Optimal Reactive Power Dispatch for Voltage Stability Improvement using Enhanced Whale Optimization Algorithm

Gayathri Devi K.S.
Noorul Islam Center for Higher Education,
Kumaracoil, Thuckalai, Tamil Nadu, India
ksgayathridevi2@gmail.com

Abstract: In recent days, the ORPD topic has attained significant consideration, since it enhances the economy and security of a power system. It includes discrete and continuous controlling parameters and thus it is considered as a complicated nonlinear issue. Thereby, this paper focuses on foremost objectives such as, diminution of loss and variations in voltage, which assists in resolving the ORPD problem under unbalanced states. For attaining these objectives, "Whale Optimization Algorithm based Parameter Optimization (WOAPO) approach" is exploited. This algorithm makes an impact on the controlling constraints that are adjusted to accomplish the optimal outcome. Finally, the superiority of the presented work is proved other other existing schemes. On observing the outcomes, the values attained under best case scenario using WOAPO scheme is 0.57%, 0.5% and 0.92% better than GA, FF and ABC. In addition, the worst case scenario of WOAPO approach is 1.16% superior to PSO model.

Keywords: ORPD; Voltage Profile; Power loss; Stability; VAR sources; WOAPO; Reactive power.

Nomenclature

Abbreviations	Descriptions
APL	Active Power Loss
ABC	Artificial Bee Colony
2ArchMGWO	Two-Archive Multi-Objective Grey wolf Optimization
FF	FireFly
GA	Genetic Algorithm
MFO	Moth-Flame Optimization
NGBWCA	Gaussian bare-bones Water Cycle Algorithm
ORPD	Optimal Reactive Power Dispatch
OPF	Optimal Power Flow
PSO	Particle Swarm Optimization
RP	Reactive Power
WOAPO	Whale Optimization Algorithm based Parameter Optimization

1. Introduction

ORPD is a major aspect for OPF in modernized power systems for stable and secure operation. The most important task of such ORPD issue is to discover optimal settings of the entire controlling factors such as "reactive power output of generators, on-load tap changer of transformers, and shunt capacitor power outputs" [3]. In an electrical system, the ORPD is said to be a major factor for reducing losses and cost, for improving the stability of voltage and so on [1] [2].

The issue of reactive power dispatches for enhancing power system control and economical operations has attained much more consideration [4] [5] [6]. Moreover, a considerable sum of money could be saved by the decrease in active power loss accomplished from ORPD. The controlling parameters includes, "generator voltage magnitude, the tap ratios of transformer, static VAR sources" and so on. Accordingly, the parameters includes the "tap ratio limits, buses voltage limits, VAR source limits as well as voltage limits of generators" etc [11].

Several methods were introduced for the accomplishment of ORPD in power systems [7] [8] over the previous few decades. Traditional approaches such as "Mixed integer Programming, Predictor Corrector Primal Dual Interior Point Method, Nonlinear Programming, Linear Programming, gradient method, interior point method Successive Quadratic Programming" etc. are deployed for resolving ORPD issues [9] [10]. However, these approaches had failed to deal with the ORPD issues owing to their non-smoothness and multi-modal characteristics.

The paper is arranged as: Section II portrays the reviews on ORPD and section III explains the modelling of ORPD under unbalanced conditions. Section IV elucidates the WOAPO based optimization for resolving ORPD issues. Finally, section V explains the results, and sections VI conclude the paper.

2. Literature Review

2.1 Related works

In 2014, Mojtaba et al. [1] established an effectual and consistent approach that depends upon ABC approach for resolving the ORPD issues. Accordingly, ABC approach is exploited for attaining "generator voltage magnitude, tap position of tap changing transformer and reactive power output of the compensation devices". Moreover, better convergence rate was attained that proved the superiority of presented model over the existing schemes.

In 2017, Ali et al. [2] introduced a NGBWCA oriented model for overcoming and dealing with the issues occurring in ORPD. In this work, the resistive losses and voltage discrepancies were considered as objectives that need to be reduced. The efficiency of the adopted NGBWCA method was examined over other schemes and the results were obtained. In the end, the numerical tests and experimental results has revealed the efficacy of the NGBWCA model in solving ORPD problems.

In 2017, Kasem et al. [3] established an original 2ArchMGWO approach for solving the issues in ORPD. In this context, the optimizer was improved from its usual form by the update of reproduction function and by summing the 2-archive hypothesis to the system. In addition, the optimal outcomes obtained from a number of optimizers were evaluated over one another depending on hypervolume indicator, and it was proved that the adopted method was apparently enhanced than the compared ones.

In 2017, Rebecca et al. [4] introduced a new technique to cope up with the ORPD problem by adopting the concept of well known optimization scheme called MFO. In addition, optimal grouping of controlling parameters were carried out by means of MFO, by which minimal total power loss and minimal voltage deviations could be attained. Eventually, the enhancement of the presented approach was proved other existing schemes by carrying out mathematical analysis.

In 2015, Rajan and Malakar [5] had suggested a novel hybridized technique, which combined FF approach for resolving the issues associated with ORPD. In addition, it was observed that the adopted scheme has improved robustness and convergence rates when compared over the actual FF model and other conventional models. As a result, it was revealed that the introduced method has presented superior solutions.

3. Modelling of ORPD Under Unbalanced Conditions

3.1 Objective Model

The minimisation of APL and development of voltage stability is a most significant factor of ORPD. The dependent parameters is shown in Eq. (1), where P_G symbolizes the dropped bus power, V_{li} signifies the voltage bus PQ $(i=1,2....MPQ)$, Q_{Gi} indicates the RP output of generator $(i=1,2....MG)$, MG and MPQ refers to the count of generator bus and PQ bus respecievly. The control variable vector is specified by Eq. (2).

$$Z = [P_{G1}, V_{l-1}.......V_{l-MPQ}, Q_{G-1}......Q_{G-MG}] \qquad (1)$$

$$J = [V_{G-1},.....V_{G-MG}, Q_{C-1}.....Q_{C-MC}, B_1,.....B_{MB}] \qquad (2)$$

In Eq. (2), "V_{Gi} refers to the terminal bus voltage, Q_{Ci} signifies the output of shunt VAR compensator, B_i indicates the tap setting of tap changing transformer, MC and MB denotes the count of shunt VAR compensator and tap clanging transformer" respecievly.

The objective function of this work is specified in Eq. (3), in which D_b point out APL, and D_o signify the difference in voltage.

$$f_i = \alpha D_o + (1-\alpha)D_o \tag{3}$$

3.2 Minimization of APL

The APL minimisation is modelled as per Eq. (4), where P_l point out the APL, M refers to transmission line's count, g_k points out the conductance of kth branch. Also, δ_n and δ_m refers to the voltage phase angles of nth and m^{th} buses in that order.

$$D_b = P_l = \sum_{k=1}^{M} g_k[V_m^2 + V_n^2 - 2V_m V_n \cos(\delta_m - \delta_n)] \tag{4}$$

3.3.Voltage Variations

The minimisation of voltage magnitude (V_i) at diverse loads from a fixed reference value (V^{ref}) of V_i is deployed for improving the voltage profile, which is specified in Eq. (5). Here, lb indicate the total count of load buses and $\psi(y)$ refers to the step function that is computed as per Eq. (6).

$$D_o = V_F = \sum_{i=1}^{lb} P_f \psi(V^{min} - V_m) + P_f \psi(V_m - V^{max}) \tag{5}$$

$$\psi(y) = \begin{cases} 1; & \text{if } y \geq 0 \\ 0; & \text{otherwise} \end{cases} \tag{6}$$

In Eq. (7), Q and P refers to the reactive and real powers, in that order. In addition, y and r signifies the susceptance and resistance of line respectively.

$$|V_m|^2 = |V_i|^2 - 2(P_{im} \tilde{r}_{im} + \tilde{y}_{im} Q_{im}) + c_{im}(P,Q) \tag{7}$$

$$\tilde{r}_{im} = Re\{bb^H\} \otimes r_{im} + Im\{bb^H\} \otimes y_{im} \tag{8}$$

$$\tilde{y}_{im} = Re\{bb^H\} \otimes y_{im} - Im\{bb^H\} \otimes r_{im} \tag{9}$$

$$b = \begin{bmatrix} 1 & e^{-j2\pi/3} & e^{j2\pi/3} \end{bmatrix} \tag{10}$$

$$c_{im} = [z_{im}[T_{im}^*./V_i^*]] \otimes [z_{im}^*[T_{im_0}./V_i]] \tag{11}$$

$$z_{im} = r + jy \tag{12}$$

$$T_{im} = [P_{im} + jQ_{im}] \otimes [\tilde{z}_{im}(P_{im} - jQ_{im})] \tag{13}$$

$$\tilde{z}_{im} = z_{im} \otimes (b_i \overline{b}_i^H) \tag{14}$$

The L -index value (N_n) of nth bus is specified as Eq. (15), where $n = 1,2.......,MPQ$, MPV signifies PV bus count and X_o and X_b of Eq. (16) refers to the sub-matrices. XBUS is specified by (17), after the partition of PQ and PV bus.

$$N_n = \left|1 - \sum_{m=1}^{MPV} D_{nm} \frac{V_m}{V_n}\right| \tag{15}$$

$$D_{nm} = [X_b]^{-1}[X_o] \tag{16}$$

$$\begin{bmatrix} I_{PQ} \\ I_{PV} \end{bmatrix} = \begin{bmatrix} X_b X_o \\ X_c X_d \end{bmatrix} \begin{bmatrix} V_{PQ} \\ V_{PV} \end{bmatrix} \tag{17}$$

The value of N_n is fixed as 0 or 1 that depends on the voltage fall down and no load states of nth bus. Thus, the objective function is specified by Eq. (18), in which $N_n = 1,2.....MPQ$.

$$D_c = \max(N_n) \tag{18}$$

3.4 Inequality and Equality Parameters

The power system is regulated by equality factors and it involves the load flow of voltage, which are modelled as in Eq. (19) and Eq. (20).

$$P_{Gm} - P_{Dm} - V_m \sum_{n=1}^{MB} V_n \left[F_{mn} \sin(\delta_m - \delta_n) + G_{mn} \cos(\delta_m - \delta_n) \right] = 0 \tag{19}$$

$$m = 1,2........MB$$

$$Q_{Gm} - Q_{Dm} - V_m \sum_{n=1}^{MB} V_n \left[F_{mn} \sin(\delta_m - \delta_n) + G_{mn} \cos(\delta_m - \delta_n) \right] = 0 \tag{20}$$

In Eq. (20), MB refers to bus count, Q_{Gm} and P_{Gm} refers to the generated reactive and active power at m^{th} bus, Q_{Dm} and P_{Dm} refers to demand associated with reactive and active powers, B_{mn} and G_{mn} signifies the transfer susceptance and conductance.

The upper and lower bounds for magnitude of RP and output voltage were specified by Eq. (21) and Eq. (22).

$$Q_{Gm}^{min} \le Q_{Gm} \le Q_{Gm}^{max}, \ m = 1,2,.......MG \tag{21}$$

$$V_{Gm}^{min} \le V_{Gm} \le V_{Gm}^{max} \ m = 1,2,.......MG \tag{22}$$

The upper and lower bounds of RP at output in shunt VAR compensators are shown in Eq. (23).

$$Q_{Cm}^{min} \le Q_{Cm} \le Q_{Cm}^{max} \ m = 1,2,.......MC \tag{23}$$

In addition, the lower and upper values of transformer tap setting are shown by Eq. (24). A certain limit exists for the voltage in buses and all line flows are modelled as shown in Eq. (25) and Eq. (26).

$$B_m^{min} \le B_m \le B_m^{max}, \ m = 1,2,.......MB \tag{24}$$

$$V_{Nm}^{min} \le V_{Nm} \le V_{Nm}^{max} \ m = 1,2,.......MPQ \tag{25}$$

$$T_{lm} \le T_{lm}^{max} \ m = 1,2,.......M \tag{26}$$

4. WOAPO based Optimization for Resolving ORPD Issues

4.1 Solution Encoding

The parameters namely, transformer tap setting (B), voltage magnitude (V) and RP (Q) are provided as solutions to WOAPO approach for resolving the ORPD issues. The solution encoding is shown in Fig. 1. "The RP of 5 generator buses (bus no: 1, 2, 3, 6 and 8), voltage magnitude of bus 13 and 3, transformer tap setting of buses 8, 9 and 10" are fixed optimally via WOAPO approach, which minimizes the voltage divergence and power losses.

Fig. 1. *Solution Encoding*

4.2 WOAPO Algorithm

In the conventional WOA model, the main drawbacks are that it is not good at exploring the search space. Therefore, WOAPO is exploited in this work. The mathematical modelling of WOAPO [16] model is briefly explained here.

(i) Encircling Prey: The humpback whales have the capability to spot the locality of prey and encircle them. The encircling activities of humpback whales are specified in Eq. (27) and Eq. (28), where $\vec{A}$ and $\vec{U}$ refer to the coefficient vectors and current iteration is indicated as t.

$$\vec{H} = \left| \vec{U}.\vec{R}_p(t) - \vec{R}(t) \right| \tag{27}$$

$$\vec{R}(t+1) = \vec{R}_p(t) - \vec{A}.\vec{H} \tag{28}$$

In addition, $\vec{R}$ denotes the positions and $\vec{R}_p$ denotes best position acquired so far. Furthermore, $\vec{A}$ and $\vec{H}$ are computed as per Eq. (29) and Eq. (30). In Eq. (29), the component $\vec{a}$ is lessened from 2 to 0 for diverse iterations. The random vectors ra_1 and ra_2 resides lies amongst [0, 1].

$$\vec{A} = 2\hat{a}.ra_1 - \vec{a} \tag{29}$$

$$\vec{H}=2r\vec{a}_2 \tag{30}$$

(ii) Exploitation Phase:
It is modelled depending on the "Shrinking encircling mechanism and Spiral updating position".
(a)"Shrinking encircling mechanism": It is accomplished by lessening the $\vec{a}$ value in Eq. (29).
(b) Spiral update Evaluation: A spiral formula is formed among the whale position and prey as represented in Eq. (31), in which $\vec{H}$ indicates the distances of ith whale to prey and b is a variable that denotes "logarithmic spiral shape" and l is an arbitrary integer that lies between $[-1,l]$. The arithmetical formula for $\vec{H}$ is given in Eq. (32).

$$R(t+1) = \vec{H}'e^{bl}.Cos(2\pi l) + \vec{R}_p(t) \tag{31}$$

$$\vec{H}' = \left| \vec{R}_p(t) - \vec{R}(t) \right| \tag{32}$$

During optimization, the position of whales gets updated, which is shown numerically in Eq. (33), in which ϕ refers to an arbitrary integer.

$$R(t+1) = \begin{cases} \vec{R}_p(t) - \vec{A}.\vec{H} & \text{if} & \phi < 0.5 \\ \vec{H}'.e^{bl}.Cos(2\pi l) + \vec{R}_p(t) & \text{if} & \phi \geq 0.5 \end{cases} \tag{33}$$

Exploration phase: This phase is evaluated as shown in Eq. (34) and Eq. (35). The arbitrary position vector elected from the present population is indicated by $R_{(rand)}$.

$$\vec{H} = \left| \vec{A}\,\vec{R}_{(rand)} - \vec{R} \right| \tag{34}$$

$$\vec{R}(t+1) = \vec{R}_{(rand)} - \vec{A}.\vec{H} \tag{35}$$

5. Results and Discussions

5.1 Simulation Set up

The accomplishment of ORPD using WOAPO approach was implemented in MATLAB, and the experimentation was carried out on "IEEE 14 and IEEE 39 bus systems". The analysis were performed for resolving ORPD issues under specific loading states such as voltage penalty (F_a) and APL (F_b). In addition, the superiority of WOAPO approach was evaluated over other existing optimization schemes such as, GA [12], FF [13], PSO [14] and ABC [15]. Moreover, statistical analysis was carried out for portraying the enhancement of WOAPO approach.

5.2 Statistical Analysis

The statistical analysis of WOAPO based approach for obtaining enhanced ORPD is specified by Table I and Table II for IEEE 14 and IEEE 19 bus systems. As the met heuristic models are stochastic, and to ensure fair comparison, each algorithm is executed ten times to obtain the statistics of the objective. On observing the outcomes, the values attained under best case scenario using WOAPO scheme is 0.57%, 0.5% and 0.92% better than GA, FF and ABC. In addition, the worst case scenario of WOAPO approach is 1.16% superior to PSO model. In addition, the values attained under mean case scenario using WOAPO technique is 0.12%, 0.12%, 0.78%% better than GA, FF and ABC models. Likewise, from Table II, the WOAPO approach has attained a best case scenario that is 0.24%, 0.29% and 0.29% better than PSO, FF and GA models. Also, the mean case scenario of WOAPO scheme is 4.13%, 4.68%, 0.35% and 0.2 % better than GA, FF, PSO and ABC models. As a result, the improvement of WOAPO algorithm was established from the simulated outcomes.

Table 1: *Statistical analysis: Evaluation of WOAPO approach over existing approaches on IEEE 14 bus system*

Metrics	FF [13]	GA [12]	ABC [15]	PSO [14]	WOAPO
Best	0.29496	0.29496	0.29496	0.296	0.29327
Mean	0.29496	0.29496	0.29496	0.29694	0.29462
Standard deviation	1.66×10^{10}	6.67×10^9	3.26×10^9	0.000933	0.000752
Median	0.29496	0.29496	0.29496	0.29693	0.29496
Worst	0.29496	0.29496	0.29496	0.29844	0.29496

Table 2: Statistical analysis: Evaluation of WOAPO approach over existing approaches on IEEE 39 bus system

Metrics	FF [13]	GA [12]	ABC [15]	PSO [14]	WOAPO
Best	36.298	36.298	36.298	36.28	36.192
Mean	36.303	36.301	36.359	36.413	36.286
Standard deviation	0.006306	0.003591	0.077518	0.09631	0.05332
Median	36.302	36.299	36.327	36.469	36.304
Worst	36.313	36.305	36.482	36.491	36.322

5.3 Analysis by Altering α

The WOAPO based approach accomplishes the minimal loss by changing the parameter α as specified by Eq. (3). The tabular manifestation attained by varying α using WOAPO model is shown in Table III for IEEE 14 bus system. Here, the value of α is varied and the losses, voltage penalties and final costs were computed. The loss is almost same for all α values. The VSI is minimum when selecting α =1, and the reduced final fitness is attained when choosing α =4. In Table IV, VSI is minimum when selecting α =2 and LSI is minimal when selecting α =3 and the final cost is minimal when selecting α =0.1.

Table 3: Analysis on ORPD by varying the values of α for IEEE 14 bus system

Varied values of α	LSI	VSI	Final cost
$\alpha = 1$	1	0.88	1
$\alpha = 2$	1	0.89	0.78
$\alpha = 3$	1	1	0.5
$\alpha = 4$	1	1	0.25

Table 4: Analysis on ORPD by varying the values of α for IEEE 39 bus system

Varied values of α	LSI	VSI	Final cost
$\alpha = 1$	1	0.87	0.42
$\alpha = 2$	0.99	0.4	0.62
$\alpha = 3$	0.98	0.41	0.82
$\alpha = 4$	0.99	0.99	1

6. Conclusion

This work has exploited WOAPO approach for resolving the issues in ORPD. In this work, the ORPD was portrayed as a non-linear issue and it was solved by evaluating the objectives namely minimisation of power loss and minimisation of variations in voltage. For attaining these objectives, WOAPO based optimization approach was deployed in this paper. Furthermore, the superiority of WOAPO approach was evaluated over other existing approaches and the outcomes were attained. On observing the outcomes, the values attained under best case scenario using WOAPO scheme was 0.57%, 0.5% and 0.92% improved than GA, FF and ABC. In addition, the worst case scenario of WOAPO approach was 1.16% superior to PSO model. Also, the values attained under mean case scenario using WOAPO technique was 0.12%, 0.12%, 0.78%% better than GA, FF and ABC models. Thus, the advantage of WOAPO approach for obtaining an enhanced ORPD model was validated effectively.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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