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Giovanni De Carne  
Giampaolo Buticchi  
Marco Liserre  
Costas Vournas

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# Frequency-Based Overload Control of Smart Transformers

Giovanni De Carne  
Giampaolo Buticchi

Marco Liserre

Chair of Power Electronics

Christian Albrechts University of Kiel  
Kiel, Germany  
gdc@tf.uni-kiel.de

Costas Vournas

School of Electrical and Computer Engineering

National Technical University of Athens

Athens, Greece

vournas@power.ece.ntua.gr

**Abstract**—A Smart Transformers (ST) is an automated transformer based on the latest power electronics and communication technologies. It aims not only at replacing the traditional transformer, but at providing also ancillary services to the grid, thanks to the greater flexibility offered by power electronics. However, in the case of grid overload caused by high load demand or high production from renewable energy sources, the power electronics have no extra capability. The power semiconductors can be overloaded only for few microseconds, in contrast with the grid components requirement of bearing currents higher than the rated values for several seconds. Thus the ST needs new procedures for dealing with the transients/conditions of the high current requests by the load. This paper presents the Frequency-Based Overload Control (FBOC), an innovative procedure for the overload management that acts in coordination with the droop controller of Distributed Generation (DG) systems, enabling the limitation of the transformer current.

**Index Terms**—Current Limitation - Droop Control - Smart Transformer - Solid State Transformer

## I. INTRODUCTION

The massive implementation of the DG and the presence of new components (Electric Vehicles, Battery Energy Storage Systems, etc.) are changing the operative conditions of the Low Voltage (LV) and Medium Voltage (MV) grids. These grids, initially designed for being passive, are now working with power transients, mostly caused by the Distributed Generation (DG) intermittent nature. Difficult voltage control, no proper breaker operations, and islanding detection are just some of the issues created by these resources [1].

The Smart Transformer (ST) represents an interesting option for interfacing MV with LV grids in presence of DG of different nature. Being a power electronics-based transformer, it guarantees greater flexibility in the LV and MV grids management than the traditional transformer [2].

Existing intelligent transformer technologies are already on the market. These are mostly related to the adjustment of the voltage set point, such as Load Tap Changer (LTC) technology. Hybrid solutions implementing power electronics switches have been proposed in the literature [3], [4] or implemented in real applications [5], [6] for LTC. The power electronics switches limits the current flowing in the mechanical switch during the tap changing transient in order to increase the

lifespan of the LTC mechanical switches. However these intelligent transformers can only modify the voltage ratio, but with slow dynamics. They cannot perform any fast transient optimization and neither can they provide further services to the grid. In case of harmonic compensation, current and voltage balancing, disturbance rejection, other devices with faster dynamics, e.g. FACTS, are needed. As can be noted in Fig. 1, the ST not only comply with the task to transform the voltage but it is able to provide additional services that the previous examples of transformer with some degree of intelligences cannot provide.

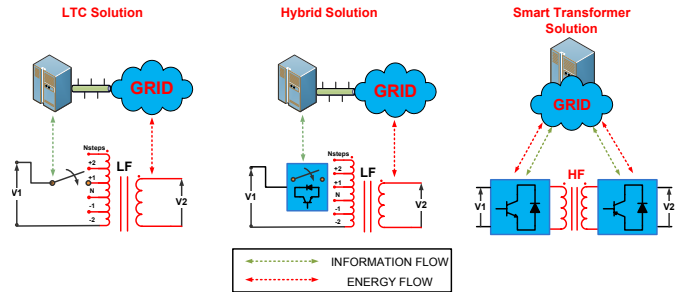


Fig. 1. Comparison between ST and the existing transformer technologies.

In contrast with other transformer technologies, the ST can decouple the LV and MV grids: the behavior of the two grids is separated and from the electrical point of view they operate independently. This feature is enabled by the presence of the two DC links, in the LV and MV sides. The inverter, interfacing the LV grid side, controls the voltage waveform in agreement with the voltage requirements of the LV grids. Thus the ST has several degrees of freedom regarding the waveforms: it manages the magnitude, the phase and the frequency of the voltage, having the possibility to modify these parameters if needed, independently of the MV grid.

Since the LV side of the transformer is electrically isolated, it operates essentially like a microgrid [7]. A microgrid in isolated operation is normally controlled by a master controller (setting the frequency), while other active power sources are

controlled by droop controllers [8]. An interesting option is proposed in [9], where the microgrid control is achieved with hierarchical controllers: a primary control regulates the inner control of the DG; a secondary control takes care of the frequency and voltage deviations from the rated value; and a tertiary control regulates the power exchange among the DG and the grid at the Point of Common Coupling (PCC).

The ST enables all of the previous options, simplifying the control aspect: the voltage and frequency control is coordinated by the ST imposing the voltage waveform. In the ST grid scenario the DG must only perform the inner control and eventually a tertiary control based on grid optimization.

The ST creates new control possibilities for both LV and MV side. In [10] the balancing of the current in MV grid and the voltage in LV grid sides in presence of unbalanced load is demonstrated. Thus power quality is improved in both grid sides without applying any further devices in the grid.

Even though power electronics devices provide new services to the grid, they tend to be more expensive than traditional components. Their design and sizing need to be studied and planned carefully in order to reduce the overall cost. Cost reduction imposes strict limits to the power electronics capability, and, in exceptional cases, the adoption of emergency procedures to avoid any damages to the components. Thus the ST must be properly designed for the application environment, but cannot be oversized to take into account extreme situations. When the current is approaching the ST current hard limits, a proper control action is needed to avoid system shutdown: the semiconductors have hard current limits, and their violations result in a reduction of components lifespan or failures, so the ST is forced to switch off in order to preserve its safety and avoid any possible damage.

The wide implementation in LV grids of DG systems, some of which have the capacity for active power modulation, can be used to perform a decentralized control action, in order to solve the overload at ST level. In this paper the Frequency-Based Overload Control of Smart Transformers (FBOC) method is presented, exploiting the presence of droop controllers in the DG. The remaining of the paper is structured as follows: Section II analyzes the ST concept and control; Section III depicts the FBOC method; Section IV describes the benchmark grid and Section V shows the simulation results. Section VI is dedicated to the conclusions.

## II. ST CONCEPT AND CONTROL

The main feature of the ST is the power electronics interfaces with the grid [2]. The ST is a 3-stage converter composed of grid connected converters at the LV and MV grid interfaces and a Dual Active Bridge (DAB) converter [11]. The DAB has the task to transform the voltage from MV to LV by means of an high frequency transformer (within the range of several kHz). The use of a DAB in transforming the voltage enables the creation of two DC links at the MV and LV side, separating electrically the two grids. Fig.2 depicts the ST concept by means of a single-line diagram:

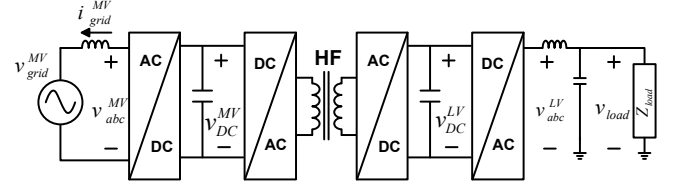


Fig. 2. ST 3-stage topology: single-line diagram.

In this paper the average model of the ST has been implemented and the control block diagrams are shown in Fig. 3. As can be deduced from Fig. 3, the ST control has been implemented as three independent controllers in parallel.

The LV side AC control is a double loop controller. The outer loop is fixing the voltage to the rated value, independently of load current values. The output of the outer loop gives the reference signal to the inner loop: being a continue value, the output of the outer controller must be transferred in a sinusoidal three-phase system, in order to be comparable with the grid voltage waveforms, before to be sent to the voltage controller. Here the inner loop compensates the difference between the grid voltage and the voltage reference by means of a Proportional+Resonant controller. Finally, the voltage reference is added to the controller output as feedforward signal in order to enhance the control action. The LV controller output represents the voltage applied at the converter side, in order to have perfectly balanced voltage profiles.

Fig. 3(b) shows the LV DC link control, where the DC-DC converter has the task to keep constant the voltage on the DC link, regulating the output power (in case of power transfer from MV to LV grid). The capacitor voltage input to the LV DC link is compared with the rated voltage value and sent to a Proportional-Integral (PI) controller. The controller output is the active power demanded from the MV side in order to keep constant the voltage in the LV DC link.

The controller in Fig. 3(c) represents the MV side converter. The Proportional controller compensates the error between the voltage reference and the voltage meter reading in the MV DC link. Here the signal is low-pass filtered and sent to the AC side controller, converting it in a three-phase system, as described in the LV controller. The new current reference value is compared with the current reading from the meters and sent to a Proportional+Resonant controller in order to minimize the error between the two signals. Finally the voltage feedforward signal is added after the resonant controller. The voltage generated is the one needed for demanding the correct amount of current from the MV grid in order to keep the DC link voltage at the rated value.

## III. FREQUENCY-BASED OVERLOAD CONTROL

With the purpose of providing ancillary services to the grid, some forms of the DG are usually equipped with a frequency droop active power controller. This controller compensates any frequency variation in the grid by modifying the generator active power. The FBOC method aims to exploit the droop

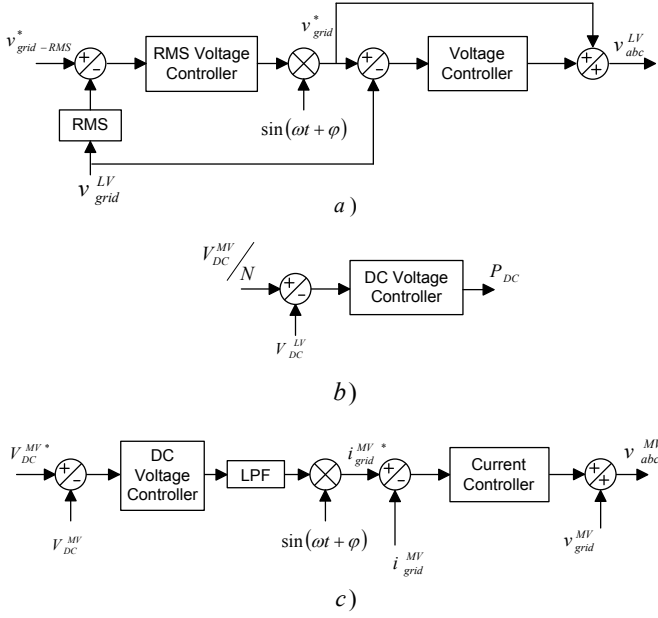


Fig. 3. ST a) LV AC voltage controller, b) LV DC voltage controller and c) MV AC current controller.

controller of the DG for limiting the current flowing in the ST. The ST solves the overloading problem modifying the grid frequency and activating the distributed generation droop controller. When the current is approaching the hard limit and exceeds the set security threshold, the ST lowers the frequency and lets the DG increase the injected active power to compensate the frequency drop. When the current returns below the security limit, the ST restores the nominal frequency and the DG comes back to the original power setpoint. It is worth mentioning that this method has a minimal impact on the normal operation of the grid, avoiding long term changes in the frequency value.

Fig. 4 describes the FBOC method: the controller decides to act on the frequency value, depending on the current reading from the LV grid. If the current rms value exceeds the current security limit, the FBOC controller changes the reference setpoint and generates a three-phase voltage waveform with the new frequency value. Here the voltage waveforms are compared with the voltage references and the error signal sent to a controller. The controller output, added to the feedforward signal of the voltage references, is sent to the LV side inverter of the ST and applied as new voltage waveform.

#### IV. BENCHMARK GRID

In modern and future LV grids a considerable part of the power can be provided locally by DG. This possibility enables the internal management of the LV grid load power. The grid shown in Fig. 5 represents a possible future grid paradigm including passive loads, renewable and controllable energy resources. The simulated grid is represented by a simple radial 4 bus system. The system is composed by an aggregate fixed

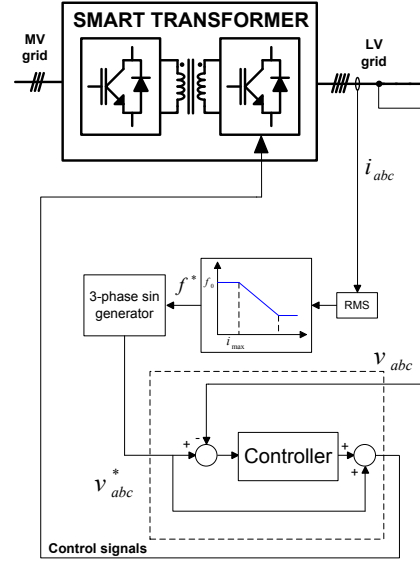


Fig. 4. Frequency-Based Overload Current (FBOC) Control.

load, emulating the grid load in the short term, a Diesel engine working as distributed controlled resource and a wind turbine system. In Table I the grid parameters are given.

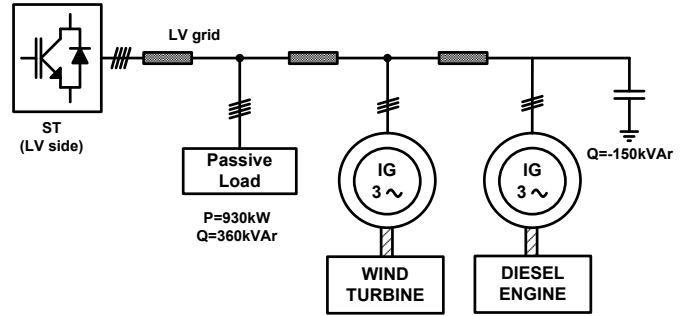


Fig. 5. Simulated grid

The Diesel generator and the wind turbine system are equipped with an asynchronous generator. The Diesel gen-

TABLE I  
GRID PARAMETERS

Rated voltage	0.4kV
Load active power	930kW
Load reactive power	360kVar
ST rating power	690kVA
Wind turbine rating power	300kW
Diesel rating power	350kW
Wind asynchronous machine	350kVA
Diesel asynchronous machine	400kVA
Capacitor bank	150kVar

erator control is achieved by means of a Woodward governor model and driven by a droop frequency controller. The asynchronous machine is directly coupled with the electrical grid, without the interposition of any converter. This represents the most common case for small Diesel generators and also the most conservative one, due to the lack of control for the reactive power absorption. In order to compensate partially the reactive power at the generator level, a capacitors bank has been added of 150 kVar. The overall controller is composed of two fuel signals, the first one coming from the governor and the second one coming from the droop controller, as described in Fig. 6. The first fuel signal is given by the active power reference signal. This reference is directly proportional to the fuel valve opening, in order to control directly the active power injection in the grid. The second fuel signal is given by the frequency droop controller that detects the difference of the grid frequency with respect to the rated value. If the frequency drops, the controller gives a positive fuel signal, increasing the opening of the fuel valve. The engine injects more power in the grid providing locally energy to the loads and reducing the current burden at the ST level.

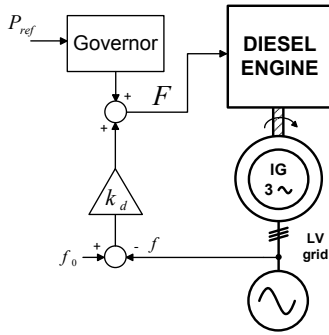


Fig. 6. Generator control with Woodward governor and droop controller

## V. SIMULATION RESULTS

The study case describes an emergency situation when the load demand exceeds the ST capacity and the LV grid is sustained with the help of the Diesel engine and the wind turbine. Due to the variability of the wind speed, the power output of the wind turbine changes. With low wind speed the wind turbine power output decreases and the feeder current increases overloading the ST. In this work two current limits are set: the Current Security Limit, set to 950A rms, that activates the overload control, and the Current Hard Limit, imposed at 1000A rms, corresponding to the real current capacity of the ST. The difference between the two limits gives the necessary security margin in the control action. The simulations have been performed in PSCAD/EMTDC®, with a timestep of 100μs.

In Fig. 7 the variability of the wind speed profile is described. When the wind speed decreases, the production of the wind power plant decreases with the cube of the wind speed and the power provided by the ST increases to compensate the difference. Imposing a fixed voltage, the amount of current

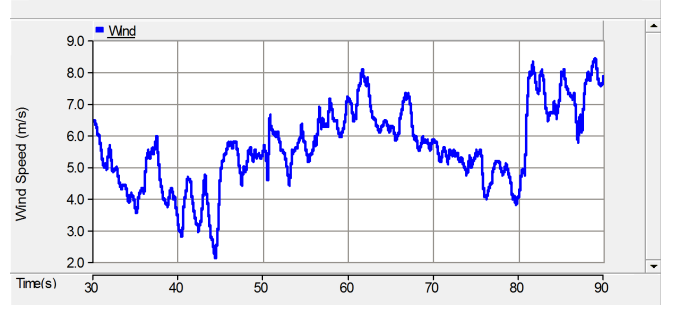


Fig. 7. Wind speed profile.

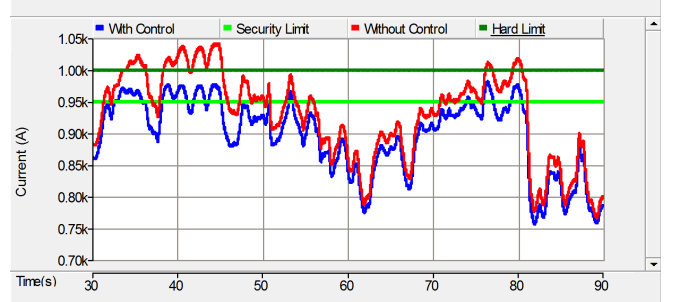


Fig. 8. Current profile with (blue line) and without (red line) current-frequency control, current security limit (light green line), and current hard limit (dark green line).

flowing in the ST increases proportionally to the power, leading towards limit violations of the ST current capability.

This is shown in Fig. 8, where, without a proper control the current goes above the ST hard limit in several points, where the wind speed is lower. If this situation persists the ST will be forced to shut down, in order to prevent any damage to the semiconductor components.

To avoid a possible ST shutdown, as soon as the current exceeds the security limit, the control explained in Section III operates and lowers the frequency obtaining the DG power increase. The current flowing in the ST is kept under control and never violates its hard limit. Due to controller time constants, small security limit violations occur, always however within the security band.

Fig. 9 depicts the frequency trend when the control action is applied. The frequency variation has been kept to the minimum, tuning properly the controller gain in the ST control. The control must always comply with the grid requirements, mostly regarding the frequency deviation from the rated value. Here a minimum value of 49.8Hz has been set in order to avoid large deviations from the rated value.

Fig. 10 shows the active power injected and reactive power absorbed (with inverted sign) by the asynchronous generator associated to the Diesel engine. During the transient, the droop control drives the generator to inject more active power, reacting to the frequency decrease. As can be stated from Fig. 10, when the control action is not applied the generator returns to its original setpoint. This minimizes the effect of the the overload control on the generator.

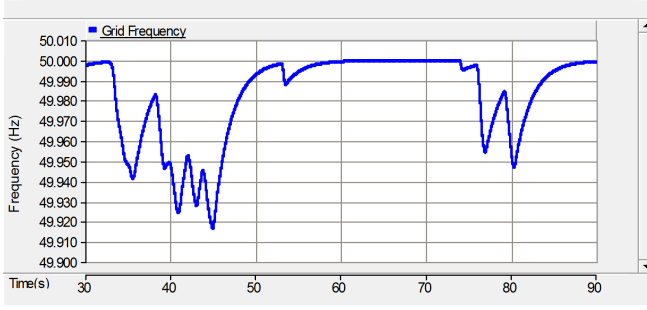


Fig. 9. Grid frequency profile applying the control action.

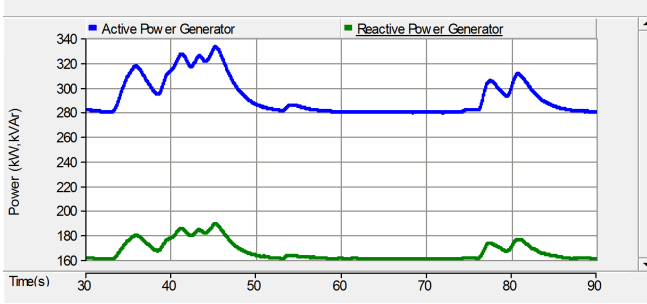


Fig. 10. Diesel generator active (blue line) and reactive (green line) power.

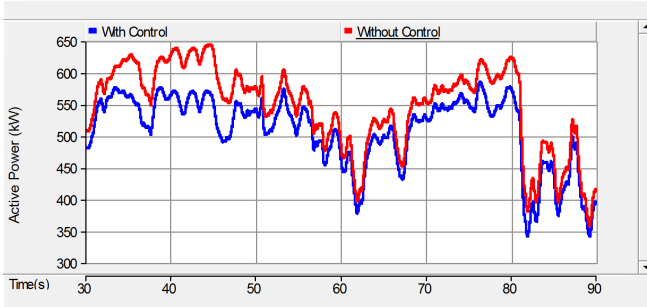


Fig. 11. Diesel generator active power with (blue line) and without (red line) control.

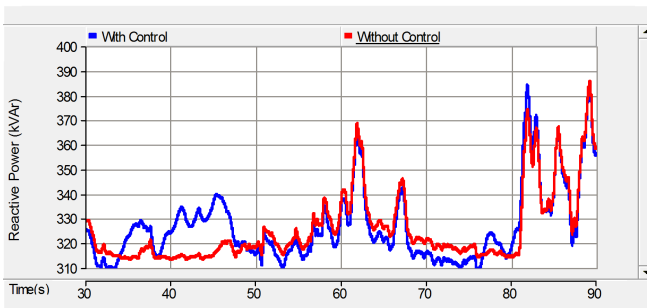


Fig. 12. Diesel generator reactive power with (blue line) and without (red line) control.

Fig.11 and Fig.12 show the active and reactive power profile of the ST. As it can be noticed, the active power decreases during the transients, due to the contribution of the Diesel engine, and the reactive power increase only marginally

during the application of the control action.

## VI. CONCLUSION

This paper has described a possible solution to the ST overloading problem in presence of controllable DG. In emergency situation, the FBOC allows the DG power re-dispatch in order to reduce the ST current burden, impacting minimally on the LV grid. The control action provides a solution to the overloading problem during the transients, letting the system work at the frequency rated value in the absence of an emergency.

## ACKNOWLEDGMENT

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## REFERENCES

- [1] R. Walling, R. Saint, R. Dugan, J. Burke, and L. Kojovic, "Summary of distributed resources impact on power delivery systems," *IEEE Transactions on Power Delivery*, vol. 23, no. 3, pp. 1636–1644, July 2008.
- [2] R. Pena-Alzola, G. Gohil, L. Mathe, M. Liserre, and F. Blaabjerg, "Review of modular power converters solutions for smart transformer in distribution system," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, Sept 2013, pp. 380–387.
- [3] D. Rogers and T. Green, "An active-shunt diverter for on-load tap changers," *IEEE Transactions on Power Delivery*, vol. 28, no. 2, pp. 649–657, April 2013.
- [4] J. Faiz and B. Siahkolah, "New solid-state onload tap-changers topology for distribution transformers," *IEEE Transactions on Power Delivery*, vol. 18, no. 1, pp. 136–141, Jan 2003.
- [5] G. Hipszki, R. Schmid, R. Maier, K. Handt, and G. Buchgraber, "Distribution transformer - ready for the smart grid," in *21st International Conference on Electricity Distribution*, 2011.
- [6] I. Solteiro. Smart transformers. [Online]. Available: [http://www02.abb.com/global/zaabb/zaabb011.nsf/bf177942f19f4a98c1257148003b7a0a/a747f0dd04d11314c1257b720036dd5e/\\$file/smart+transformers++%28trafo+asset+management%29.pdf](http://www02.abb.com/global/zaabb/zaabb011.nsf/bf177942f19f4a98c1257148003b7a0a/a747f0dd04d11314c1257b720036dd5e/$file/smart+transformers++%28trafo+asset+management%29.pdf)
- [7] F. Katiraei, M. Iravani, and P. Lehn, "Micro-grid autonomous operation during and subsequent to islanding process," *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 248–257, Jan 2005.
- [8] J. Peas Lopes, C. Moreira, and A. Madureira, "Defining control strategies for analysing microgrids islanded operation," in *IEEE Power Tech*, June 2005, pp. 1–7.
- [9] J. Guerrero, J. Vasquez, J. Matas, L. de Vicua, and M. Castilla, "Hierarchical control of droop-controlled ac and dc microgrids - a general approach toward standardization," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, Jan 2011.
- [10] G. De Carne, G. Buticchi, M. Liserre, C. Yoon, and F. Blaabjerg, "Voltage and current balancing in low and medium voltage grid by means of smart transformer," in *IEEE PES GM*, 2015.
- [11] H. Qin and J. Kimball, "Solid-state transformer architecture using ac-ac dual-active-bridge converter," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 9, pp. 3720–3730, Sept 2013.