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A Structured Approach for Design of an SST Control Architecture Based on CAFCR Framework

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***Abstract*—Solid-State Transformers (SSTs) are a promising alternative to conventional oil-cooled copper-and-iron based power transformers in the electricity grid. They offer opportunities to make secondary (MV/LV) substations flexible, intelligent and modular. This work proposes to use a generic design tool from Systems Engineering - the CAFCR framework - for the SST control system to unlock its full potential. The framework provides a structured and thorough approach for collaboration and design, connecting what is desired with what is possible. The advantages are as follows: 1) Many research on SSTs has already been done and the framework can help to collect and aggregate the performed research; 2) It also helps to ensure important aspects are not overlooked and designs meet the necessary requirements; 3) Furthermore, it can identify new areas of research and facilitate new ideas. In the paper, we apply the CAFCR framework to SST by starting with the perspective of the Distribution System Operator (DSO) as the customer and an exploration of the application surroundings (substation housing, grid embedding). We then continue to examine the functionalities that are required and desired for an SST from a black-box perspective. These functionalities are presented in a table where the functionalities are divided into a) 'additional features' vs 'mimicking a regular transformer', and b) 'normal operation' vs. 'fault conditions'. Based on this, four areas of research have been indicated to obtain a flexible, future-proof control architecture. To see how these areas could work together, a task division is proposed as well as applying distributed control to the MV side.**

***Index Terms*—Solid-State Transformer, control architecture, CAFCR framework, requirements, decentralized control**

I. Introduction

A Solid-State Transformer (SST) is a transformer made from power electronic components and small, high-frequency transformers. The purpose is to have more control over voltage, current and power characteristics. This additional control gives future electricity grid operators more options to prevent and mitigate problems due to the energy transition.

This publication is part of the FLEXstation project, which was carried out with Topsector Energiesubsidie from the Ministry of Economic Affairs.

In the Netherlands, a collaboration was started between the two largest Distribution System Operators (DSOs) Alliander and Enexis, the testing facility KEMA and Eindhoven University of Technology. This consortium project, FLEXstation, started in 2017 and aimed to explore the applicability, possibilities and potential of a power electronic substation. A power electronic substation was here regarded as a secondary (MV/LV) substation with an SST. Apart from investigating SSTs as flexible, intelligent and modular, the goal was also to examine which challenges are associated with actual application in the electricity grid, such as certification and future-proof design for long-term application.

Research to Solid-State Transformers (SSTs) is expanding rapidly. A search in IEEE Xplorer on 'Solid-State Transformer' yields nearly three thousand results. Several prototypes have been built. However, reports on a structured design process to incorporate all this research is missing. In this work, we will use the CAFCR (Customer objectives, Application, Functional, Conceptual, Realization) framework to look at control architecture development from a design and system perspective. The CAFCR framework is a generic design tool from Systems Engineering that we will introduce in the next section. We see strong benefits for applying this framework for SSTs:

1) It is a structured design method to ensure that minimum requirements are met and to enable SSTs to reach its full potential.
2) As a means for the future to collect and combine research on power electronic technologies. They can then be integrated in a design.
3) To indicate gaps in knowledge and initiate new areas of research.
4) It creates space for new ideas and can spark inspiration. E.g. new added features, new ways of implementing and new applications.

5) By creating an overview, it can help to determine priorities.

The goals of the study in this paper are to illustrate the workings of CAFCR, to connect DSOs and power electronics researchers, and to set a basic implementation of the CAFCR framework that can be further built upon in the future. In the next section, we will introduce the CAFCR framework. In sections III to VI we will explore the parts of the CAFCR framework one by one.

II. Purpose and CAFCR

A common practice in industry and design trajectories is to start from the wishes/needs of the customer, to compile the requirements of the object-under-design, to come up with conceptual plans and then work out the details of the implementation. The goal is to achieve something which is both implementable and satisfies the customer as much as possible. A very specific method for this is the CAFCR framework [1]. We claim that it is very well suited for research purposes because of its iterative nature, the freedom it allows, and the opportunities for collaboration.

A. Introduction into CAFCR

The CAFCR framework can be summarized as a reasoning tool for architecture design. The abbreviation CAFCR (pronounce 'Kafker') stands for: 1) Customer objectives, 2) Application, 3) Functional, 4) Conceptual and 5) Realization. These five words represent different views on a system under design. If we apply these views to an SST in electricity grid substations, we can define the views as follows:

1) why the customer wants it (problems, values and objectives);
2) the environment of a transformer (substations, the grid, test conditions, update possibilities);
3) a black-box view (functional requirements/wishes, power conservation);
4) conceptual drawings (architecture ideas and options, terminology definitions);
5) technological implementation (control techniques, hardware choices).

According to the CAFCR method, the architecture design should be developed in all views simultaneously. 'Simultaneously' as in time-division multiplexing. This is because insights from one view impact the other views. For example: the realization view may show what is and what isn't achievable with (available) technology, the application view may show what the intended application environment of the system demands or requires, and the customer objectives view shows what is really of importance. What is important and what is demanded by the application environment, influences which technologies are under examination and which technologies might want to be developed. The other way around, the limits of implementation may need us to adapt our expectations or adapt the application environment.

The framework is explicitly not a process definition: there is no fixed order for switching between the views. The idea is to switch between the views on a short time basis, which may be as short as 15 minutes at the very start of the project, and may extend to longer periods of time as the project progresses.

B. Application of CAFCR

Related work in literature can be divided over the five CAFCR views. Much research has been done that can be categorized in the Realization view. These are specific technologies and implementation details of hardware and control. The knowledge in these papers somehow needs to be combined and classified. The results in this paper can help to do this (see Section VI). Published content that is linked to the other four views (Customer Objectives, Application, Functional, Conceptual) is scattered and limited in amount. In papers where this content occurs, it is often mixed with a considerable amount of Realization view content [2] [3]. Mixing elements of the different views and not working them out well poses the risk of tunnel vision in choosing the concept and implementation.

This paper therefore aims to make a clear distinction between the parts and set the standard for further development. It is not possible to create a complete overview, but it aims to serve as a starting point in the discussion and for further interaction between the CAFCR views. It does this by focusing on the first four CAFCR views, because a thorough examination of these is missing so far. Then, there can be a further dialogue between the what is possible (implementation details, view 5 of CAFCR) and what is desired (high-level view, first three views of CAFCR). In the following sections, the first four CAFCR views will be treated one by one.

III. View 1: Customer understanding

The first CAFCR view, Customer objectives, is about understanding the customer. It aims to create a broad picture about the customer: what are their values, problems and objectives? The later stages of the design can then be verified against this understanding of the customer. This is crucial for efficiency and fast adoption. For an SST, the future customers are the DSOs.

A. The DSO work

In essence, the objective of the DSO is to provide reliable energy supply for customers, on a safe electricity grid, and thereby adhering to the grid code. While doing so, they aim for the lowest possible costs to keep societal costs low and to keep their service affordable. Therefore, they have been interested in reducing the total investment costs, reducing the total maintenance costs and enable a full lifetime of 40 years for the components of the distribution grid. The quality aspects of the distribution grid are: safety, load capacity, power quality, and reliability.

Concerns and important aspects for DSOs are:

- the hosting capacity for renewable energy (the amount of renewable energy that can be dealt with by the system);
- scarcity of materials, especially copper;
- scarcity of trained people to perform installations, including new cables;

- safety: dealing with voltage safely, avoiding oil is preferred;
- societal costs (the cheapest solution for the whole system, including elements outside direct DSO responsibility);
- complying with regulations: legal obligations, grid code;
- simplicity and reliability (DSOs prefer 'fit and forget', smart grid advancements are complex);
- being decoupled from the market: storage operation by DSOs is currently prohibited.[1]

B. The DSO's current problem

The DSO's central problem follows from the two trends related to the energy transition:

1) an increase in distributed generation (renewable energy);
2) an increase in electrification (households, vehicles, factories).

The combination of these trends leads to fluctuating demand/response at neighbourhood level. This, in turn, leads to the following bottlenecks: 1) voltage violations, and 2) overloading (and hence replacement) of transformers and cables.

These conflict with the DSO responsibilities and quality aspects. Voltage violations are a violation of the grid code and in parallel affecting power quality, load capacity and reliability. Fast replacement due to overloading gives rise to high costs and material usage, and affects reliability and load capacity.

IV. View 2: Application and environment

This view focuses on the environment where the product will be applied. This is meant to retrieve hidden requirements that come from the application environment /that appear during application. Below we will first introduce the situation and then highlight some relevant aspects that should be taken into account in the design.

A. General

Conventional MV-LV transformers are located in substations. These are small houses or cabinets which contain the transformer, short-circuit protection and splitting or switching mechanisms. On the LV side, this entails a rack to split the current to the different LV feeders, with fuses for every feeder. On the MV side, it entails MV switch gear, which contains fuses for the transformer and switch disconnectors for each connected MV line. The switch disconnectors are mechanical springs that enable fast manual disconnect of power, e.g. when performing maintenance. The electrical diagram of a substation is drawn in Fig. 1.

The MV side of a transformer is usually connected in delta, the LV side usually in star. Before use, a transformer is tested according to the IEC60076 standard. Currently, the standard for conventional transformers is applicable for SSTs as well. This puts extra demands on the system.

[1] This is applicable in countries where technical grid service and energy trade are separated.

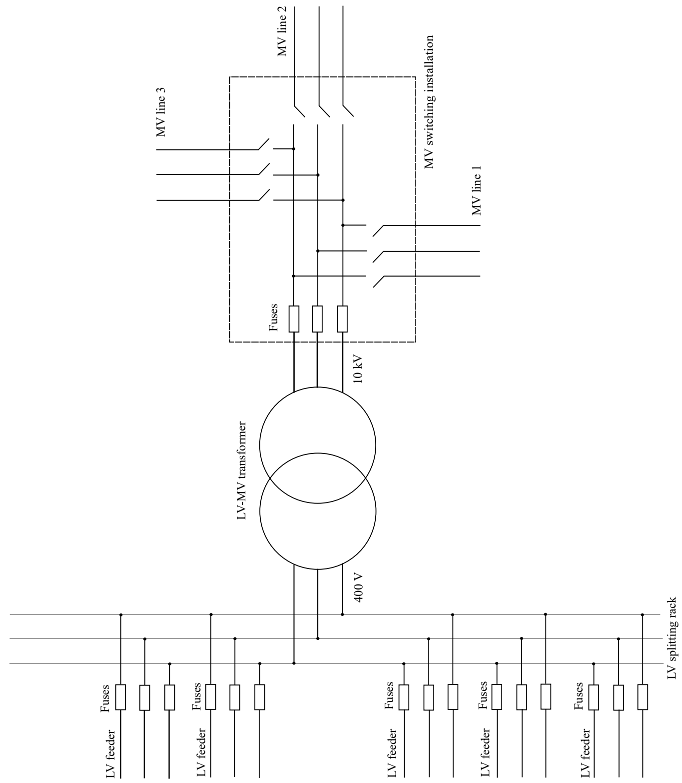

Figure 1. Electric diagram of a MV-LV substation.

B. Maintenance and repair

The substations are of minimum size to reduce the impact on the limited space in the surroundings of the substations. In the substations there is usually just enough space to fit in the mentioned elements. First of all, this means that easy maintenance and repair is important. It should be easy to replace parts and easy to troubleshoot. Second of all, it is important to have as few occasions as possible for maintenance and repair. Attention should be paid to reliability. Apart from the limited space, there is also not always a lamp in the substation. This increases the need for easy and limited maintenance and repair. Ideally, an SST would fit in existing substations.

C. Impacting control hardware

Firstly, there is no power supply in a substation apart from those provided by the transformer itself. This means a) if power is lost, there are no auxiliaries as well, b) start-up of the SST is not straightforward since there is no external power supply. Secondly, European testing standards for transformers require a galvanic isolation between MV and LV side of 28 kV RMS (40 kV peak) at 50 Hz for 40 seconds. This affects the control cables that can be used to connect MV with LV and vice versa. Glass fibres need to be used.

D. Protection

As mentioned, in the substation, protection is present to protect the system from short-circuit currents. Both on MV and on LV side these are implemented by fuses. These fuses rely on high overcurrents to detect a fault and disconnect. This allows for ‘selectivity’: only the faulty parts of the network are switched off, so that the other parts can stay operational. In this way, power is maintained for as many customers as possible. It is essential for DSOs that this property is maintained.

However, the need for those high overcurrents poses challenges for power electronics, which is limited in the current it can generate due to the necessary protection against breakdown. Heavy oversizing is expensive and it is not straightforward to change the protection. Smart solutions need to be found to satisfy both selectivity and safety, which are feasible for power electronics.

Another consideration regarding protection is that the current protection may be blinded on the LV side when high loads and high generation even each other out. This means that the LV cables may be overloaded and there is (yet) no way to know.

V. View 3: Black box functionality

This view considers the functionality of the SST seen as a black box, i.e. it described how the system should/could behave seen from externally, without knowing how the system is implemented internally. In this regard, it can be said that if the SST is to replace a regular transformer, it should first and foremost exhibit the behaviour that one would expect from a transformer.

A. Power transfer

A regular transformer is a passive component. It transfers power from the supply side to the load side, where the amount of transferred power is dependent on what the load and generation demand. The SST should provide the same service. In the past, the MV side was the supply side and the LV side was the load side, where the power drawn by the load dictated the amount of power delivered from the supply. With distributed generation and other changes in the grid, it depends on the net demand and net supply. When the LV grid has more generated power (due to distributed generation) than consumed power (due to load on the LV side) it will feed power back to the MV grid. The LV side will then be the supply and the MV the load. See Fig. 2.

One of the advantages of an SST is that it can also exchange DC power, both at an MV and an LV level. This is thanks to the AC/DC and DC/AC conversion stages which are already present in the power electronics of the SST, provided that an appropiate topology has been selected. Having an DC output at both MV and LV level enables connecting battery storage as well as (fast) charging of vehicles, without requiring the additional power electronics that is normally required. Connecting battery storage can also help to realize other SST benefits such as compensating voltage dips. To include the exchange of DC power, the full power balance is shown in Fig. 3.

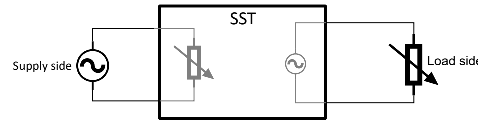

Figure 2. Seen from the outside, the SST always has a supply side and a load side on a net basis. Either MV is acting as supply and LV as load, like in regular transformer operation from the past. Or LV acts as supply due to distributed generation, and MV acts as a load when the power is transferred to other parts of the grid.

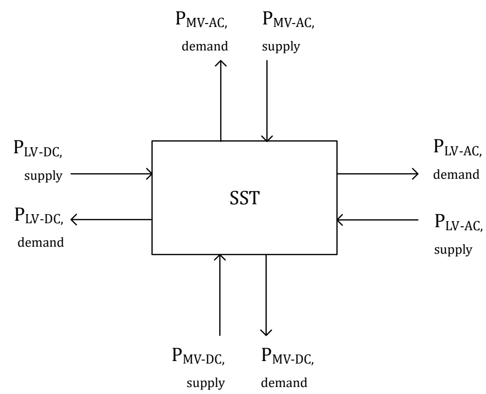

Figure 3. Exchange of power between SST and environment. On a system level these need to be balanced. Both at MV voltage level as at LV voltage level there is an AC port as well as the option for a DC port, e.g. for DC loading of vehicles.

B. Collection of needs and possibilities

There are more aspects that should be maintained from a regular transformer. Next to that, there are possibilities that the SST can offer which a regular transformer cannot. These needs and possibilities have been collected[2] in Table II. In the table, both categories are split in ‘normal operation’ and ‘response to fault conditions’. The table is meant as a starting point for further discussion and new ideas, and by no means claims to be comprehensive.

VI. View 4: Conceptual design

View four and view five are about the internal working of the SST. How to obtain a design for the SST which incorporates the previous perspectives and also is implementable by current or developable technology? View four is the connection between the system functionality at view three (the previous view) and the detailed implementation of the system at view five (not a part of this paper). It entails considering design options on an abstract, conceptual level.

A. Development areas

Based on the previous sections (view 1-3), we can distinguish four areas that need to be filled in with technological solutions and that need to co-operate together (view 5). This is depicted in a Venn diagram in Fig. 4. Thereby these components need to function on different levels of availability and reliability.

[2]This content is based on discussions with the Dutch DSOs involved in the project, and is partly based on the project deliverable [4].

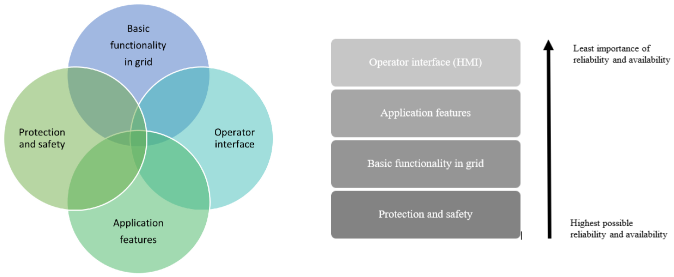

Figure 4. Four aspects influencing the core architecture. These are areas where research needs to be done and combined for proper control architecture design. They have varying availability and reliability needs.

Table I
REQUIREMENTS PER PART OF THE SYSTEM

MV AC - LV DC	LV DC - LV AC
* Power transfer based on setpoint from LV DC - LV AC stage	* Provide setpoint for power transfer to MV AC - LV DC stage
* Frequency of MV output current follows MV grid voltage	* Frequency of LV output voltage according to local standard (50 Hz or 60 Hz)
* Inrush current should not let the fuses trip	* Cope with LV over-current due to transformer inrush
* Start up SST in case of a black start	* Control gradual loading on LV side in case of a black start
* Provide virtual inertia for storage	* Power Quality improvement for LV grid
* Interaction with other equipment on MV grid	* Interaction with other equipment on LV grid
* Adaptability to different MV voltage level	* Balancing load and generation
* Cope with module failure	* Diagnosis on LV grid
* Replacement of modules possible during operation	* Standalone operation in case of communication failures
Both	
* No DC current injection	
* No common mode current	
* Option for 30 deg MV-LV phase shift	

B. Task division

Looking at Table II, most of the advanced control solutions are required on the LV AC side of the SST. This means we can divide the main tasks of different hardware sections as follows: the LV DC-AC stage controls the LV voltage (thereby being in charge of LV grid forming and power quality), the MV AC - LV DC stage(s) controls the power transfer. This leads to a requirements division as shown in Table I.

C. Reliable power transfer

If the most important task of the MV AC - LV DC stage is to transfer power, the next question is how to get this power transfer to the high reliability level that is required. For this purpose we propose a decentralized control concept, i.e. to omit a central and a Cascaded H-bridge (CHB) controller. For the design considerations in this paper we will base ourselves on the power electronics topology as used in the FLEXstation project [5], which is created for the purpose of practical application in the grid. For this topology, the hardware for the decentralized control looks like Fig. 5.

The proposed decentralized control concept enhances the reliability in three ways. Firstly, there is decreased risk of failure due to cable problems. The SST is quite a large machine, hence the cables outside of the modules span long distances. These cables can now be omitted. This eases the routing of cables, both during design as during production as during maintenance and repair. There is also a strongly reduced risk of human errors in connecting the wrong cables during production and service. Furthermore there is a reduced mechanical wear and tear of cables, as well as reduced EMC problems. The second way in which reliability is enhanced is because the system controller poses a single point of failure. If the system controller is not needed, this single point of failure is removed. The third way is that there is an increased chance of continued operation after module failure. The modules have been overdesigned such that the power can be handled even when one module fails. Due to this redundancy, using decentralized control allows the other modules to compensate fast for the loss of the module.

The decentralized control concept also has other advantages that meet the needs of DSOs. In Section IV we already mentioned that in the substation cabinets there is very little space. Hence, there is the advantage of reducing cables with distributed control. Also easy maintenance, repair and swapping of parts is enabled. In Section III and the introduction, we mentioned the costs of the SST and the importance of reducing these. Removing the system controller saves approximately €5000 in costs. Removing the system controller also saves electronic waste, which is in line with reducing climate and environmental impact, and in line with the DSO's societal role as mentioned in Section III.

On a conceptual level, the distributed control can be implemented as follows. The LV grid demands or delivers a certain amount of active power P, depending on the amount of load and generation in the LV grid. This power needs to a) be divided over the modules as shown in Fig. 5, b) be withdrawn from or supplied to the MV grid. The DC//DC stage of the modules can automatically share the required LV power through their joint connection at the LV DC busbar by using DC voltage droop control. Because there is a voltage and current sensor in the modules at the interface with the LV DC busbar, every module knows how much power is processed by the DC//DC stage. This power can serve as a setpoint for the AC/DC stage of the module, which is responsible for pushing the power to or withdrawing the power from the MV grid.

D. Protection considerations

The power electronics topology can be extended to provide for solutions for protection mechanisms. As mentioned in Section IV, new solutions are needed to ensure both safety and selectivity for protection of the distribution grid against short-circuit currents. When a fault occurs, it is important to shut down the power to the feeder where the fault occurs and to let the other feeders continue functioning unharmed. Therefore, one potential solution is to have at the LV side one inverter per feeder. See Fig. 6. This limits the flexibility and amount

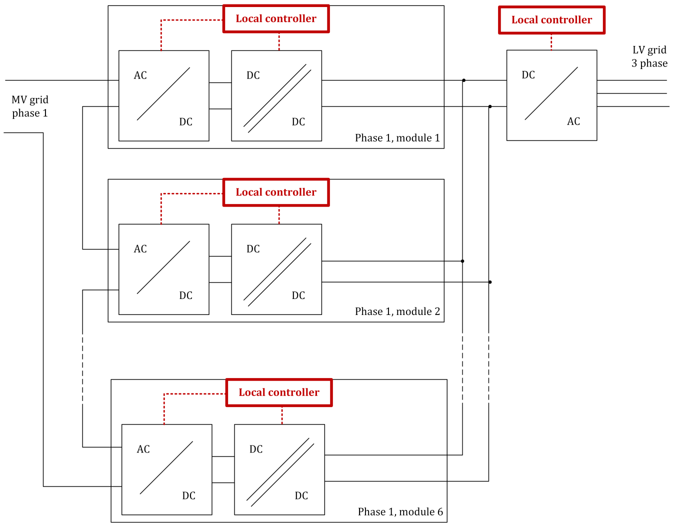

Figure 5. Decentralized control for the power electronics topology in the FLEXstation project

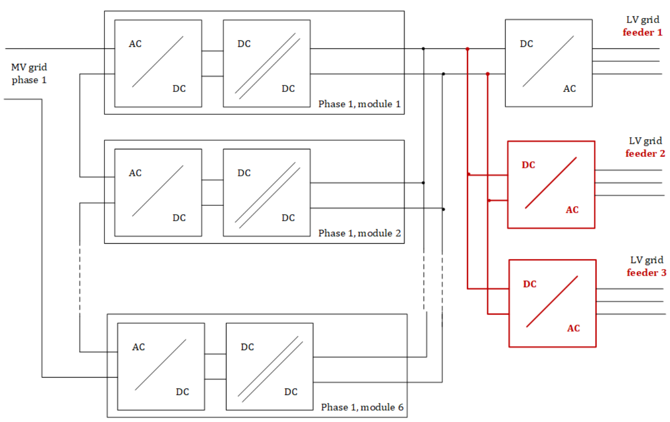

Figure 6. Potential solution for short-circuit protection mechanism.

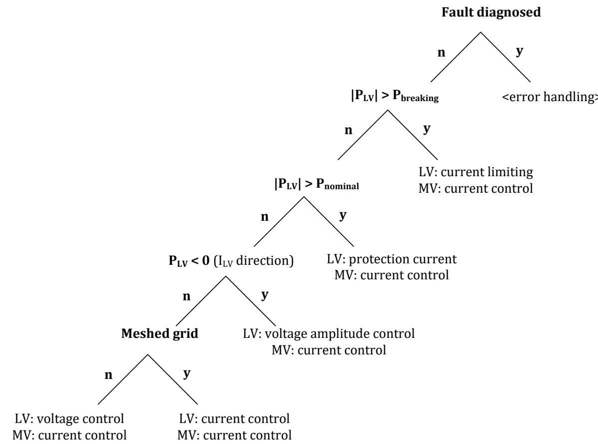

Figure 7. Decision tree for control modes for different scenarios.

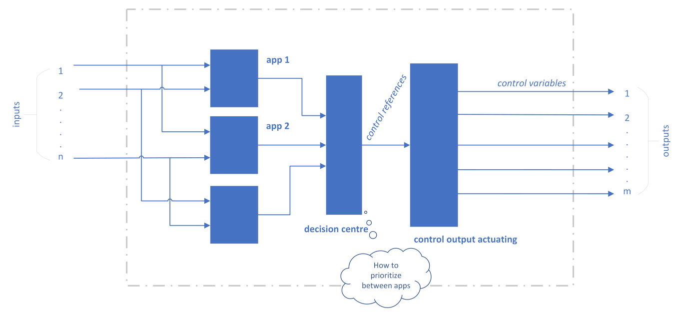

Figure 8. Structure to decide on a high-level between different advanced functionalities.

of loading, but it does allow the SST to shut down power to a specific feeder. One concern is whether a fail-proof operation is guaranteed: a bug or fault in the control system may limit appropriate intervention in case of a fault.

Also mentioned in Section IV is overloading of cables. Potential solutions could be: a) SST receiving measurement data on the impedance and hence temperature of cables, b) communication with other devices in the network. For the latter, the reliability/availability risk and cybersecurity risk need to be examined.

E. Control modes

In this section we will discuss the control modes, which relate to the application features and the operator interface. Different control modes will be needed for different scenarios. First of all, there are different grid situations. The decision tree in Fig. 7 specifies some required control modes for some grid situations. Second of all, the advanced functionality of the SST requires decisions and trade-offs during operation. Most likely there will be different control solutions for the several added features of the SST. These need to be prioritized, and also a way needs to be found to switch between control modes without raising problems during operation. To our best knowledge, switching between different controllers has not been solved yet in practice. With regards to the prioritization, this could be done via a structure like in Fig. 8. Here the input of the operator could/should be incorporated. In the operator interface, the operator needs to have an overview of the status of SST and grid, and be able to indicate priorities. For example whether frequency, voltage level or Rate of Change of Frequency (RoCoF) is most important at that moment.

VII. Conclusion

The CAFCR framework is a useful tool to obtain all relevant information and to channel research towards actual implementation. By illustrating the workings of CAFCR in this paper, we demonstrated the clarity and thoroughness it provides.

This lead to a description of the DSO as customer, against which designs and research choices can be verified, and a description of the demands and specifics that the substation poses as application environment. Against the latter also designs and research choices can be verified, and it urges for new research on short-circuit protection mechanisms. These two views were an inspiration to classify the collection of black box functionality in a table with 'normal operation' vs. 'response to fault conditions' and 'maintained aspects of a regular transformer' vs. 'added features'. This classification ensures that both minimum requirements and the full potential are warranted. The table can be continuously added upon and updated whenever new ideas, insights and possibilities come up. Lastly, all these requirements somehow need to work together. A sketch is made of a conceptual architecture that could realize this.

ACKNOWLEDGMENT

Thanks to all the people who have been involved in the FLEXstation project at some point. First of all, the people from DSOs Alliander and Enexis: thank you for your discussions, input and involvement. Thanks to everyone at the university who reviewed the functionality table and added some new points, and Maurice Roes for suggesting the 'inverter per feeder' idea for the protection. And finally, thanks to the people involved in managing and starting up this project.

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Table II
BLACK BOX FUNCTIONALITY

<table>
<tr><th></th><th>NORMAL OPERATION</th><th>RESPONSE TO FAULT CONDITIONS</th></tr>
<tr><td>MIMICKED + MAINTAINED ASPECTS OF REGULAR TRANSFORMER</td><td>Power transfer
- ‘Passive’: load/generation dependent
- 4 quadrant power flow: bi-directional, active+reactive power
- Real-time & continuous operation
- Nominal power rating + overloading constraints
- LV over-current (transformer inrush)

Voltage characteristics
- Ratio MV LV $\approx$ 10.5k : 400 (take nominal ratings into account)
- MV grid frequency following for MV
- Minimal harmonic distortion for LV voltage and MV current
- 30°MV-LV phase shift (option)

Current
- No DC current injection
- No common mode current
- No significant inrush current (preferred), no fuse trip by inrush current (must). Both for MV and LV energizing.

Boundary conditions
- MV earthing compliant
- Sufficient galvanic isolation between MV and LV terminals
- Low energy losses
- Multiple can be combined in grid (avoid resonances)
- Compatible with other grid entities and grid improvement strategies, such as inverter curtailment
- Meshed grid operation possible
- No need for MV neutral
- Able to take auxiliary power from both MV and LV terminal</td><td>Protection
- Voltage level (earth fault – overvoltage, earth fault – dip, switching transient, lightning surge, arcing transient)
- Current level (MV short circuit current, comply with standard LV protection schemes and existing protection devices, no SST damage from MV or LV short circuit)
- Power (control prepared for LV overload, nominal power rating in case of module failure)
- Power quality events (no damage due to resonances / unbalanced loading / inrush currents)
- Internal failure (modules/parts)
- Quickly dischargeable to human-safe levels

Operation
- Fault ride through (as mentioned in grid code)
- Stand-alone. No dependency on external communication (master controller)</td></tr>
<tr><td>ADDED FEATURES</td><td>Grid improvement
- Power quality improvement (regulation voltage level on a seconds timescale (especially LV terminal), virtually step-free regulation of voltage level, (partially) independent regulation of MV and LV voltage levels, reduce harmonics – especially resonances, phase angles settable, reduce inrush current effects, compensate unbalanced loading)
- Different frequency on LV vs MV side
- Use of storage (stabilization MV grid frequency (virtual inertia), balancing load/generation on LV side i.e. less/lower peaks)

Modularity/flexibility
- Communication to other entities, e.g. other SST’s or higher level controller (for goals like energy routing). Also including remote control and monitoring.
- Adaptable to higher/lower MV level
- Destruction/disabling of one module does not affect the others (allow for continued operation)
- No-current condition prior to module replacement (hot swappable)
- Variable voltage level for LVDC bus
- System is fully renewable by replacing parts
- Possibility to connect multiple converters at LV side (regulate voltage level and power quality of each feeder, only one feeder with outage after short circuit, provide different DC levels)

Other use cases
- DC connection (nominal power freely dividable over DC and AC)
- Diagnosis (prediction of component life time / failure, detection of weed plantations)
- DC grids instead of AC grids</td><td>Mitigation of faults
- MV fault localization
- Temporary LV power supply during single (/multiple) phase MV faults
- Protect MV grid from LV faults and vice versa
- Bridge voltage dips
- Support at black start
- Mitigate other grid faults known to DSOs</td></tr>
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