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### **Smart Transformer requirements for integration in distribution grids and power quality improvement**

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# Smart Transformer requirements for integration in distribution grids and power quality improvement

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**Abstract**—The Smart Transformer (ST), a power electronics-based transformer, allows DC-distribution, reactive power control, storage integration, and meshing networks. These features are needed to avoid or defer infrastructure investment and are normally possible with the installation of single devices. The ST is a global solution but it represents also a new object for the power system, and it does not have any reference rule for its installation in the grid. This paper wants to show the results from the joint work of Kiel University, SP Energy Network and WSP, to determine the connection rules that a ST shall respect in the distribution grid. Furthermore, ancillary services, such as current and voltage harmonics compensation, are described in this work, to demonstrate the control capability of the ST in the grid.

**Index Terms**—Smart transformer, grid codes, grid connection requirements, harmonic compensation, voltage and frequency limits.

## I. INTRODUCTION

High penetration of Distribution Generators (DG) and charging stations for Electric Vehicles (EVs) challenges the management of the electric distribution grid. Among the several issues, low power quality, resonant issues, voltage limit violations and components overload can be identified. Hence, a reinforcement of the distribution grid and its infrastructure upgrade are needed. The grid controllability can be improved installing extra hardware in the grid, such as energy storage systems (ESS) [1] or STATCOMs [2], or exploiting the converters capability in power electronics-based DGs [3] Fig. 1a. However, these solutions aims to solve specific issues, without offering a general solution to the grid control. Currently, the Distribution System Operators recur to system upgrades to solve problems, substituting grid components (e.g., transformers, cables, etc.) with larger size ones. It is trivial to notice that these upgrades are costly, time consuming and may lead to disruption of customers during the component replacement.

The Smart Transformer [4] (Fig. 1b), which is based on a three-stage solid-state-transformer (SST) [5] architecture, increases the grid controllability, interacting with loads and generators [6], [7], enables the DC connection for loads and generators [8] and at reduces the infrastructure upgrade

costs, postponing replacement of components. In the OFGEM-funded project "LV-ENGINE" [9], it is estimated that the ST can save up to £60m in grid upgrade costs by 2030, and avoid the construction of 16% new substations, just adding more control to the existing distribution grid.

This paper introduces the joint work of Kiel University, SP Energy Network and WSP on defining the connection rules for the Smart Transformer in the distribution grids. Particular attention is given to the voltage and frequency limits to be respected, and how to handle large disturbance, like the Low Voltage Ride Through (LVRT) capability of the ST. This work closes with two study cases, where the ST harmonic compensation capabilities are described in MV and LV grids.

## II. SMART TRANSFORMER CONTROL

The ST architecture can be divided in 3 stages: MVAC/DC stage, DC/DC stage and LVDC/AC stage [4]. The MV AC/DC converter is controlled as a conventional front-end converter for DG applications, to control the MV DC link voltage. The DC/DC converter adapts the voltage between the MV to LV DC links and guarantees the galvanic isolation between the two voltage levels. The LV DC/AC converter controls the LV AC grid voltage at the nominal value.

The Smart Transformer control mode can be divided in 2 main categories: "meshed network mode" and "radial network mode":

**Meshed network mode** (Fig. 2a), the ST should is not in charge of the voltage control since the ST is connected to another grid, thus it behaves as a controllable power source. Regarding the active power control, the converter connected at the MV grid controls the DC link voltage, while the converter in the LV side controls the active power flow. Both converters can control independently the reactive power. In this case, the ST works similarly to a Distributed Energy Resource (DER) that is connected to the distribution grid.

**Radial network mode** (Fig. 2b) the MV converter works like in the "meshed network mode", due to the need to balance the DC link voltage. However, in radial network mode,

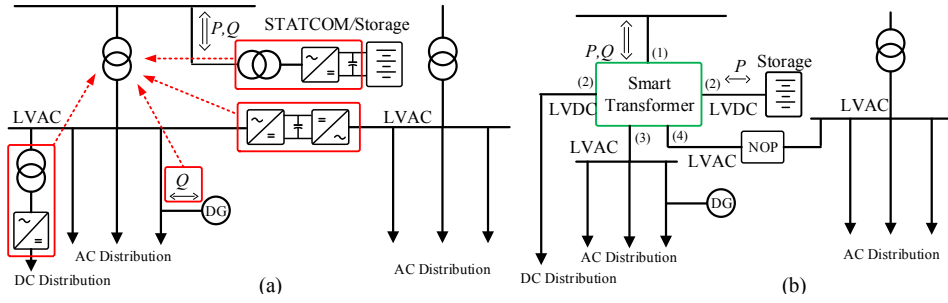


Fig. 1. Configuration of current distribution network with (a) conventional solution, and (b) ST solution.

the LV converter does not control the power flow, but it controls the voltage waveform in the LV grid. This implies that the power demand is not decided by the ST, but by the load/generation consumption/injection. It is not possible to control the reactive power injection into the LV grid in this case, due to the fact that the load and generators decide the reactive power consumption. However, the power consumption, both active and reactive, can be influenced by voltage waveform variation (magnitude and frequency) if voltage dependent loads are present (e.g. constant impedance loads) [6]. In the radial network mode, the ST works similarly to an Uninterruptible Power Supply (UPS), guaranteeing high power quality standard in the LV grid.

Besides aforementioned basic control, the more advanced ancillary services can provide as well to support the distribution grid. The MVAC/DC converter can provide voltage support by means of reactive power injection [10], harmonic compensation [11] and frequency support in MV/HV AC grid. The DC/DC stage enables the DC grids [8] and allows the integration of energy storage. The LV DC/AC converter has filtering [12] and power flow capability in LV grids that allows to shape the consumption/production of voltage- and frequency-dependent loads [6] and generators [7] by means of voltage or frequency variations.

### III. GENERAL CONNECTION RULES IN DISTRIBUTION GRID

The ST can offer more services to the distribution grid than the conventional transformer. Among these services, the basic ones are the capacity to remain connected during large disturbances and reducing the impact of these disturbances on the loads. In this section, the connection rules that the ST shall respect for being installed in the distribution grid are described.

#### A. Voltage limits

1) *LV converter*: During the steady-state operations, the ST shall remain in operations with full capacity within the 10 min mean r.m.s. value range of 85% and 110% of the nominal voltage, as stated in the EN 50160 [13] as minimum requirements for LV grids. During transients, the ST shall remain connected within the following voltage range:

- Minimum voltage

- Setting  $-20\%$  of the nominal voltage within 3.0 s
- Maximum voltage
  - Setting  $+14\%$  of the nominal voltage within 1.0 s
  - Setting  $+19\%$  of the nominal voltage within 0.5 s

On the opposite of distributed energy resources, where the disconnection outside the aforementioned ranges can be considered, the ST shall remain operative. However, a reduced operation capability shall be designed for this situations, in order to not oversize the ST hardware. The connection rule for depending on the voltage values, after a grid perturbation (e.g., fault) is shown in Fig. 3. In case of over-voltage violation, the Smart Transformer must trip, in order to avoid any damage to itself and the connected grid. In case of under-voltage ( $< 0.8$  pu) the ST, with its controllers, is allowed to transfer the disturbance from its primary to secondary side (i.e., reducing the secondary voltage), and continue to operate within the time limit (i.e., 3.0 s) with reduced capacity.

2) *MV converter*: For the MV converter, the steady-state rules described for the LV converter still apply. However, the maximum voltage thresholds are decreased with respect to the LV converter, and shown in Fig. 4:

- Minimum voltage
  - Setting  $-20\%$  of the nominal voltage within 3.0 s
- Maximum voltage
  - Setting  $+10\%$  of the nominal voltage within 1.0 s
  - Setting  $+13\%$  of the nominal voltage within 0.5 s

#### B. Operating frequency range

Following what described in the British code [14], the ST shall be able to work in the frequency range  $[49 \div 51]$  Hz in steady state without any changes in the output power. However, the ST shall be able to remain connected in the largest number of cases, including the emergencies. For these reasons, the ranges normally applied in the distribution grid rules have been expanded:

- $[46.5 \div 49]$  Hz for 90 minutes
- $[49 \div 51]$  Hz continuous operation
- $[51 \div 52.5]$  Hz for 90 minutes

For the over- and under-frequency time delay for tripping, the rules as in [14] can be adopted:

- delay of 0.5 s and setting 52.5 Hz  $\Rightarrow$  disconnection and breaker opening.

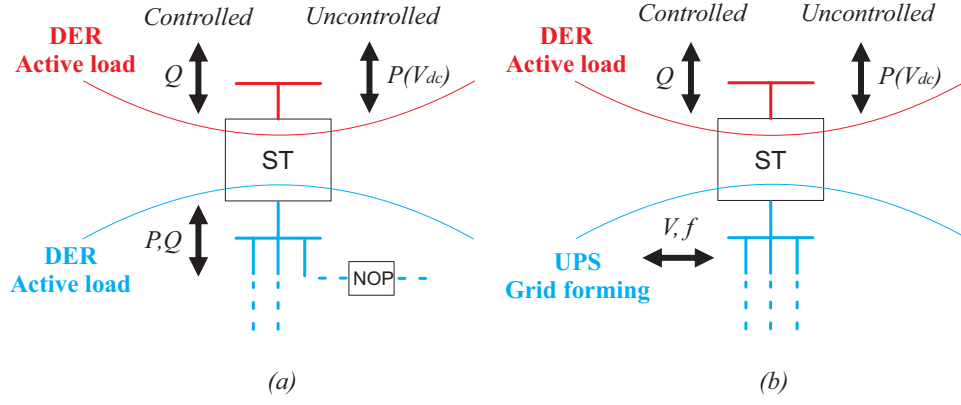


Fig. 2. (a) Meshed network mode control scheme: the ST is working as DER in both LV and MV side; (b) Radial network mode control scheme: the ST is working as DER in MV side and as UPS in low voltage side.

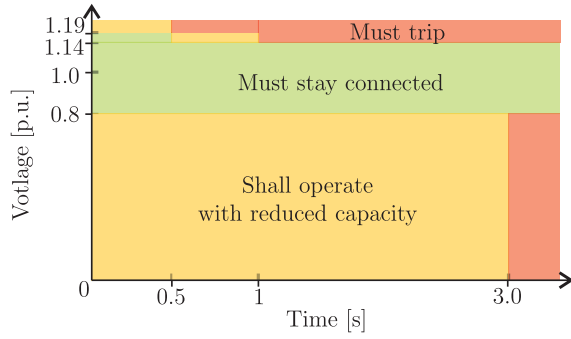


Fig. 3. Low Voltage Ride Through rules for the LV converter of Smart Transformer

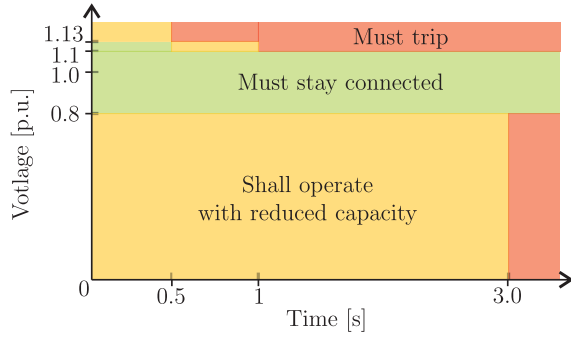


Fig. 4. Low Voltage Ride Through rules for the MV converter of Smart Transformer

- delay of 0.5 s and setting 46.5 Hz  $\Rightarrow$  disconnection and breaker opening.

#### IV. HARMONIC COMPENSATION CAPABILITY OF ST

In distribution grids, the loads may have non-linear current consumption, increasing the current and voltage distortion in the line. These harmonic sources can be typical home appliances, like refrigerators, washing machines or televisions, as described in [15], with high presence of 3<sup>rd</sup> and 5<sup>th</sup> order current harmonic. On the other side, photovoltaic converters may contribute to the current harmonic injection, as

demonstrated in [16]. Particularly in low power condition, the harmonic current results be particularly high. ST shall provide the functionality of active harmonic filter in both MV and LV grids. By implementation of this functionality, the ST compensates the harmonics current to keep the harmonic injection in the distribution grid within the allowed limits. This section describes the ST harmonic compensation capability and gives practical examples in both MV and LV distribution grids.

##### A. Harmonic current compensation in MV grids

A simplified MV grid is used to demonstrate the functionality, as shown in Fig. 5. The grid has a voltage level of 11 kV. There are 2 feeders connected to the main grid at the Point of Common Coupling (PCC). In Feeder I, the ST is installed, while in the Feeder II, a LV feeder is connected through a conventional transformer. The latter contains loads with high harmonic current content, that the ST aims to compensate injecting the harmonic current that the loads need, avoiding to absorb it from the MV grid.

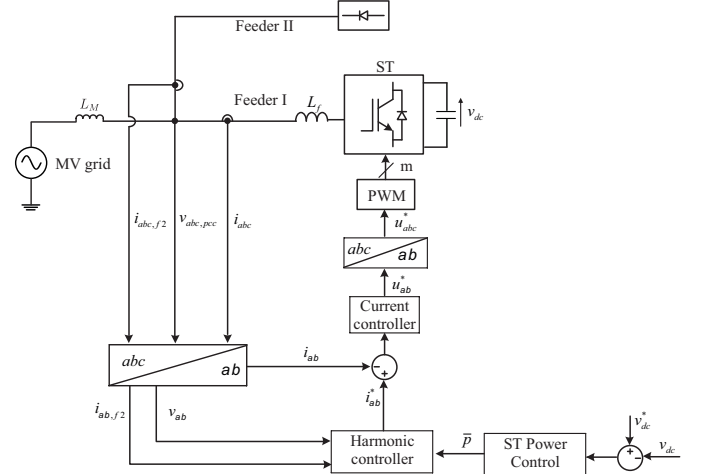


Fig. 5. Control scheme of ST MV converter

However, the proposed control in this section is applicable only in case the ST Feeder and Feeder II are connected to the same busbar (in Fig. 5 is the PCC). To apply the current harmonic compensation, indeed, high frequency measurement systems are needed (e.g., current sensors of ST or similar). In case that the Feeder II is far away from the ST busbar, fast communication is needed to perform active filtering.

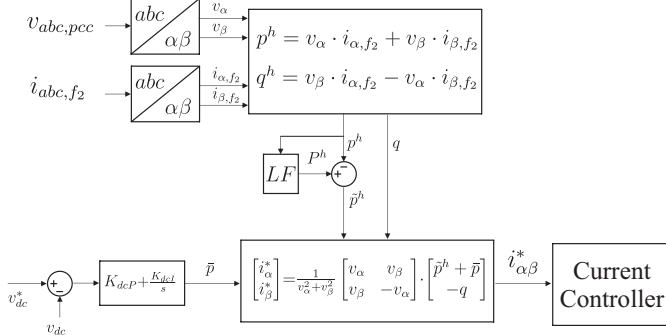


Fig. 6. MV harmonics compensation controller

The ST harmonic controller is shown in Fig. 6. The control receives as input the PCC voltage and current, and the DC-link voltage. The PCC voltage and current, once converted into  $\alpha\beta$  frame, are used to calculate the instantaneous active and reactive power. As the goal is to compensate the harmonic content of the current, only the power oscillating component  $\tilde{p}^h$  is extracted from the real power  $p^h$ . To extract this power, to the real power  $p^h$  is extract the constant component  $P^h$ , obtained filtering the real power signal  $p^h$ . The obtained oscillating power  $\tilde{p}^h$  is then summed up to the constant power reference, coming from the DC-link voltage controller  $\bar{p}$ . The reactive power  $q$ , is directly calculated at the PCC and no further contribution is added by the ST (unity power factor working condition is assumed). The new current references  $i_{\alpha}^*$  and  $i_{\beta}^*$  are then calculated following the matrix product in Fig. 6, and then sent to the ST current controller. To assess the ST capability to compensate the harmonic current, a 3-phase diode rectifier, with a 500  $\Omega$  DC resistance (corresponding to a total power of 440 kW) has been connected in the Feeder II of the MV grid (11 kV). The obtained results are always compared with the maximum allowable harmonic current following the rules in [17]. The harmonics at the PCC up to the 25<sup>th</sup> order are measured and the Fast Fourier Transformation (FFT) and waveforms of the PCC currents with and without the harmonics compensation are shown in Fig. 7, Fig. 8, Fig. 9. In Fig. 7, the purple dashed line shows the maximum allowed current of each harmonic order per phase for 11 kV grids, as required in [17]. The blue bars are the harmonic currents at PCC point before the compensation. The 5<sup>th</sup> harmonics is 1.2 A higher than the UK requirements. The yellow bars are the harmonic currents after the compensation. It can be noted in Fig. 7 that the harmonics from 5<sup>th</sup> to 13<sup>th</sup> orders have been decreased with the compensation controller, and the 5<sup>th</sup> harmonic current is now within the limit. The harmonics above 13<sup>th</sup> order are increased by the action of the compensation

controller, due to limitation in the bandwidth and in the DC-link voltage, but are still within the limits of UK [17]. In Fig. 8 is plotted the waveform of the current at the PCC without the harmonic controller, and thus the current contains high low voltage harmonic content and the resulting waveform is clearly distorted. Applying the harmonic controller, the current becomes more sinusoidal, with reduced low order harmonic content, as shown in Fig. 9.

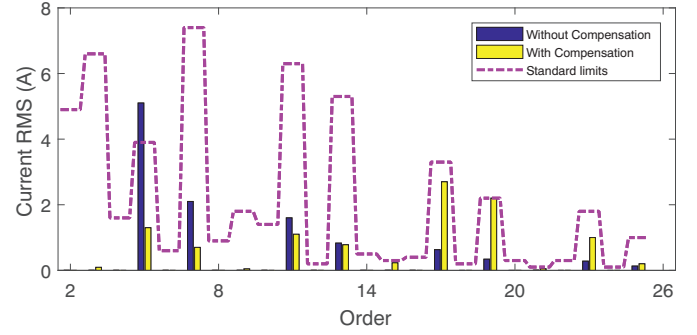


Fig. 7. FFT of the PCC current

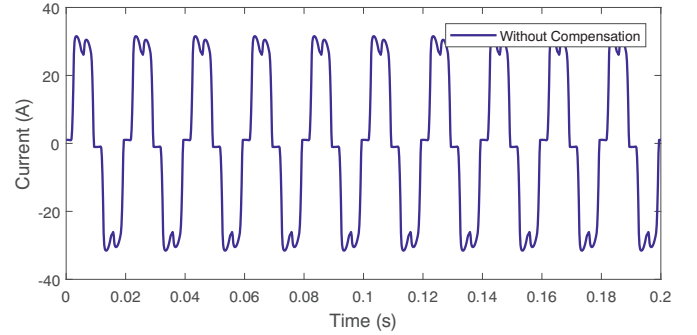


Fig. 8. Waveform of PCC current without compensation

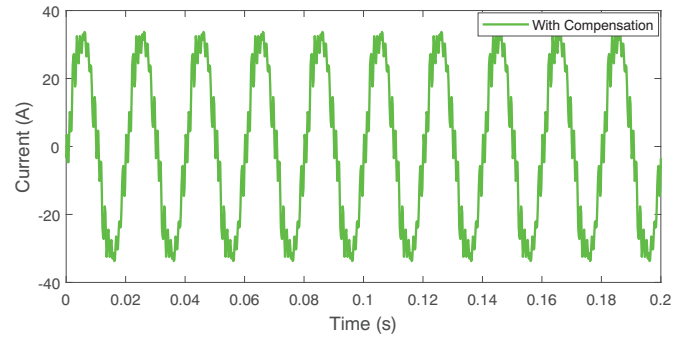


Fig. 9. Waveform of PCC current with compensation

### B. Harmonic compensation in LV grids

To perform current harmonic compensation in the LV grid, the control scheme, shown in Fig. 10, is adopted. The control principle in LV grid is similar to that of the MV grid, with the difference that, in the LV grid, several feeders may be

connected to the LV busbar of the ST. The ST shall compensate the harmonics of a chosen feeder, where the harmonic current can have more effect on the power quality (e.g., the feeder connected to other transformers/STs through the NOP). The control scheme shown in Fig. 10 is similar to the one shown for the MV converter. The grid shown in Fig. 11 is used as test case for verifying the performance of ST as active filter in LV grids, with 3 feeders connected to the LV busbar of ST. The ST compensates the harmonic current flowing in the NOP feeder, preventing the absorption of harmonic current from the MV grid through the conventional transformer.

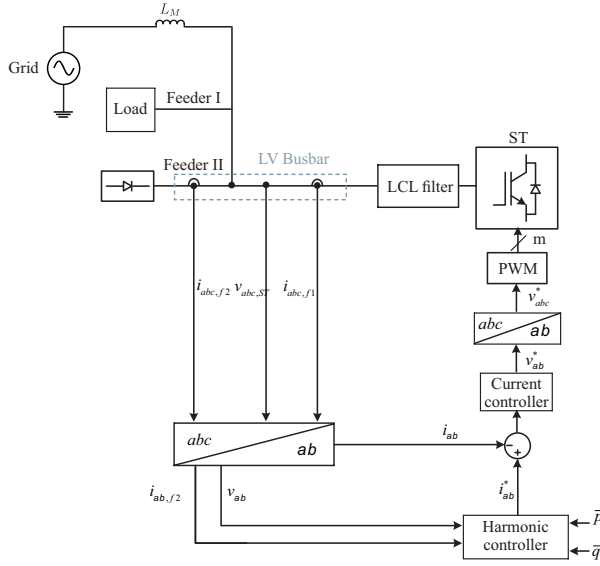


Fig. 10. LV harmonics compensation scheme

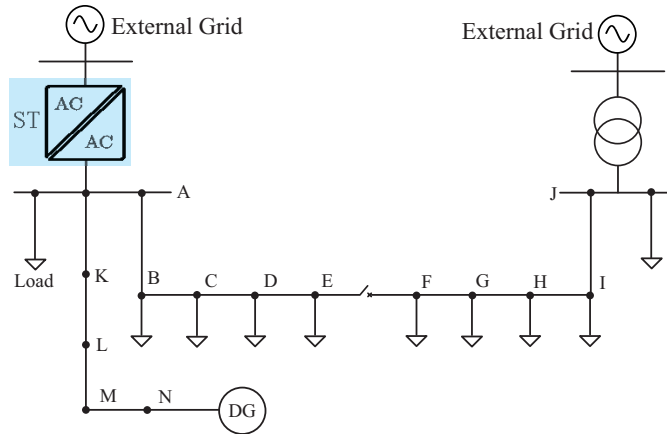


Fig. 11. LV grid used for evaluating the ST active filtering capability

The loads that are connected in the studied LV grid are described in Table III, whereas the DG connected at bus N is injecting 100 kVA with unity power factor. To assess the ST capability to compensate the harmonic current, a 3-phase diode rectifier, with a  $3.5\Omega$  DC resistance (corresponding to a nominal power of 83 kW) has been connected in the Bus "B"

TABLE I  
LINE IMPEDANCE OF THE GRID IN FIG. 11

| Node I | Node II | Line Type | Length (m) | R (pu) | X (pu) |
|--------|---------|-----------|------------|--------|--------|
| A      | B       | 3         | 50         | 4.73   | 2.14   |
| B      | C       | 3         | 50         | 4.73   | 2.14   |
| C      | D       | 2         | 50         | 7.25   | 2.17   |
| D      | E       | 2         | 50         | 7.25   | 2.17   |
| E      | F       | 2         | 50         | 7.25   | 2.17   |
| F      | G       | 2         | 50         | 7.25   | 2.17   |
| G      | H       | 2         | 50         | 7.25   | 2.17   |
| H      | I       | 3         | 50         | 4.73   | 2.14   |
| I      | J       | 3         | 50         | 4.73   | 2.14   |
| A      | K       | 2         | 100        | 9.45   | 4.28   |
| K      | L       | 2         | 100        | 14.49  | 4.35   |
| L      | M       | 2         | 100        | 14.49  | 4.35   |
| M      | N       | 1         | 100        | 17.26  | 0.46   |

TABLE II  
BASE VALUES ADOPTED IN TABLE I

| Line Type | Line Name      | $R_{base}$ ( $\Omega/\text{km}$ ) | $X_{base}$ ( $\Omega/\text{km}$ ) |
|-----------|----------------|-----------------------------------|-----------------------------------|
| 1         | LV 0.1 Cu PILC | 0.274                             | 0.0073                            |
| 2         | LV 0.2 Al PILC | 0.230                             | 0.069                             |
| 3         | LV 0.3 Al PILC | 0.150                             | 0.068                             |

TABLE III  
LV GRID LOAD PARAMETERS

| Node | P (kW) | Q (kW) | Node | P (kW) | Q (kW) |
|------|--------|--------|------|--------|--------|
| A    | 200    | 50     | B    | 15     | 3.8    |
| C    | 15     | 3.8    | D    | 15     | 3.8    |
| E    | 15     | 3.8    | F    | 25     | 6.3    |
| G    | 25     | 6.3    | H    | 25     | 6.3    |
| I    | 25     | 6.3    | J    | 200    | 50     |

of the LV grid (0.4 kV). The performance of the controller is analyzed by means of PSCAD simulations. Fig. 12 shows the current FFT analysis of the conventional transformer LV bus (bus J), where the maximal allowable harmonic currents for LV grids, as required in [17], are shown in the dashed purple line. The harmonic of the NOP feeder are measured up to the 25<sup>th</sup> order. The blue bars are the current harmonic contributions without the compensation. It can be seen that the 5<sup>th</sup> harmonic exceeds the UK requirements. The yellow bars are the harmonics current with the harmonic controller activated. As can be seen, the 5<sup>th</sup> harmonic current is now within the allowed limit, and the other harmonics are still kept within the limits. To compare the results in time-domain, Fig. 13 and Fig. 14 show the current waveform in the NOP feeder (bus A) without and with harmonic controller. As can be seen in Fig. 13, the waveform is highly distorted, while in Fig. 14, where the compensation is active, the current THD is decreased. As consequence, also the voltage THD is smaller after the activation of the compensation control, as can be seen in Table IV, passing from 4.3% to 3.4% at the ST connection with the NOP feeder, and from 1.7% to 1.2% at the conventional transformer bus.



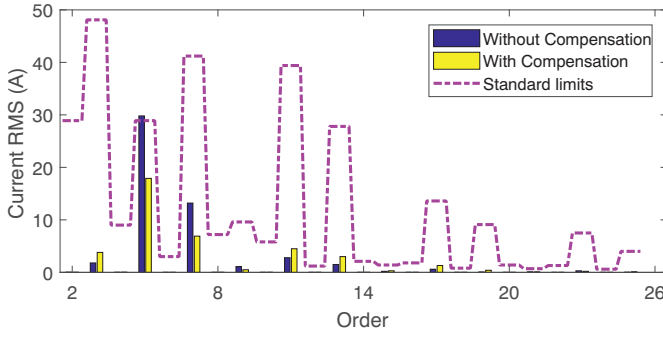


Fig. 12. FFT of LV bus current of conventional transformer (Bus J)

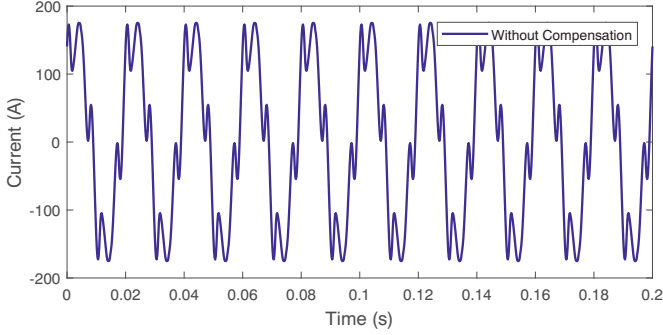


Fig. 13. Waveform of current of NOP feeder without compensation (Bus A)

TABLE IV  
VOLTAGE THD

| Bus | No harmonic control | With harmonic control |
|-----|---------------------|-----------------------|
| A   | 4.3%                | 3.4%                  |
| J   | 1.7%                | 1.2%                  |

## V. CONCLUSION

The Smart Transformer is a promising solution for the modern distribution network with high penetration of distribution generator and EV charging stations. This work introduces the connection rules that a ST shall respect to be connected in the distribution grid, particularly regarding voltage and frequency range in steady-state and during transients. The ST also shall guarantee high power quality standard in the distribution grid, acting as harmonic active filter. This work shows the harmonic current reduction achieved by means of ST-based harmonic compensation controller.

## VI. ACKNOWLEDGMENT

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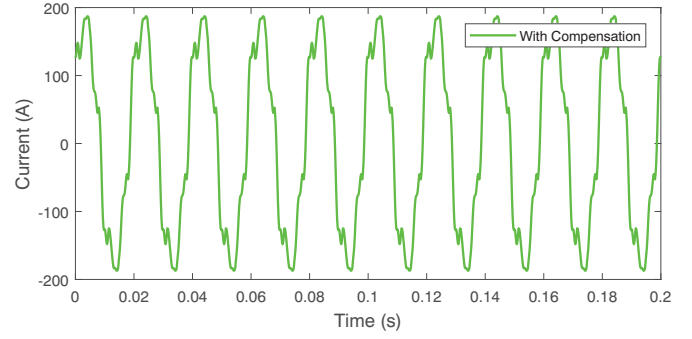


Fig. 14. Waveform of current of NOP feeder with compensation (Bus A)

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