Security Constrained Optimal Power Flow for HVAC and HVDC Grids

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Abstract—This paper includes security constraints in OPF calculations for combined HVAC and HVDC grids. Two formulations of the problem are considered: a preventive and a corrective formulation. The outages of lines, generators and terminal stations are included. The preventive control method assumes that no control actions are taken after a contingency happens, meaning that all actions must be performed in advance. Linear sensitivity factors are used to calculate the influence of the contingency. Under the corrective control method, control actions can be performed both before and after a contingency, using fast controllable HVDC terminals. The two methods are applied to the IEEE14 and the RTS96 test cases, both expanded with an HVDC grid. The corrective control is computationally more intensive, but, in general, gives more economical results.

Keywords—Generalized Generator Distribution Factors, HVDC, Line outage distribution factors, Optimal Power Flow, Power System Planning, SCOPF

I. INTRODUCTION

Current trends in energy politics, such as the increased penetration of renewable generation, and the reduction of CO2-emissions, greatly affect the transmission grid. The fluctuating infeed from renewable generation, coupled with an increasing electricity demand as other sources of energy are replaced, are necessitating a rethinking of the existing transmission grid. One possible solution to these problems is an grid expansion using High Voltage Direct Current (HVDC) technology, which has many advantages compared to High Voltage Alternating Current (HVAC) technology [1], [2], with the main expansion envisioned to be made using the Voltage Source Converter (VSC) technology.

The primary cost-driver in HVDC grids are the terminals. The amount of terminals can be reduced significantly if an Multi Terminal HVDC (MTDC) grid is constructed instead of using point-to-point links. To integrate this new grid into the existing HVAC grid operational procedures need to be investigated. The Optimal Power Flow (OPF) of a combined grid was investigated with a nonlinear model in [3] and [4]. A linearized, usually known as DC-OPF [5], version is given in [6]. A study about the Security Constrained Optimal Power Flow (SCOPF) in AC only grid is given by [7]. A SCOPF for point-to-point HVDC links with post-contingency control is given in [8]. This paper expands research to meshed grids and presents two different SCOPF formulations: a preventive formulation, reflecting the classical N-1 secure operation, and a corrective formulation which uses the flexibility introduced by the HVDC terminals to allow the grid to react after a contingency.1 The assumption here is that the terminals are able to react sufficiently fast, which usually is not possible using only the relatively slowly controllable generators in the HVAC grid. Furthermore, a re-dispatch of generators incur additional costs for the system operation.

The structure of the paper is as follows. Section II introduces the preventive formulation, while Section III details the corrective formulation. In Section IV a case-study is performed to evaluate the two methods. Section V summarizes the findings and concludes the paper.

II. PREVENTIVE SECURITY CONSTRAINED OPTIMAL POWER FLOW

This section describes the formulation of the problem. It begins with a summary of the existing formulation and then adds the different parts to form the extended model presented in this paper.

A. Linearized mixed HVAC-HVDC Optimal Power Flow

The basis for the model presented in this paper is the linearized mixed HVAC-HVDC OPF. For the HVAC grid the common known linearized OPF is used [9]. Here only a summary is given, the detailed derivation can be found in the appendix of [9]. The derivation of a linear HVDC power flow is performed in [6]. The nonlinearities are composed in the power flow equation, both in the HVAC and HVDC grid. These are linearized to equations (1) and (2),

$$p_{AC}^{km} \approx \frac{\delta_k - \delta_m}{X_{km}}$$

(1)

$$p_{DC}^{km} \approx \frac{(U_{DC}^k - U_{DC}^m)}{R_{km}}$$

(2)

where $X_{km}$ is the reactance in per-unit values of the HVAC line between $k$ and $m$ and $R_{km}$ is the resistance of the HVDC line between $k$ and $m$. In this paper the dispatch of the generators is done according to a quadratic cost model. This corresponds to energy markets with a market clearing model including a grid representation, however it can not be applied one-to-one to other energy markets. Using the linearizations together with a quadratic cost function for the generators, the OPF can be formulated as a Quadratic Problem (QP) with linear constraints. The objective function $f(x)$ includes also

1HVDC is assumed to mean all direct-current technologies, and HVAC for all alternating-current technologies. The presented models are also valid in lower voltage ranges.
penalty terms for the flows,
\[
f(x) = \min \left( \sum_{i=1}^{l} \left[ c_i P_G + c_q P_q^2 \right] + \sum_{k} \pi_{km}^{AC} [\delta_k - \delta_m]^2 + \sum_{k} \pi_{km}^{DC} [U_{k}^{DC} - U_{m}^{DC}]^2 \right)
\]
(3)
where \( P_G \) is the power generation, \( c_i \) and \( c_q \) are the linear and quadratic cost parameters, \( \delta_k \) is the voltage angle at bus \( k \) and \( U_{k}^{DC} \) is the HVDC voltage at bus \( m \). The terms \( \pi_{km}^{AC} \) and \( \pi_{km}^{DC} \) are flow penalties for each line depending on their reactance or resistance respectively. They add additional costs to the objective function representing the line losses. They are employed to penalize the total flows in the mixed grid. In [3], it is shown that this formulation is a good approximation of the nonlinear OPF.

The physical terminal losses are neglected here. Half of those losses are constant loses [10], and the rest power transfer dependent. Since physical the losses are neglected in the HVAC and HVDC lines, the consideration the terminal losses would lead to a major change of power flows, since the flow through the terminal would be minimized.

The solution is constrained by equality and inequality constraints.
\[
\Pi_G P_G - \Pi_L P_L - \Pi_T^A P_T - B^{AC} \delta = 0 \quad (4)
\]
\[
\Pi_G P_G - \Pi_L P_L + \Pi_T^D P_T - B^{DC} U^{DC} = 0 \quad (5)
\]
Eq. (4) ensures the total power balance at all HVAC buses, with (5) doing the same for HVDC buses. \( \Pi_G, \Pi_L, \Pi_T \) assign generation \( P_G \), load \( P_L \) and terminal powers \( P_T \) to the corresponding buses. \( B^{AC} \) is the admittance matrix of the HVAC grid, which, when multiplied with the voltage angles, gives in the total flows for each line. \( B^{DC} \) is the admittance matrix in the HVDC grid.

Beside the equality constraints the following inequalities have to be fulfilled.
\[
\begin{align*}
P_G & \leq \bar{P}_G \quad (6) \\
P_L & \leq \bar{P}_L \quad (7) \\
P_T & \leq \bar{P}_T \quad (8) \\
F^{AC} & \leq \bar{F}^{AC} \quad (9)
\end{align*}
\]
\[
F^{DC} \leq \bar{F}^{DC} \quad (10)
\]
Eq. (6) to (9) denote the physical limits of the grid components. The generators, terminals power, as well as HVAC and HVDC lines flow have to be within their capability limits.

B. HVAC grid Security Constrained Optimal Power Flow with line and generator outages

The security of the system against single component outages is evaluated under the N-1 criterion. Several formulations to include the N-1 criterion in a HVAC OPF are described in [11]. This paper uses the formulation for the HVAC lines described in [9]. An outage of a transmission line is approximated with Line Outage Distribution Factors (LODF). They are defined in Eq. (12) for each line \( k \) in any possible outage of another line \( m \).
\[
LODF_{k,m}^{AC} = \frac{\Delta F_{k,m}^{AC}}{F_{m,0}^{AC}} \quad (12)
\]
, where \( \Delta F_{k,m}^{AC} \) is the change in flow on line \( k \) and \( F_{m,0}^{AC} \) is the flow on line \( m \) before the contingency occurred.

The same can be done for generators using the Generalized Generator Distribution Factors (GGDF). With the GGDF the flow change over a line if an generator has an outage can be calculated.
\[
GGDF_{k,i}^{AC} = \frac{\Delta F_{k,m}^{AC}}{\Delta P_i} \quad (13)
\]
where \( \Delta P_i \) is the change in generation at bus \( i \). The outage of a generator is compensated by all controllable generators proportional to their maximum power.

C. HVDC grid Security Constrained Optimal Power Flow with line and generator outages

The method for the LODF and GGDF can be adapted to the HVDC grid. To date, the LODF and GGDF have only been formulated for the HVAC grid, this section shows how they can be adapted to the HVDC grid.

1) LODF in the HVDC grid: The principles used in the HVAC grid can be applied in the HVDC grid. As for the HVAC lines, the outage of a HVDC line is modeled as the additional injection of the line flow at the incident nodes. This results in a incremental change \( \Delta U^{DC} \) of the HVDC voltages, since we assume that the terminals are in power control mode. One terminal is controlling the voltage in the HVDC grid, as for the HVAC lines, the outage of a HVDC line is modeled as the additional injection of the line flow at the incident nodes. This results in a incremental change \( \Delta U^{DC} \) of the HVDC voltages, since we assume that the terminals are in power control mode. One terminal is controlling the voltage in the HVDC grid, a voltage change at this terminal, changes the reference value and all voltages have to be adjusted. The relationship between the change in the power injections \( \Delta P \) and the voltages are described by the \( Z \) matrix.
\[
\Delta U^{DC} = Z \Delta P \quad (14)
\]
For a line outage from node \( k \) to \( m \) we have:
\[
\Delta P = [0 \ldots \Delta P_k \ldots 0 \ldots \Delta P_m \ldots 0]^T \quad (15)
\]
where \( \Delta P_k = -\Delta P_m \). Then
\[
\Delta U^{DC}_k = (Z_{kk} - Z_{km}) \Delta P_k \quad (16)
\]
\[
\Delta U^{DC}_m = (Z_{mm} - Z_{km}) \Delta P_k \quad (17)
\]
The flows over the outaged line \( \hat{P}_{km} \) can then be calculated from the original flows \( P_{km} \) and the change in the flows \( \Delta P_{km} \).
\[
\begin{align*}
\hat{P}_{km} &= \frac{\hat{U}_{DC}^{km} - \hat{U}_{DC}^{km}}{R_{km}} \quad (18) \\
\hat{P}_{km} &= P_{km} + \Delta P_{km} \quad (19) \\
\hat{P}_{km} &= P_{km} + \frac{\Delta U^{DC}_k - \Delta U^{DC}_m}{R_{km}} \quad (20) \\
\hat{P}_{km} &= P_{km} + \frac{Z_{kk} + Z_{mm} - 2Z_{km}}{R_{km}} \Delta P_k \quad (21)
\end{align*}
\]
The injected power $\Delta P_k$ has to be equal to the flow on the line after the disturbance, to compensate for the outage of the line.

$$\Delta P_k = \frac{P_{km}}{1 - Z_{km}Z_{km} - 2Z_{km}}$$

(22)

It is thus possible to calculate the difference in power flow over the line from $k$ to $m$ caused by the outage of another line from $i$ to $j$.

$$LODF_{km,ij}^{DC} = \frac{\Delta P_{km}}{P_{km}}$$

(23)

$$LODF_{km,ij}^{AC} = \frac{1}{R_{km}} \left( \frac{\Delta U_{km}^{DC}}{P_{km}} - \frac{\Delta U_{km}^{DC}}{P_{km}} \right)$$

(24)

$$LODF_{km,ij}^{DC} = \frac{R_{km}}{R_{km}} (Z_{ik} - Z_{ji} - Z_{im} + Z_{jm})$$

(25)

2) GGDF in the HVDC grid: GGDF are used to calculate the injected power $\Delta P_i$ after the disturbance, to compensate for the outage of the terminal $i$.

$$\Delta P_i = \sum_{i \neq p}^{P_{G_i}} (-1)$$

(26)

This gives $\Delta P$ as follows.

$$\Delta P = \begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_l \end{bmatrix}^{DC} = \begin{bmatrix} 1 \\ -1 \\ \vdots \\ -1 \end{bmatrix} \frac{dP}{dP_p}$$

(27)

The influence on line $km$ in case of an outage of generator $p$ can then be calculated.

$$GGDF_{km,pi}^{DC} = \frac{dP_{km}}{dP_p} = \frac{1}{R_{km}} \left( \frac{dU_{km}^{DC}}{dP_p} - \frac{dU_{km}^{DC}}{dP_p} \right)$$

(28)

$$Z_{kp} - Z_{mp}$$

D. Terminal Outage Distribution Factors

The Terminal Outage Distribution Factors (TODF) are a new contribution of this paper. It is calculated similar to the GGDF. They give a factor about how much of the terminal transfer power is shifted to an HVAC or HVDC line in case of the outage of a terminal. In such a case, it is assumed that the remaining terminals take over the power proportional to their maximal capacity power. The maximum capacity has to be adhered in this case as well. This result in a similar solution as the idea of a decentralized control structure of sharing the power deviation of a disturbance in the HVDC grid by adjusting the voltages [12]. The outage of a terminal leads to new flows in the HVAC and HVDC grid.

$$\Delta P_i = \frac{P_T}{P_T}^{(-1)}$$

(29)

The same steps as (27) and (28) lead to the solution for the TODF in the HVAC side.

$$TODF_{km,pi}^{AC} = \frac{dP_{km}}{dP_p} = \frac{1}{z_{km}} \left( \frac{dU_{km}^{DC}}{dP_p} - \frac{dU_{km}^{DC}}{dP_p} \right)$$

(30)

If the terminal powers are changed, not only the HVDC side is affected, the TODF on the HVAC side are calculated analogous to the GGDF.

$$TODF_{km,pi}^{AC} = \frac{dP_{km}}{dP_p} = \frac{1}{z_{km}} \left( \frac{dU_{km}^{DC}}{dP_p} - \frac{dU_{km}^{DC}}{dP_p} \right)$$

(31)

E. Preventive Security Constrained Optimal Power Flow Problem Formulation

The objective function (3), as well as the equality constraints (4) and (5) remain the same. Eq. (6) to (9) are complemented by the following inequalities, to guarantee N-1 security criterion for all possible outages.

$$P_{G} \leq (1 + \gamma_{G})P_{G} \leq P_{G}$$

(32)

$$P_{T} \leq (1 + \gamma_{T})P_{T} \leq P_{T}$$

(33)

$$P_{AC} \leq (1 + LODF_{AC})B_{AC} \delta \leq P_{AC}$$

(34)

$$P_{AC} \leq B_{AC} \delta + GGDF_{AC} P_{G} \leq P_{AC}$$

(35)

$$P_{AC} \leq B_{AC} \delta + TODF_{AC} P_{T} \leq P_{AC}$$

(36)

$$P_{DC} \leq (1 + LODF_{DC})B_{DC}U_{DC} \leq P_{DC}$$

(37)

$$P_{DC} \leq B_{DC}U_{DC} + GGDF_{DC} p_{DC} \leq P_{DC}$$

(38)

$$P_{DC} \leq B_{DC}U_{DC} + TODF_{DC} P_{T} \leq P_{DC}$$

(39)
III. CORRECTIVE SECURITY CONSTRAINED OPTIMAL POWER FLOW

This section explains the description of the problem formulation including post-contingency corrective control actions. In general the assumption that only the terminals can react fast enough to counteract overloading is used. Therefore generators units will not react to any non-generator contingency. The corrective control is formulated as a QP problem.

A. Basic Problem

The objective function Eq. (3) remains as before. The generators must respect their limits, therefore Eq. (6) is still valid. To consider all possible outages, all equalities and inequalities from Eq. (40) to (49) need to be fulfilled as explained below.

B. Line Outages

For any possible N-1 outage in the grid, the flows in all lines and terminals are calculated. If contingency c is the outage of an HVAC line, then the grid topology is different and the \( B^{AC} \) matrix changes to \( B^{AC} \). The terminal powers \( P_T \) can be changed to \( P_T^c \). The topology in HVDC grid stays the same, therefore Eq. 9 is still valid.

\[
\Pi_G P_G - \Pi_L P_L - \Pi^{AC}_T P_T^c - B^{AC}_c \delta_c = 0 \tag{40}
\]

\[
\Pi_G P_G - \Pi_L P_L + \Pi^{DC}_T P_T^c - B^{DC}_c U^{DC}_c = 0 \tag{41}
\]

\[
P_T \leq P_T^c \leq \bar{P}_T \tag{42}
\]

\[
E^{AC} \leq B^{AC}_c \delta \leq \bar{P}^{AC} \tag{43}
\]

If a HVDC line has an outage, the \( B^{DC} \) matrix changes to \( B^{DC} \), which represents the new grid topology of the HVDC grid. The equations look similar to Eq. (40) to (43).

\[
\Pi_G P_G - \Pi_L P_L - \Pi^{AC}_T P_T^c - B^{AC}_c \delta_c = 0 \tag{44}
\]

\[
\Pi_G P_G - \Pi_L P_L + \Pi^{DC}_T P_T^c - B^{DC}_c U^{DC}_c = 0 \tag{45}
\]

\[
P_T \leq P_T^c \leq \bar{P}_T \tag{46}
\]

\[
E^{DC} \leq B^{DC}_c U^{DC}_c \leq \bar{P}^{DC} \tag{47}
\]

C. Generator Outages

We assume that the generators are not flexible enough to contribute post-contingency corrective control actions, this means there is no re-dispatch of the the generators in case of an outage. However the generation has to be shifted to the remaining generators if a generator has an outage according to (29), analogous to in the preventive case. The terminals can still react to this different generation, but have to fulfill Eq. (42).

D. Terminal Outages

If a terminal has an outage, the controls of the other terminals can react and adjust their power set-points to find a new suitable solution. The new power set points \( P_{T,c} \) have to stay within the normal operation limits.

\[
P_T \leq P_{T,c} \leq \bar{P}_T \tag{48}
\]

To limit the power change of the terminals, a new constraint is introduced.

\[
|P_{T,c} - P_T| \leq \Delta P_T \tag{49}
\]

where \( \Delta P_T \) is defined as the maximal possible change in the terminal power between the pre-contingency case and the post contingency case. If \( \Delta P_T \) is set to 0, there is no flexibility at all. If \( \Delta P_T \) is set to any value equal to, or higher than \( P_T - P_T \), the maximal flexibility can be used in all terminals.

IV. CASE STUDY

The method is applied in two different grids, to compare the performance in a small and rather large grid. The simulation was performed using MATLAB, with the CPLEX solver within TOMLAB.

A. Test grid IEEE14DC

The smaller grid is based on the IEEE14 test case with an overlay HVDC grid and it will be referred to as IEEE14DC. The combined grid is shown in Fig. 1. The HVAC line capacities are 100 MW in the lower part, including the area with the buses 1-7, and 50 MW in the upper part, as well as in the transformers in the middle of the grid. In the middle of the HVDC grid is Bus 25, a HVDC only bus, which has no connection to the HVAC grid. The HVDC terminals have a maximum capacity of 100 MW, but all HVDC lines are limited to 50 MW. Two generators are added directly to the HVDC grid. One at HVDC Terminal 4, which is connected to HVAC Bus 13 and another one at the HVDC Bus 25, each with a capacity of 20 MW. The generator at Bus 25 has the same cost as the one at Bus 1. The generator connected to the HVDC Bus 4 has the same cost as the one at HVAC Bus 2.

1) Cost for different operation schemes: The first case study compares the costs in the IEEE14DC grid. Five different operation schemes are evaluated. First the basic operation scheme of the HVAC grid is tested, with the limits described above. This means that the HVDC grid is not in operation. In a second scheme the security criterion for the HVAC grid is introduced. Line and generator outages are considered for this step.
different loading levels, compared to nominal loading level, a threat to the dynamic stability of the HV AC grid. Therefore is a substantial difference.

saving of about 10% compared to preventive control, which can see that post-contingency corrective control gives cost not no security. Comparing the last two bars in Fig. 2, we but 16.2% higher cost than the case including an HVDC grid, HVDC case has 15.3% lower costs than than the HV AC case, security , the case with HVDC grid is 18.6% cheaper, since the cases in all operation schemes. In the scheme without any operation and has a higher power level for almost all contingencies. The two exception are the outage of the HVDC lines be prepared for a outage of one out of the three connections, HVDC Terminal 1 is connected with two HVDC lines, each with a capacity of 50 MW. If one of this two line fails the HVDC terminal station needs to down regulate to this level. With an allowed delta of 0.25, the HVDC terminal station can be operated at 75 MW, this allows it to reach 50 MW and 100 MW, depending on the contingency. If these two points can be reached, the generator at Bus 1 can produce 200 MW. This is possible for an allowed change of at least 0.25.

The case for $\Delta P_T = 0.25$ is shown in Fig. 4. The cross marks the undisturbed operation point for each of the four HVDC terminals. The circles are the operation points for all possible contingencies. The blue lines limit the range of plus and minus 0.25 from the undisturbed point. As described above, Terminal 1 is at power flow of 0.75 pu. for nominal operation and has a higher power level for almost all contingencies. The two exception are the outage of the HVDC lines connected to Terminal 1, then the power is set to 0.5. Terminal 3 is undisturbed at -0.445, for all contingencies it changes to its upper limit. The exceptions here are the outage of the two heavily loaded HVAC connections to Bus 1. In such a case much more power is transported in the HVDC grid from Bus 1 to Bus 3. This requires an increase of the power in HVDC Terminal 3 for this two contingencies.

For the other operation schemes, the HVDC grid is included. First the whole grid is operated without any security constraints, so each contingency could possibly lead to severe interruptions. The preventive security scheme is the next case to be investigated. All line, generator and terminal outages are considered in this dispatch, and no corrective control actions are allowed to be done in case of a contingency, except for the generator set points which have to be adjusted in case of a generator outage according to the GGDF. Finally the post contingency corrective control is investigated. This means the terminal set point can be adjusted after an contingency and this introduces a lot more flexibility to the grid. The flexibility of the HVDC terminals is not constrained according to (29) for these investigations. Fig. 2 shows the cost of the different operation schemes. The terminal change derived from Eq. (49) were not active for this study.

The results quantifies the differences for the costs. If security measures are considered the cost rises by 14.8% in the HVAC only case, since the dispatch has to consider an outage of lines, forcing the cheap generator at Bus 1 has to reduce its production. The additional transmission capacity with the HVDC grid leads to a reduction in the cost for the comparable cases in all operation schemes. In the scheme without any security, the case with HVDC grid is 18.6% cheaper, since the cheap generator at Bus 1 can now supply almost the entire system load. If preventive security is taken into account, the HVDC case has 15.3% lower costs than than the HVAC case, but 16.2% higher cost than the case including an HVDC grid not no security. Comparing the last two bars in Fig. 2, we can see that post-contingency corrective control gives cost saving of about 10% compared to preventive control, which is a substantial difference.

2) Flexibility of the HVDC terminals: A rather quick change in the terminal set point after a disturbance can impose a threat to the dynamic stability of the HVAC grid. Therefore a study is performed to investigate the influence of the allowed deviation before and after a contingency. $\Delta P_T$ is introduced in Eq. (49) was varied between 0 and 0.4. Then the costs for different loading levels, compared to nominal loading level, are calculated and shown in Fig. 3. Each load was linearly scaled with the load factor, all other parameters stayed the same. The cost are normalized to the value without constraint in the power change for the specific load level.

The results for this grid show the dependency on the allowed changes in the terminal flows, before and after a contingency. The effects are more visible at higher loading levels, which is reasonable since the additional load has to be covered by more expensive generator units.

The effect starts to be visible at an allowed deviation of 0.25. The reason for this behavior is the grid topology. Bus 1 has a generator with capacity of about 332 MW and it is the cheapest generator in the whole grid. Bus 1 is connected with 2 HVAC lines and a converter station. Each of them has a limit of 100 MW, this limits the generator to 200 MW to be prepared for a outage of one out of the three connections. HVDC Terminal 1 is connected with two HVDC lines, each with a capacity of 50 MW. If one of this two line fails the HVDC terminal station needs to down regulate to this level. With an allowed delta of 0.25, the HVDC terminal station can be operated at 75 MW, this allows it to reach 50 MW and 100 MW, depending on the contingency. If these two points can be reached, the generator at Bus 1 can produce 200 MW. This is possible for an allowed change of at least 0.25.

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3) **Peak infeed:** A further study was done to compare the maximum infeed capability with the same five different operating scheme as above. The generator at Bus 1 was assumed to be a renewable generation with marginal generation costs close to zero. The allowed peak production are shown in Fig. 5. The maximum allowed peak is reached for the unsecured operation scheme with a HVDC grid, in this case the infeed is slightly below 250 MW. In general the capability to cover generation peak is increased with the HVDC grid for the comparable cases.

![Fig. 4. IEEE14DC - Terminal operation points for normal operation and during contingencies with changes limited to 0.25 pu.](image)

![Fig. 5. Allowed peak infeed at Bus 1 in the IEEE14DC grid.](image)

**B. Test grid RTS96DC**

The second test grid is an extended version of the RTS96 test case [13], with overlay HVDC grid added, which will be refereed to as RTS96DC. Fig. 6 shows the grid topology. Each HVDC terminal has a capacity of 500 MW and all HVDC lines are able to transfer 300 MW. The exact data is available in [14], [13]. For this study a slight change is done: HVDC Terminal 1 is shifted to Bus 118, where an new generator with low marginal cost and high capacity is assumed. Additionally 3 small HVDC generators, each with a capacity of 20 MW, are added to the HVDC grid directly at HVDC Bus 3, 4, and 5 respectively.

![Fig. 6. Test system RTS96DC - RTS96 test case with overlay HVDC grid.](image)

1) **Cost for different operation schemes:** The same five operation scheme are applied to the RTS96DC system. A similar cost behavior as in the IEEE14DC case is visible. The added HVDC grid has less influence on the cost than in the previous case. This is not surprising since the the HVAC grid is big relative to the HVDC grid, unlike for the previous test grid. Another reason is the positions of the HVDC terminals. With an optimized placement, however the overall grid would benefit more, but such an investigation is not part of this paper.
2) Flexibility of the terminals: The terminal limitations are investigated for the RTS96DC system. Again the more heavily loaded grid benefits more from the higher flexibility. In this case the distribution is not as clearly distinguished as in the IEEE14DC case. In the RTS96DC system an increased load changes the generator which defines the marginal cost, since the grid is much larger than the IEEE14DC case. The influence on the overall cost is strongly dependent on whether the cheap generators can benefit from a HVDC grid, or if the HVAC side is constrained before. Also visible is the rather small influence of the costs. The reasons for that are again the ratio in size and the placement.

Fig. 7. Normalized costs for different operation schemes in the RTS96DC test grid.

Fig. 8. RTS96DC - Compare costs of different terminal flexibility under different loading factors.

V. CONCLUSION AND OUTLOOK

This method extends the known and widely used operation principles for HVAC grids to incorporate HVDC grids. The preventive method is state-of-the-art for HVAC-only grids. Including the extension presented here, it works also in the combined HVAC and HVDC grid and can cover all possible outages, even the outage of an HVDC terminal. The full range of functions of the terminals can be used with the corrective control method, which lead to lower costs than the preventive method, but requires adjustments if any contingency happens. The benefits of a HVDC grid depend strongly on the grid topology, therefore the placing of the HVDC converter should be optimized. This is a further research topic, along with including the security assessments into the nonlinear OPF for combined HVAC and HVDC grids. Also a similar approach other fast controlled devices (FACTS and phase shifters) will be investigated.

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REFERENCES


