

Techno-economic Unified OPF Modeling for VSC-HVDC Converter Installation

Sunilkumar Agrawal^{id}, Prasanta Kundu^{id}

Department of Electrical Engineering, S.V. National Institute of Technology, Surat, India

Cite this article as: S. Agrawal, P. Kundu. "Techno-economic Unified OPF Modeling for VSC-HVDC Converter Installation", *Electrica*, vol. 21, no. 3, pp. 352-365, Sep. 2021.

ABSTRACT

This paper demonstrates the analysis of novel methodology developed to select optimal buses for installation of converter stations in the hybrid voltage source converter based high voltage direct current system. Here, a modified unified optimal power flow model is developed for the optimal power flow problem and solved using the particle swarm optimization technique for the voltage source converter-based high voltage direct current network. The analysis has been performed for optimizing the various techno-economic objective functions, including generation cost, voltage deviation, and total power system losses, for better power system operation. The developed unified optimal power flow model's effectiveness and methodology for deciding the high voltage direct current converter's optimal location are examined, with several tests performed with modified five-bus and IEEE-30 bus system. The impact of high voltage direct current line replacement is decided based on optimal results obtained for selected techno-economic objective functions by replacing each AC line with high voltage direct current independently. The obtained results have proved the voltage source converter-high voltage direct current controller's impact on optimization of generation cost, voltage deviation, and total power system losses.

Index Terms—Optimal power flow, particle swarm optimization algorithm, power system optimization, unified optimal power flow modeling, voltage source converter-based high voltage direct current.

Corresponding Author:

Sunilkumar Agrawal

E-mail:

sunil11187@gmail.com

Received: February 11, 2021

Accepted: May 8, 2021

Available Online Date: August 23, 2021

DOI: 10.5152/electrica.2021.21014



Content of this journal is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License.

Nomenclature

AC system		DC System	
PG	Active power generation	VSC	Voltage Source Converter
QG	Reactive power generation	Ps	Real power injected at converter AC side terminal
QC'	Reactive power compensator	Qs	Reactive power injected at converter AC side terminal
V_G	Generator bus voltages	Vdc	DC bus voltage magnitude
V_D	Load bus voltages	Vc	Converter AC side bus voltage
T	Transformer tap setting	Gtc	Conductance at converter AC side
Slm	Apparent power through line	Btc	Susceptance at converter AC side
NL	Number of load buses	Ndc	Number of DC buses
Ng	Number of generator buses	<i>nldc</i>	Number of DC lines
<i>Nlac</i>	Number of AC lines	Sc	Converter power in MVA
ak, bk, ck	Generation cost coefficient of kth generator	a_i, b_i, c_i	Average loss model coefficient for VSC converter

OPF terminology		PSO terminology	
$f(x, u)$	Objective Function	k	Index for PSO iteration
$g'(x, u)$	Set of unified AC/DC power flow equation	c_1, c_2	PSO acceleration coefficients
x	State variables	y	Particle position
u	Control variables	v	Particle velocity
l, m, n	Index for OPF model	ω	Inertia weight
		$rand_1, rand_2$	Random variables

I. INTRODUCTION

With the continuous increase in demand for electric power, and the availability of different options for electrical power sources, transmission systems are operated under huge stress to maintain a balance between demand and sources. Electrical power systems have witnessed various progressive changes in all dimensions. Recent developments in electrical networks, such as large-scale offshore wind power generation, distribution generation, large-scale photovoltaic (PV) generation, and electricity market reforms, have changed the traditional structure of electrical power networks. This emphasizes the need for more cognitive electricity networks which are rapid and accurate, which is possible due to technological advancements in fast-acting control devices, such as flexible AC transmission systems (FACTS) controller and HVDC technology. A power engineer's prime responsibility is to manage electricity flow for reliable and uninterrupted electrical network operation by surmounting such difficulties.

The progressive developments in the field of power electronics have given birth to various controller technologies for power systems. These control strategies are much more reliable and faster than traditional strategies that required extensive manual support. Many transmission line controllers are grouped in one basket and termed FACTS [1]. The various works in the literature have studied and covered different aspects of the power system, including planning, security, stability, reliability, and economic operation with the FACTS controller. Another promising technology that has emerged in parallel is the HVDC transmission system, which can transfer a larger amount of power over the long-distance transmission network compared with the AC network. In recent developments, the VSC-based HVDC system is more advantageous over the conventional current source converter (CSC)-based HVDC system that works based on the line commutation technique. These advantages include separate control of active and reactive power, uninterrupted operating bi-directional power transfer, reduced harmonics components, and smaller filter requirements [2-6].

These new structural changes require detailed planning for better operation and control in any power system. The optimal power flow (OPF) analysis is a perfect method to overcome this

problem, as it satisfies the operational and economic requirements of the power system. It identifies an optimal state of control variables of the power system for a particular objective function by limiting the other operational constraints [7]. Many traditional methods have been used so far, mainly categorized as deterministic solution techniques with excellent convergence ability. However, they possess certain disadvantages, for instance, they may not find a global optimal point and may converge at the local optimal point. They are not suitable with binary models, and these methods possess many assumptions such as convexity and differentiability, and are also limited to continuous variable OPF. Most of them have been applied so far for traditional AC transmission networks and emerging HVDC networks.

Various stochastic methods have been developed within the last two decades and have attracted researchers' attention to the OPF problem related to the power system. These methods have overcome the drawbacks of traditional numerical techniques. They can handle non-convex, nonlinear, and discrete problems such as OPF, and provide global optima. Some widely tested methods in OPF problems are evolutionary algorithm (EA) [8]; genetic algorithm (GA) [9]; particle swarm optimization (PSO) [10]; ant bee colony (ABC) [11]; teaching-learning based optimization (TLBO) [12]; and tabu search (TB) [13]. All these references have applied the heuristic methods for AC networks only.

As discussed earlier, various heuristic methods have been applied on a large scale for traditional AC networks, and heuristic methods have produced better and more promising results compared with numerical methods. There are impressive efforts that have been made for solving OPF problems for HVDC networks [14-16], but they have considered the current source converter HVDC (CSC-HVDC) system, which possesses technical limitations as compared to the voltage source converter HVDC (VSC-HVDC). Little effort, so far, has been put into VSC-HVDC OPF problems. They have either used numerical methods [17-22] or heuristic methods [23-25]. The HVDC and FACTS controller technologies have been developed in parallel with the advancement of semiconductor materials. Both are now at their mature state, with the introduction of fast-acting controller switches. The worldwide applications of HVDC and FACTS controllers in transmission networks have

increased since their inception. Many studies in the literature have optimized different techno-economic objective functions by applying the FACTS controller in the transmission network [26-34]. The optimal location of FACTS controllers is suggested in [35-39] by optimizing the power system performance indices. By comparing this work with an increasing share of HVDC in transmission networks, it is found that limited efforts have been made for the HVDC OPF problem.

Various aspects remain untouched for the hybrid AC/DC (networks including AC and HVDC lines) OPF problem compared with the FACTS controller installation OPF problem. The HVDC technology also has a controlling phenomenon that operates the power system in a stable and secure mode. In this analysis, various techno-economic aspects are studied by performing unified OPF analysis for the hybrid AC/DC network with a VSC-based HVDC controller. The installation of a converter at a particular AC bus and its impact are also analyzed here. The main contributions of this study are

- An extension of the unified power flow algorithm application, to develop the unified OPF problem for hybrid AC/DC network containing a VSC-HVDC converter;
- The development of a unified OPF model which is solved using the most efficient meta-heuristic algorithm;
- The identification of the impacts of HVDC line replacement and converter setting on various techno-economic objective functions for the OPF problem;
- The suggestion of a novel methodology for optimal location of the converter station with satisfying well-known techno-economic objective functions; and
- Testing of the methodology with a modified five-bus test system and an IEEE-30 bus test system with their intact condition.

This paper identifies a new methodology for converter station installation and understands the effect of converter location on power system operation, while satisfying the objective function(s). The modified unified power flow model has been used for the analysis, which is explained in Section 2. A brief explanation for the PSO algorithm is given in Section 3. Different case studies and simulation results are elaborated in Section 4. Finally, Section 5 concludes the paper.

II. UNIFIED OPF MODELING OF THE VSC-HVDC CONVERTER STATION

A modified simultaneous power flow model has been developed and represented in [40], and is used for solving line flows and state variables for a hybrid AC/DC transmission network. The VSC terminals' equations are derived based on the single line diagram of the VSC converter station, as shown in Fig. 1. The detailed modeling and proposed modifications applied for the VSC-HVDC converter are explained along with the OPF modeling. The power flow injection equations are modified for AC buses where converters are connected. Accordingly,

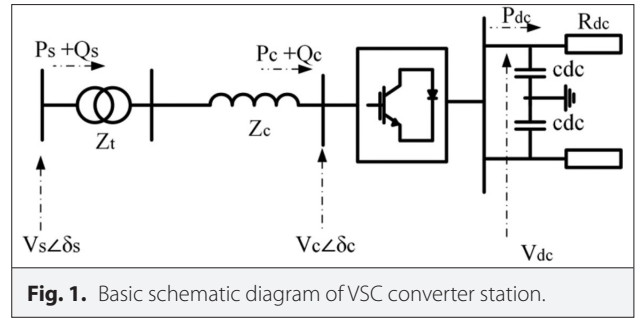


Fig. 1. Basic schematic diagram of VSC converter station.

modifications have been made in the impedance bus matrix. The generalized OPF problem is expressed as (1)

$$\begin{aligned} & \text{minimize } f(x, u) \\ & \text{such that } g'(x, u) = 0 \\ & \quad h'(x, u) \leq 0 \end{aligned} \quad (1)$$

A. Objective Functions

The different techno-economic objective functions considered for this analysis are explained as follows.

(1) Total Generation Cost

This is a generalized objective function that decides the economic aspects of any power system. This function is formulated using (2):

$$f_1 = \sum_{l=1}^{N_g} f_l(P_{G_l}) \quad (2)$$

The fuel cost of the l^{th} generator that is calculated using a quadratic expression

$$f_l = a_l + b_l \cdot P_{G_l} + c_l \cdot P_{G_l}^2 \quad (3)$$

The values of cost coefficients for different test systems are given in the Appendix.

(2) Minimization of Bus Voltage Deviation

The two-fold objective function is formulated (4) for cost and voltage deviation. The voltage deviation is calculated for all AC load buses and DC buses. Voltage deviation is a security and service quality index used for voltage profile measurement, that calculates bus voltage deviation from standard 1.0 p.u. (per unit) value.

$$f_2 = \sum_{l=1}^{N_g} f_l(P_{G_l}) + wV_D \quad (4)$$

$$V_D = \sum_{l=1}^{N_l} |v_l - 1.0| + \sum_{l=1}^{N_{dc}} |v_{dc_l} - 1.0| \quad (5)$$

(3) Minimization of Bus Voltage Deviation

The global objective function for minimizing transmission losses, including both AC and DC system losses, is formulated and expressed by (6):

$$f_3 = \sum_{l=1}^{N_{ac}} V_l \sum_{m=1}^{N_{ac}} V_m (G_{lm} \cos \theta_{lm} + B_{lm} \sin \theta_{lm}) + P_{dc_loss} \quad (6)$$

P_{dc_loss} term includes both DC transmission line losses and converter station losses. The converter losses are evaluated using the average loss model suggested in the literature [41].

B. Equality Constraints

These constraints have to be enforced, and are always mathematically binding. The standard static load flow equations with the suggested modification done as per (9)–(10) are included simultaneously as a set of equality constraints for the hybrid AC/DC OPF problem. A unified power balance approach is applied for the buses at which converters are connected.

(1) AC System

The static load flow equation (polar form) for any l th AC bus can be mathematically represented as (7)–(8). These nonlinear equations are the formed equality set of any OPF problem, and solved using the well-known Newton–Raphson method:

$$P_{G_l} - P_{D_l} - V_l \sum_{m=1}^{N_{ac}} V_m (G_{lm} \cos(\delta_l - \delta_m) + B_{lm} \sin(\delta_l - \delta_m)) = 0 \quad (7)$$

$$Q_{G_l} - Q_{D_l} - V_l \sum_{m=1}^{N_{ac}} V_m (G_{lm} \sin(\delta_l - \delta_m) - B_{lm} \cos(\delta_l - \delta_m)) = 0 \quad (8)$$

These equations are modified for a particular bus at which the converter is connected. For non-converter AC buses, the above equations remain unchanged. This modification is mathematically formulated as

$$P_{G_l} - P_{D_l} - V_l \sum_{m=1}^{N_{ac}} V_m (G_{lm} \cos(\delta_l - \delta_m) + B_{lm} \sin(\delta_l - \delta_m)) - P_s = 0 \quad (9)$$

$$Q_{G_l} - Q_{D_l} - V_l \sum_{m=1}^{N_{ac}} V_m (G_{lm} \sin(\delta_l - \delta_m) - B_{lm} \cos(\delta_l - \delta_m)) - Q_s = 0 \quad (10)$$

(2) VSC-HVDC System

Equality constraints for converter stations comprise different converter control modes and power balance at the converter station. Based on four different control modes as suggested for VSC-HVDC converter, the equality constraint equations for a particular converter terminal are selected from the expressions (11)–(14):

$$P_s^{sp} - V_s^2 \cdot G_{tc} - V_s V_c (G_{tc} \cos(\delta_s - \delta_c) + B_{tc} \sin(\delta_s - \delta_c)) = 0 \quad (11)$$

$$Q_s^{sp} - V_s^2 \cdot B_{tc} - V_s V_c (G_{tc} \sin(\delta_s - \delta_c) - B_{tc} \cos(\delta_s - \delta_c)) = 0 \quad (12)$$

$$V_c^{sp} - V_c = 0 \quad (13)$$

$$(V_{dc}^{slack})^{sp} - V_{dc}^{slack} = 0 \quad (14)$$

One bus is selected as a slack bus in the DC network that balances the DC power flow equation. The power balance formula between the AC and DC side of each converter terminal can be expressed as

$$P_c - P_{dc} - P_{loss} = 0 \quad (15)$$

P_{c} , P_{dc} and P_{loss} are active power injected at the converter terminal, DC bus, and the converter loss, respectively. The converter loss can be calculated based on the average loss model [41] and expressed as

$$P_{loss} = a_i' + b_i' I_c + c_i' I_c^2 \quad (16)$$

C. Inequality Constraints

These constraints are never binding. However, in the problem of the power system OPF, the limits on a few variables ensure the power system's stability. A unified AC/DC OPF problem following inequality constraints includes:

(1) AC system Inequality Constraints

$$P_{G_l}^{low} \leq P_{G_l} \leq P_{G_l}^{up}, \text{ for } l=1,2,\dots,N_g \quad (17)$$

$$Q_{G_l}^{low} \leq Q_{G_l} \leq Q_{G_l}^{up}, \text{ for } l=1,2,\dots,N_g \quad (18)$$

$$Q_{C_l}^{low} \leq Q_{C_l} \leq Q_{C_l}^{up}, \text{ for } l=1,2,\dots,N_{qc} \quad (19)$$

$$T_l^{low} \leq T_l \leq T_l^{up}, \text{ for } l=1,2,\dots,N_T \quad (20)$$

$$V_{G_l}^{low} \leq V_{G_l} \leq V_{G_l}^{up}, \text{ for } l=1,2,\dots,N_g \quad (21)$$

$$V_{D_l}^{low} \leq V_{D_l} \leq V_{D_l}^{up}, \text{ for } l=1,2,\dots,N_L \quad (22)$$

$$S_{lm} \leq S_{lm}^{up} \quad (23)$$

(2) VSC-HVDC Inequality Constraints

$$V_{dc1}^{low} \leq V_{dc1} \leq V_{dc1}^{up} \quad (24)$$

$$V_{cn}^{low} \leq V_{cn} \leq V_{cn}^{up}, \text{ for } n=1,2,\dots,N_c \quad (25)$$

$$P_{dc\text{line}} \leq P_{dc\text{line}}^{up} \quad (26)$$

$$|S_c| \leq S_c^{rated} \quad (27)$$

It is important to note that the control variables are self-constrained. The violation of limits is mainly checked for the state variables. This violation is augmented with the primary objective function using quadratic penalty terms.

$$\begin{aligned}
 J_{aug} = & J + \lambda_p (P_{G_i} - P_{G_i}^{lim})^2 + \lambda_{V_D} \sum_{l=1}^{N_l} (V_{D_l} - V_{D_l}^{lim})^2 \\
 & + \lambda_{Q_G} \sum_{l=1}^{N_g} (Q_{G_l} - Q_{G_l}^{lim})^2 + \lambda_S \sum_{l=1}^{n_{dc}} (S_{lm_l} - S_{lm_l}^{max})^2 \\
 & + \lambda_{V_{dc}} \sum_{n=1}^{n_{dc}} (V_{dc_n} - V_{dc_n}^{max})^2 + \lambda_{P_{dc}} \sum_{n=1}^{n_{dc}} (P_{dc_n} - P_{dc_n}^{max})^2 \\
 & + \lambda_{S_c} \sum_{n=1}^{N_c} (S_{c_n} - S_{c_n}^{lim})^2 + \lambda_{V_c} \sum_{n=1}^{N_c} (V_{c_n} - V_{c_n}^{lim})^2
 \end{aligned} \tag{28}$$

III. BRIEF ON PSO ALGORITHM

The particle swarm optimization (PSO) algorithm is a widely adopted meta-heuristic stochastic algorithm developed based on the movement of organisms such as fish schools and bird flocks [42]. This algorithm works in a multidimensional search space where many simple entities are defined as particles are placed, and each evaluates the objective function at its current location. Its previous best value (pbest) and global best value (gbest) then decide the new trajectory of each particle. Each particle's new position is updated by (29), and its velocity is updated with (30):

$$y_i^{k+1} = y_i^k + v_i^{k+1} \tag{29}$$

$$\begin{aligned}
 v_i^{k+1} = & \omega v_i^k + c_1 \cdot rand_1() \times (Pbest_i^k - y_i^k) \\
 & + c_2 \cdot rand_2() \times (Gbest_i^k - y_i^k)
 \end{aligned} \tag{30}$$

The acceleration coefficients c_1 and c_2 , are responsible for particle velocity toward pbest and gbest, and the inertia weight parameter dynamically adjusts the speed of the particle.

The inertia weight parameter selection is crucial as its lower value tends to a local search and higher value tend to a global search. An initially higher value of inertia is selected at the start of the PSO algorithm and then decays in successive iteration, such that the search algorithm starts from the global and moves to local search at execution. The inertia weight is updated based on (31):

$$\omega(k) = \omega_{max} - \left(\frac{\omega_{max} - \omega_{min}}{iter_{max}} \right) \times k \tag{31}$$

The following steps have been followed for solving the unified HVDC OPF model using the PSO algorithm.

- Step 1: Select the initial value of PSO parameter, numbers of particles, velocity, and numbers of iteration, and generate the initial population.
- Step 2: Run a unified power flow model for a hybrid AC/DC network by replacing a single AC line with an HVDC line.
- Step 3: Calculate objective function with a particular test configuration for each particle in the current position.

Step 4: Evaluate pbest and gbest values for all particles and store them.

Step 5: Upgrade the velocity and particle position.

Step 6: Check for iteration; if less than maximum iteration, jump to step 2 or move to step 7.

Step 7: Note down the output and repeat from step 1 for all AC lines independently.

IV. CASE STUDIES AND RESULT ANALYSIS

A novel effort has been made here to identify the optimal location of the HVDC converter station by minimizing the defined operational and economical objective functions. The effect of the VSC-HVDC converter and its control parameters are analyzed for two sample systems (modified five-bus and IEEE-30 bus) by replacing each AC line with the HVDC line iteratively. The analysis is performed on MATLAB (R2013) software with the Intel i3-core processor, 2.10 GHz, 3 GB RAM.

Since the objective of this work is to identify the most optimal location of converter installation by observing the effectiveness of a particular HVDC line replacement on the different operational objective functions, the unified OPF problem is analyzed for different case studies as follows:

- Case I: Minimization of total generation cost, where the generation cost is formulated using (2) and (3). The cost coefficient values given in MATPOWER [43] are used for two different test systems.
- Case II: Minimization of the total active power includes AC transmission losses and HVDC system losses.
- Case III: The two-fold objective function includes cost with voltage deviation, and is minimized for voltage profile improvement of the overall buses.

A. Modified Five-Bus Test System

The individual results for different case studies with different modified five-bus system test configurations are analyzed and discussed. This system consists of two generator buses and seven transmission lines with an active and reactive power demand of 165 MW and 40 MVAR, respectively. The name of each bus is indicated in Fig. 2, with its corresponding bus

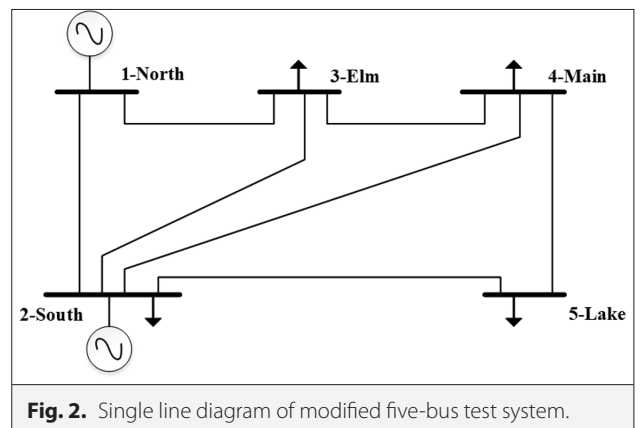


Fig. 2. Single line diagram of modified five-bus test system.

TABLE I. LIMITS OF HYBRID AC/DC SYSTEM CONTROL VARIABLES FOR MODIFIED FIVE-BUS (ALL VALUES ARE INDICATED IN P.U.)

Control variables	Lower	Upper
AC system		
South—PG2	0.1	2.0
North—VG1	0.90	1.1
South VG2	0.90	1.1
DC system		
Converter 1—PS	1.0	1.0
Converter 2—QS	1.0	1.0
Converter 1—VDC	0.90	1.1
Converter 2—V	0.90	1.1

numbers. The upper and lower limits of the AC and DC system control variables are given in Table I. In this analysis, each AC transmission line is replaced by an HVDC line with a bilateral (point-to-point) transmission configuration. In any DC network, one converter must be operating as a slack bus to maintain a power balance in DC transmission network. In this work, one converter is operated in (PC-QC) the control mode and another converter in the DC slack bus control mode (VDC-V).

To analyze the effect of the HVDC converter and the particular line replacement, the results obtained for various HVDC configurations are also compared with results obtained for only the AC base case (without HVDC) for the same objective functions. This comparison assesses the effectiveness of HVDC replacement for the optimal location of the converter station. The results obtained for all three objective functions with the AC base system (without HVDC) are represented in Table II. The optimal cost, voltage deviation, and transmission losses for the modified five-bus AC base system (without HVDC) are obtained as \$748.0624/h, 0.006048 p.u., and 2.61043 MW, respectively.

TABLE II. SIMULATION RESULT OBTAINED FOR OPTIMIZING INDIVIDUAL OBJECTIVE FUNCTIONS WITH DIFFERENT TEST CONFIGURATIONS

Test Configuration	Objective Function	Case I	Case II	Case III
Test Configuration I (Base System)	Generation cost (\$/h)	748.0624	750.0707	774.2091
	Voltage deviation (p.u.)	0.230511	0.006048	0.244168
	P losses (MW)	3.065	3.550	2.61043
Test Configuration II (line 1–3 replaced with HVDC)	Generation cost (\$/h)	741.0670	742.2401	741.1287
	Voltage deviation (p.u.)	0.1462	0.002007	0.21767
	P losses (MW)	1.1828	1.4723	1.1104
Test Configuration III (line 2–3 replaced with HVDC)	Generation cost (\$/h)	744.3732	745.9498	783.8671
	Voltage deviation (p.u.)	0.1717	0.002231	0.1842
	P losses (MW)	2.0014	2.3848	1.1473
Test Configuration IV (line 2–4 replaced with HVDC)	Generation cost (\$/h)	743.4884	745.8406	783.549
	Voltage deviation (p.u.)	0.20744	0.004073	0.20319
	P losses (MW)	1.768138	2.308656	1.12515
Test Configuration V (line 2–5 replaced with HVDC)	Generation cost (\$/h)	742.7996	744.002	773.2025
	Voltage deviation (p.u.)	0.22568	0.002048	0.20750
	P losses (MW)	1.62614	1.900275	1.11974
Test Configuration VI (line 3–4 replaced with HVDC)	Generation cost (\$/h)	747.9562	749.9282	773.7079
	Voltage deviation (p.u.)	0.232071	0.004701	0.240054
	P losses (MW)	3.035492	3.511149	2.595798

TABLE III. COMPARISON TABLE FOR ALL SIMULATION RESULTS OBTAINED WITH ALL TEST CONFIGURATIONS

	Test Configuration					
	Base system	Line 3–4	Line 2–3	Line 2–4	Line 2–5	Line 1–3
Cost (\$/h)	748.0624	747.9562	744.3732	743.4884	742.7996	741.0670
Voltage deviation (p.u.)	0.006048	0.004701	0.002231	0.004073	0.002048	0.002007
Active power losses	2.61043	2.595798	1.1473	1.12515	1.11974	1.1104

The results are obtained for minimizing individual objective functions using the PSO algorithm.

The unified OPF analysis using the PSO algorithm is carried out for replacing each AC with an HVDC line. First, the AC line between buses one and three is replaced with the HVDC line with a point-to-point bilateral transmission. Here, the converter connected at bus one is operated in the PQ control mode, and the converter connected at bus three is operated as a DC slack bus. The results obtained for all three cases are given in Table II. The obtained generation cost, voltage deviation, and transmission losses are respectively 0.93%, 66.81%, and 57.46% lower than the base case results for the respective objective functions.

Next, the line between AC buses two and three is replaced in the same point-to-point transmission mode. In this test, the converter at the second bus is operated in PQ control mode, and the converter at the third bus is operated in DC slack bus control mode. The result obtained with this test configuration is again shown in Table II. The optimized results are more promising than the AC base system. The obtained cost is \$744.3732/h, voltage deviation is 0.002231 p.u., and transmission losses are 1.1473 MW.

Similarly, the other test configurations which result by replacing line (2–4), (2–5) and (3–4), respectively, are shown in Table II. These results are obtained for individual test configurations for the defined objective function. The proposed unified OPF model is converged for all configurations.

(1) Comparative Analysis

The comparative analysis of different test configurations is shown in Table III. The results are arranged in decreasing order of total generation costs achieved for all test systems. By comparing the results of different HVDC configurations with a base system for all objective functions, it is clear that the HVDC line has improved the performance and reduced the generation cost for the given permissible control variables.

The change in generation cost is very significant for the most optimal configuration (test configuration II—line 1–3 replaced with HVDC), which reduces the cost of generation by around

0.935%. Moreover, the total power system losses for most the optimal configuration are 57.46% lower as compared to the base case transmission loss, and 25.82% lower than the average of transmission losses obtained with the other HVDC configurations (1.4969 MW). The optimized value of state and control variables for the most optimal hybrid AC/DC system (test configuration II—line 1–3 replaced with HVDC) is given in Table IV. The variation in cost, voltage deviation, and active power losses with each iteration for the most optimal configuration are shown in Fig. 3, Fig. 4, and Fig. 5, respectively.

B) Modified IEEE 30 Bus Test System Results

The base system consists of six generator sets, 41 transmission lines, five lines with transformer tapping, and active and reactive power demand of 283.40 MW & 126.20 MVAR. As mentioned

TABLE IV. THE OPTIMAL VALUE OF CONTROL AND STATE VARIABLE WITH MOST OPTIMAL TEST CONFIGURATION (LINE 1–3)

Control and State Variables	Case I Generation Cost	Case II Voltage Deviation	Case III Total Transmission losses
Pg1	83.18714	83.09647	88.72052
Pg2	83.19542	83.57449	77.61649
Vg1	1.059934	1.027852	1.081915
Vg2	1.05981	1.027211	1.081915
VI3	1.0543	1.00019	1.0784
VI4	1.052117	1.001817	1.076048
VI5	1.039779	1.00003	1.063228
Pc1	83.07611	79.97817	88.71996
Qc1	−0.00881	−0.05834	−23.8089
Vc1	0.998359	0.985304	1.082881
Vc2	1.000393	1.030073	1.106161
Vdc1	1.00004	1.00014	1.000092
Vdc2	1.000922	1.000887	1.000984

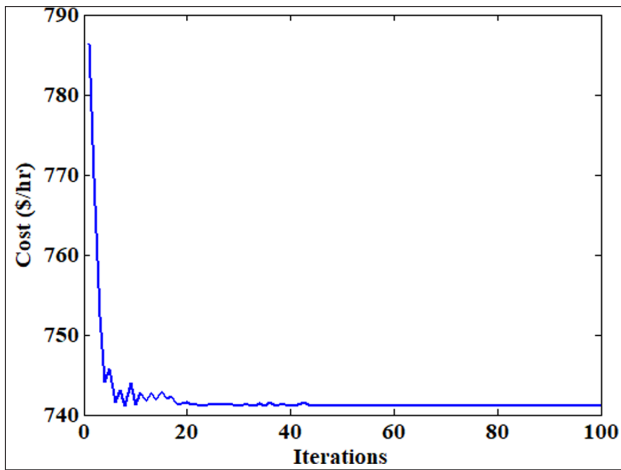


Fig. 3. Variation in generation cost with iterations for line 1–3 replaced with HVDC.

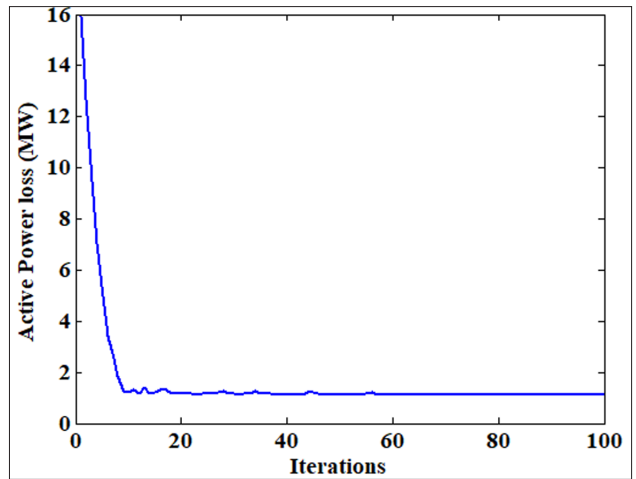


Fig. 5. Variation in total transmission losses with iterations for line 1–3 replaced with HVDC.

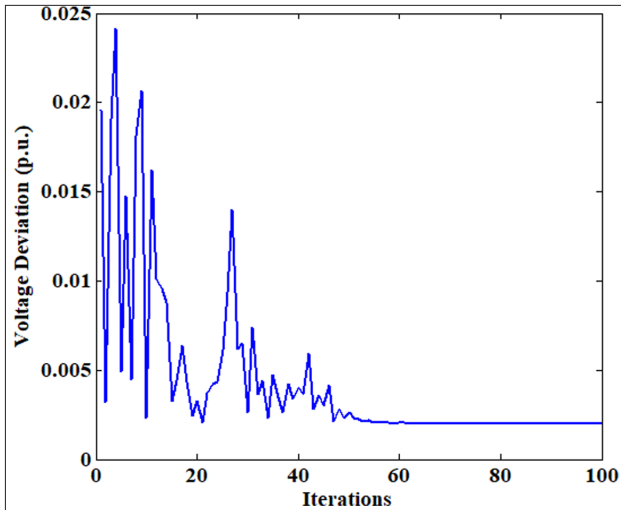


Fig. 4. Variation in voltage deviation with iterations for line 1–3 replaced with HVDC.

in the earlier test, to understand the proposed methodology's effectiveness, the analysis is performed by replacing each AC line with the DC line of the IEEE 30 bus system. The generation coefficient, line limits, and generation limits are taken as considered in the literature [44]. Only the results obtained with the top 4 most optimal HVDC configurations are demonstrated here, due to the space limitation. The single line diagram of modified IEEE 30 bus AC/DC system is shown in Fig. 6.

The suggested unified OPF model converged for different converter control modes, and its validation is published in the literature [40]. In this test, the DC slack bus controls the reactive power flow injected to the AC side (Vdc-Qs) control instead of AC side voltage (Vdc-V) control. The lower and upper limits for the control variable are given in Table V. The HVDC control variables are decided based on the PQ compatibility chart for voltage source converter [45].

The results obtained by optimizing different techno-economic objective functions independently for the top four most optimal test configurations are represented in Table VI. In the second test configuration for the IEEE 30 bus, the line between buses one and three is replaced by the HVDC line. The converter connected at AC bus 1 is operated in (Pc-Qc) control mode, which controls the AC power injection at the converter terminal, and the converter at bus three is operated as a DC slack bus which is operated as (Vdc-Qc) control mode. The table of results shows that the generation cost and transmission line losses are reduced to 0.893% and 16.70%, respectively, compared with the AC base case (without HVDC).

This analysis is further carried out for other test configurations, including replacing line 2–4, 2–5, and 2–6 with HVDC. The converter at bus terminal two is operated in PQ control mode in all test configurations, while the converter at the other bus terminal is operated as DC slack (Vdc-Qs) control mode. The obtained results are more promising and better compared to the system without the HVDC line. The generation cost obtained for the respective test configurations (2–4), (2–5), and (2–6) are \$795.5352/h (0.44% lower), \$789.6382/h (1.18% lower), and \$792.5321/hr (0.81% lower) compared with base case, respectively. The total power transmission losses, including the AC as well as DC lines for respective configurations, are 2.4095 MW (15.48% lower), 1.6882 MW (40.78% lower), and 2.0840 MW (26.90% lower), compared to the losses obtained for base case, respectively. The voltage deviation in the HVDC configuration includes AC as well as DC buses. The AC system's voltage profile is significantly improved with the inclusion of HVDC, and it is also affected by the location of the converter station.

(1) Comparative Analysis

While comparing the results of different configurations as represented in Table VII, it is clear that the HVDC system improves the system performance and reduces the total generation cost and transmission line losses of the overall system. The results

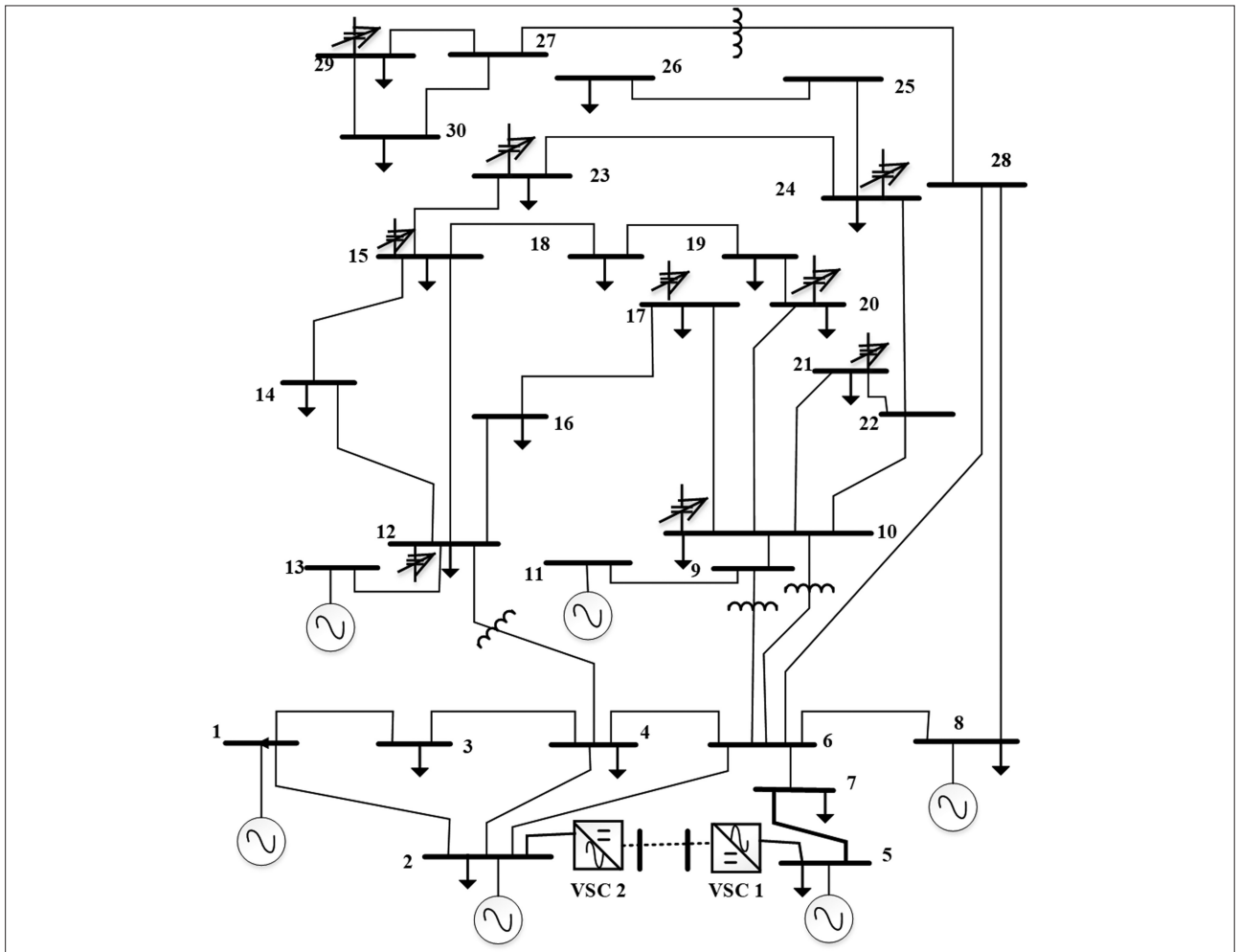


Fig. 6. Single line diagram of modified IEEE 30 bus test system with line 2–5 replaced with HVDC.

are arranged in decreasing order of total generation cost obtained for different configurations.

The improvement in power system performance due to HVDC as compared with the traditional AC system has already been discussed. This comparison table also helps us to decide the optimal configuration for replacing the AC line with a HVDC line in the IEEE 30 bus system for point-to-point transmission. From the table, it is clear that the test configuration with the replacement of line between buses two and five with HVDC gives the most promising results of reduced total generation cost and total transmission losses. The generation cost and transmission loss for the most optimal configuration are 0.63% and 27.32% lower than the average cost and the loss value obtained for the other top three optimal configurations, respectively. The optimal settings of all control variables for the most optimal configuration (line 2–5 replaced with HVDC) with all objective functions are given in Table VIII. The variation in objective function values with iteration is shown in Fig. 7, Fig. 8, and Fig. 9, respective to cost, voltage deviation, and total transmission losses.

V. CONCLUSION

The new methodology suggested here for identifying the optimal location of the converter station for HVDC installation has shown promising results. VSC-HVDC converters can independently control active and reactive power injecting to and from the AC to DC side; they can also control the AC side terminal voltage, which results in an improvement in power system performance. The optimization of various techno-economic objectives is also affected by the particular line replacement.

Here, the method is proposed by implementing a novel unified OPF model for VSC-HVDC. The unified model is primarily adopted for the load flow solution of hybrid AC/DC networks. The developed unified OPF model is very well converged with the PSO algorithm, and its effectiveness and robustness are tested and demonstrated for modified five-bus and IEEE 30 bus systems with bilateral point-to-point HVDC transmission lines. The simulation converged properly with different converter control modes at the appropriate time. This method also helps

TABLE V. LIMITS OF HYBRID AC/ DC SYSTEM CONTROL VARIABLES FOR IEEE 30 BUS (ALL VALUES ARE INDICATED IN P.U.)

Control Variables	Lower	Upper	Control Variables	Lower	Upper
AC system control variables					
P_{g1}	2.0	0.5	$T_{11(6-9)}$	1.1	0.9
P_{g2}	.80	.20	$T_{12(6-10)}$	1.1	0.9
P_{g5}	.50	.15	$T_{15(4-12)}$	1.1	0.9
P_{g8}	.35	.10	$T_{36(28-27)}$	1.1	0.9
P_{g11}	.30	.10	Q_{C10}	0.05	0
P_{g13}	.40	.12	Q_{C12}	0.05	0
V_{g1}	1.1	0.9	Q_{C15}	0.05	0
V_{g2}	1.1	0.9	Q_{C17}	0.05	0
V_{g5}	1.1	0.9	Q_{C20}	0.05	0
V_{g8}	1.1	0.9	Q_{C21}	0.05	0
V_{g11}	1.1	0.9	Q_{C23}	0.05	0
V_{g13}	1.1	0.9	Q_{C24}	0.05	0
V_{g1}	1.1	0.9	Q_{C29}	0.05	0
HVDC system control variables					
V_{dc1}	1.1	0.9	P_{s2}	1.00	-1.00
Q_{s1}	1.00	-1.00	Q_{s2}	1.00	-1.00

TABLE VI. SIMULATION RESULT OBTAINED FOR OPTIMIZING INDIVIDUAL OBJECTIVE FUNCTION WITH DIFFERENT TEST CONFIGURATIONS (IEEE 30 BUS SYSTEM)

Test Configuration	Objective Function	Case I	Case II	Case III
Test Configuration I (Base System)	Generation cost (\$/h)	799.0717	803.8096	967.0699
	Voltage deviation (p.u.)	1.857571	0.09548	2.03891
	P losses (MW)	8.62495	9.87325	2.85115
Test Configuration II (lines 1-3 replaced with HVDC)	Generation cost (\$/h)	791.9341	795.5026	966.4023
	Voltage deviation (p.u.)	0.770341	0.106836	1.97428
	P losses (MW)	6.532738	7.476602	2.37499
Test Configuration III (line 2-4 replaced with HVDC)	Generation cost (\$/h)	795.5352	837.6692	966.3355
	Voltage deviation (p.u.)	1.93265	0.10452	1.97267
	P losses (MW)	7.46880	7.054567	2.40953
Test Configuration IV (line 2-5 replaced with HVDC)	Generation cost (\$/h)	789.6382	793.3672	964.718
	Voltage deviation (p.u.)	1.869551	0.11241	1.92393
	P losses (MW)	5.79751	6.70482	1.68882
Test Configuration V (line 26 replaced with HVDC)	Generation cost (\$/h)	792.5321	880.648	965.6875
	Voltage deviation (p.u.)	1.9915	0.1022	2.04084
	P losses (MW)	6.5726	5.8415	2.08403

TABLE VII. COMPARISON TABLE FOR ALL SIMULATION RESULTS OBTAINED WITH ALL TEST CONFIGURATIONS

	Base System	Test Configuration			
		Line 2-4	Line 2-6	Line 1-3	Line 2-5
Cost (\$/h)	799.0717	795.5352	792.5321	791.9341	789.6382
Voltage deviation (p.u.)	0.09548	0.10452	0.10227	0.106836	0.11241
Active power losses (MW)	2.85115	2.409532	2.08403	2.37499	1.68882

TABLE VIII. OPTIMAL SETTING OF CONTROL VARIABLE WITH TEST CONFIGURATION (LINE 2-5) FOR ALL OBJECTIVE FUNCTIONS

Control Variables	CASE I Generation Cost	CASE II Voltage Deviation	CASE III Total Transmission Losses
Pg1	177.8979	50.26459	176.5013
Pg2	49.0996	49.04617	79.99999
Pg5	19.90794	20.08574	49.99995
Pg8	19.28996	21.11096	34.99999
Pg11	11.26761	11.66163	29.99995
Pg13	12	12.00047	39.99969
Vg1	1.1	1.024755	1.1
Vg2	1.083981	1.006133	1.096539
Vg5	1.086186	1.021488	1.09944
Vg8	1.073047	1.008995	1.092366
Vg11	1.093467	1.016968	1.051525
Vg13	1.089735	1.005894	1.09201
T11 (6-9)	0.949058	0.900001	0.985663
T12 (6-10)	1.02952	0.975619	1.076604
T15 (4-12)	1.022709	1.013395	1.019573
T36 (28-27)	0.996302	0.99072	0.975572
QC'10	0.001349	4.999273	1.123445
QC'12	4.269721	4.619792	1.819104
QC'15	4.492771	4.999976	4.699138
QC'17	4.999918	0.0549	4.999186
QC'20	4.270634	4.999967	4.184627
QC'21	4.999992	4.999912	4.99985
QC'23	3.668599	4.999979	3.793777
QC'24	4.999999	4.998775	4.999961
QC'29	4.463833	4.99949	0.000839
Vdc1	1.1	1.049791	1.09978
PS2	99.99991	99.99877	64.21788
QS1	0.098527	-1.0519	-1.78148
QS2	-0.17667	1.441401	2.061777

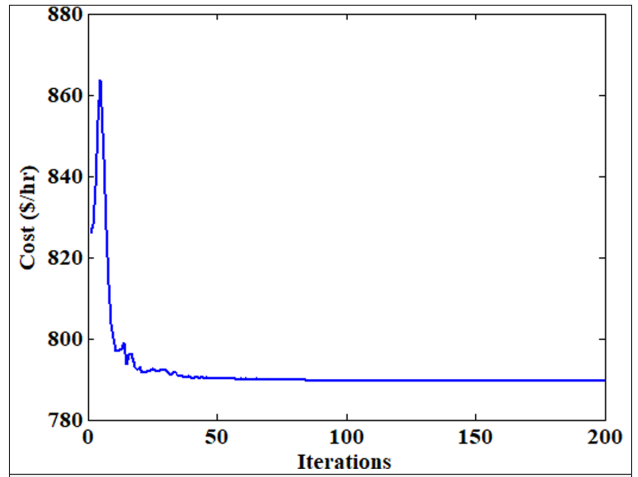


Fig. 7. Variation in generation cost with iterations for line 2-5 replaced with HVDC.

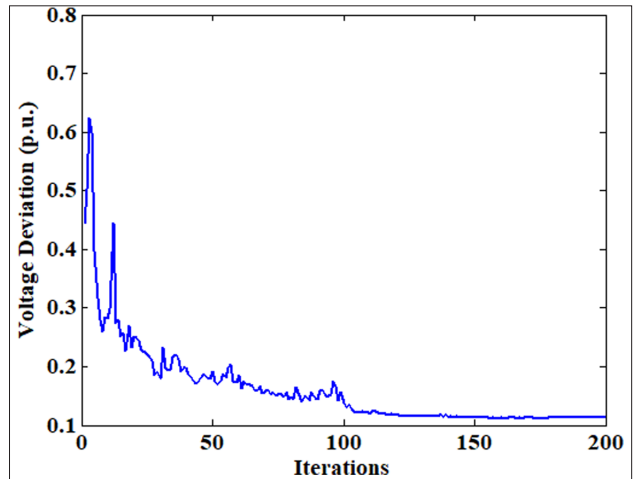


Fig. 8. Variation in voltage deviation with iterations for line 2-5 replaced with HVDC.

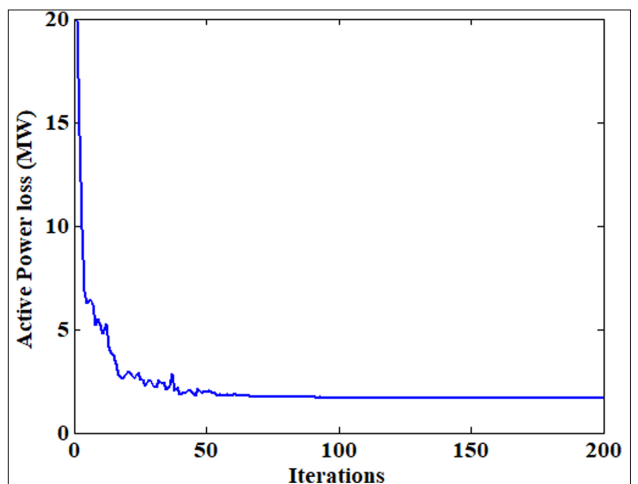


Fig. 9. Variation in total transmission losses with iterations for line 2-5 replaced with HVDC.

in planning and security analysis with a meshed HVDC transmission network.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – S.A., P.K.; Design – S.A., P.K.; Supervision – P.K.; Data Collection and/or Processing – S.A.; Analysis and/or Interpretation – S.A.; Literature Search – S.A.; Writing Manuscript – S.A.; Critical Review – P.K.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors declared that this study has received no financial support.

REFERENCES

1. K. Padiyar, *FACTS Controllers in Power Transmission and Distribution*. Tunbridge Wells: Anshan Publishing, 2007.
2. A. de Oliveira, C. Tiburcio, M. Lemes and D. Retzmann, Prospects of voltage-sourced converters (VSC) applications in DC transmission systems. *IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T&D-LA)*, pp. 491–495, 2010.
3. N. Florentzou, V. G. Agelidis and G. D. Demetriades, "VSC-based HVDC power transmission systems: An overview," *IEEE Transactions on Power Electronics*, vol. 24, no. 3, pp. 592–602, 2009. [\[CrossRef\]](#)
4. D. Krug, S. Bernet and S. Dieckerhoff, "Comparison of state-of-the-art voltage source converter topologies for medium voltage applications," *38th IAS Annual Meeting on Conference Record of the Industry Applications Conference*, vol. 1, pp. 168–175, 2003.
5. G. Radomski, "Modelling and modulation of voltage source converter," in *13th International Power Electronics and Motion Controlled Conference*, vol. 2008, 2008, pp. 504–511.
6. Z. Xu and H. Chen, "Review and applications of VSC HVDC," *Gao-dianya Jishu/High Voltage Engineering*, vol. 33, no. 1, pp. 1–10, 2007.
7. D. I. Sun, B. Ashley, B. Brewer, A. Hughes and W. F. Tinney, "Optimal power flow by Newton approach," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS–103, no. 10, pp. 2864–2880, 1984. [\[CrossRef\]](#)
8. J. Yuryevich and K. P. Wong, "Evolutionary programming based optimal power flow algorithm," *IEEE Transactions on Power Systems*, vol. 14, no. 4, pp. 1245–1250, 1999. [\[CrossRef\]](#)
9. S. R. Paranjothi and K. Anburaja, "Optimal power flow using refined genetic algorithm," *Electric Power Components and Systems*, vol. 30, no. 10, pp. 1055–1063, 2002. [\[CrossRef\]](#)
10. M. A. Abido, "Optimal power flow using particle swarm optimization," *International Journal of Electrical Power and Energy Systems*, vol. 24, no. 7, pp. 563–571, 2002. [\[CrossRef\]](#)
11. L. Le Dinh, D. V. Ngoc and P. Vasant, "Artificial bee colony algorithm for solving optimal power flow problem," *TheScientificWorldJournal*, vol. 2013, 159040, 2013. [\[CrossRef\]](#)
12. H. R. E. H. Bouchevara, M. A. Abido and M. Boucherma, "Optimal power flow using teaching-learning-based optimization technique," *Electric Power Systems Research*, vol. 114, pp. 49–59, 2014. [\[CrossRef\]](#)
13. M. A. Abido, "Optimal power flow using tabu search algorithm," *Electric Power Components and Systems*, vol. 30, no. 5, pp. 469–483, 2002. [\[CrossRef\]](#)
14. U. Kılıç, K. Ayan and U. Arifoğlu, "Optimizing reactive power flow of HVDC systems using genetic algorithm," *International Journal of Electrical Power and Energy Systems*, vol. 55, pp. 1–12, 2014. [\[CrossRef\]](#)
15. U. Kılıç and K. Ayan, "Optimal power flow solution of two-terminal HVDC systems using genetic algorithm," *Electrical Engineering*, vol. 96, no. 1, pp. 65–77, 2014. [\[CrossRef\]](#)
16. U. Kılıç and K. Ayan, "Optimizing power flow of AC–DC power systems using artificial bee colony algorithm," *International Journal of Electrical Power and Energy Systems*, vol. 53, pp. 592–602, 2013. [\[CrossRef\]](#)
17. R. Wiget and G. Andersson, "Optimal power flow for combined AC and multi-terminal HVDC grids based on VSC converters," *IEEE Power and Energy Society General Meeting*, vol. 2012, pp. 1–8, 2012.
18. R. Wiget and G. Andersson, "DC optimal power flow including HVDC grids," in *IEEE Electrical Power & Energy Conference*, vol. 2013, pp. 1–6, 2013.
19. M. Baradar, M. R. Hesamzadeh and M. Ghandhari, "Modelling of multi-terminal HVDC systems in optimal power flow formulation," *IEEE Electrical Power and Energy Conference*, 2012, pp. 170–175, 2012.
20. Z. Wei, C. Ji, G. Sun, C. Wang and W. Sun, "Interior-point optimal power flow of AC-DC system with VSC-HVDC," *Proceedings of the CSEE*, Vol. 32, no. 19, pp. 89–95, 2012.
21. A. Pizano-Martinez, C. R. Fuerte-Esquivel, H. Ambriz-Pérez and E. Acha, "Modeling of VSC-based HVDC systems for a Newton-Raphson OPF algorithm," *IEEE Transactions on Power Systems*, vol. 22, no. 4, pp. 1794–1803, 2007. [\[CrossRef\]](#)
22. W. Feng, L. B. Tjernberg, A. Mannikoff and A. Bergman, "An extended OPF incorporating multi-terminal VSC-HVDC and its application on transmission loss evaluation," *IEEE Grenoble Conference*, Vol. 2013, pp. 1–6, 2013.
23. Y. Li, Y. Li, G. Li, D. Zhao and C. Chen, "Two-stage multi-objective OPF for AC/DC grids with VSC-HVDC: Incorporating decisions analysis into optimization process," *Energy*, vol. 147, pp. 286–296, 2018. [\[CrossRef\]](#)
24. X. Liu, X. Wang and J. Wen, "Optimal power flow of DC-grid based on improved PSO algorithm," *Journal of Electrical Engineering and Technology*, vol. 12, no. 4, pp. 1586–1592, 2017.
25. M. K. Kim, "Multi-objective optimization operation with corrective control actions for meshed AC/DC grids including multi-terminal VSC-HVDC," *International Journal of Electrical Power and Energy Systems*, vol. 93, pp. 178–193, 2017. [\[CrossRef\]](#)
26. N. Rani, P. Choudekar, D. A. Ruchira and A. Singh, "Generation rescheduling using PSO–OPF," *International Journal of Pure and Applied Mathematics*, vol. 114, no. 8, pp. 233–241, 2017.
27. S. R. Inkollu and V. R. Kota, "Optimal setting of FACTS devices for voltage stability improvement using PSO adaptive GSA hybrid algorithm," *Engineering Science and Technology, An International Journal*, vol. 19, no. 3, pp. 1166–1176, 2016. [\[CrossRef\]](#)
28. A. R. Jordehi, "Particle swarm optimisation (PSO) for allocation of FACTS devices in electric transmission systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1260–1267, 2015. [\[CrossRef\]](#)
29. E. Naderi, M. Pourakbari-Kasmaei and H. Abdi, "An efficient particle swarm optimization algorithm to solve optimal power flow problem integrated with FACTS devices," *Applied Soft Computing*, vol. 80, pp. 243–262, 2019. [\[CrossRef\]](#)
30. R. Srinivasa Rao and V. Srinivasa Rao, "A generalized approach for determination of optimal location and performance analysis of

- FACTS devices," *International Journal of Electrical Power and Energy Systems*, vol. 73, pp. 711–724, 2015. [\[CrossRef\]](#)
31. K. Ravi and M. Rajaram, "Optimal location of FACTS devices using improved particle swarm optimization," *International Journal of Electrical Power and Energy Systems*, vol. 49, pp. 333–338, 2013. [\[CrossRef\]](#)
 32. M. Saravanan, S. M. R. Slochanal, P. Venkatesh and J. P. S. Abraham, "Application of particle swarm optimization technique for optimal location of FACTS devices considering cost of installation and system loadability," *Electric Power Systems Research*, vol. 77, no. 3–4, pp. 276–283, 2007. [\[CrossRef\]](#)
 33. R. P. Singh, V. Mukherjee and S. P. Ghoshal, "Particle swarm optimization with an aging leader and challengers algorithm for optimal power flow problem with FACTS devices," *International Journal of Electrical Power and Energy Systems*, vol. 64, pp. 1185–1196, 2015. [\[CrossRef\]](#)
 34. W. Ongsakul and P. Bhasaputra, "Optimal power flow with FACTS devices by hybrid TS/SA approach," *International Journal of Electrical Power and Energy Systems*, vol. 24, no. 10, pp. 851–857, 2002. [\[CrossRef\]](#)
 35. P. Choudekar, S. K. Sinha and A. Siddiqui, "Optimal location of SVC for improvement in voltage stability of a power system under normal and contingency condition," *International Journal of System Assurance Engineering and Management*, vol. 8, no. S2, pp. 1312–1318, 2017. [\[CrossRef\]](#)
 36. M. Dazahra, F. Elmariami, A. Belfqih and J. Boukherouaa, "Optimal location of SVC using particle swarm optimization and voltage stability indexes," *International Journal of Electrical Computer Engineering*, vol. 6, no. 6, p. 2581, 2016.
 37. B. V. Kumar and V. Ramaiah, "Enhancement of dynamic stability by optimal location and capacity of UPFC: A hybrid approach," *Energy*, vol. 190, p. 116464, 2020. [\[CrossRef\]](#)
 38. M. V. Suganyadevi and S. Parameswari, "Congestion management in deregulated power system by locating series FACTS devices," *International Journal of Computer Applications*, vol. 13, no. 8, pp. 19–22, 2011. [\[CrossRef\]](#)
 39. H. I. Shaheen, G. I. Rashed and S. J. Cheng, "Optimal location and parameter setting of UPFC for enhancing power system security based on differential evolution algorithm," *International Journal of Electrical Power and Energy Systems*, vol. 33, no. 1, pp. 94–105, 2011. [\[CrossRef\]](#)
 40. S. Agrawal and P. Kundu, "A unified power flow analysis for VSC-MTDC system with distributed generation," *7th International Conference on Power Systems (ICPS)*, vol. 2017, pp. 659–664, 2017.
 41. J. Beerten, S. Cole and R. Belmans, "Generalized steady-state VSC MTDC model for sequential AC/DC power flow algorithms," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 821–829, 2012. [\[CrossRef\]](#)
 42. J. Kennedy and R. Eberhart, "Particle swarm optimization," *Proceedings of ICNN'95-International conference on neural networks*, 1995, vol. 4., pp. 1942–1948.
 43. R. D. Zimmerman, C. E. Murillo-Sánchez and D. J. M. Gan, *MATPOWER: A MATLAB Power System Simulation Package*, Vol. 1. Ithaca NY: Power Systems Engineering Research Center, 1997, pp. 10–17.
 44. O. Alsac and B. Stott, "Optimal load flow with steady-state security," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-93, no. 3, pp. 745–751, 1974. [\[CrossRef\]](#)
 45. X. -P. Zhang, "Multiterminal voltage-sourced converter-based HVDC models for power flow analysis," *IEEE Transactions on Power Systems*, vol. 19, no. 4, pp. 1877–1884, 2004. [\[CrossRef\]](#)



Sunilkumar Agrawal received M.Tech. from IIT-BHU, Varanasi, and currently pursuing a Ph.D. degree in the Electrical Engineering Department at S.V. National Institute of Technology. He is also serving as an Assistant Professor in Government Engineering College, Gandhinagar. His area of research is power system modeling, power system optimization, VSC-HVDC modeling, congestion management, and implementation of various metaheuristic methods in power system optimization problems.



Prasanta Kundu received M.E. from IISc Bangalore and a Ph.D. degree from IIT Kharagpur in Electrical Engineering. He is working as an Associate Professor in the Electrical Engineering Department at S.V. National Institute of Technology, Surat. His area of research is partial discharge & condition monitoring, application of DSP in high voltage engineering, electromagnetic field computation using finite element method, and modern power system analysis. He is a Fellow of the Institution of Engineers (India) and a senior member of IEEE.

APPENDIX**APPENDIX I. GENERATOR COST COEFFICIENT FOR MODIFIED FIVE-BUS TEST SYSTEM**

Bus No.	Cost coefficient		
	A	b	c
1—North	60	3.40	0.004
2—South	60	3.40	0.004

APPENDIX II. GENERATOR COST COEFFICIENT FOR IEEE 30 BUS TEST SYSTEM

Generator bus	Cost coefficient		
	a	b	c
Gen. 1	0.0000	2.0000	0.003750
Gen. 2	0.0000	1.7500	0.017500
Gen. 5	0.0000	1.0000	0.062500
Gen. 8	0.0000	3.2500	0.008340
Gen. 11	0.0000	3.0000	0.025000
Gen. 13	0.0000	3.0000	0.025000