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Loadability analysis of DC distribution systems

Ram Krishan[a,*], Ashu Verma[a], Sukumar Mishra[b]

[a] Centre for Energy Studies, Indian Institute of Technology Delhi, India
[b] Department of Electrical Engineering, Indian Institute of Technology Delhi, India

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ABSTRACT

DC distribution networks and micro grids are gaining importance enabling the integration of hybrid distributed generation, energy storage units, modern loads including electric vehicles and different micro grid topologies, thus permitting the consequent development of DC Distribution Systems (DCDS). For maximum utilization of distribution network without compromising the security and reliability of the supply system, determination of critical loading is crucial. With this objective, this paper proposes a modified DC continuation power flow based approach for determining the loadability limit of the active DCDS. DC-DC converters play an important role in bus voltage regulation and system loadability. Impact of these converters must be accounted in any analysis and planning of active DCDS. In this paper, two different mathematical models of lossless DC-DC converters are developed to account them in power flow model of the system. The proposed approach can be applied to both radial and meshed DCDS. Impacts of integration of converters in the system are illustrated by results of two realistic DCDS and results are compared with the corresponding AC Distribution Systems (ACDS).

1. Introduction

Increasing demand for electricity and exhaustion of conventional sources are the impetus to design and develop the distributed generation (DG) towards the maximum utilization of existing power system infrastructure. DG systems are found to be an effective solution to meet electricity demand within the transfer limits of the transmission line [1]. Most of the DG systems and alternative sources are prevailingly DC (Direct Current), whereas; existing power distribution system is AC. Therefore, number of power electronic converters are needed to integrate the DGs into existing power systems, which lead more AC/DC conversion steps and additional power losses. This problem can be mitigated by power transfer through DC network which may converted from legacy AC power system. In order to minimize the complexity and maximize the system efficiency, DCDS has received great attention. Small-scale DGs such as solar photovoltaics, wind, fuel cell, and energy storage devices can be easily integrated into distribution network [2]. Also, many loads are supplied by DC, particularly in residential, hospital, data servers, administrative, and commercial areas. These DC applications and development in DC distributed generations (DCDG) in power system have witnessed increasing interest in the concept of 'Direct DC'. In the recent years, DC distribution/micro grid system has emerged as a most economical and promising solution to meet the future network requirements to transfer the increasing energy demand at customer end [3–5]. In [6], a case study has been carried out to evaluate the possibilities and merits of the DC distribution system in terms of resilient and economic operations in steady state.

For development and operation of DCDS, analysis of steady-state behavior of the system is very important. In the power system analysis, load flow and Continuation Power Flow (CPF) are the essential tools. In the early 1960s, with advent of digital computers, different methods of load flow algorithms have been developed to solve AC transmission systems. Over the decades, various power flow approaches with different power flow models and numerical methods are published. Recently, different approaches of the load flow analysis have been developed for different power systems as LV (Low Voltage), HV (High Voltage) and hybrid AC/DC systems [7,8]. In [8], sequential AC/DC power flow algorithms have been presented for different applications. An NR based method has been used for DC network in the LV/HV hybrid AC/DC power systems. DC networks in the hybrid system are solved sequentially or simultaneously using conventional load flow method. In [9,10], many efforts have been made for High Voltage Direct Current (HVDC) transmission system development. In an HVDC system several converters are connected to operate in different modes, DC voltage regulator mode and power dispatcher mode, in a way to maintain the power balance in DC network [11,12]. A control methodology of the converter is discussed in [13] to provide the high quality of power supply service in the DCDS accompanied by distributed generation. Similarly, In the near future consideration of impacts of power electronics converters into the power system analysis is essential for the

* Corresponding author.
E-mail addresses: ramkrishan.iitd@gmail.com (R. Krishan), averma@ces.iitd.ac.in (A. Verma), sukumar@ee.iitd.ac.in (S. Mishra).

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Nomenclature

Δ	symbol of small change in values
I_{di}	current injection at ith node
J^{DC}	Jacobian matrix of DC load flow
K	number of power controlled nodes
$\mathscr{L}$	set of lines
λ	loading factor
m	number of nodes
M	input/output voltage ratio
P_{di}	power injection at ith node
P_G	generator power
P_{load}	active load
$\mathfrak{R}$	set of nodes
V_{di}	DC voltage at ith node
V_S	pre-specified voltage
Y	admittance matrix
Z	line impedance

successful and reliable operation of DC power system [14,15].

DCDS has appeared as the effective solution to the power distribution and other environmental challenges. Like HVDC system, DCDS accompanied by DC distributed generations may play a vital role in reliable power supply to the load. In order to harness the full benefit of DC Distributed Renewable Resources (DCDRR) there is a requirement of mathematical/software tool to manage the operation and control of the system. The basic idea of steady-state analysis of DC power system has been presented in [16]. With increase in the load demand and renewable integration, some DCDS has experienced the issue of power flow over the lines and loading capability of the system. Modern power electronic controller is used to solve these issues at the cost of network complexity [17]. Different topologies of these devices are used for different applications depends on various factors, including power rating, voltage ratio, need of galvanic separation, power flow control capability etc. in DC power system [18]. The transfer capability of DC system has been discussed without consideration of converters connected in the system [4]. A converter model in DC load flow analysis has been proposed in [19]. A mathematical modeling and stability analysis of DC micro grid system (DCMG) has been discussed in the [20] where sliding mode control of DC converters is used for voltage stability of the system. This mathematical model has not included the converters and cannot be useful for the power flow analysis. Whereas, Zhao et al. have advocated that power loss of converters integrated into DC system must be accounted in the steady-state analysis [21]. However, voltage and control limits of the converters are not discussed much. In [22–24], sequential CPF approach has been proposed for evaluation of available transfer capability (ATC) of AC/DC systems. In the modified CPF [23], impact of control variables of modern lossless converters is ignored. As per the author's knowledge, impact of the DC-DC converters in DC power flow analysis have been less or not been tailored to that extent. Also, its application in loadability analysis of DCDS with detailed DC-DC converter model is not attempted so far.

In this paper, mathematical models of DC-DC converters are proposed and used in the formulation of modified continuation power flow for steady-state analysis of DCDS (DCCPF). Proposed lossless models of the converters can offer an easy way to introduce the converter impacts into steady-state analysis of the power system through modified impedance or Jacobian matrix. In this model of converter, impacts of control strategies of converters may also be considered. The main contributions of the approach proposed in this paper are as follows-

- Lossless modeling and formulation of DC-DC converters for steady-state analysis of DCDS.
- Application and investigation of loading capability of the DC power system having DC-DC converters using modified DCCPF have been carried out.

The remaining sections of this paper are organized as follows: Section 2, describes the DC distribution system and DC power flow modeling in brief. Detailed converter modeling and its integration into DC power flow are presented in Section 3. The modified algorithm of DC continuation power flow is given in Section 4. Results and discussions for different distribution systems are reported in Section 5. Effectiveness and benefits of DC power supply are also discussed in Section 5. Finally, conclusions of the paper are presented in Section 6.

2. DC power flow modeling

2.1. DC distribution system model

A DCDS can be represented by an interconnected resistive network and generally have four types of DC terminals: generation, load, energy storage system and grid connection using power electronic converters as shown in Fig. 1. The structure of DCDS or DCMG can be either a radial or a meshed network. In the system, AC and DC loads are integrated through the converters as shown in the Fig. 1. In this work, both AC and DC types of loads, looking from the grid are considered as DC loads. However, different types of loads can be accounted in the proposed approach as in [23]. Unlike the AC system, DC power system has only two bus types (voltage controlled and power controlled bus) with two unknowns as given in Table 1. In DCDS, the slack bus is a voltage controlled bus. If DC power system has m nodes, index the swing bus by 1 and other buses by 2 to m. Let $\mathfrak{R}: = \{1,\dots m\}$ denote the collection of all nodes. Collection of all lines represented by $\mathscr{L}$. Line(s) between jth and kth nodes can be represented by $\{j, k\} \in \mathscr{L}$. Voltage, current and power injections at the ith node are abbreviated as V_{di}, I_{di}, and P_{di}, respectively. Line current and conductance between nodes $j \sim k$ is denoted by I_{jk} and $Y_{djk} := 1/R_{jk}$, where R_{jk} is line resistance between nodes $j \sim k$. It should be noted that for a DC power system, V, I, P, Y, and R are all real values. Later on, these variables are used without subscripts to denote a vector.

Current injection I_{di} at node i is equal to the algebraic sum of the current flowing to the other $m-1$ nodes in the system. It can be

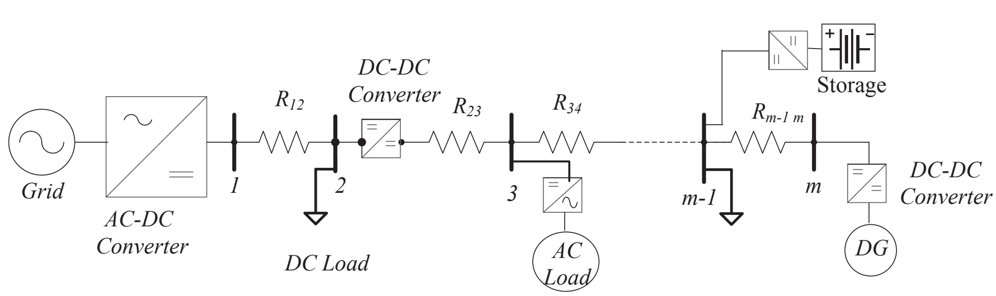

Fig. 1. DCDS with loads and generation.