The Journal of CPRI,
Vol. 12, No. 2, June 2016 pp. 201-218

Voltage stability constrained optimal power flow – a critical review

Telang A S* and Bedekar P P**

Power system researchers have looked upon the problem of Voltage Stability Constrained Optimal Power Flow (VSC-OPF) making use of classical and advanced methods of optimization. Many efforts have been made to optimize the power system by optimizing control variables of VSC-OPF problem for improving voltage profile. This paper compiles the significant developments made in the area of VSC-OPF using conventional and artificial intelligence based optimal power flow solution methodologies. After a thorough study of vast literature available on VSC-OPF, critical review with future scope has been presented to make the review study most focused and optimistic. Owing to poor speed and convergence characteristics of classical methods of optimization problem, intelligent computational methods have been emerged as one of the effective and efficient method. However, as an appropriate setting of control parameters involved in these meta-heuristic techniques is a key factor for success, the possibility of utilizing hybrid approaches should be considered for VSC-OPF problems. Another interesting feature of this study is that it is found that one algorithm cannot be superior to other algorithms in all kinds of cases; hence for the class of problem being studied, one has to find out which algorithm is better.

Keywords: *Voltage stability constrained optimal power flow, voltage stability index, optimal power flow, L-index, VCPI-Index, MSV, classical method, artificial intelligence.*

1.0 INTRODUCTION

Present day,modern power systems are becoming more interconnected and are being subjected to heavily stressed conditions forcing to operate very near to load ability limit. Thus the complexity of planning and operation of large interconnected power systems is growing. The rapid increase in load and non-optimal use of transmission lines adversely affect the stability of the power system. Under the scenario of reduced stability margins, incorporation of power systems is now–a-days,gaining great importance. Therefore, voltage stability is being regarded as one of the most important aspect to maintain secured and reliable operation of power system. Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and supply from the power system [1, 2]. The term voltage collapse is also often used. It is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system [1, 3]. In recent years, several voltage collapse events throughout the world have been found out. Thus incorporation of voltage stability criteria in power system operation and planning is very essential. In this regard, the optimal power flow has become a powerful tool in the field of research with potential applications for power

*Assistant Professor, Electrical Engineering Department, P. R. P. College of Engineering, Amravati. E-mail: aparna_telang2002@yahoo.com
** Associate Professor, Electrical Engineering Department, Govt. College of Engineering, Amravati. E-mail: bedekar_pp@rediffmail.com

system planning and operation [4].The optimal power flow (OPF) problem in simple words can be effectively defined as meeting consumer's energy needs with the minimum cost of energy production. Many conventional optimization techniques were developed to solve the OPF problem, the most popular being non-linear programming, Newton-based techniques, linear programming, gradient method, Interior point method, quadratic programming method etc.

Though some of these techniques have excellent convergence characteristics, and various among them are widely used in the industry, they suffer with the following disadvantages as [52-53]-

1. They might converge to local solutions instead of global ones if the initial guess happens to be in the vicinity of a local solution.
2. Each technique is tailored to suit a specific OPF optimization problem based on the mathematical nature of the objectives and/or constraints.
3. They are developed with some theoretical assumptions, such as convexity, differentiability, and continuity, among other things, which may not be suitable for the actual OPF conditions.
4. They are weak in handling qualitative constraints.
5. They become too slow if number of variables is large.
6. They are computationally expensive for solution of a large system.
7. They cannot readily handle binary or integer variables.

Since there are recent attempts to overcome the limitations of the classical optimization techniques, the application of Artificial Intelligent (AI) techniques to solve the optimization problem has emerged. Some of AI techniques such as Simulated Annealing (SA), Tabu Search (TS), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colonyalgorithm, Differential Evolution (DE), Evolutionary programming etc. are used often owing to their major advantages such as [52]-

1. They are relatively versatile for handling various qualitative constraints.
2. They have excellent convergence characteristic; in most cases they can find the global optimum solution.
3. They are fast in computation and possess learning ability.

A comparison between conventional and advanced optimization techniques is presented in Table 1 [52].

Under the recent power system scenario, it is necessary to expand the OPF with different restrictions apart from equality and inequality constraints. Security constraint, harmonic constraint, voltage stability constraint and the transient stability constraint can be given as examples of such type of restrictions.

Several blackouts around the world have been related to voltage phenomena; hence power system planning engineers have focused their attention to the VSC-OPF problem [6]. The main purpose of a VSC-OPF is to include voltage stability criteria as additional constraint in the conventional OPF to improve power system security, reliability and voltage stability margins.

There are several methods to calculate voltage stability margin of the system using OPF algorithm. Figure 1 shows vast applications of various intelligent optimization algorithms for VSC-OPF problem, indicating how rapidly their use is increasing in this field. Numbers 1 to 6 indicate various algorithms as EP, ES, GA, ANN, SA, and PSO respectively.

This paper presents review on different effective methodologies of VSC-OPF problem. It will provide a good starting reference and a rich resource for the operation researchers.

TABLE 1

A COMPARISON BETWEEN CONVENTIONAL AND ADVANCED OPTIMIZATION TECHNIQUE

Property	Advanced	Traditional
Search space	Population of potential solutions	Trajectory by a single point
Motivation	Natural selection and Social adaptation	Mathematical properties (gradient, Hessian)
Applicability	Domain independent, Applicable to variety of problems	Applicable to a specific problem domain
Point Transition	Probabilistic	Deterministic
Prerequisites	An objective function to be optimized	Auxiliary knowledge such as gradient vectors
Initial guess	Automatically generated by the algorithm	Provided by user
Flow of control	Mostly parallel	Mostly serial
CPU time	Large	Small
Results	Global optimum more probable	Local optimum, dependant of initial guess
Advantages	Global search, parallel, speed	Convergence proof
Drawbacks	No general formal convergence proof	Locality, computational cost

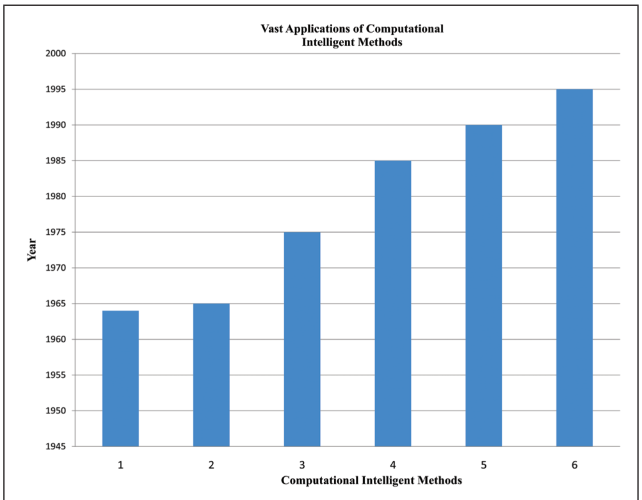

FIG. 1 VAST APPLICATIONS OF COMPUTATIONAL INTELLIGENT METHODS

2.0 VOLTAGE STABILITY AND OPTIMAL POWER FLOW

Factors like financial, regulatory and environmental are forcing electrical utilities to operate to the maximum use of transmission capability. Consequently, voltage stability has become one of the important constraints in power system planning. Optimal power flow can play important role in an early detection of voltage stability problems [6]. It finds the optimal settings of a given power system network which optimize one of the objective function such as total generation cost, system loss, bus voltage deviation or voltage stability enhancement while satisfying its power flow equations, system security and equipment operating limits.

In general,the OPF problem can be mathematically formulated as follows [7-12]-

Minimize-

$$f\ (x, u) \qquad ....(1)$$

$$\text{Subject to } g\ (x,u) = 0 \qquad ....(2)$$

$$h\ (x, u) \leq 0 \qquad ....(3)$$

where f is the objective function to be optimized, g is the equality constraint representing non-linear power flow equations and his the system operating constraints. U is the vector of independent control variables including-

1. Generator active power output P_G except at slack bus P_{G1}.
2. Generator bus voltage V_G.
3. Transformer tap setting T.
4. Shunt VAR compensation Q_C.

X is the vector of dependent variables including-

1. Slack bus generated active power P_{G1}.
2. Load (PQ) bus voltage V_L.
3. Generator reactive power output Q_G.
4. Transmission line loading (line flow) S_L.

3.0 METHODOLOGIES USED TO ACHIEVE VSC-OPF

As has already been stated, planning and operation of large interconnected power systems with stability and security improvement became important concerns in routine modern power system operation. Hence incorporating voltage stability criteria in the power system operations began receiving great attention. Various methodologies in OPF use voltage stability indices as the voltage stability enhancement indicator. These indices are an approximate measure of the closeness of the system to voltage collapse. A number of voltage stability indices have been proposed in the literature. Some of the important indices which are mostly used for VSC-OPF problem are-

1. L-index
2. Voltage Collapse Proximity Indicator (VCPI).
3. MSV.

3.1 L-index

The indicator L is a quantitative measure for the estimation of the distance of the actual state of the system to the stability limit. It is defined for each load bus j as

$$L_j = \left| 1 - \frac{\sum_{i \in \alpha_G} F_{ji} * V_i}{V_j} \right| \quad ....(4)$$

The index Lj indicates proximity of voltage collapse of a power system. A value Lj=1 indicates voltage collapse condition at bus j. Hence for complete system a global indicator L is given-

$$L = \max\left(\sum_{j \in \alpha_L} L_j \right) \quad ....(5)$$

Where α_L and α_G are the set of load and generator buses, respectively. Vi and Vj are voltage phasors and the elements of F_{ji} are calculated from the [Y] bus matrix for the network. The L-index varies in a range between 0(no load) and 1 (voltage collapse).

3.2 Voltage Collapse Proximity Indicator (VCPI)

The index, voltage collapse proximity is based on the concept of maximum power transferred through a power line. The index VCPI (power) is defined as follows-

$$VCPI_{(power)} = \frac{P_r}{P_{rmax}} = \frac{Q_r}{Q_{rmax}} \quad ....(6)$$

Where the values of Pr, Qr are obtained from conventional power flow calculations and Pr (max) and Qr (max) are the maximum active and reactive power that can be transferred through a line. The VCPI indices varies from 0 (no load condition) to 1 (voltage collapse).

3.3 Power flow Jacobian Matrix based Minimum Singular value (MSV)

The minimum singular value (MSV) of the power flow jacobian matrix has been used by many researchers as an index to improve the voltage stability margin.

The superiority in terms of computational time is more evident for larger power systems. Reference [35] reveals that the average computing time of the VSC-OPF based VCPI-index is less than that of L-index approach or other techniques. This is indicated in Figure 2.

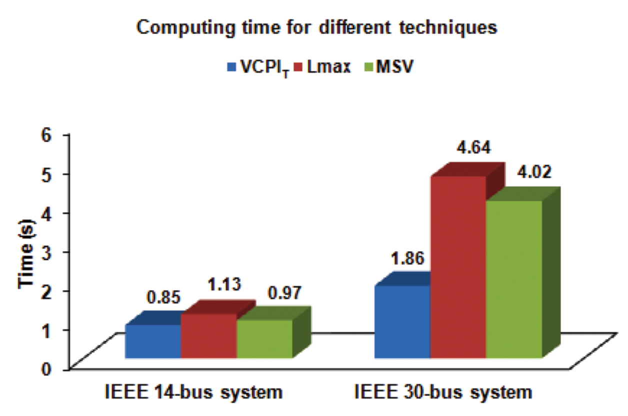

FIG. 2 COMPUTING TIME FOR DIFFERENT VSC-OPF TECHNIQUES

Thus for further analysis of VSC-OPF problems, these voltage stability indices are either considered as an objective function in OPF or as a constraint in OPF.

This section offers a review of most of the research work conducted with regard to the VSC-OPF. Reviewed papers are extracted from major journals associated with power system studies and categorized based on the conventional and advanced computational intelligence tool as follows-

3.4 Conventional/Traditional OPF methodologies

The conventional methods are based on mathematical programming approaches and used to solve different size of OPF problems. The popular conventional methods are [36-43]-

(a) Gradient Method

(b) Newton Method

(c) Linear Programming Method

(d) Quadratic Programming Method

(e) Interior Point Method

A brief description of all these methods is presented in Table 2. Based on this, the application of the various classical optimization methods to VSC-OPF problem has been discussed below-

VAR planning involves maintenance of acceptable bus voltages and protection against the possibility of voltage collapse. To meet both criteria, optimization methods based on either heuristic procedures or mathematical programming techniques can be adopted. VAR planning incorporating voltage stability constraints poses a difficult non linear mixed integer programming (MINLP) optimization problem. Simplified MINLP model using statistical approximation of the locus of the point of collapse (poc) based on a standard linear/quadratic ordinary least square (OLS) multivariate regression model had been explored in [7]. Such simplified model is found superior in terms of reduced computational time. Authors of [8] evaluated optimal VAR planning and voltage stability applications [VSTAB] with accurate results. In [9], authors had proposed OPF formulations that "optimize" a system considering both costs and voltage stability criteria. Such multi objective OPF formulation was implemented based on non-linear primal–dual predictor corrector interior point method and a Han-Powell Second order method. Advantages and disadvantages of these methods were discussed.

Under stressed conditions, power systems are being operated closer and closer to their stability limits. As the overall stability limits can be closely related with voltage stability of the network, the incorporation of voltage stability into a traditional OPF problem can result in accuracy at higher loading conditions. The use of interior point methods together with goal programming and linearly combined objective functions as the basic optimization techniques had been explained in [10]. Detailed generator, exponential load and static VAR compensator models were incorporated into traditional and voltage stability constrained optimal power flow problem [11]. Effect of these different models on cost and system loadability had been studied using interior point method of optimization. A unique method based on OPF for improving both static and dynamic voltage stability had been proposed in [12]. The uniqueness lies in proper reactive power rescheduling along with reactive reserve margin optimization. The proposed reactive reserve margin power management model (RRMP) improves voltage stability using robust interior point method along with Bender's decomposition technique. Comparison of two methods, least square method and interpolation approximation for VSC-OPF for reactive power planning was effectively done [13].

William Rosehart *et al.* [3], had demonstrated that the voltage stability and optimal power flow studies can be performed simultaneously using Lagarangian analysis. Impact of VSC-OPF using L-index as a constraint in closed form have been shown using interior point methods(Primal-dual interior point algorithm)in[14] and primal dual interior point method (IPM) based on Karush-Kuhn-Tucker, KKT conditions in [15].

3.5 Advanced optimal power flow methodologies

The optimal power flow is the backbone tool which has been extensively used by power system researchers. Power system researchers have attempted to apply most optimization techniques,conventional as well as advanced to solve the OPF. Owing to certain drawbacks of conventional optimization methods such as dependency of convergence to the global or local solution on selected initial guess,dependency on the mathematical nature of the objectives and/or constraints and also dependency on theoretical assumptions like convexity, differentiability and continuity etc. Computational intelligence tools have been emerged as one of the powerful optimization tool. The main modern techniques include Evolutionary Programming (EP), Genetic Algorithm (GA), Evolutionary Strategies (ES), Artificial Neural Network (ANN), Simulated Annealing (SA), Ant Colony Optimization (ACO), Fuzzy Set Theory (FST), and Particle Swarm Optimization (PSO). Comparison of these methods has been represented in Table 3 [44-53]. Application of these methods to VSC-OPF problem has been well organized in the following section-

3.5.1 Genetic Algorithms based VSC-OPF approach

Authors of [16] proposed multi objective evolutionary algorithm with Enhanced Genetic Algorithm (EGA)-Decoupled Quadratic Load Flow(DQLF) model. It will solve the OPF problem with the three objective functions as fuel cost, real power loss and voltage stability enhancement index(L-index). A Strength Pareoto Evolutionary Algorithm (SPEA) is used for EGA-DQLF model and the results were compared with PSO-Fuzzy approach where proposed method provides better optimal solution than later one. A similar OPF formulation was considered with the inclusion of the emission of gases without considering real power loss as objective function in [17]. Here the multi objective VSC-OPF problem is formulated using Non-dominated Sorting Genetic Algorithm-II (NSGA-II) and results were compared with multi objective GA. J. Preetha Roselyn, D. Devaraj, Subhransu Sekhar Dash[18], had proposed Multiobjective Genetic Algorithm (MOGA) for VSC-OPF using voltage stability indicator, L-index, as objective function. Authors treated optimal reactive power dispatch ORPD as a multiobjective problem by considering minimization of real power loss and system static voltage stability(L-index)improvement as competing objectives [19].Here they addressed an application of Modified Non-dominated Sorting Genetic Algorithm-II (MNSGA-II).

3.5.2 Particle Swarm Optimization based VSC-OPF approach

A. Shunmugalatha and S. Mary Raja Slochnal[20] have used maximum loadability limit (MLL) approach for estimating voltage stability. The algorithm named Hybrid Particle Swarm Optimization (HPSO) incorporating breeding and subpopulation process of Genetic Algorithm into Particle Swarm Optimization is applied. In [21], Particle Swarm Optimization (PSO) method was applied for determination of global optimal solution for power system real and reactive power dispatch with voltage stability index as one of the operational constraint.

3.5.3 Evolutionary Technique

Differential Evolution Optimization algorithm was proposed to solve non-linear optimization problem as well as reactive power dispatch problems [22-23]. Various objectives functions have been considered as to minimize the fuel cost, to improve the voltage profile and to enhance the voltage stability in both normal and contingency conditions (L-index as voltage stability indicator). The effectiveness and superiority of the proposed DE is confirmed by comparing the results with the classical and heuristic techniques. The application of Multi objective Differential Evolution (MODE) algorithm to solve voltage stability constraint in reactive power planning and in optimal power flow was nicely presented in [24-25]. Minimization of total cost of energy loss, reactive power production cost of capacitors, minimization of transmission losses, and minimization of fuel cost and maximization of voltage stability margin(L-index as voltage stability indicator) were taken as objectives. Authors [26] proposed an Improved Voltage Stability Index (IVSI) and Total Voltage Stability Index (IVSIT) to assess the overall stability for a system with compensation devices and both are used as the objective functions. Hybrid Differential Evolutionary (HDE) algorithm was used to solve such voltage stability enhancement optimization problem.

Elimination the need of control parameter tuning was proposed in [27] by using new Adaptive Differential Evolution with Variable Population Size Algorithm namely JADE-VPS to solve VSC-OPF where objective function of minimization of cost of power generation with sufficient voltage stability margin (λ) was formulated. M. Tripathy and S. Mishra [28], had represented a new evolutionary algorithm known as Bacteria Foraging Algorithm (BFA) for solving a combined CPF-OPF problem of real power loss minimization and voltage stability limit λ, maximization of the system. A good combination of advanced and classical methods of optimization had been showed in [29]. A new and effective evolutionary algorithm, Differential Search Algorithm (DSA) along with classical Interior Point Method(IPM) was applied for minimization of objective function as voltage stability enhancement (FVSI as Voltage Stability Indicator) and fuel cost. One of the most simple, novel and powerful optimization algorithm namely Opposition Based Self Adaptive Modified Gravitational Search Algorithm (OSAMGSA) was used in [30] to solve multiobjective reactive power dispatch (MORPD) problem with the formulation of objective functions such as voltage deviation, transmission loss and voltage stability enhancement (L-index as voltage stability index).

3.5.4 Other Techniques

Optimal Power Flow (OPF) is one of the most important problems for power researchers. A number of Heuristic algorithms like Artificial Bee Colony (ABC) algorithm,Teaching-Learning Based Optimization Technique (TLBO), Cat Swarm Optimization techniques (CSO) had been proposed in [5, 31-32]. These algorithms identify the optimal values of generation bus voltage magnitudes, transformer tap settings and output of the reactive power sources. Objective functions like transmission loss, fuel cost, voltage stability enhancement(L-index as voltage stability index) and voltage profile improvement had been formulated. In [33], Hybrid method between Artificial Neural Network (ANN) and Ant Colony Optimization (ACO) had been successfully applied to solve voltage stability constraint optimal reactive power dispatch (VSCORPD) with the objective to minimize energy losses and cost of adjusting control devices maintaining voltage stability margin (VSM).

Tarik Zabaiou *et al.* [34], had proposed a novel methodology for VSC-OPF based on static line voltage stability indices to simultaneously improve voltage stability and minimize power system losses under stressed and contingency conditions. A voltage collapse proximity indicator (VCPI) was used there and it was incorporated into optimal power flow formulation in two ways; first it can be added as a new voltage stability constraint in the OPF constraints or used as a voltage stability objective function. "fmincon" function from standard optimization tool box of MATLAB and line search method has been used for the same. Three VSC-OPF techniques for both voltage stability improvement and power loss minimization were well presented and compared in [35]. These techniques were based on static voltage stability indices as voltage collapse proximity indicator (VCPI), bus voltage stability indicator (L-index) and minimum singular value (MSV) of power flow Jacobian matrix. “fmincon”function from standard optimization tool box of MATLAB had been used to such type of VSC-OPF problem.

Various advanced optimization methodologies have been discussed in previous section. To quantify their usability in terms of time or any other parameter like robustness, superiority etc. different standard IEEE test systems have been considered [20] for analyzing the VSC-OPF problem. It had been shown in ref. [20] that the premature convergence of Genetic Algorithm (GA) degrades its performance and reduces its search capability leading to a local optimum. The Particle Swarm Optimization technique can generate high quality solutions within short calculation time and have more global searching ability. Amongst all variations of PSO suggested in the literature by various authors, it is seen that Hybrid PSO (HPSO) converges nearly 1.5416 times, 1.1571 times and 1.3667 times faster than PSO for standard IEEE 30 bus, IEEE 57 bus and IEEE 118 bus systems, respectively. The computation time by this method is 5.0739 times, 7.1324 times and 1.999 times faster than classical method of λ iteration method and 4.3013 times, 6.9954 times and 1.7824 times faster than GA for standard IEEE 30 bus, IEEE 57 bus and IEEE 118 bus systems, respectively.

The review presented in this paper is summarized in Table 4.

TABLE 4

REVIEW OF VSC-OPF AT A GLANCE

Sr. No	Ref. No.	Major findings
1.	[7,8,9]	Evaluation of optimal VAR planning and voltage stability applications using conventional OPF method of MINLP and non-linear primal–dual predictor corrector interior point method.
2.	[10-12, 14,15]	Use of basic optimization technique of “interior point method” with different techniques for VSC-OPF for effective reactive power planning.
3.	[3,13]	Use of Lagarangian analysis and robust interior point method along with Bender’s decomposition technique for voltage stability studies.
4.	[16-19]	Solution of multiobjective VSC-OPF problem with the use of multiobjective evolutionary algorithm with Genetic Algorithm and its various modified versions.
5.	[20-27]	Use of PSO and Evolution techniques such as DE along with their hybrid models for solving VSC-OPF problem.
6.	[28,30]	Use of Bacteria Foraging Algorithm (BFA) for solving a combined CPF-OPF problem and Opposition Based Self Adaptive Modified Gravitational Search Algorithm (OSAMGSA) for solving multiobjective reactive power dispatch (MORPD) problem.
7.	[29]	Use of combination of advanced and classical methods of optimization such as Differential Search Algorithm (DSA) along with classical Interior Point Method (IPM) for voltage stability study.
8.	[5,31-33]	Use of various Heuristic algorithms like Artificial Bee Colony (ABC) algorithm, Teaching-Learning Based Optimization Technique (TLBO), Cat Swarm Optimization techniques (CSO), Hybrid method between Artificial Neural Network (ANN) and Ant Colony Optimization (ACO) for voltage profile improvement.
9.	[34,35]	Use of “fmincon” function from standard optimization tool box of MATLAB for solution of VSC-OPF problem based on static line voltage stability indices.

4.0 CRITICAL COMMENTS AND FUTURE SCOPE

1] Though the optimal power flow algorithms are much faster and more robust, they are very difficult to implement practically. For this purpose, a lot of work on OPF based on automatic control considering dynamics of the system yet to come.

2] In both normal and emergency operation of power systems, voltage/var control is very essential. There is an acute need for automated real time voltage control in the global optimized sense to achieve secure economic power system operation.

3] It is necessary to modify objective functions of VSC-OPF problems not only by monitoring the bus voltage limits and reactive reserve in the system but also by using OPF function to calculate the load ability of the system as a measure of voltage stability margin.

4] Voltage/Var problems, inherently nonlinear, are very difficult to solve by operators regularly especially in non-predicted situations. A significant amount of work yet to be done to implement an automatic real-time voltage/Var control functions.

5] For most of the potential voltage stability problems, prominent research is required considering contingency constraints.

6] Major issue of coordination between two control actions, aimed at resolving active power related problems and resolving voltage stability problems through OPF function have yet to be addressed.

7] For real time application of VSC-OPF algorithm, significant improvements in problem formulation and power system modeling has to be made.

8] More work yet to be done to simplify and generalize VSC-OPF as an optimum allocation/ scheduling tool of the future.

9] Remarkable efforts should be taken to gain higher accuracy of VSC-OPF problems for different loading conditions.

10] Most of the researchers have mainly focused on reactive power rescheduling for VSC-OPF problems consideration, while very few of them tried to propose unique solution strategy of reactive reserve margin optimization.

11] Future work may be carried out for simultaneous scheme of optimizing both FACTS device variables and transformer taps together which have proven beneficial compared to sequential OPF.

12] Dynamic and transient stability constraints should be included into multi-objective optimization problem with advanced optimization techniques.

13] Very few researchers have used line stability indices in VSC-OPF problem formulation. Since line stability indices such as FVSI, Lmn, LQP are very easy and simple to calculate and can be easily implemented for on line real time coded voltage stability analysis, they should be used for effective VSC-OPF.

5.0 SUGGESTED MODIFICATIONS IN COMPUTATIONAL INTELLIGENCE TECHNIQUES FOR VSC-OPF PROBLEM

All papers discussed in this review, had used various advanced optimal power flow methodologies for implementation of VSC-OPF problem in standard IEEE systems. Few of them are listed PSO with time varying inertia weight (PSO-TVIW), PSO with constriction factor (PSO-CF). Few of them used GA, hybrid PSO-GA, Differential Evolution (DE) etc. Although these methods are capable to provide the good quality results at faster rate but when compared with other evolutionary optimization methods, their ability to fine tune the optimum solution is comparatively weak, mainly due to lack of diversity at the end of search. Hence to increase the ability of global optimal solution at later stage, various versions of evolutionary strategies may be used, such as PSO with time varying acceleration coefficient, Active target PSO (APSO) etc.

6.0 CONCLUSIONS

To increase the possibility of making the VSC-OPF as versatile tool for power systems engineers, proper mathematical formulation VSC-OPF problem is very essential and all practical constraints should be taken into account. Various intelligent optimization techniques have paid a lot of attention for solution of such problems. Most of the computational intelligence tools are population based methods, which result in key feature of reduction in the OPF computation time. This paper has taken review on the work reported in the literature, specifically on various advanced optimization methods in the field of VSC-OPF problem but still further improvement in algorithms are required as present versions of techniques have slower convergence at later stage and also not be able to provide optimal solution for real time application. For this PSO with time varying acceleration coefficient, Active target PSO (APSO), hybrid GA-PSO etc. may be considered.

REFERENCES

[1] P Kundur, J Paserba, V Ajjarapu, G Andersson, A Bose, C Canizares, N Hatziargyriou, D Hill, A Stankovic, C Taylor, T V Cutsem and V Vittal, Definition and Classification of Power System Stability, IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, IEEE Trans. on Power Systems, Vol. 19, No. 2, pp.1387-1401, May 2004 .

[2] J P Roselyn, D Devaraj, S S Dash, Multi Objective differential evolution approach for voltage stability constrained reactive power planning problem, Electrical Power and Energy Systems, Vol. 59, pp. 155-165, March 2014.

[3] W Rosehart, C Canizares, V Quintana, Optimal power flow incorporating voltage collapse constraints, University of Waterloo, Department of Electrical & Computer Engineering Waterloo,1996.

[4] M A Abido, NAAl-Ali, Multi-Objective optimal power flow using differential evolution, Arab J. Sci. Eng, Vol. 37, pp. 991-1005, April 2012.

[5] H R E H Bouchekaraa, M A Abidob, M Boucherma, Optimal power flow using Teaching - Learning - based optimization technique, Electric Power Systems Research, Vol. 114, pp. 49–59, May 2014.

[6] J A Momoh, R J Koessler, M S Bond, B Stott, D Sun, A Papalexopoulos, P Ristanovic, Challenges to optimal power flow, IEEE/PES Winter Meeting, pp. 1-11, August 1995.

[7] D Chattopadhyay, B B Chakrabarti, Voltage stability constrained VAR planning: Model simplification using statistical approximation, Electric Power and Energy Systems, Vol. 23, pp. 349-358, September 2000.

[8] E Vaahedi, J Tamby, Y Mansour, WLi, DSun, B C Hydro, Burnaby, Cegelec ESCA, Large scale voltage stability constrained optimal VAR planning and voltage stability applications using existing OPF/Optimal VAr planning tools, IEEE Trans. on Power Systems,Vol. 14, No. 1, pp. 65-74, February 1999.

[9] C Cañizares, W Rosehart, A Berizzi and C Bovo, Comparison of voltage security constrained optimal power flow techniques, IEEE-PES Summer Meeting, July 2001.

[10] W Rosehart, C A Canizares, V H Quintana, Multi-objective optimal power flows to evaluate voltage security costs in power networks, IEEE Tans. Power Systems, pp. 1-10, October 2002.

[11] W Rosehart, C A Canizares, V H Quintana, Effect of detailed power system models in traditional and voltage-stability-constrained optimal power flow problems, IEEE Trans. on Power Systems, Vol. 18, No. 1, pp. 27-35, February 2003.

[12] F Dong, B H Chowdhury, M L Crow, L Acar, Improving voltage stability by reactive power reserve management, IEEE Trans. on Power Systems, Vol. 20, No.1, pp. 338-345, February 2005.

[13] W Zhang, F Li, and L M Tolbert, Interpolation approximation of voltage stability constrained OPF (VSCOPF) for reactive power planning, Euro. Trans. Electr. Power, Vol. 21, pp. 155-164, April 2010.

[14] S Kim, T Y Song, M H Jeong, B Lee, Y H Moon, J Y Namkung, G Jang, Development of voltage stability constrained optimal power flow (VSCOPF), IEEE, pp. 1664-1669, 2001.

[15] H Huang, Y Kong, J Zhang, The analysis on the L-index based optimal power flow considering voltage stability constraints,WSEAS Trans. on Systems, Vol. 7, No. 11, pp. 1300-1309, November 2008.

[16] M S Kumari, S Maheswarapu, Enhanced Genetic Algorithm based computation technique for multi-objective optimal power flow solution, Electrical Power and Energy Systems, Vol. 32, pp. 736–742, January 2010.

[17] S Panuganti, P R John, D Devraj, S S Dash, Voltage stability constrained optimal power flow using NSGA-II, Computational Water, Energy, and Environmental Engineering, Vol. 2, pp. 1-8, January 2013.

[18] J P Roselyn, D Devaraj, S S Dash, Multi-Objective Genetic Algorithm for voltage stability enhancement using rescheduling and FACTS devices, Ain Shams Engineering Journal, Vol. 5, pp. 789–801, May 2014.

[19] S Jeyadevi, S Baskar, C K Babulal, M W Iruthayarajan, Solving multi objective optimal reactive power dispatch using modified NSGA-II, Electrical Power and Energy Systems, Vol. 33, pp. 219–228, 2011.

[20] Shunmugalatha, S M R Slochanal, Optimum cost of generation for maximum loadability limit of power system using hybrid Particle Swarm Optimization, Electrical Power and Energy Systems, Vol. 30, pp. 486–490, April 2008.

[21] P Dutta, A K Sinha, Voltage stability constrained multi-objectiveoptimal power flow using Particle Swarm Optimization, International Conference on Industrial and Information Systems, ICIIS,August 2006.

[22] A A A El Elaa, M A Abido, S R Spea, Optimal power flow using differential evolution algorithm, Electric Power Systems Research, Vol. 80, pp. 878–885, January 2010.

[23] A A A El Elaa, M A Abido, S R Spea, Differential evolution algorithm for optimal reactive power dispatch, Electric Power Systems Research, Vol. 81, pp. 458–464, October 2011.

[24] J P Roselyn, D Devaraj, S S Dash, Multi objective differential evolution approach for voltage stability constrained reactive power planning problem, Electrical Power and Energy Systems, Vol. 59, pp. 155–165, March 2014.

[25] M A Abido, N A Al-Ali, Multi-objective optimal power flow using differential evolution, Arab J. Sci. Eng, Vol. 37, pp. 991–1005, April 2012.

[26] C F Yang, G G Lai, C H Lee, C T Su, G W Chang, Optimal setting of reactive compensation devices with an improved voltage stability index for voltage stability enhancement, Electrical Power and Energy Systems, Vol. 37, pp. 50–57, January 2012.

[27] W Nakawiro and I Erlich, A new adaptive differential evolution algorithm for voltage stability constrained optimal power flow, 17th Power Systems Computation Conference Stockholm Sweden, August 2011.

[28] M Tripathy and S Mishra, Bacteria Foraging based solution to optimize both real power loss and voltage stability limit, IEEE Trans. on Power Systems, Vol. 22, No. 1, pp. 240-248, February 2007.

[29] Y Amrane, M Boudour, M Belazzoug, A new optimal reactive power planning based on differential search algorithm, Electrical Power and Energy Systems, Vol. 64, pp. 551–561, August 2015.

[30] T Niknam, M R Narimani, R A Abarghooee, and B B Firouzi, Multi objective optimal reactive power dispatch and voltage control: anew opposition based self adaptive modified gravitational search algorithm, IEEE Systems Journal, Vol. 7, No. 4, December 2013.

[31] M R Adaryani, A Karami, Artificial Bee Colony algorithm for solving multi-objective optimal power flow problem, Electrical Power and Energy Systems, Vol. 5 3, pp. 219–230, April 2013.

[32] P Suryakumari, P Kantarao, Voltage stability enhancement using Cat Swarm optimization algorithm, World Academy of Science, Engineering and Technology,International Journal of Electrical, Computer, Electronics and Communication Engineering, Vol. 7, No.11, 2013.

[33] W Nakawiro and I Erlich, A hybrid method for voltage stability constrained optimal reactive power dispatch, IEEE, pp. 1-8, 2010.

[34] T Zabaiou, L A Dessaint,I Kamwa, Preventive control approach for voltage stability improvement using voltage stability constrained optimal power flow based on static line voltage stability indices, IET Gener. Transm. Distrib., Vol. 8, Issue. 5, pp. 924–934, 2014.

[35] T Zabaiou, L A Dessaint, I Kamwa, A Comparative study of VSC-OPF techniques for voltage security improvement and losses reduction, IEEE, 2014.

[36] J A Momoh and J Z Zhu, Improved interior point method for OPF problems, IEEE Trans. on Power Systems, Vol.14, No. 3, pp. 1114-1120, 1999.

[37] J A Momoh, M E El Hawary, and R Adapa, A review of selected optimal power flow literature to 1993 part I: nonlinear and quadratic programming approaches, IEEE Trans. Power Systems, Vol. 14, No.1, pp. 96-104, 1999.

[38] J A Momoh, M E El Hawary, and R Adapa, A review of selected optimal power flow literature to 1993 part II: nonlinear and quadratic programming approaches, IEEE Trans. Power Systems, Vol. 14, No. 1, pp. 105-111, 1999.

[39] X Yan, and V H Quintana, Improving an interior point based OPF by dynamic adjustments of step sizes and tolerances, IEEE Trans. on Power Systems, Vol.14, No. 2, pp. 709-717, 1999.

[40] M A Abido, Optimal power flow using Particle Swarm Optimization, International Journal of Electrical Power and Energy Systems, Vol. 24, pp. 563-571, 2002.

[41] R Burchett, H Happ, D Vierath, K Wirgau, Developments in optimal powerflow, IEEE Trans. on Power Apparatus and Systems, Vol. 100, No. 2, pp. 406-414, 1982.

[42] Al Rashidi, M R El Hawary, Applications of computational intelligence techniques for solving the revived optimal power flow problem, Electric Power Systems Research, Vol. 79, No. 4, pp. 694-702, 2009.

[43] G D Costa, C Costa, D Souza, Comparative studies of optimization methods for the optimal power flow problem, Electric Power Systems Research, Vol. 56, pp. 249-254, 2000.

[44] M A Abido, Optimal power flow using Tabu Search algorithm, Electrical Power and System components, Vol. 30, pp. 469-483, 2002.

[45] 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, pp. 851-857, 2002.

[46] W Ongsakul and P Bhasaputra, Optimal power flow with multi-type of FACTS devices by hybrid TS/SA approach, in Proc. IEEE, ICIT, 2002.

[47] W Ongsakul and P Bhasaputra, Optimal power flow with FACTS devices by improved evolutionary programming, Electrical Power Components and Energy Systems, Vol. 34, No. 1, pp. 79-95, 2006.

[48] M A Abido, Multiobjective evolutionary algorithms for electric power dispatch problem, IEEE Trans. on Evolutionary Computation, Vol. 10, No. 3, pp. 315-328, June 2006.

[49] F Capitanescua, JL M Ramosb, P Panciatici, D Kirschend, AM Marcolinib, L Platbroode, L Wehenkela, State-of-the-art, challenges, and future trends in security constrained optimalpower flow,Electric Power Systems Research, Vol. 81, pp. 1731–1741, 2011.

[50] G R MdaCosta, CEU Costa, AMde Souza, Comparative studies of optimization methods for the optimal power flow problem, Electric Power Systems Research, Vol. 56, pp. 249–254, 2000.

[51] J A Momoh, Electric Power System Applications of Optimization, Marcel Dekker, Inc., 2001.

[52] B K Panigrahi, A Abraham, S Das, Computational Intelligence in Power Engineering, Vol. 302, Springer, 2010.

[53] T Kritsana, Development of an efficient calculation method based on evolutionary programming for optimal power flow considering transient and voltage stabilities, PhD dissertation, Graduate School of Engineering, Tokyo, December 2009.

TABLE 2

COMPARISON OF CLASSICAL OPTIMIZATION TECHNIQUES

Sr. No.	Method	Formulation	Comments	Pros and cons	
				Pros	**Cons**
1.	Gradient Method	$\nabla f^T = [\frac{\partial f}{\partial x1}, \frac{\partial f}{\partial x2} \dots]$ Where f is objective function	-uses knowledge of derivative information to locate optimum point. -gradient of the function tells what direction to move locally. -Functional inequality constraints require use of penalty terms.	-better fitted to highly constrained problems. - can accommodate non linearities easily. - are very efficient, reliable, accurate and fast.	-difficulty of handling all the inequality constraints. -the direction of the Gradient has to be changed often leading to a very slow convergences.
2.	Newton Method	Lagrangian equation $L(z) = f(x) + \mu^T h(x) + \lambda^T g(x)$, μ, λ are lagrange multipliers.	-Developed for unconstrained NLP. - use with OPF requires identication of binding constraint set and use of penalty terms for functional constraints. - Quadratic convergence characteristic. -Used as local solver.	-ability to converge fast and is a flexible formulation. -can handle inequality constraints very well. - efficient and robust solutions can be obtained for problems of any practical size.	-the convergence characteristics sensitive to the initial conditions and may even fail to converge due to inappropriate initial conditions. -The penalty near the limit is very small by which the optimal solution will tend to the variable to float over the limit.

3.	Linear Programming Method	Succession of linear approximations.	-requires linearization of OPF equations. -excellent speed in most applications. -both the objective and constraints are linear.	-completely reliable and very fast. -easily handles Non linearity constraints. -efficient in handling of inequalities. - ability for incorporation of contingency constraints and there is no requirement to start from a feasible point.	-requires monitoring to ensure convergence and exhibits numerical instability and/ or oscillation for certain problem types. - suffers lack of accuracy.
4.	Quadratic Programming Method	Non Linear Programming (NLP)	-special form of NLP with quadratic objective function and linear constraints. -Active-set method. Faster than SLP for many OPF formulations; competitive with IPMs. -Used in several commercial OPF packages. -Active area of research	-suited to infeasible or divergent starting points. -does not require the use of penalty factors or the determination of gradient step size, hence faster convergence. - accuracy is much higher compared to other established methods.	-complexity and reliability of quadratic programming algorithms

TABLE 3

COMPARISON OF ADVANCED OPTIMIZATION TECHNIQUES

Sr. No.	**Method**	**Standard Parameters**	**Comments**	**Pros and Cons**	
				Pros	**Cons**
1.	SA	initial temperature, annealing rate	only suggested as a hybrid method for OPF due to slow convergence speed	- can optimize functions with arbitrary degrees on nonlinearity, stochasticity, boundary conditions, and constraints. -is statistically guaranteed to find an optimal solution.	-the annealing procedure is very CPU consuming. - is very slow - its efficiency is dependent on the nature of the surface it is trying to optimize and it must be adapted to specific problems.

2.	TS	tabu list length	-conceptually very simple. - a good starting point for OPF algorithms. - is basically a gradient descent search with memory.	-it is possible to avoid being trapped in local minima by using short-term and long- term process. - has the advantage of not using hill-climbing strategies. -its performance can also be enhanced by branch-and-bound techniques.	- the mathematics behind this technique is not strong. -requires knowledge of the entire operation at a more detailed level.
3.	DE	differentiation constant, crossover constant, population size	- good convergence properties for OPF problems. - uses real coding of floating point numbers. -powerful stochastic real parameter algorithm. -handle mixed integer discrete continuous optimization problem.	-simple and straightforward for implementation. -better performance in terms of accuracy, convergence speed and robustness. -very few control parameters. -low space complexity.	-improper scaling factor and crossover ratio may lead poor convergence speed.
4.	EP	population size, number of generations	conventionally very simple. - well suited when uncertainty is present in OPF and in hybrid methods for OPF -works on real value coded strings.	As a powerful and general global optimization tool	- more research needed in the mathematical foundation for the EP or its variants with regard to experimental and empirical research - more parameter tuning is required. -require more computational time in most cases. - heavily involved programming skills are required to develop and modify competing algorithms to suit different classes of optimization problems.

5.	GA	crossover probability, mutation probability, population size	-suitable for large-scale OPF due to parallelism of GAs. - work with a coding of the parameter set. -GA is computational evolution based algorithm works on the rule "survival of fittest".	GAs can provide a globally optimal solution. -can deal with non-smooth, non-continuous and non-differentiable functions which are actually exist in a practical optimization problem. - GAs use probabilistic transition rules, not deterministic rules. -GAs can handle the Integer or discrete variables. - can provide a globally optimum solution as it can avoid the trap of local optima. - are adaptable to change, ability to generate large number of solutions and rapid convergence. - GAs can be easily coded to work on parallel computers.	- are stochastic algorithms and the solution they provide to the OPF problem is not guaranteed to be optimum. -The execution time and the quality of the solution, deteriorate with the increase of the chromosome length, i.e., the OPF problem size. If the size of the power system is increasing, the GA approach can produce more in feasible off springs which may lead to wastage of computational efforts.
6.	PSO	swarm size, cognitive parameter, social parameter	-theory reasonably well understood. -reasonably robust to parameters for OPF problems. - population based evolution technique. - non-gradient, derivative-free method	- modern heuristic algorithms capable to solve large-scale non convex optimization problems like OPF. - simple concept, easy implementation, relative robustness to control parameters and computational efficiency. - fast convergence speed. -can be realized simply for less parameter adjusting.	- candidate solutions in PSO are coded as a set of real numbers. But, most of the control variables such as transformer taps settings and switchable shunt capacitors change in discrete manner. Real coding of these variables represents a limitation of PSO methods as simple round-off calculations may lead to significant errors.

				- can easily deal with non differentiable and non convex objective functions. -has the flexibility to control the balance between the global and local exploration of the search space. - by utilizing the fitness function value, eliminates the approximations and assumption operations that are often performed by the conventional optimization methods upon the problem objective and constraint functions, -flexible enough to allow hybridization and integration with any other method if needed, whether deterministic or heuristic, Unlike many other metaheuristic techniques.	- Slow convergence in refined search stage (weak local search ability). - There is no solid mathematical foundation for the PSO metaheuristic Method. - Compared to GA, EP algorithms, PSO has fewer published books andarticles.