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Operational Challenges and Economics in Future Voltage Control Services

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Abstract

Purpose of Review Decarbonizing the power system entails the need to update voltage control strategies, traditionally based on synchronous generators, and energy flows from transmission to distribution grid level. We analyze the voltage control strategies implemented up to now, considering both the technical and economic views.

Recent Findings We study how the transmission and distribution grid operators in Spain, Croatia, and Thailand improved their voltage control strategies to exploit potentials from power electronics from wind and photovoltaic generation. Moreover, we analyze economic fundamentals and market design issues related with the implementation of these new strategies, essential to set efficient economic incentives for their successful implementation.

Summary We discuss recent innovative projects and solutions implemented in some countries that show promising and relevant potential from the implemented renewable-based voltage control strategies. However, we highlight that there are very few empirical analyses in real conditions, which are essential to implement improved and efficient voltage control strategies.

Keywords Voltage control · Renewables · Power electronics · Reactive energy · Ancillary services · Real-time set points

Introduction

The shift towards renewable energy sources (RES) replacing large conventional plants fed by pollutant fuels is transforming the power system and their flows due to the specific location of RES [1]. Moreover, the technological transformation of the generation mix is a new operational challenge related to voltage control strategies. RES, that are also connected to the distribution grid level, determine new challenges since they have different characteristics than conventional plants. RES typically have a smaller installed capacity, they are more numerous and more distributed into medium and low voltage (LV) networks, their production is variable and constrained to the availability of their primary resource, and their technology is based on power electronics instead of synchronous machines [2–4].

Moreover, the decarbonization of the energy mix coincides in time with the increasing commissioning of new underground cables in the urban areas, which behave as capacitors and also increase the need for controlling reactive energy flows, aggravating, even more the need to implement strategies to control the reactive energy flows. Some countries already face relevant voltage-related problems, such as the UK, particularly overnight when the demand is lower and specific synchronous plants do not generate [5].

In this framework, the traditional voltage control strategies implemented by the transmission system operators (TSOs) and distribution system operators (DSOs) need to evolve and consider relevant improvements to exploit the potential of power electronics technologies. Up to now, large synchronous generators mostly connected to the transmission grid provided voltage control through the generator's

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electromagnetic excitation, thus injecting or consuming reactive power depending on the grid needs in real time. RES equipped with power electronics can participate in voltage control; however, specific technological solutions and configuration are required to provide a similar response. Moreover, RES do not face the same operational costs as synchronous generators when they provide reactive energy, which also hinders the implementation of non-discriminatory economic incentives across different technologies. In this paper, we analyze the operational challenges related with the voltage control in this new scenario, as well as the economic fundamentals and market design issues related with the implementation of new operational solutions.

This paper is organized as follows. The "Impacts of RES on the Voltage Control Strategies" section analyzes traditional voltage control strategies and potential impacts related to the wide connection of RES from both sides: the power system operation and the economic support strategies. The "Innovative Voltage Control Strategies" section studies some alternatives to deal with the previous impacts, also from both the operational and economic points of view. Finally, conclusions are provided in the "Conclusions" section, including relevant gaps to be addressed in the literature.

Impacts of RES on the Voltage Control Strategies

Operational Challenges for Voltage Control

In the power system, voltage control is set based on the characteristics of the grids, consumers, and generators as is shown in Table 1. Before the energy transition era, the electric power system was characterized by unidirectional power flows, from the generation source connected to the meshed transmission network to the loads connected mainly to the radially operated passive distribution network [6]. The voltage control was based on large synchronous generators in coal, combined cycle, or fuel plants. These structure and topology of the power system allowed for 2-level hierarchical voltage control schemes that take advantage of the drooping profile of bus voltage magnitudes along generation to consumption [7]. At the transmission system level, steady-state and dynamic voltage control relies mainly on the contribution of synchronous generators whose first goal is to meet the power demand. However, dedicated equipments such as dynamic compensators (e.g., synchronous condenser, FACTS devices) and static devices (e.g., capacitors banks, reactors, tap changers of transformers) are also part of the voltage control procedures [8]. A multi-layer control scheme addresses the dynamic and steady-state voltage control by coordinating the involved resources using a centralized or multi-area approach [9–13]. A three-layer multi-area approach is exploited in Italy and France [10, 12, 14], while other countries adopt a two-layer centralized approach in which there are local (primary) and central (national) control levels; hence, there is no secondary layer for multi-area control; there is a single control area that covers the entire power system area (e.g., Belgium, Switzerland, Austria, Hungary, Lithuania) [9, 13].

Both multi-area and centralized approaches envisage a primary voltage regulation (PVR), i.e., a local control loop of bus voltage addressed by an Automatic Voltage Regulator (AVR) that acts on synchronous generators' operating

Table 1 Impact of different assets on the power system voltage control

Asset	Impact on the power system voltage control
Grids	• Nominal voltage: high voltage grids have higher resistance over impedance rate (R/X); thus, voltage control is based on reactive power flows. Low voltage grids have lower R/X rate; thus, voltage control is based on active power flows • Configuration: underground cables generate more capacitive reactive power flows than overhead lines • Congestion level: low-loaded grids generate more capacitive reactive power flows than high-loaded ones
Dedicated equipment	• Capacitor bank: injects reactive energy • Reactor: consumes reactive energy • Synchronous compensator: generates or consumes reactive energy • Flexible AC transmission system (FACTS): active and reactive power compensators installed at the transmission grid level • Static synchronous compensator (STATCOM): generates or consumes reactive energy • Transformer winding: consumes reactive energy • Transformer tap-changer (TC): regulates the turn ratio of the transformer and the voltage ratio • On-load Transformer tap-changer (OLTC): in addition to TC impact, it is useful to control reactive power flows in meshed networks
Consumers	• Generate or consume reactive energy depending on their internal assets
Generators	• Synchronous generators: traditionally had the most important role in actively controlling the reactive energy using its automatic voltage regulation (AVR) • Power electronics: control reactive energy, but need specific technical characteristics

Source: [5, 15, 16] and own elaboration

point [9, 17]. In the centralized approach, the PVR set point is defined depending on the centralized voltage regulation (CVR) results that optimize the voltage considering the whole transmission system. In the three-layer multi-area approach, the secondary voltage regulation (SVR) loop is an intermediate layer that defines the set points for the PVR depending on the voltage measured at the pilot node of the related area and the voltage target for that pilot node established by the tertiary voltage regulation (TVR) which optimizes the entire system [9, 17]. Hence, PVR deals with dynamic voltage support, and steady-state voltage control is addressed by the overarching layers (i.e., CVR or SVRs and TVR) that dispatch the available resources by defining local voltage targets [18].

In the distribution system, characterized by the higher resistance over impedance rate (R/X) and mostly radially operated, the voltage regulation approach exploits the monotonic decreasing of voltage magnitude along the feeders [19]. The voltage value at the sending bus is defined to guarantee voltage compliance at the furthest node of the feeder [2, 20]. HV/MV transformers are generally equipped with an AVR, which drives the on-load tap changer (OLTC), whereas MV/LV transformers typically exploit an off-load tap changer [21]. Transformers with tap changers can provide voltage regulation following two different schemes. First, setting a voltage setpoint on the secondary side of the transformer to neutralize the transformer voltage drop or voltage changes in the primary side of the transformer. Second, modifying the tap position depending on the measured loading condition to counteract the expected voltage drop. Moreover, the control loop can embed a partial compensation of the voltage drop along the line. The voltage regulation dynamic in the distribution system is comparable with the steady-state loops in the transmission system. This voltage control works when the energy flows from the higher voltage grid level (or transmission grids) to the lower voltage grid level (consumers connected in the distribution grid level) and no generators are connected to the same feeder. A review of voltage regulation with tap changers in the distribution system is discussed in [22]. In addition, shunt capacitor banks and inductors are complementarily used, but only in Medium Voltage grids [16, 23]. The connected loads participate in distribution voltage regulation adopting power factor (PF) correction measures to comply with the PF requirements imposed to minimize the network's reactive power flows and voltage drops [24, 25].

The ongoing power system transformation characterized by the wide connection of RES equipped with power electronics and decentralization drivers hampers the effectiveness of the traditional voltage regulation approaches as energy flows become bidirectional depending on the weather conditions, sun or wind, and the grid level where they are connected to (i.e., directly to transmission grid or distribution grid, or behind the meter) [26]. In consequence, the most critical node could not coincide with the furthest node of the feeder and be different at each time. In the distribution system, bidirectional flows constrain the effectiveness of voltage regulation strategies since voltage profiles are no longer decreasing monotonic [21, 27]. Moreover, the decentralized energy production may determine voltage imbalance issues in low voltage networks [28]. The voltage control is not designed to handle the effect of RES power injections; the control may lead to voltage violations for some buses. Moreover, the decommissioning of the thermal power plants, mostly connected to the transmission grid level, decreases the number of synchronous generators connected, shortening the voltage regulation support. In addition, the electric behavior of the network is also changing due to the commissioning of many new underground cables to substitute aerial cables, especially in urban areas. All these underground cables behave as natural capacitors, injecting reactive energy, increasing the need to control the reactive energy flows even more [29].

However, the ongoing power system transformation also offers alternatives to deal with the mentioned voltage control issues. Large size RES are typically interfaced through controllable power electronic converters that can be embedded in the existing voltage regulation loops. Similarly, the electronic interface for small RES can be controlled according to the voltage control needs [30, 31]. There is a dependency between the provision of reactive power and the active power output; however, the advancements in power electric allowed to obtain a great diversity of PQ capability curves for electronic interfaced resources, as discussed in [30, 31] for different technology. Nevertheless, in the context of network connection requirements and service provision, technology neutrality should be pursued. To this aim, generalized PQ characteristic curves are introduced in grid codes. Figure 1 depicts the characteristic curve representing the connection requirements in Spain for large renewable energy source (RES) generators. This curve specifically pertains to the reactive power capacity (Q) while considering the active power (P) provision. A similar characteristic curve is also introduced in [32] for Germany, the UK, and Ireland. Moreover, the approach at the distribution grid level, the voltage control strategies should be mostly based on controlling active energy flows due to the higher R/X of these networks. In both cases, the novel control resources need to be characterized to quantify the technical potential available from the different technologies and estimate the related costs [8]; additional investments are required to unlock the resources' potential (e.g., dedicated control equipment, communication infrastructures and platforms), and novel grid voltage support algorithms to optimize reactive and active power flows in presence of RES [33].

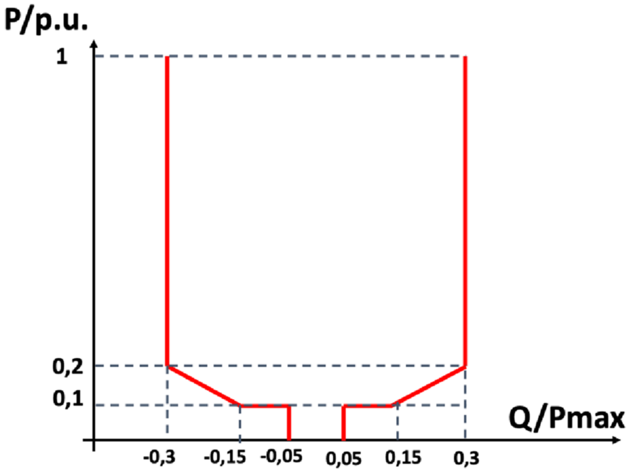

Fig. 1 Curve characteristic pertaining the reactive power capacity (Q) while considering the active power (P) provision considered for the Spanish power system for large RES generators. Source: [34] cite

Voltage Control Economics

Economic power support strategies can be based on free mandatory requirements or reactive energy pricing strategies, considering the function costs of the potential providers of the voltage control, i.e., generators and consumers. The costs of voltage control provision are related to the Capital Expenditure (CAPEX) for the necessary equipment and the Operating Expenses (OPEX) related to the active and reactive power support [8]. Considering voltage control with active power support, the OPEX related to the control action coincides with the active power cost or the corresponding loss of opportunity cost in case of generation curtailment [8]. The OPEX of reactive power control actions are related to the internal energy losses in the used equipment (i.e., synchronous generator exciter, power electronic converter) [8, 35].

In the last years, the provision of reactive energy has been mainly based on pricing mechanisms: static tariffs or rates to force to consumers and generators to operate under specific power factors to limit the injection or consumption of reactive energy [13]. This approach is especially relevant when potential providers face some specific operational or capital expenditures, such as the installation of a capacitor or reactance in a large industrial consumer, higher electricity losses in transformers behind the point of connection, or lower active energy in some generators, among others.

The tariff-based remuneration of the voltage control can be classified into three parts. First, depending on the product remuneration, there can be remuneration for the capacity (related to capital investments) and/or for the provided energy (related to operational costs). In most European countries, the remuneration is based on the delivered reactive energy. Second, the pricing scheme can be based on regulated prices or free prices, also considering the possibility of setting technology-based pricing or universal pricing for all the providers [36]. In both cases, there might be fixed prices or different prices for reactive power bands, creating positive discrimination across the providers. However, as higher the price discrimination, the higher the risk of ending with cross-subsidies problems, windfall profits or higher losses for specific technologies or providers because of an asymmetric information problem between the potential providers and the regulator [36].

In the new decarbonization scenario, these static rates might not reflect the temporal and spatial needs of the power system [37]. In small consumers, the wider connection of domestic electronic loads based on power converters and digital controllers is changing their reactive energy patterns. In this context, [38] proposes a specific tariff scheme for low voltage consumers, considering an incentive according to both their support to the network voltage and their harmonic pollution. The European electrical system has evolved over the last decade, becoming more capacitive, especially during off-peak hours, and also more changeable due mainly to the variability of renewable generation and power transfers within TSOs [39].

Innovative Voltage Control Strategies

Operational Solutions for Voltage Control Challenges

Directive (EU) 2019/944 defines voltage control as a non-frequency ancillary service which TSO and DSO shall use to ensure operational security [20]. Therefore, some TSOs have designed new automatic schemes which send voltage, reactive power, or power factor set points in real time instead of the current methodology described in the “Operational Challenges for Voltage Control” section. Below, we list three real cases followed by TSOs worldwide to implement improved voltage control strategies.

First, the Spanish TSO, Red Eléctrica [19], has implemented the VOLTAIREE platform, which comprises an Optimized Voltage Regulation (OVR) and a SVR, initially tested in the CoordiNet European Project [41]. They operate in adjacent timescales to improve their performance and stability when facing system perturbances. The OVR aims to maintain pilot nodes’ voltage inside an appropriate range by running an Optimal Power Flow (OPF), which considers the current network state estimation. The SVR automatically sends voltage setpoints in real time to service providers (RES) to minimize the difference between the voltage setpoint calculated by the OVR and the voltage measurement of the interconnection point between the service provider and the transmission network (PCR). It is important to highlight that RES provide reactive power following a voltage setpoint, which is an improved strategy compared to the traditional power factor or reactive energy setpoints.

VOLTAIREE also prequalifies potential service providers and allows grid operators (TSO or DSOs) to select in real time the set point modality (voltage, reactive power, or power factor) that better fits its system. VOLTAIREE also considers the case of meshed evacuation grids shared between several RES generators, a common case in Spain. In these cases, the service can be provided in its own busbars (BC) or aggregated with other providers. Voltage modality is the TSO predilect option because providers would automatically change their reactive output immediately after an incident. However, in some cases, such as meshed evacuation grids with OTC transformers, reactive modality may be used to avoid non-desired dynamic interactions. The prequalification process for the voltage control providers is based on the compliance process for the commissioned generators in Spain [42]. Coordination between TSO and DSOs is defined through a set of measures to be applied in their frontiers according to the transmission network voltage profile to control the reactive power flow through these frontiers.

Second, the Croatian Transmission System Operator HOPS [43] has implemented Volt Var Control (VVC) to increase voltage quality in the transmission network and minimize the active power system losses in the supervised power network. VVC system is an OPF-based application which calculates the optimal solution regarding the desired objective function, available control variables. and a defined set of constraints. To achieve the calculated optimal power system state, control of field devices is included in the optimization process by shifting tap changer positions or changing setpoint values of reactive power injection. Voltage and reactive power constraints are set accordingly to available regulating devices included in the optimization. The advantage of the VVC system implemented in HOPS is the possibility of operating the VVC in a closed loop without operator intervention.

Third, the Electricity Generating Authority of Thailand (EGAT) and HITACHI [44] have designed an Optimized Performance Enabling Network for Volt/Var (OPENVQ). It executes two analyses called prediction-based analysis and real-time analysis. The first one creates a schedule of optimized voltage control actions and voltage distribution for the future network state to formulate a control action with a small number of controls. The second one validates the control action and the voltage profile scheduled by prediction-based analysis in terms of voltage stability and reduction of transmission loss.

In every case, the TSOs and DSOs have designed and implemented improved voltage control algorithms aimed to optimize the electrical grid voltage profile by the use of every reactive power source, either discrete ones such as reactances, capacitors, and line opening or dynamic ones such as OTC, STATCOMs, HVDCs, conventional generation, and moreover the increasing RES generation. In all the cases, the voltage control strategies evolve to the implementation of real-time setpoints.

Economics of the Innovative Voltage Control Solutions

As we have explained before, the traditional voltage control strategies are becoming ineffective as large synchronous generators are replaced by RES based on power electronics, including large and small size plants [37]. In addition to the different operational characteristics, the operational cost function from RES is very different from the replaced large synchronous generators.

In Europe, voltage control as an ancillary service provision is mostly mandatory, and market procurement is not implemented. Only Belgium and Slovakia have a hybrid scheme. Moreover, the participation of RES in the voltage control ancillary services is limited to a few countries yet [13].

In decarbonizing the generation mix, the transmission system can face extreme situations related to a lack or an excess of reactive power [45]. In countries with a high penetration of RES, the current need to solve reactive energy needs is behind the high volumes of redispatched energy [46]. Precisely in Spain, the redispatched energy from synchronous generators increases when their production decreases due to a higher RES production [15].

Regarding the provision of the reactive voltage control, [47] finds that small RES could be more competitive and efficient than switched capacitors owned by TSO or DSO because of the inverter efficiencies. Moreover, RES can also provide voltage control service in the absence of wind or sun (i.e., P = 0 operating point in Fig. 1), but it is important to consider potential impacts on the inverter lifetime as another indirect cost for RES [48]. For all these cases, the provision of voltage control services should move from static tariffs, or rates approach, to incentivize consumers and generators towards new ancillary services to provide local voltage control [49]. However, the procurement of reactive energy is still mostly based on mandatory requirements, and tenders are specific in a few cases, such as the UK or Belgium [50].

According to the European Regulation 2019/944, the voltage control and the rest of the ancillary services should be procured under a market-based approach [40]. However, implementing market-based solutions in voltage control and ancillary services is challenging due to their particularities as is shown in the Table 2.

Voltage control products can be made of capacity and/or energy products, and be asymmetric, considering the injection or consumption of reactive energy. There might be several pricing approaches, such as marginal price, zonal price,

Table 2 Challenges related with the implementation of market-based voltage control ancillary services

Challenge	Description	Potential solutions
The effectiveness of the reactive energy is local	• The number of potential providers (suppliers) is limited affecting the market liquidity • Market power might be a problem	• Increase network mesh • Important regulatory oversight
Some providers might face additional entry costs to participate in a voltage control market	• Costs are related to the need to upgrade or retrofit their equipment, i.e. in the oldest RES plants, or also depending on the technology	• Long-term markets can provide efficient signals for investments • Implement specific funds or subsidies to ensure equal footing on technologies
The available reactive energy and capacity made by generators depends on the active scheduled power and energy	• Both the reactive and active energy markets are correlated	• Close the reactive energy auctions after clearing the active energy market
The operational cost structure might differ between synchronous machines and power electronics used in RES	• Synchronous generators: marginal operational costs are low when they are already running, just the losses because of the increasement of the reactive power flow. However, it could become very high if they must start only to provide this service • RES: very low costs in terms of losses, but they become more relevant when the primary source -wind or sun- is limited due to the energization of the converters that has to be done buying the active power in the market	• Long-term markets can provide efficient signals for investments in the two technologies • RES and synchronous generators need dedicated auditing process to estimate the corresponding marginal cost
Reactive energy needs are difficult to be assessed in the long term	• Reactive energy needs depend on variable issues: the aggregate demand, location of RES and network configuration • Reactive energy needs are know just the day ahead • Difficult to procure a quantity in the long term (risk of overprocuring)	• Long-term markets for reactive power capacity availability reservation • Short-term markets for reactive power energy

Source: own elaboration

nodal price, pay-as bid, or directly regulated tariffs. It is also possible to set non-remunerating solutions. [51] provides an interesting overview of 33 reactive power markets in the literature published from 1996 to 2021, and finds that 82% of these markets are in the transmission grid level, in most cases for synchronous generators. In recent years, several studies assess the vale staking possibility to enhance profitability for DERs based on different technologies (e.g., storage, PV, wind turbines) of providing reactive power support in combination with other services such as balancing and congestion management [52–57].

[58] studies the benefits related to the introduction of reactive power markets for DER in the scope of an innovative pilot sited in an area with high penetration of RES. They find savings from 8 to 21% related to business-as-usual assets and lower electricity losses.

The literature provides several examples of theoretical market-based approaches for reactive energy services procurement. [37] proposes a distribution-level reactive energy market to set variable payments and compensate DER considering a distribution-level locational Marginal Price for both the active and reactive power. Under their solution, they accommodate between 5 and 160% of additional generation. However, they do not consider the possibility of providing reactive power support from flexible loads or storage, which would be necessary to fulfil the neutral technological approach. Finally, [59] proposes a market-based active and reactive OPF to determine the optimal capacity of RES. The market structure includes bilateral contracts and active and reactive energy pools. Flexible loads and RES send offers, and DSO combined offers and bid prices to minimize the cost of energy.

Lastly, the Spanish TSO has designed new reactive capacity zonal markets both day ahead and in real time [39]. These markets communicate each provider reactive capacity assignation to VOLTAIREE platform which calculate the proper setpoint and validates the service in real time according to them. This makes available and useful the additional reactive capabilities of service providers, including RES. All these new functionalities imply a huge benefit in the voltage control of the Spanish system in terms of flexibility and security, resulting in both improving the quality of the service and making it cheaper since, currently, it entails a high cost in voltage ancillary services. However, the implementation of this new voltage control strategy and markets requires some tests in real environments, and the Spanish National Regulatory Authority approved a specific regulatory sandbox for this aim [60].

Conclusions

This paper analyzes the voltage control strategies implemented in the power systems and the new operational challenges related to the generation mix's decarbonization. We also discuss the economic fundamentals and market design issues of future voltage control strategies.

Before the connection of RES, power systems were characterized by unidirectional flows from the transmission to distribution grids. In transmission grids, large synchronous generators provide voltage control using two-level hierarchical voltage control strategies. In distribution grids, voltage control is mostly based on AVR equipment installed in the HV/MV transformers to drive OLTC, and customers follow predetermined PF requirements to control reactive energy flows.

This voltage support provision is typically based on non-remunerated mandatory requirements for third-party resources or specific economic incentives considering the potential OPEX and CAPEX of all the involved agents (i.e., TSOs, DSOs, third parties). In some cases, these incentives can also fund the need to install specific capacitors or reactances behind the meter of a customer.

Reactive energy setpoints for generators (RES) and transformers (OLTC) are becoming dynamic in real time and regional, considering both the operational needs of the grid at each node and location through OPF calculations. Advanced technological solutions enable them.

Implementing these new voltage strategies requires aligning the economic incentives to the new potential providers. RES face different cost functions than synchronous generators when they provide the voltage control services, and the oldest RES might need specific costly retrofit. At this point arises the opportunity to create dedicated markets for voltage services, but some operational and economic constraints cannot be neglected: the efficiency of reactive energy is local and constraints the number of providers, operational cost structure differs between RES technologies, and the provision of reactive energy depends on the scheduled active energy defined in markets (day-ahead or intraday markets).

In the literature, many theoretical studies concern innovative voltage control strategies, but very few empirical analyses in real conditions, which are essential to implement efficient voltage control strategies in the following years. Several challenges and gaps characterize the literature on voltage support as very little historical information and evaluation methodologies, or a lack of empirical experience in market-based mechanisms for voltage support procurement. Additionally, there is a lack of assessment frameworks ensuring a level-playing field comparison for traditional and system service–based voltage control support actions and related technologies. Furthermore, acknowledged approaches for integrating network congestion management and voltage control to co-optimize both are still missing.

However, the recent innovative projects and solutions implemented in some countries are already promising and show the significant potential of implementing voltage control strategies based on RES. In this process, it is essential that knowledge and experience are shared not only between TSOs and DSOs but also with manufacturers of power electronics and controllers.

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Declarations

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Conflict of Interest The authors declare no competing interests.

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