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Analysis of Power Redispatch Schemes for HVDC Grid Secondary Voltage Control

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Abstract—In a droop-controlled High Voltage Direct Current (HVDC) grid, the line voltage drops throughout the system influence the voltage control. This paper introduces and compares five distinct methods for establishing droop setpoints in order to restore the voltage profile after a contingency and evaluates the ability of these methods to track the setpoints. Furthermore, the influence of the network and of the droop characteristics on the offsets is derived analytically. To ensure accurate setpoint tracking, the problem can be circumvented by redefining the redispatch as an optimization aiming at minimizing the changes in converter powers whilst achieving a predefined average system voltage. In order to avoid the need for solving the non-linear power flow problem, the voltage deviations from the post-contingency operation can also be scaled to obtain an approximate solution. Simulations on a 4-terminal meshed HVDC grid demonstrate the degree to which the different methods allow to track the setpoints.

Index Terms—HVDC transmission, Voltage control, VSC HVDC, Load flow analysis.

I. INTRODUCTION

In recent years, the power industry is showing an increased interest in High Voltage Direct Current (HVDC) grids based on Voltage Source Converter (VSC) technology.

Different schemes have been presented in literature to maintain a power balance in the system in case of a contingency [1]. The control scheme that has received most attention is based on a proportional feedback of the local DC voltage, the so-called voltage droop control [2]. In such a droop-controlled HVDC grid, the proportional droop control action results in an offset of the system voltage after a contingency. The initial primary control action in this case is a quasi-instantaneous control based on local measurements aiming at limiting the voltage rise or drop after a contingency. The objective of a slower secondary control is to bring the system back to pre-fault operating conditions, which is achieved by changing the controller setpoints [3]. Different methods have been presented to determine setpoints for this system-wide control [4]–[6]. However, the focus in previous work is usually on minimising system losses or restoring power exchanges after a contingency.

An objective of this secondary control, that has not received much research attention so far, is to restore the voltage profile by compensating for the offset caused by the proportional

droop action in order to bring that the overall system voltage profile back to the pre-contingency operating range [7]. A straightforward definition of the new setpoints, however, is hampered by the variations of the voltages throughout the network and normally a power flow calculation is required to guarantee setpoint tracking [8]. In [9], the interaction of the droop control objectives with voltage drops in the system was studied. In this paper, the analysis from [9] is taken a step further to study the more general case for interactions of the droop characteristics when setpoints are changed to control the system voltage after a contingency. Furthermore, five distinct redispatch methods are proposed to update the setpoints in order to compensate for the voltage offset caused by the proportional control action. Section II introduces a linearized model to predict the offsets caused by setpoint changes. Section III presents five redispatch schemes for secondary voltage control. Section IV discusses the ability of the different schemes to track powers and voltages in case all converters can change setpoints. Lastly, the performance degradation is investigated when one converter cannot change setpoints.

II. SETPOINT TRACKING WITH VOLTAGE DROOP CONTROL

In a power-based voltage droop control, the relation between the power and voltage at a droop-controlled bus is given by

$$P = P_0 - g \cdot (U - U_0), \quad (1)$$

with P the local DC power injection, U the local DC voltage, g the droop gain and ‘0’ denoting setpoints. For a constant power converter, a similar equation can be used with $g = 0$, whilst converters facing an outage imply that also $P_0 = 0$. With the equations of all converters written in this form,

$$P = P_0 - G \cdot (U - U_0), \quad (2)$$

for an n -bus system, with $G = \text{diag}[g]$ and g , P and $U \in \mathbb{R}^n$. In g , the elements $g_i \neq 0$ for the droop-controlled DC buses. The power flows in the DC system are governed by

$$I = YU, \quad (3)$$

$$P = U \odot I, \quad (4)$$

with $I \in \mathbb{R}^n$ the current injection vector and $\odot$ the Hadamard or element-wise matrix product. Two different approaches can be taken to linearize the system. Either the power flow

equations [8] or the converter characteristics [9] can be linearized. This paper takes the approach from [9], where the droop equation and constant power characteristics are linearized around the setpoints $U_0, I_0 \in \mathbb{R}^n$ with $I_0 = P_0/U_0$. Assuming an operation at these setpoints before the outage, the power-based droop and constant power buses are respectively linearized as

$$I \approx I_0 - \frac{1}{U_0} (g + I_0) (U - U_0), \quad (5)$$

$$I \approx I_0 - \frac{I_0}{U_0} (U - U_0). \quad (6)$$

It is clear that these linearized equations result in equivalent current-based droop characteristics

$$I \approx I_0 - g^* \cdot (U - U_0), \quad (7)$$

$$I \approx I_0 - l \cdot (U - U_0), \quad (8)$$

with

$$g^* = \frac{1}{U_0} (g + I_0), \quad (9)$$

$$l = \frac{I_0}{U_0}. \quad (10)$$

Defining vectors with the deviation from the setpoints after the outage as $\Delta U = U - U_0$, $\Delta I = I - I_0$ and $\Delta P = P - P_0$, the droop-controlled and constant power buses from (5)–(6) can, in analogy to the original power-based droop equation, be approximated as a current-based characteristic

$$\Delta I = -G^* \Delta U, \quad (11)$$

$$\Delta I = -L \Delta U, \quad (12)$$

with $G^* = \text{diag}[g^*]$, $L = \text{diag}[l]$ and $g^*, l \in \mathbb{R}^n$. Either $G_{jj} = g_j^*$ in case of a droop-controlled bus or $L_{jj} = l_j$ in case of a constant voltage bus. Alternatively, a matrix G' can be defined

$$G' = G^* + L, \quad (13)$$

simplifying the linearized equations (11)–(12) to

$$\Delta I = -G' \Delta U, \quad (14)$$

thereby accounting for the effect of the droop controlled buses and the constant power buses.

In [9], this approach was used to analyze the power sharing after a contingency. This paper aims at addressing the setpoint tracking after a change of the references U_0, I_0 instead. We define a set of new setpoints as U_0^ν, P_0^ν (Fig. 1) and perform a new linearization of the system around these new setpoint values as

$$U^\nu = U_0^\nu + \Delta U^\nu, \quad (15)$$

$$P^\nu = P_0^\nu + \Delta P^\nu, \quad (16)$$

The corresponding current setpoint values are linearized

$$I^\nu = I_0^\nu + \Delta I^\nu, \quad (17)$$

and a new matrix G'^ν is defined such that

$$\Delta I^\nu = -G'^\nu \Delta U^\nu, \quad (18)$$

Fig. 1: Converter droop control setpoint redefinition.

also taking into account the new network state: i.e. $G'_{jj}^\nu = 0$ for a outage of converter j . The set U^ν, I^ν satisfies the power flow equations (3) or substituting from (15) and (17)

$$I_0^\nu + \Delta I^\nu = Y (U_0^\nu + \Delta U^\nu). \quad (19)$$

With the current deviations from the new setpoints ΔI^ν given by (18), the voltage deviations are now given by

$$\Delta U^\nu \approx \Delta U_{\text{lin}}^\nu = (Y + G'^\nu)^{-1} \cdot (I_0^\nu - Y U_0^\nu). \quad (20)$$

The subscript 'lin' has been used to indicate that these deviations are approximations based on a linear model. The corresponding current deviations are given by (18). The corresponding power variations are found using

$$P^\nu = (U_0^\nu + \Delta U^\nu) \odot (I_0^\nu + \Delta I^\nu), \quad (21)$$

$$\approx U_0^\nu \odot I_0^\nu + U_0^\nu \odot \Delta I_0^\nu + I_0^\nu \odot \Delta U_0^\nu. \quad (22)$$

With $P_0^\nu = U_0^\nu \odot I_0^\nu$, ΔI^ν from (18) and accounting for the diagonal structure of G'^ν , the expression are simplified to

$$\Delta P^\nu \approx \Delta P_{\text{lin}}^\nu = (I_0^\nu - G'^\nu U_0^\nu) \odot \Delta U_0^\nu, \quad (23)$$

resulting in the original droop equation (2) for the converters not facing an outage and a constant power for the power controlled converters. Equations (20) and (23) show that, in order to track the new setpoints perfectly (i.e. $\Delta U^\nu = 0$ and $\Delta P^\nu = 0$), these setpoints need to satisfy the power flow equations. In case this assumption does not hold, voltage and power deviations are influenced by the network structure, the droop values and the setpoints themselves.

III. VOLTAGE DROOP SETPOINT REDEFINITION

Let now $x = [P^T U^T]^T \in \mathbb{R}^{2n}$ describe the system state. Without a lack of generality, x_0 and x can reflect pre- and post-contingency operation. Let $\tilde{\Delta}_U = U - \tilde{U} \cdot \tilde{\mathbf{1}}_n$ with $\tilde{U}$ denoting the arithmetic mean voltage and $\tilde{\mathbf{1}}_n$ the ones vector with $\dim(\tilde{\mathbf{1}}_n) = n$.

A. Constant current setpoint change

Keeping DC current injections constant before and after the setpoint change and predefining a new mean system setpoint voltage $\tilde{U}_0^{*\nu}$, the new setpoints (Fig. 1) become

$$U_0^\nu = \tilde{U}_0^{*\nu} \cdot \tilde{\mathbf{1}}_n + \tilde{\Delta}_U, \quad (24)$$

$$P_0^\nu = U_0^\nu \odot (P \oslash U), \quad (25)$$

with $\odot$ the Hadamard or element-wise matrix division. Keeping converter currents constant at all buses, the new operation state $\mathbf{x}^\nu = [\mathbf{P}^{\nu T} \ \mathbf{U}^{\nu T}]^T \in \mathbb{R}^{2n}$ is exactly defined by the corresponding setpoints $\mathbf{x}_0^\nu$ since the setpoints satisfy the power flow equations by definition. Consequentially, $\tilde{U}^\nu = \tilde{U}_0^{\nu*}$ since the voltage profile can be arbitrarily shifted. However, the powers need to be updated accordingly, not necessarily resulting in the smallest power changes. Furthermore, setpoint tracking only holds exactly if all converters can change setpoints, implying that also the constant power converters should change their setpoints to guarantee tracking.

B. Constant power setpoint change

An approximation to the constant current setpoint change is to use post-contingency power injections as power setpoints, and to update the setpoints $\mathbf{x}_0^\nu$ according to

$$\mathbf{U}_0^\nu = \tilde{U}_0^{\nu*} \cdot \tilde{\mathbf{I}}_n + \tilde{\Delta}_U, \quad (26)$$

$$\mathbf{P}_0^\nu = \mathbf{P}. \quad (27)$$

By only shifting the voltage profile, one assumes that the change in system losses remains small and will not affect the converter powers much. However, this assumption results in an offset operation since the new setpoints $\mathbf{x}_0^\nu$ do not satisfy the DC system power flow equations.

C. Scaled voltage offset setpoint change

Alternatively, the power flow expressions can be reformulated analytically so that the power changes resulting from the setpoint redefinition can be minimized, whilst satisfying the power flow equations. The change in power injections before and after the setpoint redefinition is given by

$$\mathbf{P}^\nu - \mathbf{P} = \mathbf{U}^\nu \odot (\mathbf{Y} \mathbf{U}^\nu) - \mathbf{U} \odot (\mathbf{Y} \mathbf{U}). \quad (28)$$

The voltage profile before and after the redispatch can be written in terms of deviations around the arithmetic mean value. The voltages after the contingency and the setpoints after the redispatch are then given by

$$\mathbf{U} = \tilde{U} \cdot \tilde{\mathbf{I}}_n + \tilde{\Delta}_U, \quad (29)$$

$$\mathbf{U}_0^\nu = \tilde{U}_0^{\nu*} \cdot \tilde{\mathbf{I}}_n + \tilde{\Delta}_U^\nu, \quad (30)$$

Aiming at a set of voltages and power injections that satisfy the power flow equations, hence $\mathbf{U}^\nu = \mathbf{U}_0^\nu$, (29)–(30) are substituted in (28). The power change from (28) can now be simplified to

$$\mathbf{P}^\nu - \mathbf{P} = \Delta \mathbf{P}_\alpha^\nu + \Delta \mathbf{P}_\beta^\nu, \quad (31)$$

with

$$\Delta \mathbf{P}_\alpha^\nu = \mathbf{Y}(\tilde{U}_0^{\nu*} \tilde{\Delta}_U^\nu - \tilde{U} \tilde{\Delta}_U), \quad (32)$$

$$\Delta \mathbf{P}_\beta^\nu = \tilde{\Delta}_U^\nu \odot (\mathbf{Y} \tilde{\Delta}_U^\nu) - \tilde{\Delta}_U \odot (\mathbf{Y} \tilde{\Delta}_U). \quad (33)$$

$\tilde{U}_0^{\nu*}$ and $\tilde{U}$ are typically around 1 p.u. and the voltage deviations from the arithmetic means $\tilde{\Delta}_U^\nu$ and $\tilde{\Delta}_U$ are much smaller. Consequentially, the first term $\Delta \mathbf{P}_\alpha^\nu$ tends to increase more than the second term $\Delta \mathbf{P}_\beta^\nu$ when the voltage profile is changed. To find values for $\mathbf{P}^\nu$ close to the post-contingency

settings $\mathbf{P}$, one can therefore eliminate $\Delta \mathbf{P}_\alpha^\nu$. Putting this term equal to zero results in the set of voltage deviations

$$\tilde{\Delta}_U^\nu = \frac{\tilde{U}}{\tilde{U}_0^{\nu*}} \tilde{\Delta}_U, \quad (34)$$

and corresponding power changes are found by substituting expression (34) into (33), hence

$$\mathbf{P}^\nu - \mathbf{P} = \left[\left(\frac{\tilde{U}}{\tilde{U}_0^{\nu*}} \right)^2 - 1 \right] \cdot (\tilde{\Delta}_U \odot (\mathbf{Y} \tilde{\Delta}_U)), \quad (35)$$

with $\mathbf{Y} \tilde{\Delta}_U = \mathbf{Y} \mathbf{U} = \mathbf{I}$. The setpoints satisfy the power flow equations and hence, they are perfectly tracked. The solution implies that every converter that injects or withdraws power from the system needs to update its power setpoint, provided that $\tilde{\Delta}_U \neq 0$. Similar to Section III-A, this method thus implies a setpoint change of all converters in the system.

D. Scaled voltage offset with constant power setpoint change

Combining the approximation of using post-contingency powers as setpoints with voltages updated according to the scaled offsets dictated by (34), results in setpoints

$$\mathbf{U}_0^\nu = \tilde{U}_0^{\nu*} \cdot \tilde{\mathbf{I}}_n + \frac{\tilde{U}}{\tilde{U}_0^{\nu*}} \tilde{\Delta}_U, \quad (36)$$

$$\mathbf{P}_0^\nu = \mathbf{P}. \quad (37)$$

This results in an offset operation, as the setpoints no longer satisfy the power flow equations. To account for this offset, the linearized equations (20) & (23) can be used to correct the setpoints. This way, setpoint tracking can be improved.

E. Optimization-based setpoint change

To guarantee setpoint tracking, also when not all converters can change setpoints, the problem is rephrased as an optimization, aiming at keeping the new active power setpoints as close to post-contingency power injections as possible, by minimizing

$$f(\mathbf{x}_0^\nu) = \|\mathbf{P}_0^\nu - \mathbf{P}\|^2, \quad (38)$$

with $\|\cdot\|$ the Euclidean norm. The problem is subject to the DC system power flow equations and an additional predefined average system voltage equality constraint

$$\mathbf{h}^\alpha(\mathbf{x}_0^\nu) = \mathbf{U}_0^\nu \odot (\mathbf{Y} \mathbf{U}_0^\nu) - \mathbf{P}_0^\nu, \quad (39)$$

$$\mathbf{h}^\beta(\mathbf{x}_0^\nu) = \tilde{U}_0^\nu - \tilde{U}_0^{\nu*}. \quad (40)$$

In case constant power controlled buses are present, their setpoints can also be kept constant by including

$$\mathbf{h}_i^\gamma(\mathbf{x}_0^\nu) = P_{0_i}^\nu - P_i \ \forall i \in \mathcal{I}^P, \quad (41)$$

as equality constraints, with $\mathcal{I}^P$ the set of indices of constant power converters. A similar approach holds for converters facing an outage. The optimization problem now takes the form

$$\text{minimize } f(\mathbf{x}_0^\nu), \quad (42)$$

$$\text{subject to } \mathbf{h}(\mathbf{x}_0^\nu), \quad (43)$$

$$\underline{\mathbf{x}} \leq \mathbf{x}_0^\nu \leq \bar{\mathbf{x}}. \quad (44)$$

with $\underline{x}$, $\bar{x}$ lower and upper converter limits.

IV. IMPLEMENTATION RESULTS

The five distinct redispatch methods are implemented with a ± 320 kV 4-terminal HVDC grid test system shown in Fig. 2. All converters have a rated output of 1200 MW and a

Fig. 2: Initial power flow situation before contingency.

converter current limit at 1.2 p.u. (resulting in a power limit of 1440 MVA). Full details on the test system are given in [9]. The generic non-linear optimization routine `fmincon` from the optimization Toolbox in Matlab has been used to solve the optimization problem from Section III-E. The setpoint tracking of the different redispatch methods is evaluated with the open-source power flow software MATA CDC [10]. A first study considers the ideal case in which all converters are represented by power-based droop-controlled buses that can change their setpoints. A second case considers a constant power injection for one of the converters. This case represents an offshore wind farm, but also provides a conservative indication of the effects of hitting a converter power limit.

A. Droop control in all converters

Table I shows post-contingency power flow results with droop setpoints initialized at the pre-contingency power flow results, with $\tilde{U}_0 = 1$ p.u. After the contingency (outage of

TABLE I. POST-CONTINGENCY POWER FLOW RESULTS AND SETPOINTS

Conv	Active power P [MW]		Voltage U [p.u.]	
	P_0	P	U_0	U
1	1175.0	825.39	1.00473	1.03387
2	-1026.32	0	0.99572	1.03310
3	-1083.55	-1411.24	0.99648	1.02379
4	951.54	598.92	1.00306	1.03244

converter 2) the voltage profile is offset with $\tilde{U} = 1.0308$ p.u. The offset is roughly inversely proportional to the droop gains, here equal to 10 (p.u. values) for all converters. Converter 3 is operating close to its current limit, but no limits are violated. Table II shows the power flow results for the five setpoint redefinition methods, with $\Delta P^\nu = P^\nu - P_0^\nu$ and $\Delta U^\nu = U^\nu - U_0^\nu$ indicating the setpoint tracking and $\Delta P_0^{\nu\nu} = P_0^\nu - P$ the power setpoint deviation from post-contingency operation.

All five redispatch methods achieve tracking of the new voltage references and consequentially yield an average voltage $\tilde{U}^\nu \approx \tilde{U}_0^{\nu*} = 1$ p.u. The power differences ΔP^ν are negligible for the constant current (A), the scaled voltage (C)

TABLE II. SETPOINT CHANGES AND TRACKING-ALL DROOP

	Conv	Active power P [MW]			Voltage U [p.u.]	
		P_0^ν	ΔP^ν	$\Delta P_0^{\nu\nu}$	U_0^ν	ΔU^ν
A	1	800.80	7.50e-12	-24.589	1.00307	-1.78e-15
	2	0	0	0	1.00230	-1.55e-15
	3	-1368.78	1.84e-11	42.455	0.99299	-1.00e-15
	4	581.05	7.96e-12	-17.867	1.00164	-1.55e-15
B	1	825.39	-1.0871	0	1.00307	9.06e-5
	2	0	0	0	1.00230	6.85e-5
	3	-1411.24	2.4643	0	0.99299	-2.05e-4
	4	598.92	-0.5973	0	1.00164	4.98e-5
C	1	825.54	-2.27e-13	0.1532	1.00316	-6.66e-16
	2	0	-1.71e-11	0	1.00237	0
	3	-1410.64	4.55e-13	0.6043	0.99278	-6.66e-16
	4	598.98	-8.75e-12	0.0596	1.00169	-6.66e-16
D	1	825.39	0.2666	0	1.00316	-2.22e-5
	2	0	0	0	1.00237	-2.21e-5
	3	-1411.24	0.2933	0	0.99278	-2.44e-5
	4	598.92	0.2638	0	1.00169	-2.20e-5
E	1	825.66	2.84e-11	0.2719	1.00316	-8.88e-16
	2	0	0	0	1.00237	-4.44e-16
	3	-1410.96	2.00e-11	0.2781	0.99277	-9.99e-16
	4	599.19	-2.27e-11	0.2734	1.00169	-4.44e-16

Legend A: Constant current, B: Constant power, C: Scaled voltage, D: Scaled voltage with constant power, E: Optimization-based.

and the optimization-based (E) redispatch. Setpoint tracking is guaranteed with these three methods as the new setpoints x_0^ν satisfy the power flow equations, which is clear from the values of Δx^ν . The constant current method results in significant changes to the power injections that could have been avoided. The constant power redispatch (B) results in an offset operation, but yields a reasonably close approximation. Comparison of the scaled voltage deviation method (C) with the optimization-based method (E) shows that both methods yield similar voltage setpoints and allow to track the setpoints with small converter power changes. The approximation using a scaled voltage profile whilst keeping the power injections constant (D), results in an offset operation with powers close to the setpoints of the optimization-based scheme (E).

B. Constant power at converter 3, droop control for others

This section studies the performance degradation of the five distinct methods when one of the converters is set to constant power mode and consequentially does not participate in the control. Table III shows the post-contingency power flow results and the setpoints of the converters. Table IV show the power flow results and the setpoint tracking. Only the optimization-based method takes the constant power infeed of converter 3 into account. The other methods assume power setpoint changes for all converters. However, due to the constant power infeed, the requested setpoint change is not taking place in converter 3.

TABLE III. POST-CONTINGENCY POWER FLOW AND SETPOINTS – P_3 FIXED

Conv	Active power P [MW]		Voltage U [p.u.]	
	P_0	P	U_0	U
1	1175.00	659.56	1.00473	1.04769
2	-1026.32	0	0.99572	1.04699
3	-1083.55	-1083.55	-	1.03995
4	951.54	431.52	1.00306	1.04639

TABLE IV. SETPOINT CHANGES AND TRACKING – P_3 FIXED

	Conv	Active power P [MW]			Voltage U [p.u.]	
		P_0^ν	ΔP^ν	$\Delta P_0^{\nu'}$	U_0^ν	ΔU^ν
A	1	631.07	23.821	-28.489	1.00243	-1.99e-3
	2	0	0	0	1.00173	-2.00e-3
	3	-1036.40	-47.151	47.151	0.99470	-2.33e-3
	4	412.85	24.055	-18.662	1.00114	-2.00e-3
B	1	659.56	0.0178	0	1.00243	-1.49e-6
	2	0	0	0	1.00173	-3.16e-5
	3	-1083.55	0.0000	0	0.99470	-3.54e-4
	4	431.52	0.6872	0	1.00114	-5.73e-5
C	1	659.70	0.2584	0.1418	1.00254	-2.15e-5
	2	0	0	0	1.00181	-2.16e-5
	3	-1083.04	-0.5114	0.5114	0.99446	-2.53e-5
	4	431.56	0.2610	0.0434	1.00119	-2.17e-5
D	1	659.56	0.3533	0	1.00254	-2.94e-5
	2	0	0	0	1.00181	-2.93e-5
	3	-1083.55	0.0000	0	0.99446	-3.31e-5
	4	431.52	0.3513	0	1.00119	-2.93e-5
E	1	659.91	2.32e-11	0.3516	1.00254	-2.67e-15
	2	0	0	0	1.00181	-2.89e-15
	3	-1083.55	0	0	0.99445	-3.00e-15
	4	431.87	1.02e-11	0.3525	1.00119	-2.44e-15

Legend See Table II

The constant current setpoint change (A) results in large power setpoint changes compared to the post-contingency situation ($\Delta P_0^{\nu'}$), but these setpoints are not tracked. As a result, the power injections after the setpoint change P^ν are actually closer to the post-contingency power injections P . This can be observed since $P^\nu - P = \Delta P^\nu + \Delta P_0^{\nu'}$. With the power injection in converter 3 fixed, the constant power approximation (B) now leads to a better setpoint tracking (low values for ΔP^ν and ΔU^ν) compared to the case with droop control on all converters. The scaled voltage deviation method (C), which previously held results similar to the method relying on the optimization (E), now suffers from the fact that the requested setpoint change from (35) also implies a contribution from converter 3, which cannot change its setpoint. In the case of the scaled voltage deviation with constant powers (D), the setpoints are not fully tracked, but the offset powers ΔP^ν are again similar to the setpoint changes $\Delta P_0^{\nu'}$ determined by the optimization (E).

Since the deviation from the post-contingency operating point is small, the linearized model from (20) and (23) can be used to predict the offset operation ($\Delta x_{\text{lin}}^\nu$) and to compensate for it by having $P_0^\nu = P_{0_1}^\nu + \Delta P_{\text{lin}}^\nu$ and $U_0^\nu = U_{0_1}^\nu + \Delta U_{\text{lin}}^\nu$, with $x_{0_1}^\nu$ the initial setpoints without compensation. Applying this compensation to setpoints for the method using scaled voltages with constant powers (D), $x_{0_1}^\nu$ is given by (36)–(37). Consequentially, in this example with $P_{0_1}^\nu = P$, by definition $\Delta P_0^{\nu'} = \Delta P_{\text{lin}}^\nu$. Table V shows the results.

Comparing the results for $\Delta P_0^{\nu'}$ and $\Delta U_{\text{lin}}^\nu$ in Table V with the corresponding offsets (Δx^ν , case D) from Table IV, it is observed that the power and voltage deviations caused by the network are relatively well predicted by the linearized model and that the setpoints are tracked accurately when using the linearized model to update the initial setpoints from (36)–(37).

TABLE V. SETPOINT TRACKING – SCALED VOLTAGE & CONSTANT POWER (D), INCLUDING PREDICTIONS FROM (20) & (23) – P_3 FIXED

Conv	Active power P [MW]			Voltage U [p.u.]	
	P_0^ν	ΔP^ν	$\Delta P_0^{\nu'}$	$\Delta U_{\text{lin}}^\nu$	ΔU^ν
1	659.91	7.90e-4	0.3524	-2.94e-5	-6.58e-8
2	0	0	0	-2.93e-5	-6.62e-8
3	-1083.55	-1.58e-3	0.0016	-3.30e-5	-7.75e-8
4	431.87	7.98e-4	0.3506	-2.93e-5	-6.65e-8

V. CONCLUSION

The voltage offset after the proportional droop control action in an HVDC grid can be compensated by redefining the setpoints. Five distinct setpoints redefinitions are developed and compared in this paper. When all converters can change setpoints, constant current redispatch yields accurate setpoint tracking, but involves large and unnecessary changes in converter powers. Keeping power setpoints at post-contingency operation values whilst updating voltage setpoints only compromises the setpoint tracking to a minor extent and results in a close approximation. Optimization-based redispatch guarantees accurate setpoint tracking with very small modifications to the converter power setpoints. However, it requires solving the power flow equations to guarantee setpoint tracking. Scaling the voltage offsets from the post-fault contingency operation yields results that closely resemble those obtained by the optimization. When converters with a constant power injection are included, only the optimization-based method guarantees setpoint tracking. A close approximation is obtained when the voltage deviations are scaled, while using the linearized system model to determine a correction to the converter voltage and power setpoints.

REFERENCES

- [1] W. Wang and M. Barnes, "Power flow algorithms for multi-terminal VSC-HVDC with droop control," *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1721–1730, July 2014.
- [2] R. Hendriks, G. Paap, and W. Kling, "Control of a multi-terminal VSC transmission scheme for connecting offshore wind farms," in *Proc. European Wind Energy Conference & Exhibition*, Milan, Italy, May 7–10, 2007, 8 pages.
- [3] A. Egea-Álvarez, J. Beerten, D. Van Hertem, and O. Gomis-Bellmunt, "Primary and secondary power control of multiterminal HVDC grids," in *Proc. IET ACDC 2012*, Birmingham, UK, Dec. 4–6, 2012, 6 pages.
- [4] M. Aragüés-Peñalba, A. Egea-Álvarez, O. Gomis-Bellmunt, and A. Sumper, "Optimum voltage control for loss minimization in HVDC multi-terminal transmission systems for large offshore wind farms," *Electric Power Systems Research*, vol. 89, pp. 54–63, 2012.
- [5] K. Rouzbehi, A. Miranian, A. Luna, and P. Rodriguez, "DC voltage control and power sharing in multiterminal DC grids based on optimal DC power flow and voltage-droop strategy," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 4, pp. 1171–1180, Dec 2014.
- [6] P. Rault, "Dynamic modeling and control of multi-terminal HVDC grids," Ph.D. dissertation, Ecole Centrale de Lille, France, 2014.
- [7] R. Renner, J. Beerten, and D. Van Hertem, "Optimal DC reference voltage in HVDC grids," in *Proc. IET ACDC 2015*, Birmingham, UK, Feb., 10–12 2015, accepted for publication.
- [8] T. M. Haileselassie and K. Uhlen, "Impact of DC line voltage drops on power flow of MTDC using droop control," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1441–1449, Aug. 2012.
- [9] J. Beerten and R. Belmans, "Analysis of power sharing and voltage deviations in droop-controlled DC grids," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4588–4597, 2013.
- [10] MatACDC: <http://www.esat.kuleuven.be/electa/teaching/matacdc/>.