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Decoupled Sequential Power Flow Study in MT-MVDC Distribution Systems based on Novel NR/Estimation-Correction Algorithm

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Abstract*—In order to address the gap in comprehensive power flow (PF) analysis of multi-terminal medium-voltage direct current (MT-MVDC) distribution systems, this paper proposes a novel decoupled sequential PF algorithm based on Newton-Raphson (NR)/estimation-correction method. The presented algorithm is designed for an MT-MVDC distribution network and takes into account the PF equations of both generic ac/dc and dc/dc converters. The MVDC PF study is the main focus and the power losses of voltage source converters (VSCs) & dc/dc converters are considered for accurately deriving the dc powers at MVDC links. The proposed algorithm only requires to define a single dc power or current bus type, hence the bus type definition is simplified and the solution of multiple sub-Jacobian matrices can be avoided. A binary search method is employed to correct the estimated initial dc power/current values, which contributes to the searching time reduction. Although an external correction iteration is required in the dc PF derivation, the proposed algorithm still improves on the computation efficiency in comparison with coupled sequential ac/dc PF algorithms. An MT-MVDC distribution network incorporated into IEEE 14 bus system verifies the validity and efficiency of the proposed algorithm.

***Index Terms*—Multi-terminal medium-voltage direct current (MT-MVDC) system, voltage source converter (VSC), dc/dc converters power flow (PF).**

I. INTRODUCTION

The performance of direct current (DC) power systems can be superior to equivalent alternating current (AC) systems in many applications, such as long distance high-voltage (HV) power transmission [1] and low-voltage (LV) microgrids [2]. A future power system will see the co-existence of alternating current (AC) distribution and transmission networks in parallel with dc systems at different voltage levels. Medium-voltage dc (MVDC) (i.e., systems with dc voltage typically between ±0.75 kV to ±50 kV [3]) outperforms the equivalent ac in sub-transmission, distribution and collection grids, since the MVDC can offer *i*) improved power supply reliability/stability, *ii*) enhanced power supply capacity, *iii*) higher power quality, *iv*) greater power transmission/conversion efficiency, and *v*) more efficient corridor utilisation [4].

MVDC is expected to play a significant role in distribution networks for enhancing power supply quality, reliability, stability, and facilitating the access of devices with dc interfaces [3]. In future fully functional MVDC distribution systems, ac/dc and dc/dc converters are indispensable components that can establish connections from facilities with ac to dc interfaces [4]. Voltage source converters (VSCs) would be the dominant ac/dc converters due to the independent active/reactive power control capability and possible power delivery ability under weak grids [5]. Isolated dc/dc converters, such as dual active bridge (DAB)-based dc/dc converters and extended modular multilevel structures, provide galvanic separation allowing different grounding schemes between the MVDC systems and connected dc facilities [6]. In addition, MV terminals in the ac/dc and dc/dc converters can be interconnected in different ways to construct multiterminal MVDC (MT-MVDC) systems [3].

In order to determine the steady-state operation characteristics of MVDC networks and benefit system planning/designing for future expansions, it is necessary to conduct detailed power flow (PF) analysis. PF algorithms in HVDC transmission systems can be generally divided into unified and sequential methods that the ac and dc PF are solved together and alternatively [7], [8]. Such methods can also be used in MVDC distribution systems. Although the sequential method shows relatively poor convergence compared to the unified method, it offers reduced programming complexity since arbitrary dc PF algorithms can be coded into existing ac PF programs [7]. In addition, conventional Newton-Raphson (NR) method is efficient and effective for the ac and dc PF analysis in ac transmission systems, but it is not suitable for typical ac distribution networks with radial structure, due to high resistance to reactance ratio on lines and unbalanced ac systems [9]. However, conventional NR method can still be applied in the dc PF study of MT-MVDC systems, since only line resistance needs to be considered and typically there are only two poles in dc networks.

Unlike dc PF studies in HVDC transmission systems, dc/dc converters for dc link with different voltage levels would be incorporated in the MVDC distribution networks. In addition, distributed generators (DGs), energy storage systems (ESSs), and ac & dc loads, can also be present. Nevertheless, no specific PF analysis for MVDC distribution systems has been conducted in the current literature, while PF analysis for dc microgrids with limited scale is studied in detail [10]–[13]. In addition, different types of dc buses except the dc slack bus are predefined in current dc PF analysis for HVDC systems and dc microgrids, which complicates the bus type definition and multiple sub-Jacobian matrices have to be established. Such definition is attributed to different control modes (constant power/current or droop control) of converters.

This paper explores the PF for MVDC distribution systems considering the PF equations of VSCs and dc/dc converters. Multi-initial dc power and/or current values are known in VSCs and dc/dc converters with constant dc power, current and droop control modes. It should be noted that P/V or I/V droop bus for droop-controlled converters [14] can be respectively regarded as dc power or current bus, owing to the similarity of Jacobian matrices [15]–[17]. In order to simplify the bus type definition and avoid the solution of multiple sub-Jacobian matrices, a novel NR/estimation-correction algorithm is proposed to solve the dc PF. Only one type of dc bus (dc power or dc current) and one general Jacobian matrix needs to be defined and solved in the dc PF analysis, respectively. Moreover, binary search method is used to reduce the time complexity in the parameter correction process [18].

For the complete ac and dc PF, a decoupled sequential PF method is adopted in this paper that the ac PF is executed if the dc PF is convergent [14], [19]. Although there are additional external iterations of dc PF in the proposed algorithm, the computation speed of the proposed algorithm is still acceptable due to the limited scale of MVDC network compared to linked ac networks. In addition, the total ac PF iterations of the decoupled PF method are less than the conventional coupled one [7], hence the proposed algorithm shows better computational efficiency than the coupled method. A modified IEEE 14 bus system incorporating an MT-MVDC system is used to study the validity and efficiency of proposed NR/estimation-correction PF algorithm.

II. CONVERTER MODELING

In order to discuss the detailed PF analysis considering ac and MVDC networks, the modeling of generic VSCs and dc/dc converters will be first explored in this section.

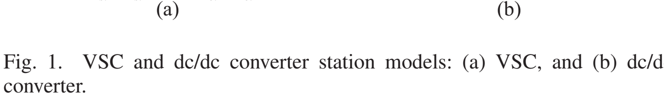

Fig. 1. VSC and dc/dc converter station models: (a) VSC, and (b) dc/dc converter.

A. VSC Station

Fig. 1(a) shows the VSC station model including ac system bus s, converter bus c and MVDC link m. The equivalent impedance of ac transformer and phase reactor between bus s and c is $R_{ei}+jX_{ei}$. The generalized converter loss derivation method for VSC-based HVDC systems can also be used in MVDC networks as:

$$P_{loss,ci}=\mathcal{A}_{1,ci}+\mathcal{A}_{2,ci}\cdot|I_{ci}|+\mathcal{A}_{3,ci}\cdot|I_{ci}|^2\,, \tag{1}$$

where $\mathcal{A}_{1,ci}$, $\mathcal{A}_{2,ci}$, $\mathcal{A}_{3,ci}$ represent the coefficients of no-load, linear, quadratic losses [7], and I_{ci} is the converter ac current which is calculated as:

$$I_{ci}=\sqrt{(P_{ci}^2+Q_{ci}^2)/V_{ci}^2}=\sqrt{(P_{si}^2+Q_{si}^2)/V_{si}^2}, \tag{2}$$

where P_{si}, Q_{si} and P_{ci}, Q_{ci} are the active power and reactive powers at bus s and bus c, respectively, V_{si} and V_{ci} refer to the corresponding ac voltages at bus s and bus c. Furthermore, the active power injected into the VSC is:

$$P_{ci}=P_{dcm,i}+P_{loss,ci}=V_{dcm,i}I_{dcm,i}+P_{loss,ci}, \tag{3}$$

where $V_{dcm,i}$ and $I_{dcm,i}$ are the MVDC system dc voltage and dc current at the dc-link, respectively. Moreover, the active power at the VSC bus can also be represented as:

$$P_{ci}=P_{si}-R_{ei}\cdot(P_{si}^2+Q_{si}^2)/V_{si}^2, \tag{4}$$

and the reactive power can be written as:

$$Q_{ci}=Q_{si}-X_{ei}\cdot(P_{si}^2+Q_{si}^2)/V_{si}^2. \tag{5}$$

A VSC in an MVDC system can control independently its active and reactive power. The active power control can be modeled into the control of *i*) ac active power, *ii*) dc power, *iii*) dc current and *iv*) dc voltage, while *i*) constant reactive power control or *ii*) constant ac voltage control can be realized in the reactive power control function [20].

B. DC/DC Converter Station

Dc/dc converters in an MVDC network can achieve dc voltage level change facilitating the access of different devices with dc interfaces, such as dc loads, PVs, ESSs. A simplified dc/dc converter station model is used as shown in Fig. 1(b). The dc powers in medium voltage sides (P_{dcm}) are expressed as (6), and the equivalent converter losses can be represented as (7).

$$P_{dcm,k}=V_{dcm,k}I_{dcm,k}=P_{dcl,k}+P_{lossm,k}, \tag{6}$$

$$P_{lossm,k}=R_{lossm,k}\cdot I_{dcm,k}^2=R_{lossm,k}\cdot(\frac{I_{dcl,k}}{\alpha})^2, \tag{7}$$

where $R_{lossm,k}$ refers to the equivalent dc/dc converter resistance, and α is the ratio of transformation.

Similar to the control modes in VSCs, dc current/power and dc voltage control can be adopted in the dc/dc converters to regulate the forward/reverse power and the dc voltage, respectively [10], [21].

III. PROPOSED POWER FLOW ALGORITHM FOR MT-MVDC NETWORKS

In the proposed MVDC network PF algorithm, the ac PF is solved after obtaining the MVDC PF by a sequential method. Single dc current or power bus type is employed by assuming the type of dc power or current bus to be dc current or power bus, respectively. The additional P/V and I/V droop buses [14] are respectively regarded as dc power or current bus, due to the similar Jacobian matrix expression.

A. DC Power Flow in MT-MVDC Networks

When the dc current at the LV side of a dc/dc converter is a known value, the dc current at the MV side can be derived by the ratio of transformation ($I_{dcm,k} = I_{dcl,k}/\alpha$). However, the dc power at the MV side of the dc/dc converters cannot be obtained directly under the LV side dc power control if the dc/dc converter losses cannot be ignored. Therefore, the dc power at the MV side is first assumed to be the corresponding power at the LV side as:

$$P_{dcm,k(0)} = P_{dcl,k}, \tag{8}$$

where subscript (0) refers to the initial values of corresponding MVDC buses in the dc PF calculation.

One dc voltage (the first VSC is assumed to operate as slack bus), f dc powers and g dc currents are known values to initialize the MVDC PF. The MVDC PF can be solved by conventional NR method, obtaining $n-1$ dc voltages [14]. If $f = 0$ $(g = n-1)$, the dc power injected to dc buses with one known dc voltage and $n-1$ known dc powers can be expressed as:

$$\begin{cases} P_{dcm,1} = V_{dcm,1} \sum\limits_{j=1}^{n} G_{dcm_{1j}} V_{dcm,j}, \\ P_{dcm,i} = V_{dcm,i} \sum\limits_{j=1}^{n} G_{dcm_{ij}} V_{dcm,j} \quad (i = 2, 3, ..., n), \end{cases} \tag{9}$$

where $V_{dcm,1}$ is dc bus voltage with known dc voltage, $V_{dcm,i}$ is dc bus voltages with known dc powers, and $G_{dcm_{ij}}$ is line conductance. Moreover, (10) can be obtained from (9).

$$\Delta P_{dcm,i} = P_{dcm,i} - V_{dcm,i} \sum_{j=1}^{n} G_{dcm_{ij}} V_{dcm,j} = 0 \tag{10}$$

Therefore, the mismatch equations building the relationship between $\boldsymbol{\Delta P_{dcm}}$ and $\boldsymbol{\Delta V_{dcm}}$ are presented as:

$$\boldsymbol{\Delta P_{dcm}} = \boldsymbol{J^{P}_{dcm}} \boldsymbol{\Delta V_{dcm}}, \tag{11}$$

where

$$\boldsymbol{J_{dcm}} = -\frac{\partial \boldsymbol{\Delta P_{dcm}}}{\partial \boldsymbol{V_{dcm}}} = \text{diag}(\boldsymbol{V_{dcm}})\boldsymbol{G_{dcm}} + \text{diag}(\boldsymbol{G_{dcm}} \boldsymbol{V_{dcm}}). \tag{12}$$

If $f = 0$ $(g = n-1)$, the dc current injected to dc buses with one known dc voltage and $n-1$ known dc currents can be expressed as (13).

$$\begin{cases} I_{dcm,1} = \sum\limits_{j=1}^{n} G_{dcm_{1j}} V_{dcm,j} \\ I_{dcm,i} = \sum\limits_{j=1}^{n} G_{dcm_{ij}} V_{dcm,j} \quad (i = 2, 3, ..., n) \end{cases} \tag{13}$$

The relationship between $\boldsymbol{\Delta I_{dcm}}$ and $\boldsymbol{\Delta V_{dcm}}$ can be established by mismatch equations (15) based on (13) and (14).

$$\Delta I_{dcm,i} = I_{dcm,i} - \sum_{j=1}^{n} G_{dcm_{ij}} V_{dcm,j} = 0 \tag{14}$$

$$\boldsymbol{\Delta I_{dcm}} = \boldsymbol{J^{I}_{dcm}} \boldsymbol{\Delta V_{dcm}} = \boldsymbol{G_{dcm}} \boldsymbol{\Delta V_{dcm}}. \tag{15}$$

In the case that $f \neq 0$ and $g \neq 0$, it is necessary to define two types of buses (dc power and current buses) in conventional dc PF solving algorithm, and multiple sub-Jacobian matrices have to be constructed and solved [14]. In order to avoid the definition of different types of buses and solution of multiple Jacobian matrices, a single bus-based NR/estimation-correction algorithm is proposed to solve the dc PF with initial condition of dc voltage, powers and currents.

The dc power or dc current for converter w with known dc current or dc power is estimated as (16) and (17), respectively when a single dc power or current bus is used.

$$P^{est}_{dcm,w} = V_{dcm,rated} I^{pre}_{dcm,w}, \tag{16}$$

$$I^{est}_{dcm,w} = \frac{P^{pre}_{dcm,w}}{V_{dcm,rated}}, \tag{17}$$

where $I^{pre}_{dcm,w}$ and $P^{pre}_{dcm,w}$ are the pre-specified dc current and dc power values for certain VSCs and dc/dc converters. This is stage 1 (power/current estimation) in the proposed algorithm. In the following stage (stage 2), correction iterations are conducted since there is a dc power or dc current deviation ($\Delta P^{cor}_{dcm,w}$, $\Delta I^{cor}_{dcm,w}$) between the estimated and actual dc power or dc current w. Hence, the actual dc power or dc current can be expressed as:

$$P^{act}_{dcm,w} = P^{est}_{dcm,w} + \Delta P^{cor}_{dcm,w}, \text{ or} \tag{18}$$

$$I^{act}_{dcm,w} = I^{est}_{dcm,w} + \Delta I^{cor}_{dcm,w}. \tag{19}$$

In the correction iteration process, a binary search method is employed to obtain the accurate dc power or current value. The binary search method can reduce the number of total correction iterations compared to linear search approach due to its logarithmic time complexity ($O(\log_2 \mathcal{N})$, $\mathcal{N}$ is input size) in the worst case. Moreover, the best-case performance is $O(1)$ [18], which indicates the accurate value can be found by executing only one search. The searching range can be obtained by the maximum allowable dc power/current deviation for the terminal w with initial dc current or dc power, which is determined by the dc voltage deviation δ_V. Thus, the left and right margins for MV terminals with known dc currents are:

$$\begin{cases} \mathcal{L}_{\Delta P_m} = -V_{dcm,rated} \delta_V I^{pre}_{dcm,w} \\ \mathcal{R}_{\Delta P_m} = V_{dcm,rated} \delta_V I^{pre}_{dcm,w}, \end{cases} \tag{20}$$

the left and right margins for terminals with known dc powers should be:

$$\begin{cases} \mathcal{L}_{\Delta I_m} = \dfrac{-P^{pre}_{dcm,w} \delta_V}{V_{dcm,rated}(1+\delta_V)} \\ \mathcal{R}_{\Delta I_m} = \dfrac{P^{pre}_{dcm,w} \delta_V}{V_{dcm,rated}(1-\delta_V)}. \end{cases} \tag{21}$$

The accurate dc powers or dc currents for certain VSCs and dc/dc converters with known dc currents or dc powers can be derived by setting the known dc currents or dc powers as iteration target ($I_{dcm,w}^{pre} = I_{dcm,w}^{tar}$, $P_{dcm,w}^{pre} = P_{dcm,w}^{tar}$). If the deviation between the target and obtained dc currents (dc powers) is acceptable as (22) and (23), the corresponding dc powers or dc currents in (9) or (13) will be substituted by the corrected values. In addition, different shortest path search algorithms, such as A* with heuristic search guide [22], can be used to first correct the dc power/current that close to the target value for accelerating the searching speed when multiple current or power values require to be corrected.

$$\left|I_{dcm,w}^{tar} - P_{dcm,w}^{act}/V_{dcm,w}^{act}\right| < \varepsilon_i \tag{22}$$

$$\left|P_{dcm,w}^{tar} - I_{dcm,w}^{act}V_{dcm,w}^{act}\right| < \varepsilon_p \tag{23}$$

The current dc power deviation at secondary dc buses of dc/dc converters is calculated as:

$$\Delta P_{dcl,k(0)} = P_{dcm,k(0)} - P_{lossm,k(0)} - P_{dcl,k(0)}, \tag{24}$$

then the $\Delta P_{dcl,k(0)}$ is added into $P_{dcm,k(0)}$ as (25) to update the dc power values at MVDC buses.

$$P_{dcm,k(1)} = P_{dcm,k(0)} + \Delta P_{dcl,k(0)} \tag{25}$$

The dc PF is finally solved when $\Delta P_{dcl,k}$ is in the scope of acceptance after few iterations as:

$$\begin{cases} \Delta P_{dcl,k(n)} = P_{dcm,k(n)} - P_{lossm,k(n)} - P_{dcl,k(n)} \\ P_{dcm,k(n+1)} = P_{dcm,k(n)} + \Delta P_{dcl,k(n)}. \end{cases} \tag{26}$$

Following the algorithm flowchart in the green box of Fig. 2, the dc PF for MT-MVDC systems is finally solved.

B. External AC Grid Power Flow

In the proposed PF algorithm, the ac grid PF is obtained after the convergence of MVDC PF, since the ac grid PF is independent of the PF in the dc side.

The active/reactive power equations in ac buses are respectively expressed as:

$$\begin{cases} P_{ge,i} - P_{lo,i} - \xi P_{si} - V_i \sum_{j=1}^{n} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \\ Q_{ge,i} - Q_{lo,i} - \xi Q_{si} - V_i \sum_{j=1}^{n} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0, \end{cases} \tag{27}$$

where $P_{ge,i}$ and $Q_{ge,i}$ are active and reactive powers of generators at ac bus i, $P_{lo,i}$ and $Q_{lo,i}$ are active and reactive powers of loads at ac bus i, $\xi = 1$ and $\xi = 0$ refer to the ac buses with and without connection of VSCs, respectively.

In the ac PF derivation process, the injected active/reactive powers (P_{si}, Q_{si}) from MVDC networks at the ac bus should be acquired first. The reactive powers Q_{si} can be obtained directly when the VSCs adopt constant Q_{si} control, or adapts the reactive power output by a constant ac voltage (V_{si}) control mode [20]. However, the active power P_{si} cannot be directly obtained, because constant dc power/current (P_{dci} or I_{dci}) is adopted for the d-axis control of VSCs except the VSC with dc voltage control. Therefore, the ac PF can be obtained if the accurate values of P_{si} in all VSC-connected ac buses are acquired.

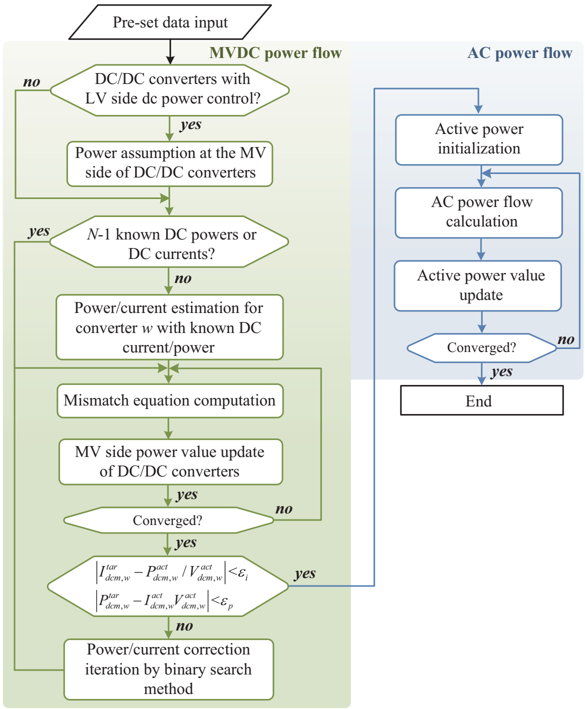

Fig. 2. Flowchart of proposed NR/estimation-correction PF algorithm.

Inheriting from the ac PF derivation method in [19], the ac grid PF is computed first, then the VSC power losses are obtained from the up-to-date ac PF. In order to decouple the ac and dc PF and obtain the accurate P_{si}, the initial ac active power is first assumed to be the corresponding dc power, and the dc power deviation ΔP_{dci} is used to check whether the dc power deviation is within acceptable error as (28) after the ac PF calculation.

$$\Delta P_{dci} = P_{si} - R_{ei} \cdot (P_{si}^2 + Q_{si}^2)/V_{si}^2 - P_{loss,ci} - P_{dci} \tag{28}$$

First, the injected active powers are assumed to be the corresponding dc powers as:

$$P_{si(0')} = P_{dci}, \tag{29}$$

where subscript $(0')$ refers to the initial value for the ac PF initialization. If the obtained $\left|\Delta P_{dci(n')}\right|$ is larger than the acceptable error, the $\Delta P_{dci(n')}$ is then added into $P_{si(n')}$ as:

$$P_{si(n'+1)} = P_{si(n')} + \Delta P_{dci(n')}, \tag{30}$$

correcting the value of injected active power $P_{si(n'+1)}$ in the ac PF.

IV. CASE STUDY

Fig. 3 shows an MT-MVDC distribution system with ±10 kV rated dc voltage incorporated into the IEEE 14 bus test system. In the MT-MVDC distribution system, VSCs and dc/dc converters are included for connecting DGs, ac/dc loads and external ac systems. Moreover, switching stations, commonly used in distribution networks, are also considered to link two terminals through inner tie switches, which are open under normal operation [23]. Two cases are simulated and implemented in Python with an Intel Core i7-10700 CPU @ 2.90GHz, 16.0GB of RAM and a 64-bit Windows 10 operating system. The initial condition of all converters under two cases are listed in Table I and Table II. In case 1, the initial condition is one dc voltage (converter 1), one dc power (converter 2) and five dc currents (converters 3-7), while there are two known dc currents and four known dc powers in case 2.

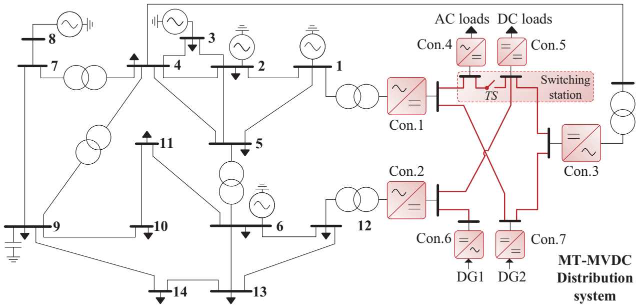

Fig. 3. Modified IEEE 14 bus system incorporating an MT-MVDC system.

TABLE I
INITIAL CONDITION OF ALL CONVERTERS IN THE MT-MVDC DISTRIBUTION SYSTEM UNDER CASE 1.

Converter	1^a	2^a	3^a	4^a	5^b	6^a	7^b
P_{dc} (MW)	-	10	-	-	-	-	-
I_{dc} (kA)	-	-	-0.5	-0.5	-0.5	0.25	0.2
V_{dc} (kV)	20	-	-	-	-	-	-

^{a}: VSCs, ^{b}: dc/dc converters.

TABLE II
INITIAL CONDITION OF ALL CONVERTERS IN THE MT-MVDC DISTRIBUTION SYSTEM UNDER CASE 2.

Converter	1^a	2^a	3^a	4^a	5^b	6^a	7^b
P_{dc} (MW)	-	-	-10	-10	-10^*	-	4
I_{dc} (kA)	-	0.5	-	-	-	0.25	-
V_{dc} (kV)	20	-	-	-	-	-	-

^{a}: VSCs, ^{b}: dc/dc converters, *: dc power at the LV side.

A. Case 1: Correction of Single Variable

In this case, the dc current in converter 2 is unknown which requires to be estimated and corrected in the dc PF study. The dc current in converter 2 is first estimated as 0.5 kA, then the accurate value can be found if $|10-V_{dcm,2}^{act}(0.5+\Delta I_{dcm,2}^{cor})|<\varepsilon_p$ ($\varepsilon = 10^{-5}$ in this paper). Moreover, the searching range in the binary search method is from -0.046 kA ($\mathcal{L}_{\Delta I_m}$) to 0.056 kA ($\mathcal{R}_{\Delta I_m}$) when the allowable dc voltage deviation δ_V is 0.1.

There are in total six external correction iterations in the searching process and two inner iterations of conventional NR method in each external iteration for the dc PF calculation. Although the additional external iterations result in long computation time in the dc PF, the proposed algorithm avoids the construction of 4 sub-Jacobian matrices in [14], and the whole computation time (268.1 ms) including the ac and dc PF is less than the coupled sequential method (522.6 ms) [7].

B. Case 2: Correction of Multi-variables

There are two unknown variables (dc powers) in converters 2 and 6 under case 2 that need to be obtained from the estimation-correction algorithm. The dc powers in converters 2 and 6 are first estimated as 10 MW and 5 MW, respectively. With the pre-defined searching ranges ([-1 MW, 1 MW] for converter 2, [-0.5 MW, 0.5 MW] for converter 6) and iteration targets based on (20) and (22), the accurate dc power values can be found. In addition, the dc power at the MVDC bus of converter 5 should be calculated based on the known dc power value at the LVDC bus (-10 MW) and equivalent dc/dc converter resistance (set as 0.1 Ω). It is noted that the A* shortest path search approach is used to accelerate the searching speed that the dc power in converter 2 or 6 close to the target value (0.5 kA for converter 2, 0.25 kA for converter 6) is selected to be first corrected. The conventional decoupled sequential method requires to establish 16 sub-Jacobian matrices for solving dc PF in this case. However, only one Jacobian matrix (12) is constructed in the proposed algorithm, although there are 12 external correction iterations.

The detailed dc PF results under the two cases with the conventional decoupled and proposed NR/estimation-correction algorithms are listed in Table III demonstrating the validity of proposed algorithm. Moreover, the algorithm efficiency comparison in Table IV shows the proposed algorithm is more efficient than the sequential coupled ac/dc PF algorithm, although more computation time in the MVDC PF solving is required compared to the conventional decoupled ac/dc PF method.

TABLE III
DC PF RESULT COMPARISON UNDER TWO CASES.

Converter		1	2	3	4	5	6	7
P_{dc} (MW)	C1^1	11.47	10.00	-9.78	-9.75	-9.91	5.31	3.98
	C1^2	11.47	10.00	-9.78	-9.75	-9.91	5.31	3.98
	C2^1	11.55	10.54	-10.00	-10.00	-10.03	5.33	5.00
	C2^2	11.55	10.54	-10.00	-10.00	-10.03	5.33	5.00
I_{dc} (kA)	C1^1	0.57	0.48	-0.50	-0.50	-0.50	0.25	0.2
	C1^2	0.57	0.48	-0.50	-0.50	-0.50	0.25	0.2
	C2^1	0.58	0.50	-0.51	-0.51	-0.50	0.25	0.20
	C2^2	0.58	0.50	-0.51	-0.51	-0.50	0.25	0.20
V_{dc} (kV)	C1^1	20.00	20.99	19.55	19.50	19.83	21.24	19.88
	C1^2	20.00	20.99	19.55	19.50	19.83	21.24	19.88
	C2^1	20.00	21.07	19.58	19.49	19.87	21.32	19.90
	C2^2	20.00	21.07	19.58	19.49	19.87	21.32	19.90

^{1}: conventional decoupled sequential PF algorithm
^{2}: proposed NR/estimation-correction algorithm

TABLE IV
ALGORITHM EFFICIENCY COMPARISON.

Methods		Iterations (DC)	Iterations (AC)	Time (ms)
Conven. coupled	C1	9	13	522.6
	C2	9	13	522.6
Conven. decoupled	C1	4	4	260.8
	C2	4	4	260.8
Proposed	C1	2×6	4	268.1
	C2	4×12	4	367.7

V. CONCLUSION AND DISCUSSION

The proposed NR/estimation-correction PF algorithm for MT-MVDC distribution systems mainly focuses on the dc PF derivation and takes the ac/dc & dc/dc converters into consideration. In the estimation and correction stages, binary search method is used to correct the initial dc power or current values based on the estimated values. Only single dc bus (power or current) type is required to be defined in the estimation-correction part, hence the solution of multiple Jacobian matrices can be avoided.

In addition, the novel algorithm inherits the decoupled sequential ac/dc PF method that the ac PF is computed after the convergence of dc PF. In the coupled sequential ac/dc PF approach [7], there are several overall ac and dc PF iterations since the ac PF is solved first and each update of dc slack bus power has to re-compute the ac and dc PF together. Hence, the total ac PF iterations of the proposed PF method are less than the coupled sequential ac/dc PF approach. The validity and efficiency of proposed algorithm is verified in a hybrid ac/MT-MVDC network simulated and implemented in Python.

It is noteworthy that the dc PF computation time only occupies a small proportion of overall calculation time in a large-scale grid incorporating ac and MVDC systems, owing to the limited size of MVDC networks in the current stage. Therefore, the computation speed of proposed algorithm is still acceptable in real project application, although there are additional external dc PF correction iterations.

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