Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2022) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

<Transport Research Arena (TRA) Conference

Railway Auxiliary Power Supply System: A Modular Multilevel Converter Approach

Nuno Rodrigues[a], Jose Cunha[a], Vitor Monteiro[a], Joao L. Afonso[a]

[a]*Centro ALGORITMI, University of Minho, Guimarães 4800-058, Portugal*

Abstract

When it comes to power railway systems, two main aspects must be considered: (i) the power of the propulsion of the train, which is responsible for the movement of the train; (ii) the power of the auxiliary services, which is responsible for the power inside the train for commodity and service of the passengers. As such, two different converters are used, namely the propulsion converter and the static converter, respectively. This paper proposes a new topology of a static converter, using a modular multilevel converter with high frequency output, with a high frequency transformer to reduce the size of the converter. The output of the converter is responsible for creating a stable single-phase voltage, with nominal values of 230 V - 50 Hz, from a highly variant input voltage available on the DC-link.

Keywords: Railway power systems, electric traction systems, auxiliary power, power converters, modular multilevel converter

1. Introduction

Ever since the 16th century the trains have been around to facilitate the transportation of both people and goods, having highly evolved through time. At first, railway systems used wooden rails and the locomotives were moved by ropes with treadwheels, being operated by human or animal power. With the invention of the steam machine during the industrial revolution, with the burn of coal, emerged the first steam locomotives, becoming the best means of transport of the era. Then came the diesel-powered train, a solution that appeared to facilitate the operation of the trains but resulted in a harmful pollution for the environment.

Nowadays, the railway systems have become electrified, with the power transmitted to the train by catenaries and pantographs. This interface exists in DC, usually for small distances, and in AC, which easily increases the voltage resulting in decreases of the current, consequently, improving the efficiency since the Joule effect losses are reduced. The usual values for AC catenaries in Europe are 15 kV or 25 kV (-24%, +10%), 50 Hz (Heising et al., 2009), (Sun et al., 2004). To power the train, a DC bus is created, typically at 2 kV, which is characterized by high voltage fluctuations, varying from -40% to +25% (Daoud et al., 2013). Therefore, the power electronics systems inside the train must be prepared to deal with such voltage fluctuations, i.e., proving stable output voltages even with such fluctuations at the input. When the power is provided to the train, two different aspects must be considered, the power necessary for the traction of the train itself (i.e., the power necessary to supply the electrical machines) and the power necessary for the auxiliary services inside the train, regarding lights, AVAC, communication systems, internal drives such as doors, and power plugs for the passengers to use (Baker et al., 2019). As such, two different power electronic

Peer-review under responsibility of the scientific committee of the Transport Research Arena (TRA) Conference

converters are needed: (i) the propulsion inverter to the traction power (ii) and the static converter for the auxiliary services. The propulsion inverter is a powerful three-phase inverter with the purpose of keeping a smooth movement on the train. The static converter can be a single-phase or three-phase inverter with the purpose of providing comfort to the passengers with steady illumination and safe to use power plugs.

In this scope, this paper proposes a single-phase static converter, which is constituted by a modular multilevel converter (MMC) (used to interface the 2 kV DC), by an isolated DC-DC converter to reduce the voltage level to 400 V DC, and by an DC-AC converter (used to create a stable 230 V 50 Hz output voltage, with low total harmonic distortion (THD)).

The proposed single-phase static converter must produce a stable 230 V 50 Hz output voltage, despite the DC bus voltage fluctuations. Particularly, the focus of this paper is to validate the application of the MMC in this kind of application, since it is an interesting solution due to the reliability, redundancy, and the increase of the equivalent switching frequency, which relates to the sum of the frequencies of the submodules of each arm, allowing the use of smaller filters and heatsinks and lowering the losses of the converter, resulting in an increase of the efficiency, and reducing the volume and weight of the converter, as well as the costs associated (Martinez-Rodrigo et al., 2017), (Yadav et al., 2017).

Nomenclature

MMC	Modular Multilevel Converter
SM	Submodule
APS	Auxiliary Power Supply
THD	Total Harmonic Distortion
PWM	Pulse-Width Modulation

2. Proposed System Topology

The electrification of a train goes through some power conversion stages, from the power lines to the powering of the traction electrical motors and the auxiliary services. The power is supplied through a pantograph from the power lines. In Fig. 1 is presented a generic diagram of the power of a train, consisting in an AC power line (15 kV or 25 kV), a pantograph, a circuit breaker, a high-power transformer and three power converters. The same concept is used to trains powered in DC, without using the power transformer and the main converter presented.

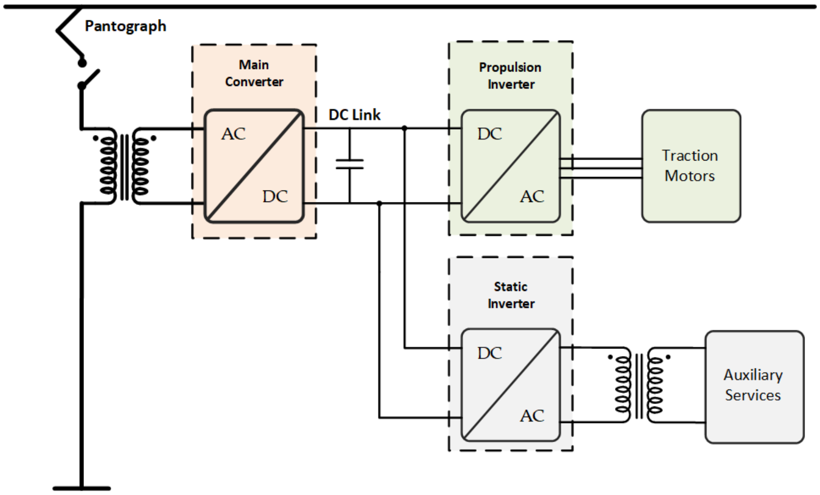

Fig. 1. Generic diagram of the power of a train.

The main converter is responsible for creating a DC link from which the propulsion inverter and the static inverter use as input voltage. The referred DC link is shared by both, as such, due to the power required for the traction motors, the DC link suffers very high fluctuations. The propulsion inverter is a powerful power converter responsible for controlling the traction electrical motors.

The static inverter is responsible for supplying the necessary power for the auxiliary services, which can be achieved in a vast array of possibilities. In Fig. 1 is presented the usual topology, consisting in a DC-AC converter followed by a single-phase 50 Hz transformer. There are also solutions for this inverter using medium frequency transformers, with a rectifier and an inverter at the secondary-side of the transformer, creating the same output in a more compact solution. The static inverter can also incorporate AC-DC converters for battery interface.

This paper proposes a new topology for a single-phase static converter, with the purpose of powering the auxiliary services of the train, such as AVAC, power plugs and illumination steadily, using an MMC, a high-frequency transformer, an active rectifier, and a power inverter. The proposed topology is presented in Fig. 2.

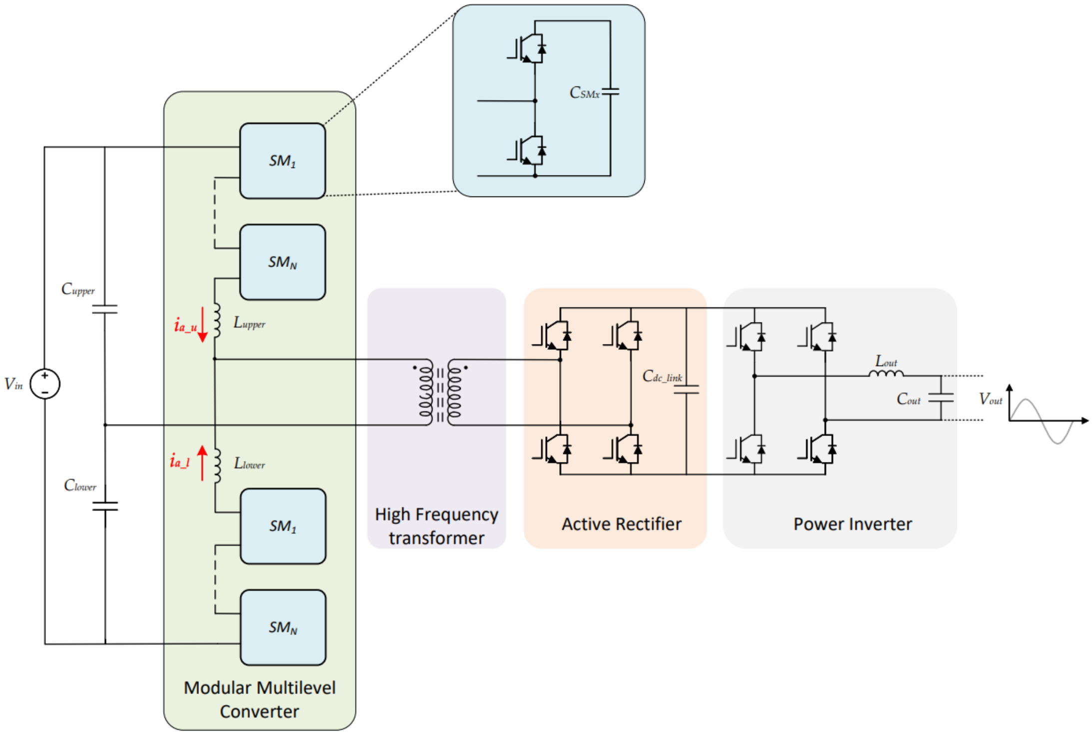

Fig. 2. Proposed topology for railway auxiliary power supply.

The MMC uses half-bridge submodules with a capacitor in the DC-link. The MMC generates a high frequency voltage signal to the input of the transformer. The MMC was selected due to the advantages that it can provide, such as: High reliability; Low dv/dt; Low THD; Low common-mode voltage; Power scalability; Fault-tolerant operation; Use of smaller filters (Maswood & Tafti, 2019). The active rectifier in a full-bridge topology is responsible for establishing a stable DC-link which serves as input to the full-bridge power inverter, that is responsible for the output of a stable single-phase voltage of 230 V, 50 Hz.

3. Control Algorithms of the Proposed Static Converter

The control of the proposed static converter is subdivided in the control of the three different power converters presented. In this section are discussed the control of the first conversion state, the MMC. The active rectifier is controlled using phase shift techniques to control the DC link , presented in (Araújo, 2019), (Naayagi et al., 2015). The power inverter is controlled using a PI controller followed by a bipolar modulation to ensure the stability in the voltage generated for the train auxiliary services.

The control of the MMC is required to keep the voltage across each submodule balanced to ensure the proper functioning of the converter, as such, there are two different stages to achieve such purpose, the individual voltage control presented in Fig. 3, and the arm voltage control presented in Fig. 4 (Tanta et al., 2020).

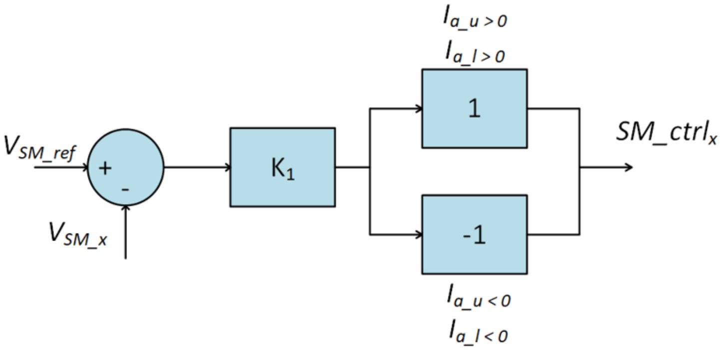

Fig. 3. Voltage control of the capacitors of each SM.

The individual voltage control consists of a proportional control of the voltage of each submodule to follow the voltage reference. Depending on the current direction, the output of the controller is multiplied by 1 if the current in the arm in which the submodule is integrated is positive, or -1 if the current is the arm is negative. As such, there is a controller unit for every submodule of the MMC.

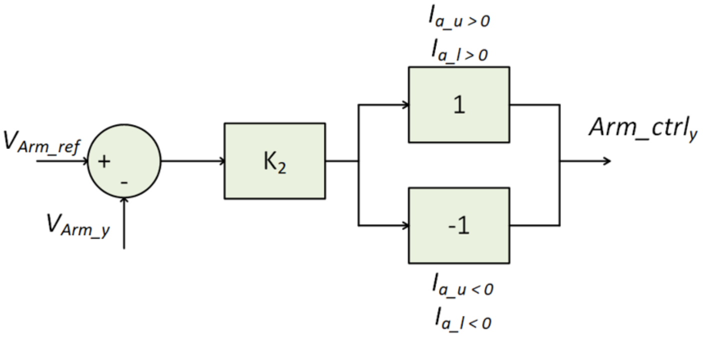

Fig. 4. Voltage control of each arm

Regarding the arm voltage control, it is similar and works as a complement to the individual voltage control, as it consists of a proportional control of the sum of the submodule voltages across each arm to keep the voltage in each arm balanced. Identical to the individual voltage control, the output of the controller is multiplied by -1 if the current in the arm is negative. Regardless the number of submodules per arm, there are two controller units for arm voltage control.

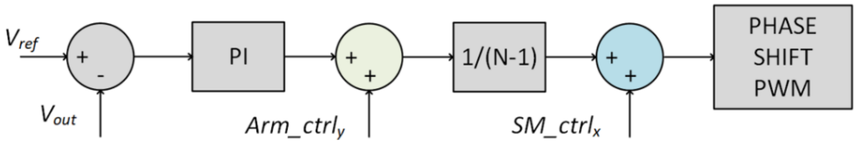

Fig. 5. Gate signal generation for each SM

For the control of the output of the MMC, a square voltage signal is given as reference, using a PI controller to ensure the output is stable and following the reference. Then it is summed the output of the arm voltage controllers, followed by a gain of 1/(N-1), where N relates to the number of submodules in each arm. Finally, the output of the controller of the voltage of each submodule is summed to the reference signal, having created the modulators for the phase shift PWM. This technique consists of the phase shift of the triangular carriers of each arm in 360/(N-1) degrees (Barros et al., 2020) .

4. Computational Validation of the Proposed Static Converter

The validation of the proposed topology was pursued recurring to computer simulations, using the PSIM software, which is a powerful simulator for power electronics systems, including the power system and digital control. In a first stage, the system was simulated with a constant voltage supplied at the input of the power converter. In Table 1 are presented the values of the components used, considering the same nomenclature as in Fig. 2. The high frequency transformer was projected to 20 kHz, which is the frequency of the output of the MMC, and with a 2:1 voltage relation.

Table 1: Values o components used in computational simulations

Component	Value
V_i	2000 V
C_{upper} C_{lower}	10 mF
C_{SM}	5 mF
L_{upper} L_{lower}	500 μH
C_{DC_link}	5 mF
L_{out}	5 mH
C_{out}	50 μF

In Fig. 6 is presented a detail of the output voltage of the MMC, followed the secondary-side of the high-frequency transformer and the current output of the MMC.

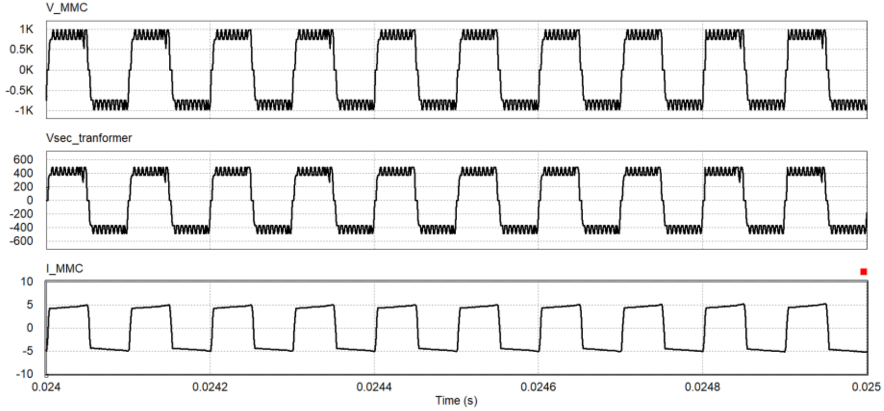

Fig. 6 Voltage output of the MMC, secondary of the high-frequency transformer and Current output of the MMC

As the static inverter is used to power the auxiliary services as power plugs for the train passengers, the simulation considers the change of loads that can occur in time, starting with a resistive linear load, and adding a non-linear load, a single-phase rectifier with RC load in t = 0.04 s to calibrate the system for a steady output.

In Fig. 7 is presented the output voltage and current of the APS, respectively, and as expected, the voltage output does not suffer variations with the change of loads. As for the current, it suffers from a slight overshoot due to the initial conditions of the non-linear load, namely the initial charge of capacitors in rectifiers.

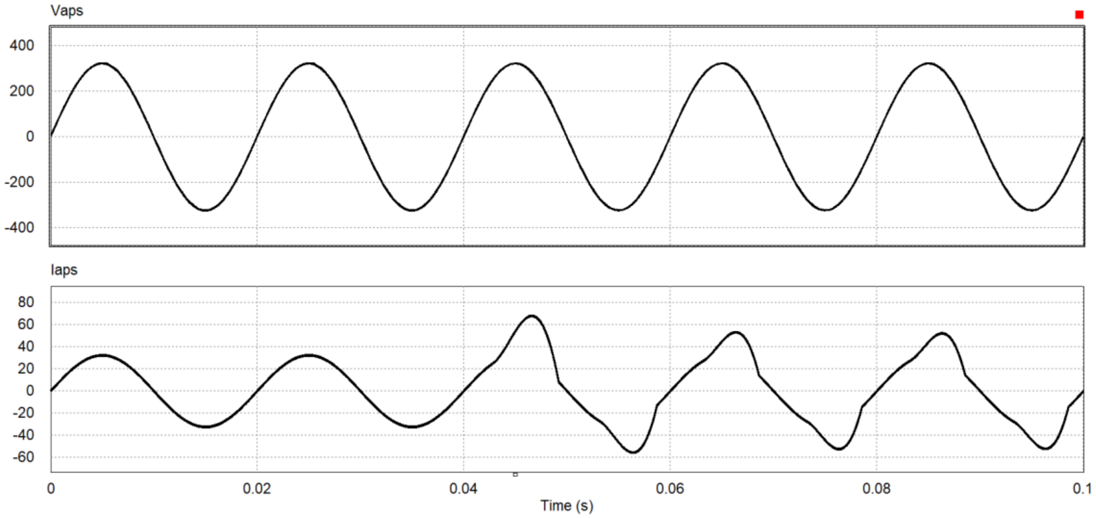

Fig. 7 Output voltage and current of the auxiliary power supply with a stable DC-link voltage.

After the validation of the static converter with a constant DC link, the input power supply was changed to simulate the variations on the DC-link, assuming the worst-case scenarios, -40 % and + 25 % to analyse the behaviour of the system. In Fig. 8 is presented the behaviour of the system for the same loads as in Fig. 7, with the referred DC-link variations.

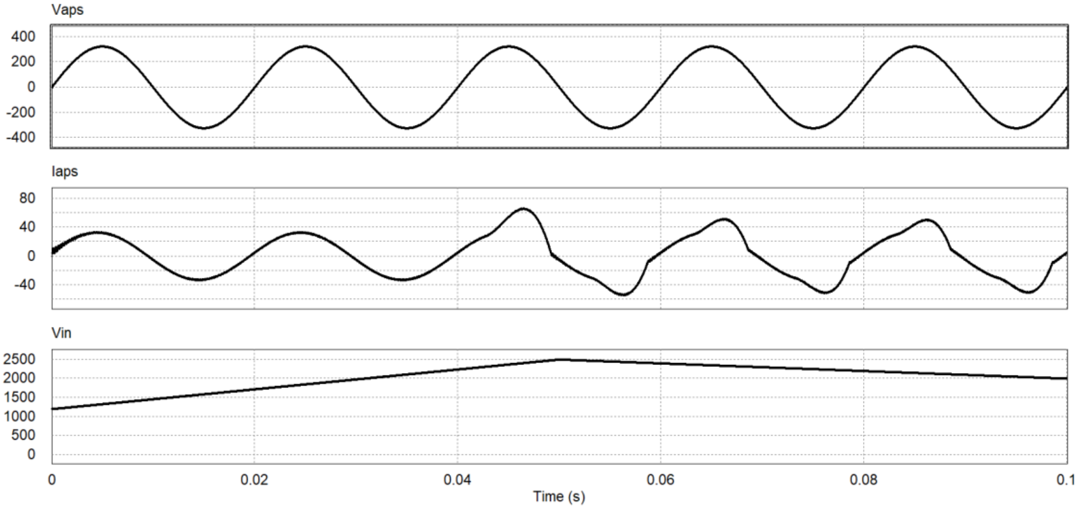

Fig. 8 Output voltage and current of the auxiliary power supply with variations on the DC-link voltage.

The voltage remains stable at 230 V, 50 Hz output and the current behaves similarly as well. These results validate the functioning of the proposed topology under the variation of the supplied DC voltage present in the DC link shared by the propulsion converter and the static converter.

5. Conclusions

This paper proposes a new topology for a static converter for an auxiliary power supply (APS) in railway systems using a modular multilevel converter (MMC) with half-bridge submodules, a high frequency transformer, an active rectifier, and a power inverter.

With the proposed topology it is possible to split the voltage by the submodules which allows use components of lower voltage. This results in less power dissipated and lower temperature spots which facilitates the management of the heat. Furthermore, it promotes the possibility to use discrete semiconductors (with better switching performance) instead of modules.

The converter was tested recurring to computer simulations, first with a stable DC-link to validate the functioning of the converter, followed by tests with variations on the input DC-link to fully validate the control techniques and the proposed topology. The results presented in the paper allow the validation of the proposed topology for the APS, which brings together many advantages associated with the modularity of the converter, however, there are some disadvantages involved, namely the number of electronic components and the complexity that follows for the control of the topology itself.

References

Araújo, A. (2019). *Desenvolvimento de um Conversor CC-CC Bidirecional Isolado para um Sistema Load-Shift Universidade do Minho*.

Baker, Nick. J., Almoraya, A., Raihan, M. A. H., McDonald, S., & Pickert, V. (2019). Electric drive train design for wave energy converters. *2019 12th International Symposium on Linear Drives for Industry Applications (LDIA)*, 1–6. https://doi.org/10.1109/LDIA.2019.8771015

Barros, L. A. M., Tanta, M., Martins, A. P., Afonso, J. L., & Pinto, J. G. (2020). *Submodule Topologies and PWM Techniques Applied in Modular Multilevel Converters: Review and Analysis*.

Daoud, M. I., Abdel-Khalik, A. S., Elserougi, A., Ahmed, S., & Massoud, A. M. (2013). DC bus control of an advanced flywheel energy storage kinetic traction system for electrified railway industry. *IECON Proceedings (Industrial Electronics Conference)*, 6596–6601. https://doi.org/10.1109/IECON.2013.6700223

Heising, C., Oettmeier, M., Staudt, V., Steimel, A., & Danielsen, S. (2009). Improvement of low-frequency railway power system stability using an advanced multivariable control concept. *2009 35th Annual Conference of IEEE Industrial Electronics*, 560–565. https://doi.org/10.1109/IECON.2009.5414982

Martinez-Rodrigo, F., Ramirez, D., Rey-Boue, A. B., de Pablo, S., & Herrero-De Lucas, L. C. (2017). Modular multilevel converters: Control and applications. In *Energies* (Vol. 10, Issue 11). MDPI AG. https://doi.org/10.3390/en10111709

Maswood, A. I., & Tafti, H. D. (2019). *Advanced multilevel converters and applications in grid integration*. John Wiley & Sons.

Naayagi, R. T., Forsyth, A. J., & Shuttleworth, R. (2015). Performance analysis of extended phase-shift control of DAB DC-DC converter for aerospace energy storage system. *2015 IEEE 11th International Conference on Power Electronics and Drive Systems*, 514–517. https://doi.org/10.1109/PEDS.2015.7203567

Sun, Z., Jiang, X., Zhu, D., & Zhang, G. (2004). A novel active power quality compensator topology for electrified railway. *IEEE Transactions on Power Electronics*, *19*(4), 1036–1042. https://doi.org/10.1109/TPEL.2004.830032

Tanta, M., Pinto, J. G., Monteiro, V., Martins, A. P., Carvalho, A. S., & Afonso, J. L. (2020). Deadbeat predictive current control for circulating currents reduction in a modular multilevel converter based rail power conditioner. *Applied Sciences (Switzerland)*, *10*(5). https://doi.org/10.3390/app10051849

Yadav, A., Singh, S. N., & Das, S. P. (2017). Modular multi-level converter topologies: Present status and key challenges. 2017 4th IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics (UPCON), 280–288. https://doi.org/10.1109/UPCON.2017.8251061