# HVAC/HVDC STRATEGY FOR SOLVING POWER DELIVERY SHORTAGES TO A LOCALISED AREA OF A NATIONAL GRID

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## Abstract

The industrial and population growth can cause power delivery problems to a localised area of a national grid. One reason for these power shortages is the insufficient current carrying capacity of existing HVAC transmission line supplying the area. Parallel HVAC line, a HVDC line or combinations of HVAC-HVDC lines are three possible solutions to improve power delivery. This paper investigates the various line possibilities using a cutting edge time domain software tool. The contribution of this work is the development of a strategy (flowchart) involving individual or combinations of HVAC and/or HVDC transmission lines taking into account important decision making factors. Simulation based case studies are conducted as part of the strategy and the results are verified. These results together with the decision making factors are then used to demonstrate that an integrated HVAC-HVDC system could be the chosen solution. The developed strategy is shown to be an effective planning tool.

## 1 Introduction

Localised areas in a large country are usually bulk supplied with electrical power via high voltage alternating current (HVAC) overhead transmission lines as part of a national grid. Due to increase in demand a localised area can experience power delivery shortages leading to controlled outages when transmission lines lack current carrying capacity and are tripped as they have reached their thermal limits, especially when the generation capacity in the localised area is by itself unable to carry the load. A load increase can cause a system to become unstable. Steady-state instability occurs when the power limits of the system are gradually exceeded. The power transferred or exchanged across a transmission line depends on the total angle (δ) between its sending and receiving end. The power angle across a long transmission line under steady-state conditions seldom exceeds 40°. Thus, lines should be operated within the range $\delta \leq 40°$ [1]. Steady-state stability can be enhanced by using multiple transmission circuits. Two circuits can deliver twice the power of one, thus parallel lines are utilized to increase capacity and provide a stabilising effect on a system [1]. HVDC systems on the other hand have characteristics that are attractive for certain transmission applications. HVDC transmission is recognized as being advantageous for long-distance bulk power delivery. Although the factors against HVDC are mostly cost, reactive power support, harmonic impact and configuration used, there are other reasons for its selection, for example, favourable economics of long-distance bulk-power transmission, smaller right-of-way (ROW) and reduction of line losses. Thus HVDC, together with its controllability, make it an interesting alternative or a complement to HVAC transmission. The fast acting controllers used with HVDC systems react quickly to load changes therefore they improve the stability of a power system [1]. However, unlike HVAC systems, line commutated HVDC are not operated independently but together with HVAC systems as they typically require a voltage source from a nation grid in order to operate [2].

The emphasis in literature has been on modelling and comparison of software tools and not on simulation investigations of power delivery of HVAC compared to integrated HVAC-HVDC transmission systems to a localised area of a national grid. Also, there are no publications on a methodology on how to go about finding a possible solution (integrated HVAC-HVDC transmission) for alleviating power shortages and the important factors associated with making a decision in this regard. There is thus a need for the development of such a strategy, incorporating associated factors together with simulation based case study results to demonstrate the effectiveness of the developed methodology.

## 2 Research Problem Definition

The problem investigated are the factors needed to develop a methodology for making a decision on transmission system types (HVAC/HVDC) used for supplying power to a localised area of a national grid experiencing delivery shortages. Also to investigate the application of a time domain software package for conducting specifically devised case studies to evaluate the effectiveness of the developed methodology.

## 3 Developed Strategy

A three-part strategy in the form of a flowchart is developed to propose a method for finding a solution to a power delivery shortage to a localised area of a national grid due to the lack of thermal capacity of overhead HVAC transmission lines.

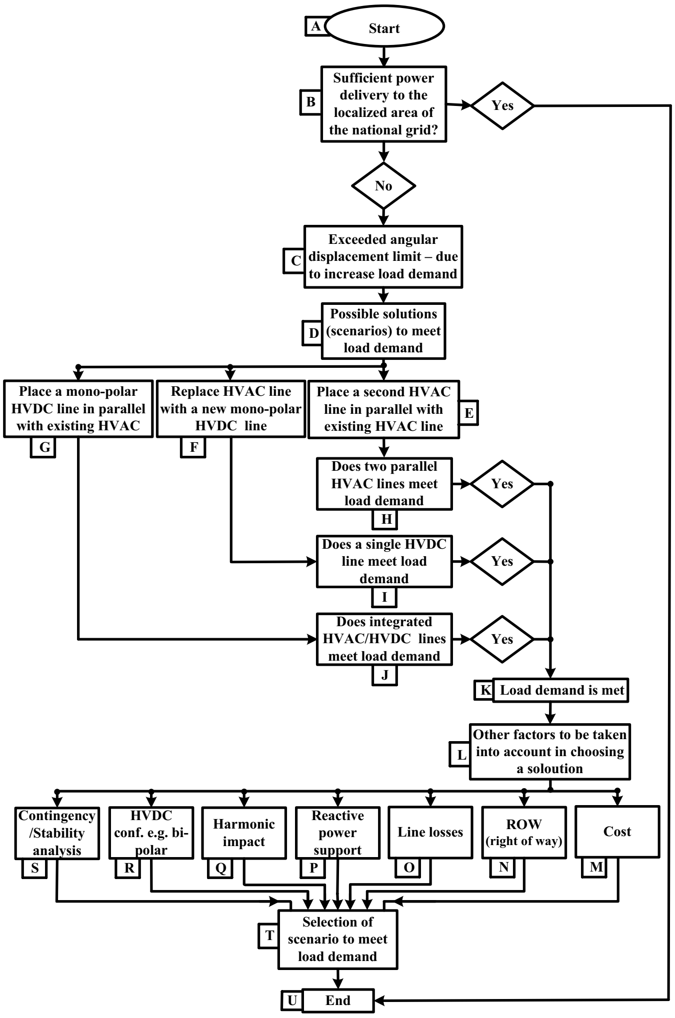


Figure 1. Strategy for solving power delivery problems

The purpose of this flowchart is to establish a decision making method to assist power system planners to make a choice between a HVAC transmission system or an integrated HVAC-HVDC supply for finding a solution to a power delivery shortage to a localised area of a national grid. This strategy includes factors that need consideration before a decision can be made on what solution to apply.

The flowchart starts at A. Here the question asked is: "Is there sufficient power delivery, (Block B)"? If yes, then the solution is to go directly to (U) as no problem exists. If no, the next question (C) is asked: "Is the angular displacement limit for the transmission line (δ) exceeded (δ > 40°) due to the load demand increasing beyond acceptable level"? If yes, (D) then the following solutions should be considered (E, F and G). The first possible solution is to add a similar HVAC transmission line in parallel with the existing one shown in Block E. The second solution is to replace to HVAC transmission line with a completely new HVDC scheme (Block F). The third solution proposed is the construction of a new HVDC transmission line in parallel with the existing HVAC transmission line. This solution is then an integrated HVAC/HVDC system (Block G).

Now questions are asked for each of the possible solutions (E, F, and G): Does the two HVAC parallel lines meet the demand (H)? Likewise, does a HVDC system (F) provide adequate power delivery (I)? Also, will an integrated HVAC/HVDC system (G) provide the solution (J)? If the answer to any of these questions is no, then it is excluded, if yes, then the increased load demand is met (K) and can be implemented. However, other factors need to be considered before making a decision, namely (L). The most important decision making factors that are needed to be considered are shown in blocks M-S. Once these factors have all been evaluated, a scenario (T) is selected as the solution and the strategy ends at U.

## 4 PSCAD/EMTDC software

This time domain software tool is selected as it has the capability to model and to perform simulation studies on HVAC or HVDC or an integrated HVAC-HVDC system as well as HVDC controllers and obtain accurate results [3], [4].

## 5 Strategy application

To prove the effectiveness of this developed three-part strategy (flowchart), five different case studies are conducted as the first-part of this methodology. The case studies are set up in a manner to demonstrate its implementation. The first case study will show a healthy system (power delivery met and δ ≤ 40°) so the flowchart is fast tracked from B-U. The second case will illustrate the problem where the angular displacement is exceeded (δ > 40°) due to load demand exceeding that which was originally planned. The remaining three case studies will evaluate the proposed solutions in blocks E-G with the emphasis on evaluation of integrated HVAC-HVDC system. The second-part introduces the decision making factors M to S and are descriptively implemented. Hypothetical case studies are utilized as the work reported is to demonstrate the strategy and its usefulness for later application to real studies. The third-part is making a scenario selection for implementation.

### 5.1 Case Study 1: HVAC transmission network

The following HVAC transmission network was investigated to illustrate a healthy network:

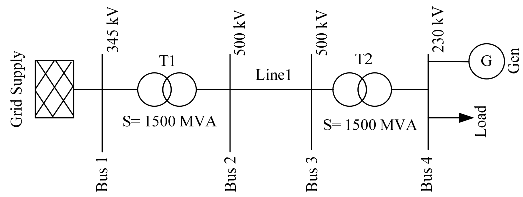


Figure 2. HVAC transmission network

#### 5.1.1 HVAC Transmission Network Modelling

From Figure 2, the three-phase HVAC network consists of a 50 Hz grid supply Bus 1 and is modelled as a slack bus

($V_{Bus1} = 1\angle 0^{\circ}\ pu$). T1 is a star-star connected transformer with 345 kV (L-L) voltage on its low voltage side connected to Bus 1 and 500 kV L-L voltage on its high voltage side connected to Bus 2. T1 has a Z% of 10% and X/R ratio of 50. The rating of the transformer is 1500 MVA. The HVAC transmission line (Line 1) is 500 km long at 500 kV L-L. The resistance of the line is 0.01 Ω/km, the reactance of the line is 0.75 Ω/km and the shunt susceptance is 1.634 μS/km. Line 1 is modelled as an equivalent-π model [5]. T2 is a star-star connected transformer with 500 kV/230 kV voltage ratings. Bus 4 is modelled as a voltage controlled bus with a fixed real power P and a fixed voltage magnitude $|V|$. The variables are the reactive power $Q$ and the voltage angle $\delta$. In this study the fixed $P$ is 500 MW. The voltage at Bus 4 is 1 pu V and its angle $\delta$ will be checked against the limit $\delta \leq 40°$. The load connected at Bus 4 represents the localised area of the national grid. The load at Bus 4 is modelled as a fixed PQ load. The load is modelled with a power rating of (700+j368.75) MVA.

### 5.1.2 HVAC Transmission Network Load Flow Results

The following PSCAD simulation results were obtained for the load flows (Table 1). The modelling and simulation results are verified using MATHCAD. The load demand is met with a $\delta = 17.97°$, that is, within the range $\delta \leq 40°$. The strategy is thus fast tracked B-U.

| Element | PSCAD/EMTDC | | Hand calc. | |
|---|---|---|---|---|
| | P (MW) | Q (Mvar) | P (MW) | Q (Mvar) |
| Grid sup | 201.23 | -76.45 | 200.85 | -76.54 |
| T1 | 201.17 | -79.53 | 200.79 | -79.62 |
| Line | 200.31 | 74.18 | 200.06 | 74.34 |
| T2 | 200.25 | 71.17 | 199.99 | 71.33 |
| Gen | 499.36 | 297.57 | 500 | 297.42 |
| Load | 699.62 | 368.73 | 700 | 368.75 |
| | V(kV) | δ | V (kV) | δ |
| Bus 1 | 345 | 0° | 345 | 0° |
| Bus 2 | 502 | -0.77° | 502 | -0.77° |
| Bus 3 | 502 | -17.22° | 502 | -17.19° |
| Bus 4 | 230 | -17.97° | 230 | -17.95° |

Table 1: Case 1: results

### 5.2 Case Study 2: HVAC Network with Increased Load

Case Study 2 illustrates the growth in load demand. The power system now needs to deliver 1000+j527 MVA. An investigation is necessary to examine if the HVAC transmission network will be able to supply this new load demand and if the angular displacement is within the allowable limit. For this simulation study the HVAC transmission system is modelled the same as in Case Study 1 and all the elements have the same parameters, only the load is increased.

### 5.2.1 HVAC Network with Increased Load Results

With the increased load of 1130 MVA the following, load flow results were obtained:

| Element | PSCAD/EMTDC | | Hand calc. | |
|---|---|---|---|---|
| | P (MW) | Q (Mvar) | P (MW) | Q (Mvar) |
| Grid sup | 506.61 | 126.61 | 506.22 | 126.05 |
| T1 | 506.24 | 108.43 | 505.86 | 105.12 |
| Line | 500.69 | -121.55 | 500.36 | -121.18 |
| T2 | 500.33 | -139.54 | 499.99 | -139.14 |
| Gen | 500.02 | 666.54 | 500.01 | 666.14 |
| Load | 1000.35 | 526.99 | 1000.00 | 527.00 |
| | V (kV) | δ | V (kV) | δ |
| Bus 1 | 345 | 0° | 345 | 0° |
| Bus 2 | 495.23 | -1.94° | 495.74 | -1.94° |
| Bus 3 | 495.97 | -48.78° | 495.98 | -48.73° |
| Bus 4 | 230 | -50.72° | 230 | -50.67° |

Table 2: Case 2: Results

From Table 2, the load demand is met but it can be seen that $\delta = 50.72°$ which exceeds the allowable practical operating $\delta$ of 40° by 10.72°. This means that the HVAC transmission network is not suitable to deliver the required load. This demonstrates the answer "No" to the question asked in (B) in Figure. 1 and the transmission line will be tripped. It is therefore necessary to investigate possible transmission solutions (blocks E-G) so that controlled load shedding will not be needed.

### 5.3 Case Study 3: HVAC/HVAC Parallel Operation

The single HVAC line is inadequate to meet this increased demand. For this reason, the first possible solution is examined and shown by Block E. Another HVAC transmission line is added in parallel as steady-state stability can be enhanced by using multiple transmission circuits. In this case study the effectiveness of parallel operation of HVAC transmission networks are investigated.

### 5.3.1 HVAC/HVAC Transmission network Modelling

The modelling of all the elements is the same as in Case Study 2. The two transmission lines connected in parallel are the same.

### 5.3.2 HVAC/HVAC Parallel Results

The following load flow results were obtained. The power delivery is met with $\delta = 22.69°$. Therefore the answer to (H) is yes.

| Element | P (MW) | Q (Mvar) |
|---|---|---|
| Grid sup | 503.16 | -116.96 |
| T1A&B | 251.49 | -62.93 |
| Line1&2 | 250.22 | 56.31 |
| T2 A&B | 250.13 | 51.96 |
| Gen | 499.89 | 423.54 |
| Load | 1000.15 | 527.52 |
| | V (kV) | δ |
| Bus 1 | 345 | 0° |
| Bus 2A&B | 501.85 | -0.96° |
| Bus 3A&B | 501.96 | -21.74° |
| Bus 4 | 230 | -22.69° |

Table 3: Case 3: Results

### 5.4 Case Study 4: HVDC Transmission Network

In this case study the single transmission line in Case Study 2 is replaced with a HVDC transmission line, which is the next possible solution (Block F). The CIGRÈ HVDC Benchmark Model with controllers is used as shown in Figure 3 [4].

#### 5.4.1 HVDC Transmission Network Modelling

The current controller for the rectifier and inverter are set to 2000 A for this investigation.

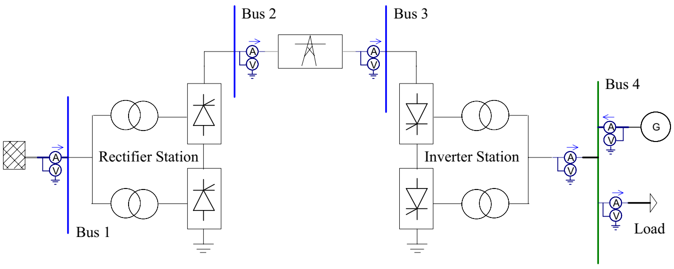


Figure 3. HVDC Transmission Network

#### 5.4.2 HVDC Transmission Network Parameters

The model is a monopolar radial line transmission system [4]. The rectifying bus, Bus 1 has a voltage magnitude of 345 kV L-L. The DC transmission voltage is 500 kV. The inverter bus, Bus 4 has an L-L voltage magnitude of 230 kV. Each 6-pulse bridge has a converter transformer. The transformer has an actual winding ratio of 1.62 pu. The Grid supply is modelled identical to that of Case Study 1, as well as the Generator but is then converted to a slack bus to supply only the needed real and reactive power. The stations are modelled as line-commutated converters with thyristor valves. The control system used in this study is a generic control system [4].

#### 5.4.3 HVDC Transmission Network Results.

The following load flow results were obtained. Some hand calculation results are generated to verify that results are accurate. The load demand is met, therefore the answer to block (I) is yes.

| Element | PSCAD/EMTDC | | Hand calc. | |
|---|---|---|---|---|
| | P (MW) | Q (Mvar) | P (MW) | Q (Mvar) |
| Grid sup | 1023.85 | -72.75 | - | - |
| Rect | 1009.02 | 0 | 1009.02 | 0 |
| Line | 988.92 | 0 | 988.92 | 0 |
| Inv | 972.52 | -79.81 | - | - |
| Gen | 26.84 | 447.03 | - | - |
| Load | 999.37 | 526.84 | - | - |
| | V (kV) | δ | V (kV) | δ |
| Bus 1(AC) | 345 | 0° | 345 | 0° |
| Bus 4 (AC) | 230 | 0° | 230 | 0° |
| Bus 2 (DC) | 504.48 | 0° | 504.52 | 0° |
| Bus 3 (DC) | 494.47 | 0° | 495.33 | 0° |

Table 4: Case 4: Results

### 5.5 Case Study 5: HVAC/HVDC OPERATION

The last scenario is an integrated HVAC-HVDC system. The models used for this investigation are the HVAC transmission line in Case Study 2 and an adapted HVDC transmission network of Case Study 4 and they are connected in parallel.

#### 5.5.1 HVAC-HVDC Transmission Network Modelling

If the DC current is left at 2000 A, the local network generator is found to absorb real power in this configuration. This is due to the fact that the power transmitted across the HVAC line and that of the HVDC line exceeds the load demand. In this scenario the HVDC controllers are set so that the DC current is halved, (1000 A) to overcome this problem.

#### 5.5.2 Integrated HVAC-HVDC transmission results

The power flow results are summarized in Table 5.

| Element | P (MW) | Q (Mvar) |
|---|---|---|
| Grid sup | 546.08 | -235.39 |
| Rect | 819.55 | 0 |
| DC Line | 807.21 | 0 |
| Inv | 791.14 | 213.625 |
| T1 | -288.95 | -39.55 |
| AC Line | -290.61 | 46.91 |
| T2 | -290.72 | 41.16 |
| Gen | 499.09 | 272.61 |
| Load | 999.49 | 527.284 |
| | V (kV) | δ |
| Bus 1 | 345 | 0° |
| Bus 2AC | 501.41 | 1.09° |
| Bus 3AC | 501.27 | 25.34 |
| Bus 4 | 230 | 26.46° |
| Bus 2 DC | 512.17 | 0° |
| Bus 3DC | 504.51 | 0° |

Table 5: Case 5: Results

The load demand is met and the angle $\delta$ for the HVAC line = 26.46° and is within the stable range of $\delta \leq 40°$. Therefore the answer to block (J) is yes.

### 5.6 LOAD DEMAND MET (Block K)

Now questions are asked for each of the possible solutions (E, F, and G): Does all three solutions meet the demand (H, I and J)? As the answers to these questions are yes, then the increased load demand is met (K) but before a selection can be made other factors need to be taken into account (L).The following decision making factors need to be considered before making any decision, namely (M to S).

### 5.7 COST AND ROW (Block M &N)

When it comes to long distance power transfer HVDC transmission can often provide a more cost effective alternative to HVAC transmission. Here, the concept of “break-even distance” frequently arises. This is where the savings in line construction costs is offset against converter station costs. Narrower ROW and smaller transmission towers are needed for comparable HVAC capacity and a rough approximation of the savings is 30%. The break-even distance is typically 500 km, yet this concept itself is misleading as in many cases more HVAC lines are needed to deliver the same power over the same distance due to system stability limitations and this was shown in Case Study 3 [2].

### 5.8 LINE LOSSES (Block O)

The $I^2R$ *losses* for HVDC are lower than for a comparable HVAC or multiple HVAC lines because fewer conductors are used and skin effect is negligible. The losses are typically 67% of HVAC lines. Also corona losses are less. [6].

### 5.9 REACTIVE POWER SUPPORT

HVDC converter stations have the disadvantage against HVAC lines as they consume reactive power in their conversion processes. Because of this, dedicated capacitors need to be installed as the reactive power demand is not usually forthcoming from the associated HVAC system [7].

### 5.10 HARMONIC IMPACT

Another disadvantage of HVDC is the injection of harmonics into HVAC systems due to the non-linear operation of converters. Harmonic filters and specified transformer connections need to be implemented to eliminate harmonics. Filters produce reactive power thus the rating of reactive power support capacitors are reduced when used in combination with filters [2] [6].

### 5.11 HVDC CONFIGURATION

Conventional HVDC transmission employs line-commutated converter thyristor valves. A monopolar system is the simplest and least expensive configuration for moderate power transfers. Another configuration used is a bipolar system with a single 12-pulse converter per pole at each terminal and can deliver twice the power of a monopolar configuration but at a higher cost and with more reliability as it has two independent HVDC systems [2].

### 5.12 CONTINGENCY AND STABILITY ANALYSIS

When parallel HVAC lines are used it has the advantage of contingency due to the fact that some of the load demand can still be met if a problem occurs on one of the lines. An important consideration is the "short circuit ratio (SCR)". The strength of an HVAC circuit at the bus of the HVDC substation is expressed by the SCR, Capacitors and filters reduce the SCR and when present the expression "effective short circuit ratio (ESCR) is preferred as it defines the relationship between the reduced short circuit level and the rated HVDC power. If a HVDC line replaces an HVAC line as in Case Study 4, its drawback is that it lacks contingency. However when an integrated HVAC-HVDC system is used as in Case Study 5, contingency analysis is improved. If either line is lost, the remaining line can still supply some of the power required by the load. An advantage of a properly controlled HVDC link is that it enhances the stability of the HVAC system in which it is embedded [6].

The third-part of the strategy is to select the scenario to meet the load demand (Block T). As the answers to blocks E, F and G in part-one are yes all three configurations are possible solutions from a pure power delivery aspect. However, in part-two it can be seen that other factors need in depth analysis before a selection of a scenario is made. Where power delivery via a transmission system to a localised area is of utmost importance and cost is not a constraint but ROW is a concern and contingency is vital, then an integrated HVAC/HVDC network should be used as it provides the best of the three configurations to increase power delivery.

## 6 CONCLUSION

The strategy developed is found suitable for decision making in regard to choosing a transmission line configuration. Five software case studies were conducted to test the developed strategy. These studies demonstrate the software tools ability to help with conducting strategies involving HVAC/HVDC networks. Case Study 1 showed a healthy system whereas Case Study 2 showed the violation of the angular displacement limit and thus portraying an unhealthy system. From the results obtained in cases 3 to 5 it was found that all possible solutions were able to supply the load demand. The results obtained from the simulations were compared to that of hand calculations and the results were similar. Each of these solutions has their own considerations. The HVDC system has the drawback that if any large component is lost the system cannot deliver any power. However the HVAC/HVDC integration has the advantage that if the AC source to the inverter is lost, the HVAC line can still supply a portion of the load, thus making it the most preferred option. This proves the effectiveness of the strategy and will have value for studying real systems.

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