Applied Energy 230 (2018) 175–188

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Impacts of a medium voltage direct current link on the performance of electrical distribution networks☆

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HIGHLIGHTS

- Assessing impacts of an MVDC link on network performance with high DG penetrations.
- Investigating the capability of an MVDC link in increasing the DG hosting capacity.
- A real-time control method for MVDC link was proposed.
- Control strategies considering multiple operational objectives were developed.

ARTICLE INFO

Keywords:
Electrical distribution network
Medium Voltage Direct Current (MVDC) link
Distributed generation
Control strategy
Multi-objective optimization

ABSTRACT

With an increasing number of distributed generators (DGs) integrated into distribution networks, operational problems such as excessive power losses, voltage violations and thermal overloads have occurred. Medium Voltage Direct Current (MVDC) technology represents a candidate solution to address these problems as well as to unlock the capacity of existing electrical network assets. In this paper, the capability of using an MVDC link to improve the performance of a distribution network, i.e. reducing power losses and increasing the hosting capacity for DG connections was investigated. A grid transformer (GT)-based control method was developed, in which the real-time data of the active power flow at GTs was used to specify the set-points of an MVDC link. The control strategies considered multiple objectives, i.e. power loss reduction, feeder load balancing, voltage profile improvement, and trade-off options among them. The response curves of these control strategies were developed through offline studies, where a multi-objective Particle Swarm Optimization (MOPSO) method was used. Case studies on a real distribution network were conducted to analyze the impacts of the MVDC link. The performances of the network were evaluated and compared between the proposed control strategies, using real demand and generation profiles. Results revealed that, for an MV distribution network, it might be beneficial to switch between different control strategies with the variations in demand and generation conditions. Results also showed that, regardless of the control strategy used, the MVDC link can significantly increase the network hosting capacity (up to 15%) for DGs, and reduce about 50% of power losses compared to a conventional alternative current (AC) line for the test network.

1. Introduction

In recent years, an increasing number of distributed generators (DGs) have been integrated into electrical distribution networks [1,2], which pose challenges for Distribution Network Operators (DNOs), such as excessive power losses, voltage violations, and thermal overloads [3]. Solutions to address these issues whilst providing enhanced capacity for distribution networks to host DGs are required.

With the rapid development of power electronic technologies, and their applications to High Voltage (HV) transmission networks and Low Voltage (LV) distribution networks, analogies are being made with the use of direct current (DC) in Medium Voltage (MV) networks [4]. DC and power electronic technologies provide controllability and flexibility to distribution networks, and can be used to increase the hosting

☆ The short version of the paper was presented at ICAE2017, Aug 21-24, Cardiff, UK. This paper is a substantial extension of the short version of the conference paper.

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https://doi.org/10.1016/j.apenergy.2018.08.077
Received 5 February 2018; Received in revised form 14 August 2018; Accepted 15 August 2018

capacity for DGs of existing networks.

Research on distribution-level power electronic devices has been conducted. The use of shunt voltage source converters (VSCs) in rural networks for voltage regulation was carried out in [5]. In [6], an intelligent node, which is implemented by several VSCs connected to a common DC-bus, was proposed to extend the current limits of feeders, as well as to improve the voltage profiles. In [7] distribution-level power electronic devices with different topologies were assessed and compared, considering their capabilities in relieving network constraints and accommodating DGs. More recently, the capability of back-to-back VSCs based Soft Open Point (SOP) to regulate voltage and therefore to increase DG penetration was quantified in [8]. The benefits of using SOPs in a distribution network were analyzed in [9]. A sensitivity method to define the optimal operating region of SOP was proposed in [10]. A few initiative pilot projects have been trialed using SOPs in MV and LV distribution networks in the UK, such as 'Network Equilibrium' [11] and 'Flexible Urban Networks Low Voltage' [12] projects.

The above studies assessed the impacts of power electronic devices on the performances of distribution networks, and the topologies were mainly back-to-back VSCs. The benefit of deploying a point-to-point application of VSCs, e.g. an MVDC link, rather than a back-to-back application is that it enables flexible power and voltage control over a wider area. Recent studies on MVDC links have been conducted from different perspectives. In [13], the utilization of DC links to enhance the integration of DGs, and to reduce power losses in distribution systems was investigated, where the DC link control set-points were determined by the optimal power flow. The benefits of incorporating DC links to radial distribution networks were assessed in [14], where the maximum load or DG that can be served by the network were determined. The benefits of using multi-terminal DC links to reduce power losses and improve voltage profiles, as well as to mitigate transient power quality perturbations were analyzed in [15]. A cost-benefit evaluation of using DC links as interconnectors in dense-load urban networks was carried out in [16]. The capabilities of using MVDC links to increase network hosting capacity for DG connections were investigated in [17,18], and different levels of communication functionalities were considered in [18]. These studies have mainly focused on the evaluation of benefits of DC links in reducing power losses, increasing system loadability or integrating more DGs, whereby centralized control schemes are required. However, the centralized control schemes rely on measurement and communication infrastructures which might be subjected to malfunctions or failure. To account for this, operational strategies to keep DC links connected in a safe manner in the case of a communication failure were proposed in [19].

Due to the limited number of available real-time measurements in distribution networks and the intermittence of demand and distributed generation, distributed control strategies requiring fewer measurements are more viable than the centralized ones. In addition, the cost of associated ICT (information and communication technology) infrastructures required for centralized control accounts for a large portion of the total costs [20], which makes centralized control less attractive. A real-time control strategy of an MVDC link which uses only the measurements at grid transformers was investigated in [21]. However, the MVDC link set-points were obtained by using sensitivity analysis, in which a range of active power values were examined with the one inducing lowest network power loss selected as the MVDC link set-point. The drawback of using sensitivity analysis is that only limited number of candidate values, rather than the entire solution space are considered. This might result in underutilization of MVDC links. Therefore, effective control strategies for MVDC link need to be investigated. Also, as the performances of an MVDC link depend on the control strategies applied, different control strategies for an MVDC link need to be assessed and compared.

In this paper, a real-time control method for an MVDC link was proposed, in which the active power flowing through the grid transformers (GTs) is used to determine the set-points of an MVDC link. GTs are the transformers that supply power to the network. This method is called GT-based control. The GT-based control requires only measurements at the GTs rather than the load and generation data at each load point (i.e. substations) of the network. This work considered control strategies with multiple objectives, i.e. power loss reduction (PLR), feeder load balancing (FLB), voltage profile improvement (VPI), and compromise strategies providing trade-offs among them. The response curves of these control strategies were developed through offline studies, where a multi-objective Particle Swarm Optimization (MOPSO) method was used. Assessments and comparisons between different control strategies were carried out. To evaluate the effectiveness of implementing MVDC link with the GT-based control method, case studies on a real distribution network were conducted.

This work has the following contributions: (1) proposing a novel real-time control method for MVDC link, namely the GT-based control method, which only requires communication links between the grid transformers and the controller of the MVDC link; (2) control strategies considering multiple objectives were developed and the network performance of these control strategies were compared; and (3) impacts of an MVDC link on the performances of distribution networks in terms of the capability of reducing losses and increasing the network's DG hosting capacity were investigated.

2. MVDC link in distribution networks

Fig. 1 shows a schematic diagram of an MVDC link connecting two distribution networks. The MVDC link is constructed via fully controllable power electronic converters. A voltage source converter (VSC) station is used for the conversion between AC and DC at each terminal of the MVDC link. The MVDC link allows for real power exchange between the two terminals as well as reactive power supports at both sides. The VSC can perform as the control of: (a) DC voltage V_{dc}; (b) active power P; (c) AC voltage V_{ac}; (d) reactive power Q and (e) AC

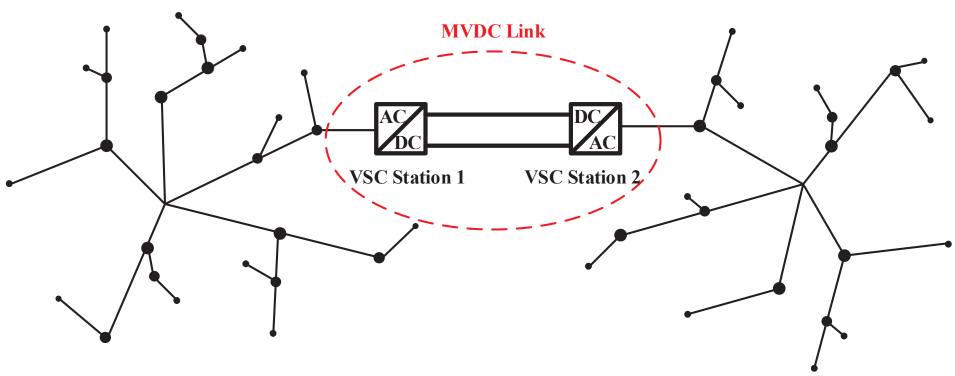

Fig. 1. An MVDC link between distribution networks.