Wide Bandgap Power Electronic Devices for Constraint Management in Distribution Networks

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***Abstract*—This paper investigates the value of wide bandgap (WBG) technology in enhancing constraint management in distribution networks. The paper firstly provides a review of existing constraint management technologies. The advantages of power electronic technology over other technologies are highlighted, while the challenges of power electronics that normally use silicon (Si) materials are discussed. To address these challenges, this paper introduces WBG semiconductor technology as an innovative solution. The benefits of WBG power electronics for network constraint management including reduced cost, high energy conversion efficiency and high applicability are then identified. Based on these benefits, their promising applications in constraint management of distribution networks are also summarized.**

***Keywords*—wide bandgap, power electronic devices, constraint management, distribution networks**

I. Introduction

To stop the trend of climate change, increasing low-carbon technologies for electricity generation and supply are developed in electricity networks [1]. With the development of distributed renewable generation and new electrified demand, the electricity distribution networks will face increasing network constraint problems [2]. These problems mainly include violations of thermal constraints of the substation transformer and power lines and overvoltage or undervoltage problems for each node of distribution networks. In this context, constraint management is required for distribution network operators to solve constraint violations in the networks while ensuring the supply-demand balance.

However, the conventional distribution networks are operating passively [3]. In other words, the power flows and the voltage profile in a distribution network are naturally distributed abide by the physical electrical law. For better management of distribution networks, active management technologies are developed [4]. An alternative is using power electronic devices, which can control the power between the devices and networks fast and accurately [5]. Therefore, they are capable of improving the power flow distribution and the voltage profile of distribution networks. Additionally, with the increasing integration of inverter-based generation (e.g., solar and wind), the use of inverters for voltage constraint management [6] becomes attractive in recent years.

The challenges faced by power electronic devices are their high manufacturing and implementing cost [5], [7]. Particularly in the application of distribution networks with high voltage, the number of components connected must be sufficient to withstand the voltage potential. This makes the size of the electronic devices very large, which requires a big space for the installation. In addition, high reliability and power conversion efficiency are also important for the use of power electronic devices for constraint management.

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With the development of WBG materials, next-generation power electronic devices using WBG semiconductors may overcome the challenges faced by conventional Si-based power electronic devices [8]. In particular, WBG power electronics are more suitable for operation in high voltage, high temperature, and high frequency switching situations [9]. In this regard, this paper presents an overview of using WBG semiconductor technology in constraint management in distribution networks. The main contributions are as follows: (1) The emerging technologies and control methods for constraint management are reviewed. In comparison with different constraint management technologies, the opportunities and challenges for power electronic technology are discussed. (2) Key advantages of WBG power electronic devices are identified from constraint management perspective. (3) Opportunities of industrial applications of WBG power electronic devices in constraint management are summarized.

II. Emerging Constraint Management Techonologies in Distribution Networks

Fig. 1 provides an overview of different technologies that are used for constraint management in distribution networks in existing studies. Accordingly, three commonly used control methods for these technologies are also identified, including the sensitivity-based control, rule-based control, and optimization-based control. These technologies and the control methods are discussed in the following two subsections.

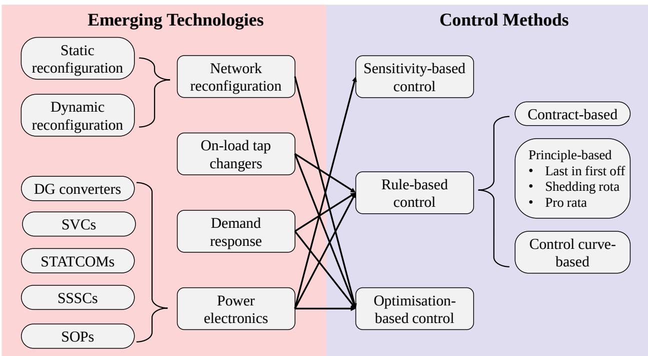


Fig. 1. Different technologies and their control methods for constraint management in distribution networks in existing studies.

A. Technologies Involved in Constriant Managemnet

To avoid the costly and time-consuming reinforcement of distribution networks, different technologies have been proposed for efficient constraint management of distribution networks. The commonly used technologies, including on-load tap changer (OLCT), network reconfiguration, demand response, and power electronic solutions, are discussed as follows.

1) On-load Tap Changers

OLTCs are mechanical devices capable of adjusting the magnitude of the secondary voltage of the transformer by changing the transformer's tap position while under load [10], [11]. An OLTC is normally equipped with the automatic voltage control relay, which monitors the secondary voltage of a distribution transformer and, when necessary, automatically signals the OLTC to make adjustments [12].

With the increase of DG integration in the distribution network, the OLTCs become less effective in maintaining the voltages across the network [13], [14]. This has sparked considerable interest in exploring coordinated voltage control strategies that synergize OLTCs with other emerging technologies.

2) Network Reconfiguration

Network reconfiguration in distribution networks is effective for constraint management of distribution networks by changing the status of sectionalizing switches and tie switches. In [15], the network reconfiguration was exploited to reduce power losses of distribution networks while satisfying the thermal and voltage constraints of distribution networks simultaneously.

[16] further categorizes the network reconfiguration into static reconfiguration and dynamic reconfiguration: static reconfiguration improves the topology of distribution networks at the planning and design stage using both manually and remotely controlled switches, while dynamic reconfiguration aims for real-time constraint management thus using only remotely controlled switches.

The effectiveness of static reconfiguration is often challenged by uncertainties in the locations and capacities of connected DG sources. The success of dynamic network reconfiguration, on the other hand, hinges on the efficiency of the measurement and communication systems and the responses of remote-controlled switching devices [17]. Moreover, practical considerations related to operations and safety typically limit the number of reconfiguration options available in distribution networks [16], [18]. Consequently, network reconfiguration is usually implemented in coordination with other technologies to enhance overall performance in constraint management [13], [19].

3) Demand Response

Demand response refers to balancing the demand on power grids by encouraging customers to shift electricity demand to times when electricity is more plentiful or other demand is lower [20]. Towards net zero target, it is projected that by 2030, the market will witness an integration of approximately 500 GW of demand side capacity globally — a significant leap, representing a tenfold increase in deployment levels in 2020 [20]. The projected increase signifies the substantial potential of demand response in service provision within distribution networks.

The location of each demand-responsive load in distribution networks has an impact on its ability to contribute to the management of system constraints [21]. Hence, when considering the application of demand response, it is important to consider the contribution of each load to both local network constraints and overall network energy balancing. Additionally, the effective deployment of demand response necessitates advanced metering infrastructure and robust digital management systems.

4) Power Electronic Solutions

Power electronic devices, such as DG converters, static var compensators (SVCs) [22], static synchronous compensators (STATCOMs) [23], static series synchronous compensators (SSSCs) [24] and soft open points (SOPs) [7], can serve as active compensators in distribution networks. Due to the power controllability, power electronic devices are capable of improving line flow and node voltage profiles, thus providing alternative solutions to the constraint management of distribution networks. However, their capabilities in active and reactive power control vary.

SVCs, STATCOMs and SSSCs can only provide reactive power support. While SVCs and STATCOMs provide shunt reactive power compensation within their capacities [25], SSSCs influence network reactive power flows by applying a series voltage between two network nodes to control their in-between impedance [24]. Therefore, the controlled power by SSSCs is determined not only by the capacities of SSSCs, but also by the network topology, the network operating point and the placement of SSSCs [24]. Regarding the differences between SVCs and STATCOMs, SVCs use thyristor-based switching of capacitors and reactors, whereas STATCOMs use voltage-source converters. Although SVCs are less expensive than STATCOMs, they have a limited range of reactive power compensation and may introduce higher harmonics due to the fixed steps of capacitors and reactors [26]. Additionally, the performance of SVCs can degrade under low voltage conditions, while STATCOMs can operate independent of the line voltages at their connected points [27].

DG converters and SOPs can conduct both active and reactive power control [5]. While DG converters can control the power injections at the connection points of DGs to conduct energy curtailment [28], SOPs allow for real power exchange between connected feeders as well as independent reactive power support at SOP terminals. Additionally, the active power injection controlled by DG converters is limited by both the converter capacities and the DG power output. In contrast, SOPs are constrained primarily by the capacities of their terminal converters.

B. Control Methods Used for Constraint Management

1) Sensitivity-based control

Sensitivity-based control can be used for power electronics [28]-[31], including DG converters for DG curtailment [28]-[29]. It is achieved by using sensitivity factors of the Jacobian matrix to quantify the contribution of P-Q injections from DG units or power electronic devices to the voltage (or thermal) constraints. The sensitivity-based control only requires knowledge of a small number of local network parameters (e.g., the local voltage measurement). However, the linearization when establishing the Jacobian matrix introduces errors to the control method [31]. Additionally, the results after the sensitivity-based control are usually not the optimum.

2) Rule-based control

Rule-based control suggests that the control strategy is established and manually configured in accordance with specific contracts, principles, or predefined control curves. With respect to the control of power electronics, a smart contract is used in [32] to determine the transferred power between two distribution networks connected by converters of a medium-voltage direct-current link. Additionally, the

Q-V curve can also be obtained for the reactive power control of converters [33], [34]. For DG curtailment, different principles can be used: “last in first off” (curtailing the newest connected DG unit first) [35], “shedding rota” (following a predefined rotation) [36], and “pro rata” (sharing the curtailment by each DG unit equally) [37].

The rule-based control is somehow subjective. To avoid this problem, data-driven methods can be used to refine the rules. For instance, [38] leverages historical operational data to establish a response curve that correlates the power flow through the substation transformer with the set point of the medium-voltage direct-current link.

3) Optimization-based control

Optimization methods have been widely used for the optimal control of different technologies in constraint management of distribution networks. Compared to the sensitivity-based control and the rule-based control, the optimization-based control can achieve optimum on different control objectives [39], [40]. Additionally, it is easy to consider the coordination of different technologies by adding them to the constraints and objective functions in the optimization models [41]-[43].

However, the nonlinearity of power flow equations and the introduction of integer variables (e.g., variables representing different tap positions for OLTC) increase the complexity of the optimization-based control model. This incurs significant computational cost and cannot guarantee the real-time control of the technologies. To solve this problem, the optimization model is usually converted to a convex programming model [44]-[46] with an acceptable error. Another problem is that the optimization-based control normally requires observability of the entire distribution network. However, the measurements across most distribution networks are not universally available [47]. To fix this problem, in [33], [48], a decentralized control based on local information of each area and boundary interaction among connected areas is developed.

C. Opportunities and challengies of using power electronic technology for constraint management

From Fig. 1, the power electronic technology offers multiple device options and flexible control methods for constraint management of distribution networks. This enables the use of power electronic technology facing different constraint violation problems. Additionally, with accurate and fast power control, power electronic devices can adapt to varying operating states of the network, which can achieve better performance than conventional technologies such as on-load tap changer and network reconfiguration. The increasing penetration of converter-based distributed generation (e.g., solar and wind generation) also enhances the potential for power electronic technologies to play a significant role in providing constraint management services.

Despite the advantages of power electronic devices, their relatively high cost, compared to the revenue generated from providing constraint management services, can hinder their widespread deployment across distribution networks. To boost the implementation of power electronic devices for constraint management, it is important to explore strategies for cost reduction. In addition, high reliability and power conversion efficiency are also important for the use of power electronic devices for constraint management. Next generation power electronic materials can be an innovative solution, which will be discussed in the next section.

III. WBG Semiconductor Power Electronic Devices

A. WBG Materials

WBG materials are semiconductor materials that have a bandgap energy greater than that of traditional semiconductors like Si. The commonly used WBG materials are SiC and GaN materials. Compared to Si materials which has a bandgap of approximately 1.1 eV, WBG materials typically have wider bandgaps ranging from about 2 to 4 eV [49]. It is worthy noting that there is another category known as ultrawide bandgap (UWBG) materials. These materials, such as diamond and sesquioxides such as gallium oxide (Ga2O3), have even larger bandgaps that exceed 4 eV [50]. However, due to the physical and process characteristics of UWBG, SiC and GaN materials have greater advantages in manufacturing process maturity, cost, reliability, and lifespan, thus receiving increasing attention.

WBG materials offer several key advantages over traditional Si materials. Firstly, WBG materials can withstand much higher electric fields before breaking down, thus allowing devices to operate at higher voltages and currents without failure. This feature is ideal for the high-power and high-voltage applications for WBG materials. Additionally, materials like SiC possess superior thermal conductivity compared to Si, leading to better heat dissipation, more efficient cooling, and a reduced need for complex thermal management solutions. WBG materials also exhibit higher switching speeds, which is beneficial for power electronics applications such as inverters and converters, where efficiency and rapid switching are crucial [51]. Furthermore, WBG semiconductors can function effectively at much higher temperatures than Si, reducing cooling requirements and increasing reliability in high-temperature application scenarios [52].

B. Next-Generation Power Electronics

Owing to the above features, WBG materials are promising in the development of next-generation power electronics. Compared to the traditional Si-based power electronics, the power elctronics using WBG semiconductors offer significant benefits in the following three aspects:

1) Reduced cost

SiC and GaN devices offer considerable system-level cost reductions, although initially costing more than their Si counterparts. This is mostly because of their capacity to function at higher frequencies, which results in smaller and less expensive passive parts like capacitors and inductors. Even though the initial cost of WBG devices is greater, the whole system cost can be lowered by around 20% [53].

2) High energy conversion efficiency

WBG power electronic devices can achieve high energy conversion efficiency due to their ability to operate at higher voltages and temperatures, lower conduction and switching losses, and superior thermal conductivity [54]. These properties enable faster switching speeds, reduced heat dissipation needs, and more compact designs, making WBG materials ideal for applications like power electronics, electric vehicles, and renewable energy systems.

3) High applicability

The superior thermal properties of WBG materials, including higher thermal conductivity and higher melting points, contribute to higher applicability of the devices [55]. These properties enable efficient heat dissipation, preventing overheating and maintaining stability even in high-temperature environments.

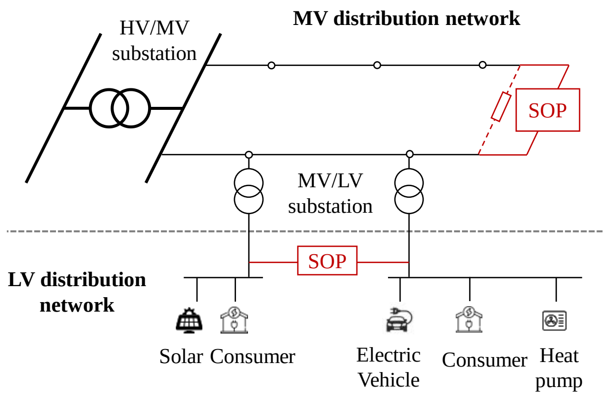
IV. Application of WBG Semiconductor Power Electronic Devices in Constraint Management

In this section, different applications of WBG semiconductor power electronic devices for constraint managemnt of distribution networks are discussed.

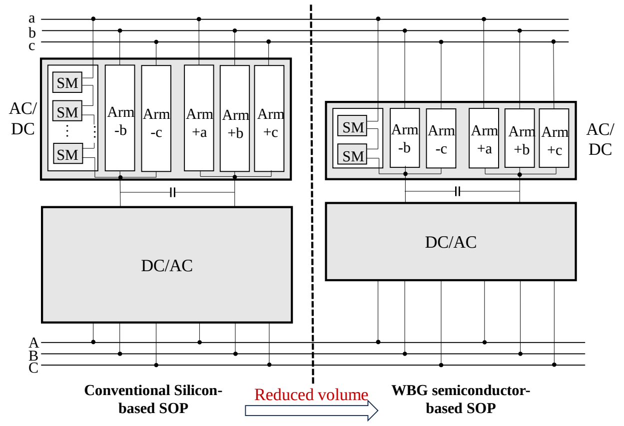
A. Soft Open Points

Typical applications of SOPs for constraint management in distribution networks can be seen in Fig. 2 (a). This figure demonstrates two examples for SOP applications, which includes constraint management for feeders and substations respectively. The first example is to exploit SOPs to replace normally open points to connect different feeders in medium volage (MV) distribution networks [7], [39]. In this application, SOPs can support thermal constraint management for the two connected feeders. For example, SOPs can transfer the power from a heavily loaded feeder to a lightly loaded feeder. Moreover, SOPs can deliver reactive power support at each SOP terminal if voltage violations occur. Besides constraint management for feeders, SOPs can also be used for constraint management of substations [56]. It is often not possible to connect the busbars of two substations in normal conditions due to circulating currents between them, excessive fault levels, protection coordination and in some cases phase differences. However, soft connection by using a SOP can overcome these problems. At the same time, the SOP enables bi-directional share of loads and generation between two low voltage (LV) distribution networks, thus reducing the peak demands/generations at both substations and avoiding thermal and voltage violations in substations.

Although the benefits of SOPs have been validated in different pilot projects [7], SOPs have not been widely deployed throughout the distribution networks worldwide due to their high cost. As shown in Fig. 2 (b), a conventional Si-based SOP normally exploits modular multilevel converters with multiple submodules (SMs) incorporated in each arm of the converters according to the required voltage level. Owing to the advantages of higher breakdown electric field in WBG semiconductors than in the conventional Si material, it is practically achievable to implement SOP topology with a smaller number of components. Simple two-level or three-level converters instead of modular multilevel converters can even be used. As a result, as presented in Fig. 2 (b), the volume of a WBG semiconductor-based SOP is smaller than that of a conventional Si-based SOP. This compact size allows SOPs to be more easily installed in existing substation spaces or in place of current normally open points without the need for additional land. Consequently, this can lead to significant reductions in the manufacturing and implementing cost for SOPs.



(a) Typical applications of SOPs for constraint management in distribution networks.



(b) Comparison between conventional SOPs and WBG semiconductor-based SOPs.

Fig. 2. Schemetic diagram of implementing WBG semiconductor-based SOPs for constraint management of distribution networks.

B. DG Converters

As stated in the part A of Section II, DG converters can deliver constraint management services to distribution network operators by exploiting energy curtailment or providing voltage support. However, power exchange through the converters introduces power losses, which increases the cost of the consumers when providing the services. Additionally, the capacities of the converters are restricted by the available installation space for consumers, which means the power support from DG converters will be limited. These problems require higher efficiency, higher density and lower cost of DG converters, where WBG semiconductors can be employed to achieve the goal.

In [57], PV inverters using SiC semiconductors can achieve a desirable weight density (e.g., 1kW/kg), compared to the weight density of less than 0.38 kW/kg when using conventional Si semiconductors. This indicates PV systems with larger capacities can be employed on a same roof. Moreover, replacing Si semiconductors with SiC semiconductors in PV inverters can lead to a significant reduction in both power losses and overall costs. As shown in TABLE I [58], the power losses in SiC PV inverters are substantially lower. Additionally, despite the current higher cost of SiC semiconductors compared to Si, the overall cost of SiC inverters is only 80% of that of Si inverters. The cost reduction is mainly attributed to the use of smaller inductors due to the higher switching frequency of SiC materials, and the use of cheaper heat sinks and inverter housings because of the lower power losses [58].

TABLE I. COMPASISON OF PV INVERTERS USING SI AND SIC SEMICONDUCTORS [58]

PV inverter	3 level Si IGBT	3 level SiC JFET	2 level SiC JFET
Power losses	732W	514W	381W
Cost	100%	82%	80%

C. Solid State Transformers

WBG technology has also been utilized in solid state transformers (SSTs), which use WBG semiconductor technology instead of traditional electromagnetic components to perform voltage conversion and regulation. Unlike conventional transformers, which rely on magnetic fields and physical coils to transfer electrical energy, WBG-based SSTs leverage power electronics to achieve the same functions in a more compact and efficient manner.

In [59], a three-phase SST employing a 15 kV/20 A SiC-based insulated gate bipolar transistor (IGBT) is used to connect a 13.8 kV MV distribution network to a 480 V LV distribution network within a three-level neutral point clamped (3L-NPC) architecture. Similarly, an MV SST that interfaces between a 4.16 kV distribution network and a 480 V distribution network using 10 kV MOSFETs in a two-level architecture is reported in [60]. In these two applications, the WBG technology enables higher operating frequencies and reduced volume of SSTs. These SSTs can perform as STATCOMs to provide reactive power compensation to distribution networks to improve the voltage profile and sustain the voltage stability as well.

V. CONCLUSIONS AND DISCUSSIONS

With the increasing development of low-carbon technologies in distribution networks, how to manage the network constraints actively and effectively becomes important. In this context, this paper explores the potential of WBG power electronic devices in constraint management of distribution networks. The key conclusions are as follows:

1) The power electronic technology offers multiple device options and flexible control methods for constraint management of distribution networks. In comparison with other technologies such as OLTCs and network reconfiguration, power electronic technology are able to actively control the power flow in distribution networks, which makes it an attractive technology for providing constraint management services.

2) From constraint management perspective, WBG power electronic devices have three main advantages over conventional devices using Si materials, which include reduced system cost, high energy conversion efficiency and high applicability. It should be noted that the cost of WBG materials is higher than Si materials nowadays. However, with smaller and less expensive passive parts like capacitors and inductors and reduced number of components within WBG power electronic devices, their overall cost can be reduced. As manufacturing techniques advance and market demand for WBG semiconductors expands, the cost is expected to decrease further in the near future.

3) Owing to the features of WBG materials, WBG semiconductors can be used in different power electronic devices, including but not limited to SOPs, DG converters and SSTs. These applications show great potential of WBG power electronics in achieving higher density, lower power losses and lower overall cost.

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