Implementation of HVDC Technology with Technical Challenges for Economic Dispatch

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Abstract – **High Voltage Direct Current (HVDC) technology has proven to be a techno-economic means of meeting high power demand while ensuring the reliability and sustainability of modern power systems. This paper addresses Economic Dispatch for HVDC incorporating the technical challenges of voltage instability, difficulty in protecting Direct Current (DC) systems, and the losses involved. A cost function is formulated to include fuel cost due to optimal power generation of each generating unit, a revenue loss term and a compensation cost due to a power outage caused by the addressed challenges. A comparison is also made between Economic Dispatch (ED) for HVDC and High Voltage Alternating Current (HVAC) considering losses. Novel Bat Algorithm (NBA) has been used to solve the problem and its effectiveness tested on IEEE 6-generator 30-bus system.**

Keywords - **Economic Dispatch (ED), HVDC, HVAC, HVDC technology**

I. INTRODUCTION

Several research projects have been done on ED with HVDC. According to J. Zhu et al [1], Multi-Terminal Direct Current (MTDC) transmission systems have technical and economic benefits. The authors used Monte Carlo simulation to emulate forced outages for DC lines and converters. A HVDC grid test system proposed by CIGRE B4-58 system was used for economic assessment of these grids. Nevertheless, the concepts outlined in the paper were not formulated. In [2], load flow analysis and optimal power flow studies were used to elaborate on the operation of a HVDC system. The authors used Improved Genetic Algorithm (IGA) to solve the ED problem. However, they failed to address the technical aspects of comparing HVDC with HVAC. Further research by Musau et al [3], introduced the concept of Multi Objective Dynamic Economic Dispatch (MODED) with Renewable Energy (RE) and still employed IGA to tackle the problem. In this paper, Probabilistic Load Flow (PLF) was used to determine the optimal cost while a Scenario Based Method (SBM) determined the HVDC link parameters. Nonetheless, the authors did not investigate the ways of overcoming challenges associated with HVDC systems.

According to Waswa [4], solution of ED for a combined HVAC/HVDC transmission system yielded lower losses and production cost than that of a pure AC system. Particle Swarm Optimization (PSO) was used to solve the combined ED problem. However, the work did not account for current levels in the converter thereby yielding approximate DC losses. In Edwin's research [5], a comparison of thermal generation with a hybrid of thermal, wind, and solar PV generation through HVDC transmission considering line losses is done. Modified Particle Swarm Optimization (MPSO) method was used in MATLAB environment for the solution. This paper did not incorporate conversion losses when formulating the ED. Additionally, J.Sun et al [6] introduced for the first time the technical challenges for viable implementation of HVDC grids. These challenges were related to the limitations of Line Commutated Converter (LCC) HVDC technology. The authors employed sequence impedance method for system modelling and analysis in the solution. Finally, B. Ojwang [7] used a different optimization technique, Improved Strength Pareto Evolution Algorithm (SPEA2), to solve ED for HVDC with Renewable Energy (RE). The author formulated more accurate HVDC-HVAC line losses putting hydro and other renewable energy constraints into play. In his work, it was assumed that conduction loss was negligible. This paper will therefore formulate ED with HVDC incorporating voltage instability, difficulty in protecting DC systems, and losses involved in the transmission and conversion processes. These technical challenges are normally encountered in many modern power systems that adopt HVDC technology hence this work will provide a practicable solution.

A. Contribution

Previously, the Economic Dispatch with Hydro Resource and other Renewable Energy Sources (RES) with their constraints were introduced [7]. Further, a better HVDC and HVAC line losses was formulated [7]. In this paper, the technical aspects of HVDC transmission have been introduced in Economic Dispatch (ED). This paper provides an improved formulation of ED with HVDC incorporating the cost incurred due to the technical challenges associated with adopting HVDC technology. The modified cost function includes the additional cost due to voltage instability, protection difficulty and losses in DC systems. Both transmission and conversion losses (switching and conduction losses) are considered in ED with HVDC. The solution employs NBA in MATLAB R2017a environment.

B. Paper Organization

The rest of the paper is organized as follows: Section II is the problem formulation, Section III is the proposed methodology, Section IV is a presentation of simulated results, while Section V is the work's conclusion and suggestions for further research. Lastly, the references used are listed.

II. PROBLEM FORMULATION

A. Thermal Cost Function

The objective cost function with valve-point loading for a thermal power plant having n generating units as stated by [5]:

$$F(P_i) = \{a_i P_i^2 + b_i P_i + c_i\} + e_i sin f_i (P_i^{min} - P_i) \quad (1a)$$

Where a_i , b_i and c_i are the fuel cost coefficients of generator i, P_i^{min} is the ith generating unit's minimum output, e_i and f_i are the coefficients of ith unit reflecting the valve-point effects.

B. Modified Thermal Cost Function after Incorporating Voltage Instability and Protection Difficulty

Voltage instability at various buses and DC system's protection difficulty may lead to tripping of the few available protection equipment and transmission lines in the affected section. A power outage hence occurs resulting in additional costs incurred due to loss of revenue and the cost of compensating the consumers in the duration of the power outage.

The cost function becomes:

$$F(P_j) = F(P_i) + \sum_{j=1}^{n} \tau E_j + \sum_{j=1}^{n} \beta\, E_j \quad (1b)$$

Where τ is a revenue loss factor, E_j is energy lost during a power outage in MWh, and β is a compensation rate in \$/MWh.

C. Transmission Loss Cost Function

Transmission line losses are calculated using Kron formula.

$$P_{TL} = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i\, B_{ij} P_j + \sum_{i=1}^{n} P_i\, B_{i0} + B_{00} \quad (2)$$

Where B_{ij} are the B-coefficients which rely on the system's operating state.

D. Conversion Loss Cost Function

The converter valve is a major contributor of losses in HVDC transmission mainly during the conduction and switching modes [8]. Considering active front end Voltage Source Converters (VSCs), the switching and conduction losses are formulated using equations (3) and (5) respectively. The cost functions of the conversion losses are formulated in equations (4) and (6).

$$P_{SW} = \frac{1}{T_{net}} \sum_{i=1}^{n} E_i \approx \frac{f_{SW}}{T_{net}} \int_{t=1}^{T} \left(\sum_{j=1}^{n} a_j\, i t^{j-1}\right) \frac{V_{DC}}{V_{ref}}\, dt \quad (3)$$

Where T_{net} is the time taken for the network to switch, E_i is the energy for the i[th] unit, f_{SW} is the switching frequency, V_{DC} is the dc voltage to be transmitted, and V_{ref} is the reference voltage.

Assuming the switching losses at the sending end is equal to the switching losses at the receiving end, the cost function becomes [7]:

$$F(P_{sw,ij}) = \left\{\sum_{j=1}^{m} a_{j,i} P_{sw\ j,i}^{j-1} + c_j\right\} \quad (4)$$

Where c_j is the error associated with the switching.

Conduction losses are obtained using a piece-wise linear approximation for the forward characteristics of the power device [9]. Total conduction loss for a diode and transistor is given by:

$$P_{cond,ij} = \{r_{T_0}(I_{T_1}^{rms})^2 + V_{T_0} I_{T_1}^{avg}\} + \{r_{D_0}(I_{D_1}^{rms})^2 + V_{D_0} I_{D_1}^{avg}\} \quad (5)$$

Where parameters $r_{T_0}, V_{T_0}, r_{D_0}$, and V_{D_0} are found on the semiconductor datasheet [9].

The cost function is expressed as:

$$F(P_{cond,ij}) = \left\{\sum_{j=1}^{m} a_{j,i} P_{cond\ j,i}^{j-1} + d_j\right\} \quad (6)$$

Where d_j is the error associated with the conduction.

E. Overall Formulation

$$F = \min\left[\sum_{i=1}^{n} F(P_{i,j}) + F(P_{TL\,i,j}) + F(P_{sw,ij}) + F(P_{cond,ij})\right] \quad (7)$$

F. Power Balance Constraint

$$\sum_{i=1}^{n} P_i = P_D + P_L \quad (8)$$

Where P_D is the total system load and P_L is the total loss.

G. Generation Capacity Constraints

$$P_i^{min} \le P_i \le P_i^{max} \quad (9)$$

H. HVDC Constraints

Converter Ignition Angle Constraint

$$\alpha_{min} \le \alpha \le \alpha_{max} \quad (10)$$

Converter Extinction Angle Constraint

$$\gamma_{min} \le \gamma \le \gamma_{max} \quad (11)$$

Voltage Constraint

$$V_{dc,min} \le V_{dc} \le V_{dc,max} \quad (12)$$

Current Constraint

$$I_{dc,min} \le I_{dc} \le I_{dc,max} \quad (13)$$

I. Voltage Stability of Multi-Infeed HVDC System

When multi-infeed HVDC systems are based on LCC HVDC links, maintaining stable tolerable voltages at all system buses under either normal operation or under a disturbance becomes difficult [10].

To investigate how Voltage Source Converter (VSC) transmission aids in improving voltage stability, a short circuit was introduced at bus 1 of the dual infeed network in figure 1 after which the real and reactive powers were monitored.

The maximum power that can be transmitted to the receiving end in a circuit without the loss of synchronism determines the steady state stability limit [11].

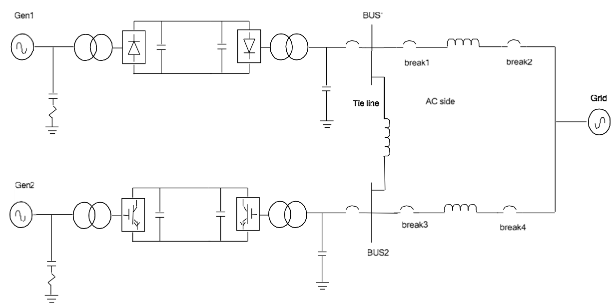

Figure 1: Dual Infeed HVDC Network

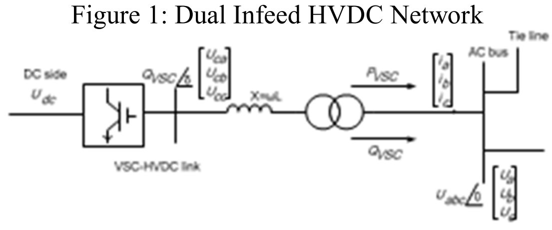

Figure 2: Basic Circuit of a VSC at Grid Side

Equations (14) to (17) are applicable in analyzing the AC voltage control strategy as given in [10].

$$P_{vsc} = \frac{U_{cabc}U_{abc}}{X} sin\delta \quad (14)$$

$$Q_{vsc} = \frac{U_{cabc}U_{abc}\cos\delta - U_{abc}^2}{X} \quad (15)$$

Where P_{vsc} is the active power transmitted by the VSC-HVDC link, Q_{vsc} is the reactive power transmitted by the VSC-HVDC link, X is reactance given by ωL, and δ is a very small phase angle difference between U_{cabc} and U_{abc} such that $sin\delta = \delta$ and $cos\delta = 1$.

J. Protection of DC Systems

In AC systems, the breaker easily interrupts the arc at natural current zero in the AC wave during which the energy to be interrupted is also zero. However, in DC systems, it is difficult to interrupt large DC currents at high voltages due to the absence of natural current zero in DC waveforms. When the circuit breaker contacts open during a fault, it is necessary for an arc to form in the medium separating the contacts; otherwise, there would be sudden interruption of current resulting in a huge switching overvoltage.

Equation (18) gives the arc voltage in a Low Voltage Direct Current (LVDC) air-break DC circuit breaker according to [12].

$$V_{arc} = V_s - IR_s \quad (16)$$

Where V_{arc} is a non-linear function of the circuit current I, R_s is the system resistance, and V_s is the system voltage.
When $V_{arc} = 0$, there is a sudden interruption of the current without arc formation causing a switching overvoltage that severely stresses the system's insulation.

III. PROPOSED METHOD

NBA developed by Xian-Bing Meng to improve on Bat algorithm is proposed for solving the ED problem. The algorithm is based on the echolocation behavior of bats where they utilize sound waves and echoes to enable them avoid obstacles and detect prey [13]. The original BAT algorithm assumes that the bats fly arbitrarily with a velocity v_i at position x_i with fixed frequency f_{min}. The wavelength and loudness A_o of these bats tend to vary. During initialization, the loudness is maximum and the emitted pulses are minimum. The loudness decreases while the pulse emission rate increases as the bats get closer to the prey [14].

NBA introduces quantum behavior to speed up the algorithm and mechanical behavior to enable global optimality [14]. Habitat selection using NBA permits the bats to move between different habitats with a given probability of appearing at any position in the whole search space [15]. The algorithm also has the ability to target a large number of prey.

The modeling of habitat selection entails a probability of selection P [0,1] and R, a uniform random number in [0,1]. If R is smaller than P, bats will select the quantum behavior, else, they would take the mechanical behavior. Equation (19) is used to determine the position of the bats with quantum behavior [15].

$$x_{ij}^{t+1} = \begin{cases} g_j^t + \theta * \left|mean_j^t - x_{ij}^t\right| * \ln\left(\frac{1}{u_{ij}}\right), if\ rand_j(0,1) < 0.5 \\ g_j^t - \theta * \left|mean_j^t - x_{ij}^t\right| * \ln\left(\frac{1}{u_{ij}}\right), otherwise \end{cases} \quad (17)$$

Where x_{ij}^{t+1} is the position of the virtual bats, g_j^t is the global best location indicating the prey's location, θ is the contraction-expansion coefficient, and u_{ij} is a number uniformly distributed between 0 and 1.

Equation (18) determines the frequency of the bats while equation (19) is used for compensation of Doppler effect. The velocity and new position of all the bats is obtained using equations (20) and (21) respectively.

$$f_{ij} = f_{min} + (f_{\max} - f_{min}) * rand(0,1) \quad (18)$$

Where f_{min} is the minimum frequency of the bat and $f_{\max}$ is the maximum frequency of the bat.

$$f'_{ij} = \frac{(c+v_{ij}^t)}{c+v_{gj}^t} * f_{ij} * (1 + C_i * \frac{(g_j^t - x_{ij}^t)}{\left|g_j^t - x_{ij}^t\right| + \varepsilon}) \quad (19)$$

Where f'_{ij} is the new prey's frequency considering Doppler effect, c is the speed of light; at time step t, v_{ij}^t is the bat's velocity, x_{ij}^t is the bat's position, and v_{gj}^t is the prey's velocity; f_{ij} is the bat's frequency, C_i is the compensation for Doppler Effect, g_j^t is the prey's location, and ε is a small constant that eliminates zero-division error in computers.

$$v_{ij}^{t+1} = w * v_{ij}^t + \left(g_j^t - x_{ij}^t\right) * f_{ij} \quad (20)$$

Where v_{ij}^{t+1} is the bat's velocity at time step t+1, w is the inertial weight of the bat, and v_{ij}^t is the bat's velocity at time step t.

$$x_{ij}^{t+1} = x_{ij}^t + v_{ij}^t \quad (21)$$

Where x_{ij}^{t+1} is the bat's position at time step t+1, x_{ij}^t is the bat's position at time step t and v_{ij}^t is the bat's velocity at time step t.

During local search by bats around their prey, the relative loudness between a given bat and the average loudness of all the bats is considered. Equation (25) computes the new position of each bat during local search.

$$If\ (rand(0,1) > r_i) \quad (22)$$

Where r_i is the rate of pulse emission.

$$x_{ij}^{t+1} = g_j^t * (1 + rand\ n(0, \sigma^2)) \quad (23)$$

Where $rand\ n(0, \sigma^2)$ is a Gaussian distribution with mean 0 and standard deviation σ^2.

$$\sigma^2 = \left|A_i^t - A_{mean}^t\right| + \varepsilon \quad (24)$$

Where σ^2 is standard deviation, A^t_{mean} is the average loudness of all bats at time step t, and ε is used to ensure that the standard deviation is positive.

When updating solutions by flying randomly, equations (27)-(30) are used.

$$If\ (rand(0,1) < A_i \ \&\&\ f(x_i) < f(x)) \quad (25)$$

$$f(x) = f(x_i) \quad (26)$$

$$A_i^{t+1} = \alpha A_i^t \quad (27)$$

$$r_i^{t+1} = r_i^0 (1 - e^{-\gamma t}) \quad (28)$$

Where α and γ are constants such that $\gamma > 0$ so that the rate of pulse emission is only restricted to increasing.

NBA Parameters

Population: The thermal sources of energy considered during the search for the optimum generation quantity, make up the population.

Individuals, N: They constitute of the generating units whose ideal generation levels are determined.

Echolocation: This represents optimizing the output of each generating unit then minimizing the cost function based on equation (7) after considering the losses.

Habitat selection: The probability P represents the likelihood of selecting a certain generating unit based on its generation level and effectiveness in minimizing the cost.

Doppler Effect: It denotes the variation in a generator's output as the load demand varies.

Loudness, A_i: This represents the overall cost of power generation normally high before optimization of the generators' outputs.

Pulse emission rate, r_i: It represents the rate of power generation by the committed generating units. During initialization, r_i has a very small value.

Environmental effect: In NBA, this denotes other sources of loudness other than the bat- induced one. A^t_{mean} in equation (26) is the average loudness of all bats including environmental effect. This represents other costs that contributed to the total generation cost beside the fuel cost.

A summary of NBA parameter mapping for the ED problem is given in table 1.

Table 1: Parameter Mapping for the ED Problem

NBA Parameter	*Mapping to the ED Problem*
Population	Thermal energy sources
Individuals	Generating units
Habitat selection	Allocation of generation levels to the generating units
Doppler effect	Variation in a generating unit's output with demand
Pulse emission rate, r_i	Amount of power output by a specific unit
Loudness, A_i	Overall fuel cost value
Environmental effect	Additional cost incurred during a power outage

Pseudocode

i. Statement of the system's parameters such as the upper and lower limits of the generating units.
ii. Specification of power demand.
iii. Setting of NBA parameters.
iv. Evaluation of a generating unit's optimal generation level.
v. Determination of power losses.
vi. Checking whether the power balance constraint is satisfied.
vii. Computation of the corresponding objective function value using equations (1a) and (1b) and (7).
viii. Updating the generating unit's output, losses and cost for a given power demand.
ix. Stopping the process once an optimum value is attained.

MATLAB R2017a has been used to implement the NBA. An IEEE 6-generator 30-bus system, whose data is obtained from [5], has been used to verify the effectiveness of the NBA algorithm.

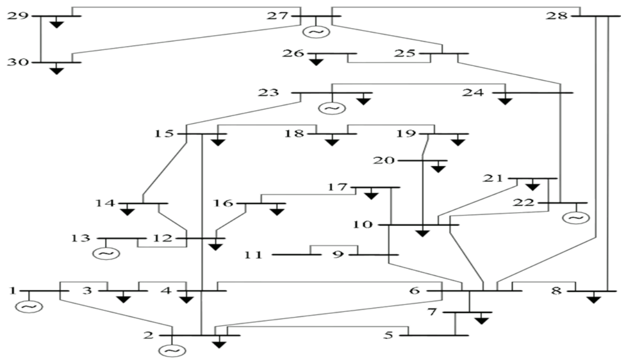

Figure 3: Validation Technique [5]

IV. RESULTS AND ANALYSIS

The optimal generation levels of six thermal generating units and the corresponding cost is determined for various power demands. The following cases are considered:

Case 1: Economic Dispatch for HVAC with Losses (Base Scenario)

Case 2: Economic Dispatch for HVDC with Losses

Case 3: Economic Dispatch for HVDC Incorporating the Challenge of Voltage Instability and Protection Difficulty in the System

Fuel Cost:

The fuel cost is given in table 2.

Table 2 and figure 4 show that the fuel cost increased with power demand for all the three cases. However, for smaller loads, such as 120MW, the margin in cost between cases 1 and 2 was lower than at higher demands (overgeneration). For instance, at 120MW, the percentage margin between cases 1 and 2 was 20.48% while at 420 MW it was 61.08%.

This clearly portrayed that at higher load demands HVDC transmission was more cost-effective than HVAC transmission. Comparing cases 1 and 3, there was an average margin of 34.76%. Case 3 yielded less fuel cost than case 1 implying that HVDC transmission incorporating technical challenges for viable implementation was still better than pure HVAC transmission. On the other hand, comparing cases 2 and 3 showed that incorporating technical challenges in HVDC transmission slightly increased the fuel cost by 7.44%. This was because of the extra cost due to loss of revenue by the generating entity during a power outage and the cost of compensating the consumers.

Table 2: Cost Comparisons for the Three Cases

Power Demand (MW)	**Total Fuel Cost ($)**		
	Case 1	**Case 2**	**Case 3**
120	2111.20	1678.80	1771.14
180	2594.45	1962.11	2100.63
240	3447.72	2327.40	2512.36
300	4934.80	2802.56	3034.21
360	7343.89	3414.68	3693.60
420	10891.00	4238.64	4565.47

This is represented graphically as shown in figure 4.

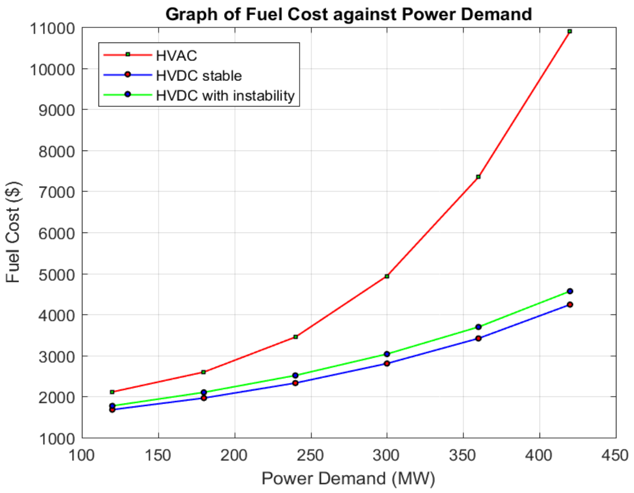

Figure 4: Line Graph of Fuel Cost for HVAC, HVDC, and HVDC with Instability against Power Demand

Losses:
The power losses versus the demand for HVDC and HVAC are represented graphically as depicted in figure 5.

From figure 5, it is depicted that the total power losses in the test system increased with increase in power demand. At all power demands, the loss in the HVAC system was higher than that in the HVDC system. The HVDC losses were approximately 75% of the HVAC losses.

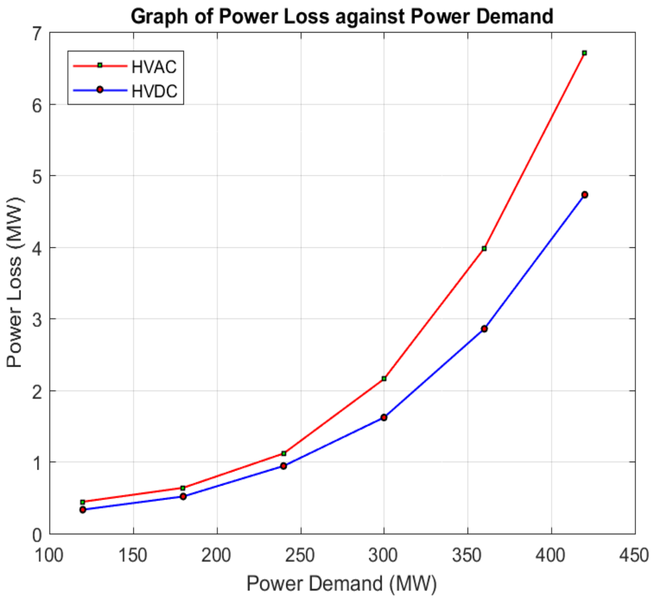

Figure 5: Line Graph of Power Loss against Power Demand for HVAC and HVDC

HVDC Losses:
These losses comprised of conduction, switching and transmission line losses. The losses are graphically represented in figure 6.

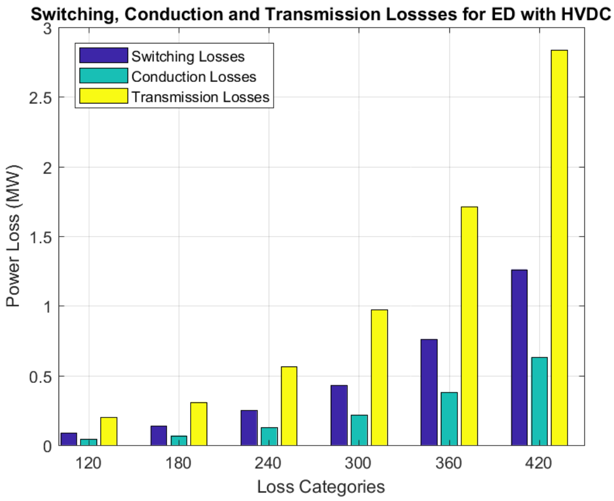

Figure 6: Comparison of Switching, Conduction, and Transmission Losses in HVDC

According to figure 6, transmission losses were higher than switching and conduction losses at all load demands. The transmission losses contributed to about 60% of the total HVDC losses while switching and conduction losses were about 27% and 13% respectively. Therefore, the conduction loss in a voltage source converter can be said to be half the loss that occurs during the switching mode.

Case 3:
Based on the results, HVDC transmission is the most viable way of minimizing power loss and fuel cost at high power demands. Case 3 incorporated the use of VSC transmission to improve stability in the dual infeed network and

considered the additional cost due to protection difficulty in DC systems. It achieved a fuel cost of 65.24% to that of the HVAC system (case 1). Additionally, the losses in the HVDC system were 25% less than those in the case of HVAC system.

Use of VSC transmission to Improve Stability in a Multi-Infeed HVDC System

VSC-HVDC transmission employs converters that have independent control of active and reactive power and are insusceptible to commutation failure. This makes them a feasible option for maintaining stability of system voltage in the multi-infeed HVDC network. The introduction of a short circuit at bus 1 (figure 1) of the LCC link led to the disconnection of the LCC link from the grid by opening of the breakers. The active power, P_{VSC}, slightly fluctuated during the occurrence of the fault but stabilized after fault clearance. On the other hand, reactive power, Q_{VSC}, increased during the transient condition induced by the fault and remained high until the breakers reclosed after the fault cleared.

The increase in the reactive power delivered by the VSC allows for sufficient compensation of the reactive power in the LCC link since during the fault condition the LCC-HVDC link is disconnected from the AC grid that normally supplies it with reactive power. This helps in overcoming voltage instability hence the power system is able to maintain steady voltages at all buses in the system when subjected to a disturbance.

Protection of DC Systems

The circuit breakers used in the model in figure 1 became useful in fault isolation. They isolated the LCC link from the grid allowing it to still deliver real power to bus 2 through the tie line and receive reactive power from the AC bus of the VSC link thereby maintaining stable operation even during the grid fault.

V. CONCLUSION AND RECOMMENDATIONS

The cost function incorporating the additional cost due to voltage instability and difficulty in protection of a DC system included a revenue loss term (obtained using a loss rate τ of 2.85$/MWh) and a compensation amount (based on a compensation rate β of $1.75/MWh) for the duration of the resulting power outage.

The most suitable transmission system for high power demands was found to be HVDC because of its efficacy in minimizing losses and the overall fuel cost. It achieved a total fuel cost averagely 39.19% less than that of purely HVAC transmission. However, considering the additional cost due to technical challenges associated with HVDC transmission, the total fuel cost achieved was 34.76% less than that of HVAC transmission. Therefore, in regards to fuel cost, with or without considering the challenges for viable implementation of HVDC transmission, HVDC is still better than HVAC transmission. Additionally, the HVDC system had 25% less losses than the HVAC system.

In a multi-infeed network, a VSC would help maintain voltage stability at the system buses by supplying reactive power to the AC bus of the LCC link during normal and transient operating conditions. Consequently, using a VSC link and an LCC link together in a multi-infeed HVDC network would minimize the need to use capacitor banks and STATCOM for reactive power compensation in the LCC link. Additionally, circuit breakers placed at various positions in the system would aid in an almost immediate isolation of the faulty sections. Considering the difficulty in designing HVDC protection schemes, auxiliary means such as vacuum interrupters would be necessary to artificially reduce the current in a DC circuit breaker to zero.

Further research should be done on ED for HVDC with transmission and conversion losses integrating renewable energy and considering harmonics in a DC system. There is need to investigate the impacts of technical aspects involved in HVDC transmission on dynamic economic dispatch considering different HVDC configurations. Moreover, comparing ED for HVDC transmission using VSC and LCC links independently to establish the best choice in a HVDC microgrid system is necessary.

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