FIRST STEP TO FULL DC-POTENTIAL: IMPROVING ENERGY EFFICIENCY IN HOUSEHOLD EQUIPMENT

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ABSTRACT

Electrification of transportation, communication, working and living continues worldwide. Televisions, telephones, servers are an important part of everyday life. These loads and most sustainable sources as well, have one thing in common: Direct Current. The Dutch research and educational programme 'DC – road to its full potential' studies the impact of feeding these appliances from a DC grid. An improvement in energy efficiency is expected, other benefits are unknown and practical considerations are needed to come to a proper comparison with an AC grid.

This paper starts with a brief introduction of the programme and its first stages. These stages encompass firstly the commissioning, selection and implementation of a safe and user friendly testing facility, to compare performance of domestic appliances when powered with AC and DC. Secondly, the relationship between the DC-testing facility and existing modeling and simulation assignments is explained. Thirdly, first results are discussed in a broad sense. An improved energy efficiency of 3% to 5% is already demonstrated for domestic appliances. That opens up questions for the performance of a domestic DC system as a whole. The paper then ends with proposed minor changes in the programme and guidelines for future projects. These changes encompass further studying of domestic appliances for product-development purposes, leaving less means for new and costly high-power testing facilities. Possible gains are 1) material and component savings 2) simpler and cheaper exteriors 3) stable and safe in-house infrastructure 4) whilst combined with local sustainable generation. That is the road ahead.

1. INTRODUCTION

As a partner in a DC project during the KITE120 programme, THU met various opinion and industry leaders and learned about the potential of DC, especially in Greenhouse Horticulture. KITE is an acronym for Knowledge and Innovation Towards Entrepreneurship. 120 Companies in four clusters served as research objects for the programme. Its aim was to stimulate innovative capacity within organizations and to stimulate regional economic growth. KITE ended in 2012. A few years later, DC is a very popular research and publicity topic [1][2]. Lots of studies, aiming foremost at energy efficiency in lighting and ICT, have been and are performed. Al these studies use various solutions, grid-layouts and voltages and therefore come to different results, almost all of them claiming positive results for DC, yet are very difficult to compare [3].

'DC – road to its full potential' is an educational and research programme initiated by The Hague University of Applied Sciences (THU). The programme started in February 2013 and the first part of the programme will end in January 2015. The programme is considered ambitious with its four objectives:

1. To gather, capture and create new knowledge on DC-systems, especially in the built environment.
2. To educate both THU students and THU staff in international and relevant projects.
3. To help our partners, especially SME's, in overcoming knowledge-related obstacles in innovation processes and introducing them to potential partners.
4. To further the cause of sustainable electrical generation by stimulating innovative behaviour of students, staff and partners.

The first stages of the programme consist of modeling, simulating and partly realizing DC-distribution-grids, with focus on residential areas. DC-Micro-Grids are grids in houses, apartments and smaller offices. DC-Mini-Grids then are streets or larger offices, built up of several DC-Mirco-Grids. Thirdly, the programme recognizes DC-Midi-Grids, which in turn are built up with two or more DC-Mini-Grids.

Furthering work of the project team and partners [4][5], THU contributes to the cause of DC as well, taking an in-house voltage level of 350VDC as ideal. This paper is not intended to rewrite a discussion about voltages and grid lay-outs. This paper aims at discussing the setting up of a testing facility, to study the assumed voltage level and to be able to evaluate it. Furthermore, this paper proposes a method to compare the energy usage of household equipment with both AC (230VAC and DC (350 VDC).

2. SETTING UP OF A DC TESTING FACILITY

The foremost question here was and still is: how to design a DC-testing facility, if you do not know the ideal, safe and use-friendly lay-out of a DC-grid? The latter is one of the required results of this two year programme, the former is needed to get to those results. Standards or best practices are largely non-existent and various suppliers and specialists all propose their own solution or have their own vision on DC grids [6][7]. Another issue is the scarce availability of DC-grid-products for 350 VDC or even the lack thereof. As a University of Applied Sciences, the education of our students is practical and implementation-driven. THU staff and thus the project team should be able to overcome these obstacles. The chosen approach is therefore a straightforward one.

The first step for the team and the partners was to come to a proper set of requirements. Proper not only relates to a good coverage of the topic of state-of-the art DC-grids, but also to be able to make valid comparison between AC and DC. The second step was to search for and create alternatives and to choose the best alternative, based on the requirements of the first step. The third and final step, from the point of view of the project, is the implementation of the testing facility on THU location.

2.1 FUNDAMENTAL REQUIREMENTS

During many a meeting, the project team and their partners discussed the electrical plug for the next generation. Alternating Current (AC), in all its appearances, plugs and sockets, is off course very familiar. For more than a century AC is being used for electrical energy distribution. AC:

- Can be transformed by simple means: low tech transformer with low distribution losses
- Has sine wave voltage and current form with both resistive and reactive loads, so do their integrals and differentials. Sine waves have zero crossings twice a period. When disconnecting, arcing will be naturally extinguished by the sine wave polarity change of the electrical current. This significantly reduces the requirements for the switches, sockets and fuses in an electrical network
- Ground leakage currents can easily be detected by means of a ground fault circuit interrupter.

With DC, both current(s) and voltage(s) are a constant value in time. Pure resistive loads will not give any trouble during switching on and off at all. However, since there is always a grade of inductivity in a DC network as well (parallel running wiring, just as with AC), the inductivity will cause the current to be maintained. Since there are no zero crossings anymore, the electrical current will not extinguish by its natural behavior. The result is arcing and longer distances between switch contacts are needed. The same goes for the socket. Where a vacuum cleaner on AC can easily be disconnected from the grid by pulling the plug while running, on DC it will severely reduce plug life and or switch life. Most of the times, the distance between AC switch contacts will be too short for disconnecting DC supplies from the load or grid.

A DC socket should thus be an innovation, rather than an upgrade of an AC socket. It should therefore have precisely specified properties:

- No mechanical disconnection allowed when current is flowing
- The load can only be switched on when the connection between load and socket is electronically checked on proper connection beforehand
- Domotics should be integrated in DC sockets: they will be able to switch on and off a load.
- Communication should not only be for proper connection check, but also for power matching between loads and supplying network

The next-generation DC socket will be a purely solid state device. Mechanical switches with wiring between supplies, switches and lights for switching on and off these lights will become obsolete. The electronic DC socket can be communicated with, via an integrated data bus that runs over the DC power supply lines as well. All inertia / short circuit capability can now fully be eliminated from the network, since power match between socket and load is established first. Soft start of loads is then easy to establish. Fusing is hardly necessary anymore, since protection is fully electronically. Ground fault interruption is now the new challenge to achieve in a proper way. Where with AC a straightforward coil can be activated to make a safety switch trip, with DC there is no alternation of current in time and a simple coil will not do. This protection circuit should be electronically executed as well.

2.2 PROPER REQUIREMENTS

The project team, the consortium and internal clients therefore agreed to commission an installation that, in random order, would be

- Safe for users (staff and students)
- Provided with ample workspace to also work with appliances as fridges and washing machines as well
- Connectable to the 18 kW-peak PV-installation (THU location Delft) and to the distribution grid
- Suitable to work with for the Dutch common household appliances
- Modularly built and transportable
- Both voltage and current adjustable, up to 350 VDC [4]
- Provided with both AC and DC outlets
- Smartness-ready
- Usable for demonstration and publicity purposes
- Modestly priced (please remember, THU is primarily an educational institution…)
- Fast to deliver, within three months after order to be able to start with experiments in spring 2014.

2.3 ALTERNATIVES AND SELECTION

With the well-known obstacles in mind, the team set to work. Several project-partners and suppliers were requested to bring out a proposal for the testing facility. Not surprisingly, plug-and-play solutions were indeed unavailable. There were offers to work jointly on developing more long-term solutions, but these didn’t fit the THU-programme, mostly because of lack of time and money. The offers selected for reviewing all shared a comparable lay-out. Each had one of more separate DC sources, used mostly known parts for electrical installations and/or ICT (USB) and all thought of storage to simulate a grid with future electric vehicles. Originally, the evaluation would primarily be about the given requirements and the financial implications. Because of the unusual combination of quite similar offers (custom built facilities), lack of bench marks and the projects ‘need for speed’, it was considered nearly impossible to come to a proper comparison based on the offers alone.

Therefor other decision-making means, not related to the content but rather to the supplier, were considered. The project was subsequently awarded to the supplier 1) closest to the Delft location of THU for easier communication, 2) proven hands-on experience to be able to coop with uncertainties3) for whom the project would at least be equally important as it is for THU to be more equal (very difficult to measure) and 4) with best existing ties with the consortium-partners to ensure a long-lasting relationship.

The selected offer consisted of three phases:

1. An analysis of the PV-installation (THU location Delft) for options to improve performance and improve feed-in possibilities to a local DC-grid.
2. Design, construction and implementation of three DC-test-benches with adjustable DC sources [8] with a contractual delivery within three months.
3. DC-bus to connect DC-test-benches to the PV power station on the roof of THU, with storage option in EV and remaining feed-in option to the grid.

2.4 PRACTICAL IMPLEMENTATION

In two to three meetings the requirements and possible solutions and or DC work-a-rounds were discussed with the supplier. Topics were above all: AC and DC sources, DC plugs and sockets, re-use of old test-benches and detailed and user-friendly instructions and a manual. In the next few parts of this paper, the outcomes and subsequent implementation will be described.

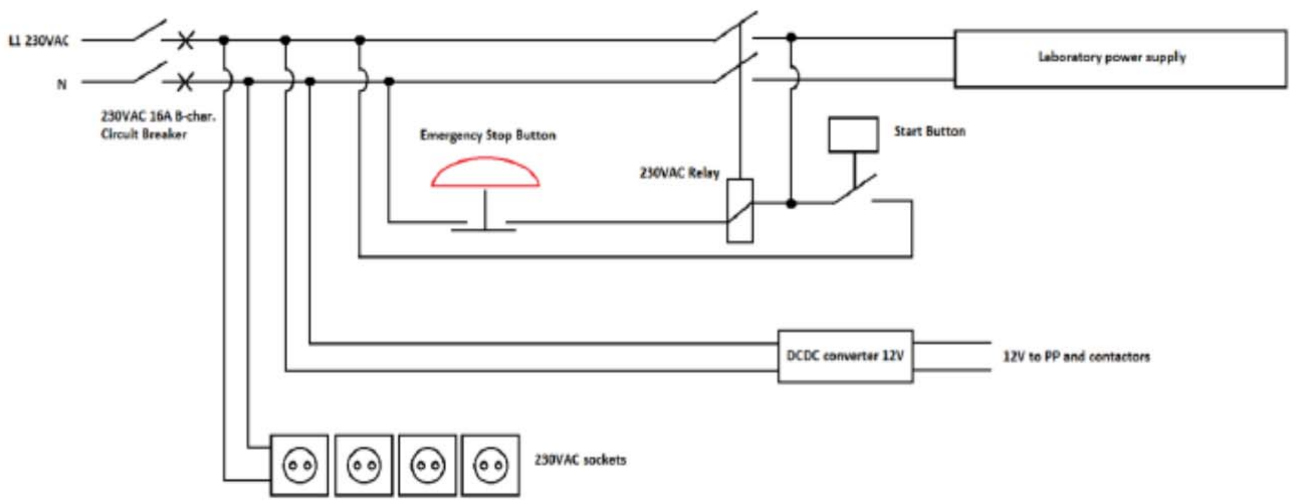


Figure 1: AC electrical setup of DC test benches

AC Electrical Setup

The figure at the bottom of this page (fig 1) shows the power-supply to the AC sockets and, more importantly, the relation between AC and DC. This relations is a double one. The AC is used as the prescribed feed-in for the DC-sources (named laboratory power supply). Next to that, AC is used to generate a 12 VDC voltage for communication purposes. In the figure below (fig 2), the blue arrow on the right points towards the AC sockets. The Emergency Stop Button is right beside them.

DC Electrical Setup

The green arrow on the left points towards the DC sockets. These are in fact off-the-shelve AC components, more specifically Perilex sockets and plugs to match, tailor-made to work on DC. The orange coloring of the sockets and cable (fig 3) is meant for indicating awareness to all users: this is something different, please pay attention.

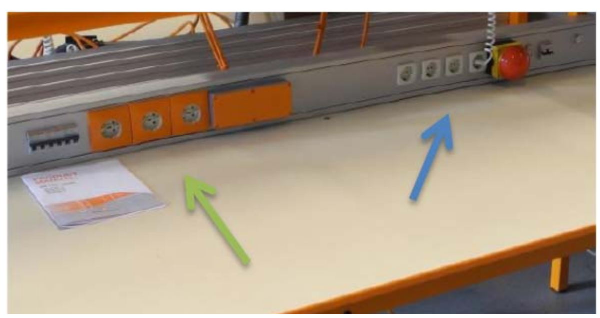


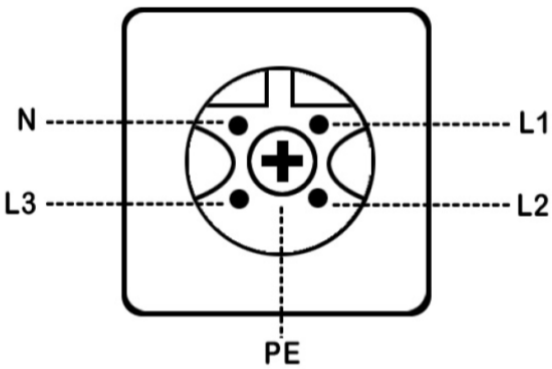
Figure 2: layout of DC Test benches

Communication-ready DC-plugs do not yet exist. Yet the ability to communicate, even in the simplest form, is crucial, as established earlier. As for now, primitive protected DC sockets and plugs are operational in the DC testing facility. In this case, there is a pilot

Figure 3: DC Plug

signal pin pair integrated in the plug. First the power pins are connected in the socket and by pushing the plug further in, two pilot pins make contact and the contactor is activated. Note the shorter pin in the figure directly above (fig 3), indicated with an orange arrow.

The detailed working of these modified Perilex plugs and sockets is further explained in the schematic and explanation below (fig 4). The figure at the bottom of the page (fig 5) shows the over-all schematics of the DC system in the testing facility.



Original socket AC coding:	New DC use:
PE	PE
N	0
L1	+350VDC
L2	PP, connects to ground when plug is inserted
L3	empty, projected for future -350VDC

Figure 4: schematics and explanation of DC socket

The benefits of this elaborate construction are that:

- A first step in switching on power- and current less is enabled with the basic proximity pilot signal.
- DC arcs during switching are automatically extinguished. The contactors are gas filled and have arc extinguishing magnets.
- Peak currents between capacitive loads are prevented with Negative temperature Coefficient resistors.

This is of course a mechanical, elaborate and thus expensive way to make a DC socket. The challenge is to skip all mechanical parts (the contactor as its most expensive part) and make it 100% solid state. In this way, DC sockets will eventually be cheaper than smart AC sockets.

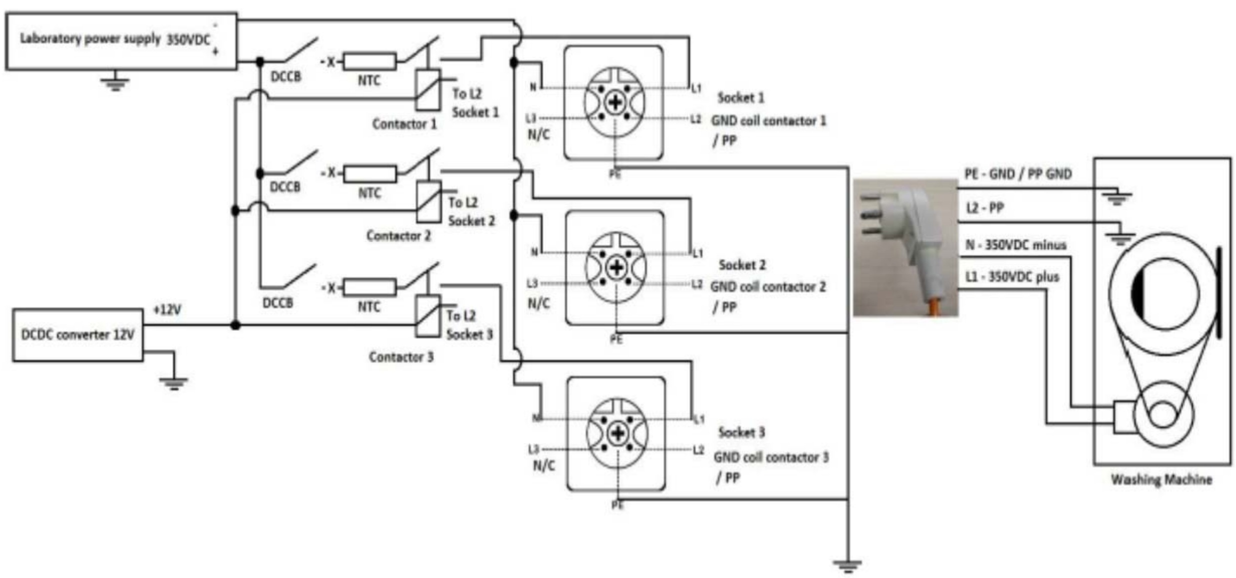


Figure 5: DC electrical setup of DC test benches

3. TESTING FOR TOPOLOGY VALIDATION

This testing facility was mostly commissioned to help fulfil the first and second objective of 'DC – road to its full potential'. Parallel with the development of the facility, several Belgian and Spanish students, seven in total, started working on their Master thesis on DC-grids. A few of these students are truly interested in the topic and have chosen for an elongated trajectory. The student-entrepreneurship programme ThinkCORE [9], presently running in GroepT / KU Leuven, combines an extended Master programme (with additional certificate) with an two-year long period, in which the students act as consultant in their own firm.

Four of these students are presently studying and simulating a DC-Micro-Grid with focus on 1) Efficiency, 2) Use of Materials, 3) Economical Constraints, 4) Distributed Generation, 5) Storage and 6) Safety and Control. Their starting point was and is a distribution topology for domestic appliances, lighting, heating and cooling. This topology would distribute 350 VDC to its end points. Using as little conversion steps as possible, modeled loads are connected to the domestic grid. Each load has its own profile. For example the washing machine will run 2.3 times per week, on a standardized programme with 40° Celsius, the television is on for 3.4 hours etc.

The test-focus for these students is the difference in electrical performance when supplied with AC and DC, not the specific electrical consumption with either AC or DC. Inaugural tests of the facility have proven a (modest) improvement in energy efficiency. The power usage (in VA) of for example vacuum cleaners and monitors when using DC directly is 3% to 5% lower than when using AC. This result is reached without any change to the apparatus. Most domestic loads have already proven to work on DC.

Results of more elaborate testing of the domestic appliances will be reached in March and April 2014. These results not only imply the improvement in energy efficiency when using DC, but also the most appropriate voltage level for each appliance. These voltage levels are useful in evaluating the proposed topology with 350 VDC as its backbone. Is this topology sufficient or are modifications required to improve the energy effectiveness of used applications? This is an important part of the assignment of the KU Leuven students. These voltage levels will also be used to think of smart ways to 'hybridize' domestic appliances. Perhaps groups of appliances require more or less the same DC input voltage. To enable these groups to work efficiently on DC, the design of special prints will be studied. The prints should be able to be retrofitted on existing AC equipment, to replace the AC prints as simply as possible.

4. FIRST RESULTS AND NEXT STEPS

The 16th of December 2013 was the date set by the project team to reveal and demonstrate the DC-testing facility to all the consortium and project partners (fig 6). All were very enthusiastic and saw lots of potential for research and education.

Figure 6: revealing of DC test benches

4.1 RESULTS

Besides the demonstrated improvement in energy efficiency of 3% to 5% for domestic appliances, the project team has captured several other, both technological and non-technological results. In random order:

- The need to study and explain the improvement in energy efficiency with DC. This is considered the starting point for the 'retrofit' prints. Savings in materials and components, as well as the effects thereof on the product itself will be made clear.
- The first two stages of the testing facility were delivered within time and budget.
- Several project partners requested the use of the facility (with or without students) for their own product-development purposes. DC fridges, LED fixtures and for example PV powered Reverse Osmosis were among the projects discussed.
- Europe's Leading dance festival organiser ID&T [10] expressed its interest in reducing their energy-usage with DC to THU and proposes to start a project to study and demonstrate possibilities.
- After having seen the potential of reducing energy usage in appliances, THU has proposed a new DC project to its board, as new part of the DC programme. Its aim is to study and develop a hybrid AC/DC system to retrofit in existing buildings and to develop a full DC infrastructure for new houses, complete with DC-DC 'switchboard', sockets, plugs etc. This is 'greenfield engineering' and very interesting for both engineering and innovation studies.
- The opportunity to present the DC-test-facility and the programme in TVVL magazine. In the Netherlands, this is the leading magazine for the installation-engineers in the build Environment.
- It is expected, as demonstrated in HPS lighting for Greenhouse Horticulture application, that DC elongates life of domestic appliances [11]. Heath-sensitive material, especially electrolytic capacitors are usual suspects for failure. These components are not used in DC prints and thus lifespan is very likely expanded.

4.2 NEXT STEPS

As mentioned in the previous paragraph, the project team sees a lot of potential for new DC-projects and studies. The new testing-facility has an important impact on the proposed activities in the next steps in the programme as well. The supplier has delivered on time and within budget, the effort has been more exhausting for the project budget.

Commissioning this testing facility has, as a side effect, proven that building test-facilities for higher voltages (up to 1500 VDC) and being able to distribute more electrical power is not feasible within present budgets. If THU chooses to follow-up on larger-scale projects, different means of funding are required. This means that for both DC-Mini-Grids and DC-Midi-Grids, the use of models and simulation will be the available methods to conduct research. Physical testing, at least on actual scale and size, is simply too expensive. The most effort will be put into building up a knowledge base on domestic appliances running on DC, DC grids for houses and small offices and on hybrid AC/DC solutions for the build environment.

The future promises plenty of study towards the energy effectiveness of domestic appliances. The project team strives for high quality results and secretly hopes for exciting results and perhaps a veritable technological breakthrough. The team can't wait to unwrap our new study-objects (fig 7) and to get started.

Figure 7: Study objects for spring 2014

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6. AUTHOR(S)

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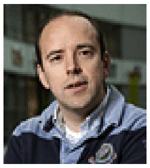

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