW de-ionized water-cooling unit, partial discharge test setup (100kV, 20kVA). Additionally, 10kV MVDC supply line is available, as well MVAC voltages up to 20kV that can be rectified to create higher DC voltage levels.

Our work is organized in five work-packages (WPs) directly related to proposed research strands. This is illustrated in Fig.6, from where it can be seen that largest effort is directed to *DC Transformer* development relying on the semiconductor and magnetic materials (**WP-1**, **WP-2**, **WP-3**). However, these research activities are closely linked to overall system related considerations in MVDC power distribution networks (**WP-4**) as well as to protection and control coordination considering DC Transformer as device and MVDC system as whole (**WP-5**). Each **WP** is further split into several tasks, and the proposed set of activities is not application specific by any means, since the paradigm we aim to develop is transferable across many DC systems. Passive, safe, highly efficient and reliable *DC Transformer* for MVDC power distribution networks needs to be applicable to any kind of DC power system.

WP-1: DC Transformer Platform

DC Transformer of the EMPOWER project will be characterized with efficient and reliable operation without any closed loop active control. Galvanically isolated high power conversion requires semiconductor (**WP-2**) and magnetic devices (**WP-3**) to be jointly optimized and integrated. To achieve high conversion efficiency, we aim to apply principles of resonant conversion, where carefully designed resonant tanks (combination of L and C elements) are excited with square-wave voltages of power semiconductor switching cells. Resonant converters allow for zero voltage switching (ZVS) and/or zero current switching (ZCS) conditions to be provided for the semiconductor devices, significantly reducing the switching losses. An example, from the previous work of PI, is shown in Fig.7. At the same time, stresses imposed on the magnetic elements can be reduced due to sine-like current waveforms. So far, resonant conversion principles have not been applied at the multi megawatt scale, and we aim to demonstrate its feasibility for the first time.



a) b) c)

Fig. 7: *Resonant conversion example an its effects: a) resonant, near-sinusoidal current waveform with turn-off current being significantly lower than rated peak/rms current; b) 6.5kV IGBT device technology curve optimization for soft switching; c) reduction of switching turn-off energies at 3.6kHz [47].*

Based on set of target specifications, semiconductor devices (**WP-2**) of interest will be sourced, specified, customized (technology curve) and fabricated externally. Similarly, magnetic materials of interest and suitable insulation materials will be sourced, characterized and compared. While semiconductor devices are readily available in discrete voltage/current ratings (e.g. 4.5kV, 6.5kV), magnetic devices are not discretized in that sense and any of their ratings (frequency, power, voltage, current) can be optimized along continuous set of possible values, resulting in unlimited number of possible designs. Main tasks are:

WP-1-a: <u>Power Electronics Topology</u>

Power electronic topologies that are easily scalable and allow for easy integration of bulk galvanic isolation will be evaluated in order to derive the platform for the *DC Transformer*. The selected topology will be theoretically modeled and compared with alternatives, both analytically and with the help of power electronics simulation tools (e.g. PLECS). In this way, design rules and tools will be defined (although with ideal components) allowing for performance benchmarking. Semiconductor devices (**WP-2**) will have major implication on the performances of different topological variants, especially considering high blocking voltage requirements in MVDC systems.

WP-1-b: <u>Resonant Tank Circuit</u>

There are several possible realizations for resonant tanks combined with power electronic switching cells. The fact that we aim not to use any active control, requires careful identification of the resonant tank structure, that guaranties good conversion efficiency, but also provides support for fault limiting features we aim to maximize (**WP-5**). Integration of the resonant tank into MFT structure, power flow reversal, start-up and shutdown, short-circuit conditions will all be devised and verified, considering requirements expected in MVDC power distribution networks.

WP-1-c: <u>Modularity and Scalability</u>

Considering broad range of operating voltages and limited range of semiconductor voltage classes, modularity and scalability of *DC Transformer* are needed for wider real world coverage. Processing high power in bulk or fractionally has severe implications on the power electronic system optimization and design. Series- or parallel-connected semiconductor devices versus series- or parallel-connected power electronic stages are two fundamentally different approaches having a great impact on the *DC Transformer* topology, its operating principles and performances.

WP-1-d: <u>Prototyping</u>

Ultimately, the *DC Transformer* prototype will be assembled and tested in our laboratory (already described before) under realistic operating conditions. This task involves all personnel of the project.

WP-2: High Voltage Semiconductors

Considering MVDC levels, high-voltage semiconductors such as IGBTs and IGCTs are primary devices of interest. When it comes to the IGBT devices, the turn-off losses caused by the stored charges have already been thoroughly studied. There are several techniques reported in the literature for the turn-off loss reduction in resonant converters: i) Turn-off of the device before the resonance has ended, leads to loss of the ZCS is series resonant converter. However, the resonant inductor current helps recombining the stored charge carriers, which can result in reduced turn-off losses; ii) By modifying the ratio between resonant and switching frequency, the hold-off time can be varied and the shape of the device current prior to the turn-off can be controlled, allowing more time for charge carriers to recombine; iii) By controlling the magnetizing inductance of the transformer, peak of the magnetizing (circulating) current can be controlled and thus support the recombination of the charge carriers; iv) Bipolar semiconductors can be optimized on their technology curve to change the ratio between conduction and switching losses. This can be achieved by creating recombination centers either by impurity atoms or defects in the semiconductor lattice. This technique has been studied and demonstrated by PI in [47] as shown in Fig.7, where anode engineering on the 6.5kV IGBT led to almost 50% reduction in switching turn-off losses.

However, there is a lack of knowledge on how various techniques described earlier for IGBT could reduce the switching losses in IGCTs, as they were never optimized for low turn-off currents or resonant operation. This is especially interesting, because the plasma density in an IGCT is higher than in an IGBT, meaning that listed techniques can have a bigger impact on the switching losses in the IGCT than they have in IGBTs. At the same time wide-band gap semiconductor devices (SiC and GaN) offer in perspective much better performances at higher switching frequencies, but their present ratings are far away from those required for medium voltage applications. For those reasons our research activities will rely on several tasks, targeting IGCTs devices as initial choice, as summarized next:

WP-2-a: **Characterization for the Resonant Operation**
Behavior of high voltage semiconductors under soft-switching conditions is not well understood, as these devices are normally designed for hard-switching conditions. We will design experimental characterization test setups, allowing us to test devices with blocking voltages up to 10kV. Operating conditions will be adjusted my means of discrete passive components for wide frequency range, and variety of possible resonant tanks. Range of candidate, off-the-shelf, devices will be tested and compared considering desired operating characteristics.

WP-2-b: **Tailored Design for the Resonant Operation**
Mixed circuit TCAD simulations will be used to identify directions for optimizations of semiconductor devices for *DC Transformer*. These research activities will help us to correlate results of previous task with device internal designs and technologies, and outline directions for improvements. Based on our technology curve requirements manufacturing of devices of interests will be carried out externally (e.g. with ABB Semiconductors, Switzerland).

WP-2-c: **Experimental Verification of Optimized Devices**
Optimized semiconductor devices will be thoroughly tested and characterized using characterization setup developed in **WP-2-a**. This will allow for direct assessment of the switching performance improvements compared to the standard devices with the same switching frequency and power ratings. At the same, tests at higher switching frequencies will be conducted to determine operational limits and gains in performances. In addition to that, we expect to develop novel gate drive unit for the optimized device and soft-switched mode of operation.

WP-2-d: **Series Connection of Devices in the Resonant Operation**
For the scalability reasons and to reach higher MVDC voltage, semiconductor devices may be connected directly in series or through power electronics stages. Since the series connection is always associated with problem of static and dynamic voltage balancing, this will be investigated in details. While the case of hard switching is well understood, the series connection of high voltage devices will be investigated for the first time for the resonant operation. For these investigations, characterization setup from the **WP-2-a** will be adapted for series connection.

WP-3: Medium Frequency Transformer

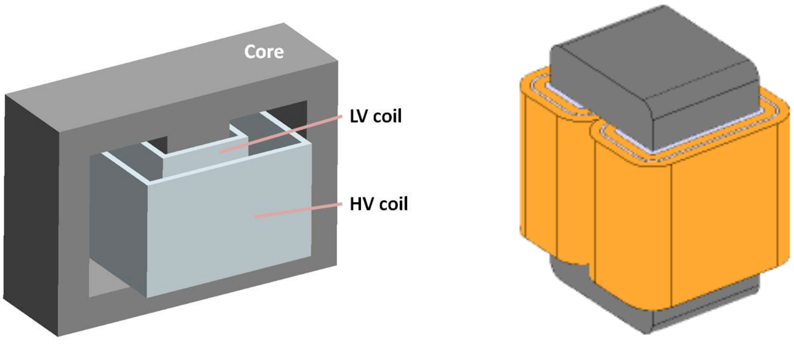
The medium frequency transformer (MFT) design and optimization, will be carried out in conjunction with topology selection (**WP-1**) and semiconductor optimization (**WP-2**) at operating frequencies of interest. The MFT is a core stage of the *DC Transformer* since it provides the galvanic oscillation and thanks to the increased switching frequency (**WP-2**) significantly reduced footprint. We will explore design space and interdependencies between magnetic and insulation materials on the implementation of high-voltage high-power MFT for resonant conversion. Suitable selection and optimization of core materials and geometries, winding layouts, dielectric and thermal management, as well as accurate control of MFT parasitic parameters are all required for the resonant operation. Different insulation materials offer different properties in terms of: dielectric strength, thermal conductivity, aging, self-healing, ease of manufacturing. Windings arrangement and materials impact overall performances and have to be analyzed and modeled. Finally, accurate modeling and design of transformer parameters (e.g. leakage inductance, magnetizing inductance, winding capacitances) is of paramount importance for the resonant operation. Tools for MFT optimization will be developed and experimentally verified on a laboratory scale prototype of the MFT operated with optimized devices in a resonant converter arrangement. The main research tasks are:

WP-3-a: **Modeling, Design and Optimization**
In a simplified representation, transformer is a combination of the magnetic core material, conductors of some sort and certain insulating material, that are all subject to thermal stresses, due to the high power processing, magnetic and Joule losses due to high switching frequency operation, and dielectric stresses due to exposure to high voltages. Increased power and insulation requirements have negative effect of the transformer volume that can be reduced by increase of the operating frequency. Yet, one must take into account thermal considerations related to heat evacuation from the available internal or external transformer surfaces. Feasible core geometries, magnetic and insulating materials and winding layouts will be identified for high voltage high power applications, together with sourcing of tools and samples of materials for characterization activities. Considering electromagnetic design, modeling of different parts of transformers will be carried out: magnetic, electrical, dielectric and thermal part. It is expected that two winding shell type and core type transformer representations (Fig.8) are sufficiently generic and can be used for optimization and design. Bearing in mind resonant operation, transformer parameters have to be precisely controlled during a design, and FEM simulation will be used to verify analytical developments.

WP-3-b: **Characterization - Core and Copper Losses**
Targeting switching frequencies in the range of several kHz and powers in the range of MWs, iron amorphous and nanocrystalline type of materials are of primary interest. To accurately model and take into account properties of these materials, characterization tests will be carried out to determine core losses, dielectric and thermal properties for design tool. Choice of material for winding is mainly limited to Copper Litz wire or Aluminum foils, that we will characterized for high switching frequencies (skin effect) as well as thermal properties. Increase of transformer operating frequency leads to a reduction of transformer volume, which in turn results in losses being contained in a reduced volume from where it have to be effectively evacuated. Thermal modeling and design is therefore crucial to understand temperature rise in different parts of a transformer, as well as heat flow towards the cooling surfaces.

WP-3-c: **Characterization - Insulation Materials**
MV applications require careful insulation coordination in order to prevent failures or premature aging during operation. While IEC standards provide guidelines, dielectric properties of the material must be considered during a design as these are subject to stresses of different kind: electric, magnetic, thermal are of primary interest for the project and related predominantly to solid insulation. Use of solid insulation implies closer integration of the winding structures into the insulating material and these activities are closely linked with previous activities. Partial Discharge test setup available at PEL (voltages up to 100kV) will be used to test different solid insulation materials as well as dielectric properties of early design prototypes of the MFT subassemblies.

WP-3-d: **Design Optimization and Prototyping**
Taking into account semiconductor operational limits as well as resonant converter circuit specifications from the **WP-2**, optimal designs of the MFT will be prototyped in conjunction with switching power stage, with inductive parts of the resonant tank integrated into the magnetic structure. MFT prototypes will be characterized as stand alone devices and further integrated into *DC Transformer* prototype to demonstrate its performances on the system level. Technologies for high power bulk power processing (MW) at elevated switching frequencies (few kHz) require significant research effort and pose challenges, which we will systematically address, solve and demonstrate solutions.



a) b)

Fig. 8: *Simplified illustration a) Shell type MFT; b) Core type MFT*

WP-4: MVDC Power Distribution Networks

As shown in Fig.1, we propose and will explore design paradigm of MVDC power distribution networks of different voltage levels interfaced through "passive" *DC Transformers*. This is the key idea and most important concept behind the EMPOWER project proposal. Considering presence of active power electronic converters, both on the side of distributed energy resources and actively controlled loads, we aim to demonstrate that intermediate power flow between different MVDC voltage levels, does not have to be actively controlled. Yet, to support such a paradigm and, at the same time, derive required characteristics for *DC Transformer*, a number of simulation case studies (off-line and in the real-time) will be carried out. Main tasks associated with this WP can be summarized as:

WP-4-a: **Power Distribution Network Architectures:**
A study will be carried out to compare various architectures expected in DC systems (point-to-point, multi-terminal, radial, ring, meshed, etc.) and implications on the power flow requirements and protection coordination. At the same time mono-pole and bi-pole distributions and their impact on the *DC Transformer* concept (redundancy) will be analyzed and compared. While we have certain experiences from work on marine MVDC power distribution networks, challenges of on-shore networks are significantly different and depend on system configuration and variety of sources/loads.

WP-4-b: **System Modeling**
Presence of various elements of different complexity requires modeling approach that is sufficiently detailed to capture relevant characteristics considering static or electromagnetic transient simulations. Generally, models and tools will differ for each scenario. For small-scale simulations switched models of relevant converters will be developed, while for large-scale simulation simplified (e.g. by averaging) models will be developed. MVDC cables will be modeled considering temperature dependent conductivity and frequency dependent parameters. Finally, in case of large dynamic system studies aggregation and clustering methods will be explored and tested.

WP-4-c: **Case studies**
Similar to AC system, where large number of CIGRE brochures and guidelines already exists, studies will be carried to characterize various DC systems. These will include: static and dynamic power flow, electric losses, short-circuit conditions and power quality considerations. Activities will be closely coordinated with the work outlined in **WP-5** related to protection coordination.

WP-5: Protection and Control Coordination

Finally, behavior of *DC Transformer* during normal operational and under external fault conditions will be investigated, in order to derive suitable control actions. While the main premise of our proposal is based on lack active power flow control or presence of closed loop control, certain low level "control" actions will be present, such as presence of pulse width modulators associated with creation of switching patterns, as well as control actions associated with power reversal or soft-start. On the other hand, availability of fast switching elements allows for fast reaction to the external events and implementation of advance protection functions, providing functions normally associated with external devices, such as DC breakers. These developments will be executed through several tasks:

WP-5-a: **Passivity and Stability**
System studies will be carried out to ensure that *DC Transformer* interactions with surrounding elements of MVDC power distribution network will results in stable operations in all scenarios. These instabilities are often associated with interactions of closed loop system with different harmonic components that may lead to positive effect amplifications. Even though, we aim to completely remove these actions, certain low-level controls as well multiple DC Transformers present in the MVDC grid, may be prone to some sort of interactions that degrade the system dynamics. These studies will be carried by means of simulations using Real-Time Hardware-in-the-Loop (RT-HIL) system, allowing for large models and multitude of scenarios to be explored.

WP-5-b: **Control Methods for Regular Operation**
Operation and terminal characteristics of *DC Transformer* will depend on the actual topology, nature of resonant tank and selected modulation scheme. Expected presence of large number of semiconductors, needs for synchronization of switching actions, coordination of power reversal maneuver and avoidance of saturation of MFT are several technical challenges that we aim to resolve. Off-line simulations will be used initially for development of basic control logic that will be ported to the digital signal controllers, which can be integrated with RT-HIL system for system studies.

WP-5-c: **Fault Detection and Reaction**

Difficulties associated with fault detection in DC and sufficiently fast reactions are well recognized, but not yet solved. In most of the cases, considering closed loop controlled converters, it is difficult to distinguish fast current change due to action of the current controller from the current rise due to nearby fault. With our control approach and suitable topological adaptions, external faults events should be easily recognized and characterized, and unused control degrees of freedom, will be completely devoted to the protection. We will trade-off controllability for the protection. At this point, it is straightforward to identify a big reward in the sense that the overall paradigm provides an original, compact and reliable solution. Various faults at various locations of the MVDC system will be analyzed and classified so that protection coordination can be defined, leading to a development of suitable fault limiting functions of a *DC Transformer* and their integration into digital controllers. Important aspect of this research work related to handling of overvoltages during fault reaction of the *DC Transformer*.

WP-5-d: **Experimental Verification**

Experimental verifications will include large system protection coordination studies on the RT-HIL system, where multiple *DC Transformers* will be integrated into the system and controlled with their respective digital controllers. Test on the prototype *DC Transformer*, will mostly be restricted to scenarios that are feasible to be carried in the laboratory environment, such as reaction to short circuits at close or remote location to terminals and overvoltage protection.

Outlook

By successfully completing this project, we will demonstrate novel design paradigm and unprecedented capabilities of the *DC Transformers* for high-power MVDC applications. We aim to integrate conversion and protection functions into a single device and resolve large technological gap in this area. Project results will be presented and published mainly in journals (e.g. IEEE Transactions, IET and EPE Journals), as well as in the regular scientific conference proceedings, in the form of scientific publications or tutorials (organized by e.g. IEEE, IET, EPE), or engineering seminars of other type (e.g. ECPE). Complete dissemination of the project results will be done in the form of three PhD theses and several MSc theses and be made publicly available. From the results originating from the project we expect novelty, and contributions to the Intellectual Property portfolio, either on the level of system, component or methods. A completely new paradigm for the conversion in DC systems will be established, supported by novel tools and experimentally demonstrated. Finally, through in depth research work carried out in described domains, we aim to develop novel teaching materials and courses, either at Master or Doctoral level.

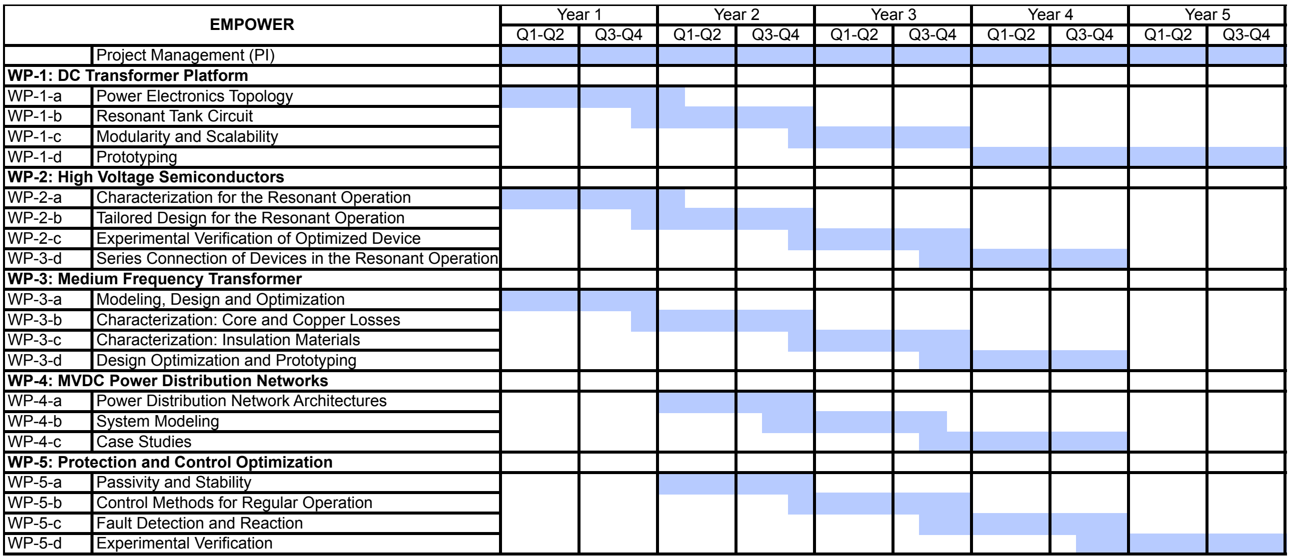
Beside its scientific impact and increase of the knowledge base, the overall project results should be directly transferable into the real-world applications, (either as advanced design guidelines, research and development optimization tools, concepts and solutions that could be further developed and commercialized. We expect to strengthen the cooperation between power electronics industry and academic researchers in the European domain. Our strategic interest is to promote the role and importance of power electronics in future energy systems. With this we have in mind not only technological benefits, such as energy efficiency or energy savings, but also societal impacts related to raw material savings (through footprint reduction), increased and efficient use of renewable energy sources, all enabled by power electronics technologies.

Finally, every research require steps into unknown, and I believe that in this project we will educate new generations of researchers and engineers; teach them how to deal with complex problems spanning across the range of disciplines; encourage them to invent and develop new power electronic technologies for future energy systems; increase their awareness and skills related to sustainable technologies; and finally increase their capacity for further learning; something fundamental for dynamic and evolving field of power electronics

3. Resources (including project costs)

This five-year project will support a team comprising the PI, Post Doc, and three PhD students. The execution of our research agenda is illustrated in Fig. 9. We plan to recruit on two PhD students in the first year, followed by the third PhD student in the second year. Postdoctoral fellow will contribute over the course of five years.

As Post Doc mentoring plan, PI will follow these steps to provide the skills, knowledge and experience to prepare the postdoctoral researcher to excel in his/her career path: i) Working with the researcher to implement an individual development plan, ii) Providing opportunities to network with leading scholars in our field, iii) Enabling travel to international conferences, with the goal that the postdoctoral fellow present a paper at the conference, iv) Promotion of project results through creation of tutorials and their presentation at key conferences in the field.



EMPOWER		Year 1		Year 2		Year 3		Year 4		Year 5	
		Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4
	Project Management (PI)	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
WP-1: DC Transformer Platform											
WP-1-a	Power Electronics Topology	▨	▨	▨							
WP-1-b	Resonant Tank Circuit		▨	▨	▨						
WP-1-c	Modularity and Scalability				▨	▨	▨				
WP-1-d	Prototyping							▨	▨	▨	▨
WP-2: High Voltage Semiconductors											
WP-2-a	Characterization for the Resonant Operation	▨	▨	▨							
WP-2-b	Tailored Design for the Resonant Operation		▨	▨	▨						
WP-2-c	Experimental Verification of Optimized Device				▨	▨	▨				
WP-3-d	Series Connection of Devices in the Resonant Operation						▨	▨	▨		
WP-3: Medium Frequency Transformer											
WP-3-a	Modeling, Design and Optimization	▨	▨								
WP-3-b	Characterization: Core and Copper Losses		▨	▨	▨						
WP-3-c	Characterization: Insulation Materials				▨	▨	▨				
WP-3-d	Design Optimization and Prototyping						▨	▨	▨		
WP-4: MVDC Power Distribution Networks											
WP-4-a	Power Distribution Network Architectures			▨	▨						
WP-4-b	System Modeling				▨	▨	▨				
WP-4-c	Case Studies						▨	▨	▨		
WP-5: Protection and Control Optimization											
WP-5-a	Passivity and Stability			▨	▨						
WP-5-b	Control Methods for Regular Operation				▨	▨	▨				
WP-5-c	Fault Detection and Reaction						▨	▨	▨		
WP-5-d	Experimental Verification								▨	▨	▨

Fig. 9: *The EMPOWER project – schedule, work-packages and activities. Post Doc will be main responsible person for the WP-1 and WP-4, while WP-2, WP-3 and WP-5 are allocated to each PhD student, respectively.*

The PI will be directly involved into the project, supervise the PhDs and advise and coordinate research activities of the Post Doc. We expect three highly cited PhD theses emerge as a result of the proposed work, revolving around the individual research work-packages (**WP-2, WP-3, WP-5)**. We will encourage cross-pollination among the PhDs to build ties and foster interaction between our research topics, as they require a diverse background.

Our budget numbers rest on the following estimates. The salaries, including the fringe benefits, consider starting salaries and social charges applied at EPFL for PhD students (57'764 EUR) and Post Docs (94'380 EUR) and include regular salary progression for follow-up years. Postdoc and students that are part of the ERC team will be employed by EPFL during their involvement in the project. Travel costs for ERC team members, considering size of the team are estimated as 61'916 EUR for the full duration of the project. These costs will cover travelling to conferences and presentation of project results and we hereby confirm that no travel costs will be charged for people not involved into project. Publications fees (10'008 EUR) are based on the projection of two open access IEEE journals per year

Total equipment costs (342'860 EUR) comprise the acquisition of small electronics and measurement equipment needed to support development and instrumentation of characterization setups for semiconductor and magnetic devices. Additionally, it also includes 200'000 EUR as major cost to acquire Real-Time Hardware-in-the-Loop simulation platform for the purpose of large-scale system studies described in **WP-4** and **WP-5**. The equipment purchased for the project will follow EPFL's depreciation policy, which is in accordance with the international accounting standards, namely the IPSAS Standards: Scientific equipment with a value higher or equal to 10'000 CHF (out of VAT) is depreciated over the duration of 5 years from the date at which the equipment is taken into service. IT equipment with a value higher or equal to 10'000 CHF (out of VAT) is depreciated over the duration of 3 years from the date at which the equipment is taken into service. Equipment with a value lower to 10'000 CHF (out of VAT) is not depreciated, but considered as Direct Costs. The equipment will be used a 100% on the ERC project. Cost of consumables (171'432 EUR) is associated with cost of materials for characterization setups, semiconductor devices, magnetic and insulations materials, and overall material costs for *DC Transformer* prototype.

As PI, I will commit 40% of my time to the EMPOWER project. PI will maintain employment by the Host Institution (EPFL) for the whole duration of the project. This 40% of time commitment is compatible with all other on-going activities and teaching duties.

Cost Category			**Total in Euro**
Direct Costs	**Personnel**	PI	0
		Senior Staff	0
		Postdocs	487’468
		Students	713’400
		Other	0
	i. Total Direct Costs for Personnel (in Euro)		**1’200’868**
	Travel		61’916
	Equipment		342’860
	Other goods and services	Consumables	171’432
		Publications (including Open Access fees), etc.	10’008
		Other (Audit)	11’432
	ii. Total Other Direct Costs (in Euro)		**597’648**
A – Total Direct Costs (i + ii) (in Euro)			**1’798’516**
B – Indirect Costs (overheads) 25% of Direct Costs (in Euro)			449’629
C1 – Subcontracting Costs (no overheads) (in Euro)			0
C2 – Other Direct Costs with no overheads (in Euro)			0
Total Estimated Eligible Costs (A + B + C) (in Euro)			**2’198’145**
Total Requested EU Contribution (in Euro)			**2’198’145**

Request for additional funding above EUR 2 000 000 for	**Justification**
the purchase of major equipment	Additional **200’000 EUR** (including overhead) are requested for purchase of a Real-Time Hardware-in-the-Loop platform for the large-scale power electronics and system simulations of MVDC power distribution networks as described in WP-4 and WP-5. This equipment is currently not available at the host institution (EPFL) and it would greatly support research activities of the EMPOWER project.

Please indicate the duration of the project in months:	**60**
Please indicate the % of working time the PI dedicates to the project over the period of the grant:	**40%**
Please indicate the % of working time the PI spends in an EU Member State or Associated Country over the period of the grant:	**100%**

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