National University of Science and Technology Politehnica Bucharest

Doctoral School of Energy Engineering

Summery

MULTI CRITERIA FRAMEWORKS FOR SOLVING OPTIMAL POWER FLOW USING METAHEURISTIC OPTIMIZATION TECHNIQUES

Thesis submitted in fulfilment of the requirements of National University of Science and Technology Politehnica Bucharest, for the degree of PhD in Electrical power Engineering

Ph.D. Student

Eng. Murtadha Mahmood Sadkhan AL-KAABI

Ph.D. Supervisor

Prof. Em. Dr. Eng. Mircea EREMIA

Romania, Bucharest, 2023

Contents

CHAPTER 1

GENERAL INTRODUCTION

1.1. Thesis context

One of the most important concerns in electrical power systems is power flow (PF), often known as load flow. The main goal of studying power flow analysis is to determine the reactive power output in transmission lines, the bus voltage, and the total system losses under normal operating conditions. In recent decades, optimal power flow (OPF) has been given extensive interest by researchers because it is one of the important tools used in the power management systems to achieve the reliable operation and planning of electrical power systems [1]. To optimize objective functions in the power system, OPF needs to set the control variables while respecting equality and inequality constraints because OPF is a non-convex, nonlinear, and large-scale problem. Active power output of the generation units without the slack bus, the voltages at PV buses, reactive power compensators, and tap transformers setting are the control variables that are tuned. generation fuel cost (GFC), real power loss (RPL) in the transmission lines, emission (Em), voltage deviation (VD), and voltage stability index (VSI) in the whole system are the objective functions will be optimized. OPF was firstly presented by Carpentier in 1962 [2].

The main aim of studying of OPF is achieve the optimal objective functions such as total fuel cost, real power losses, total emission, voltage profiles at load bus, and voltage stability index of whole system by setting the control variables with satisfying the equality and inequality constraints [3]. The control variables of optimal power flow (OPF) involve the real power output of generation units, voltage magnitude of generation bus, reactive power compensators of VAr source, and tap changer setting of transformers. The state variables that will be set in the power system are real power generators at slack bus, reactive power output of generation units, magnitude voltage at load bus, and apparent power flow in transmission lines. The constraints will be classified into equality and inequality constraints. The first one represents the balance equations of optimal power flow (OPF). The inequality constraints represent the boundaries of the state variables and control variables. The OPF is a non-convex, nonlinear, static, and large-scale problem with discrete and continuous control variables. [4].

1.2. Main objective

The main objectives of this thesis are to solved single and multi-objective optimal power flow problems using four recent intelligent optimization techniques. The optimization techniques that have been selected to solve single objective optimal power flow (SOOPF) problems in power systems are Grey Wolf Optimizer (GWO), Harries Hawks Optimizer (HHO), Hunger Games Search (HGS), and Slime Mould Algorithm (SMA). Multi-objective optimal power flow (MOOPF) is very most important in power systems operation and planning because of its ability to find the best compromise solution for more than one objective function simultaneously [5]. Pareto concept incorporates many optimization methods to arrange the non-dominated solutions and set generation probability for individuals. The selected Algorithms (GWO, HHO, HGS, and SMA) have been developed to solve single and multi-objective optimal power flow (OPF) problems and achieve economic, environmental, and technical benefits. The Pareto concept is incorporated with the proposed algorithms (GWO, HHO, HGS, and SMA) to solve multi-objective OPF problems. The approach used to extract the best compromise solution is fuzzy set theory. Generation fuel cost (GFC), emission (Em), real power losses (RPL), voltage deviation (VD), and voltage stability index (VSI) are the objective functions that will be optimized.

1.3. Thesis structure

To achieve the above-mentioned objectives, it can be briefly explaining the steps for each section as follows:

Chapter One is an overview of the introduction of optimal power flow (OPF), conventional and intelligent optimization methods, literature review, objective of the thesis, and the methodology of this thesis. The first part of this chapter presents the importance of studying the optimal power flow to achieve the economical, technical, and environmental benefits. The second part of this chapter represents the literature review of optimal power flow applications in power systems. Also presents the classification of objective functions in optimal power flow into single and multi-objective functions. The fourth part includes the main objective of studying this thesis. The last part is the methodology used for this thesis.

Chapter Two includes the mathematical model of optimal power flow. This chapter presents the objective functions that will be optimized by set control variables as optimally with satisfied the equality and inequality constraints. These objective functions are total fuel cost, emission, active power losses, voltage deviation, and voltage stability index. The control variables that will be set to achieve the optimal objective functions are real power output of generation units except the real power of slack bus, the voltages of generator bus, and the tap ratios of transformer, and the VAR sources compensators. The objective functions will be optimized by single and multiobjective functions. Also, this chapter will express the mathematical model of Pareto concept optimization, fuzzy set theory, and crowding distance to solve multi-objective functions.

Chapter 3 explains four modern metaheuristic optimization techniques, Grey Wolf Optimizer (GWO), Harris Hawks Optimizer (HHO), Hunger Games Search (HGS), and Slime Mould Algorithm (SMA). These algorithms have been proposed to solve single objective optimal power flow (SOOPF) problems in power systems. Pseudo-codes and flowchart of the proposed algorithms (GWO, HHO, HGS, and SMA) have been presented in this chapter.

Chapter 4 describes the approaches have been used to solve multi objective functions optimal power flow (MOOPF) problems. The author was developed the proposed algorithms (GWO, HHO, HGS, and SMA) into developed approaches named multi-objective grey wolf optimizer (MOGWO), multi-objective harries hawk's optimization (MOHHO), multi-objective hunger games search (MOHGS), and multi-objective slime mould algorithm (MOSMA) to adaptive with solving multi-objective optimal power flow (MOOPF) problems. Also, this chapter presents the flowchart, and the programs process to apply and solve MOOPF problems of the developed algorithms (MOGWO, MOHHO, MOHGS, and MOSMA).

Chapter 5 deals with the application of metaheuristic optimization techniques to solve single and multi-objective optimal power flow in power systems. The proposed algorithms (GWO, HHO, HGS, and SMA) will be used to solve single objective optimal power flow (SOOPF) problems. The developed approaches (MOGWO, MOHHO, MOHGS, and MOSMA) have been proposed to solve multi objective optimal power flow (MOOPF) problems. The objective functions that will be optimized are total fuel cost of generation units, real power loss on transmission lines, total emission issued by fossil-fueled thermal units, voltage deviation at load bus, and voltage stability index of the whole system. To investigate the performance of the proposed algorithms; the author used two standardized test power systems; IEEE 30-bus system (small system) and IEEE 57-bus system (medium system); and practical system; Iraqi Super Grid High Voltage 400 kV. Also, this chapter will compare the optimal results of objective functions obtained by proposed algorithms (GWO, HHO, HGS, and SMA) and the developed approaches (MOGWO, MOHHO, MOHGS, and MOSMA) over the optimal results obtained by modern metaheuristic optimization techniques reported in the literature to prove the viability and efficiency of the proposed algorithms and the developed approaches. Various frameworks have been applied to achieve single and conflicting multi-objective functions simultaneously (single, Bi, Tri, Quad, and Quinta objective functions) for solving single and multi-objective OPF problems. The author applied 46 cases studies on IEEE 30-bus, IEEE 57 bus systems, and Iraqi super grid high voltage 400 kV of proposed algorithms (GWO, HHO, HGS, and SMA) and developed approaches (MOGWO, MOHHO, MOHGS, and MOSMA); 14 cases studies for single objective function; 12 cases studies for Bi objective functions; 12 cases studies for Tri objective functions; 6 cases studies for Quad objective functions; two cases studies for Quinta objective functions. Pareto concept is the optimization method that has been used to find non-dominated solutions. The fuzzy set theory is the technique that has been applied to extract the best compromise solution (BCS). To rank and reduce the non-dominated solutions, the crowding distance is the technique that has been applied.

The last chapter deals with conclusion and future work. The References and the Appendixes of the data for the systems IEEE 30- bus, IEEE 57-bus, and Iraqi Super Grid High Voltage 28-bus are tabled in the end of this thesis.

CHAPTER 2

THE FORMULATION OF THE OPF PROBLEM

2.1. Conventional and intelligent optimization methods of OPF

Conventional and intelligent optimizations are the techniques that will be employed to address OPF problems. Conventional techniques based on random, calculus, and enumerated. Metaheuristic algorithms have been presented to address the limitations of these methods, allowing for the efficient resolution of single and multi-objective functions OPF problems. **Fig. 2.1** depicted the classification of optimization methods.

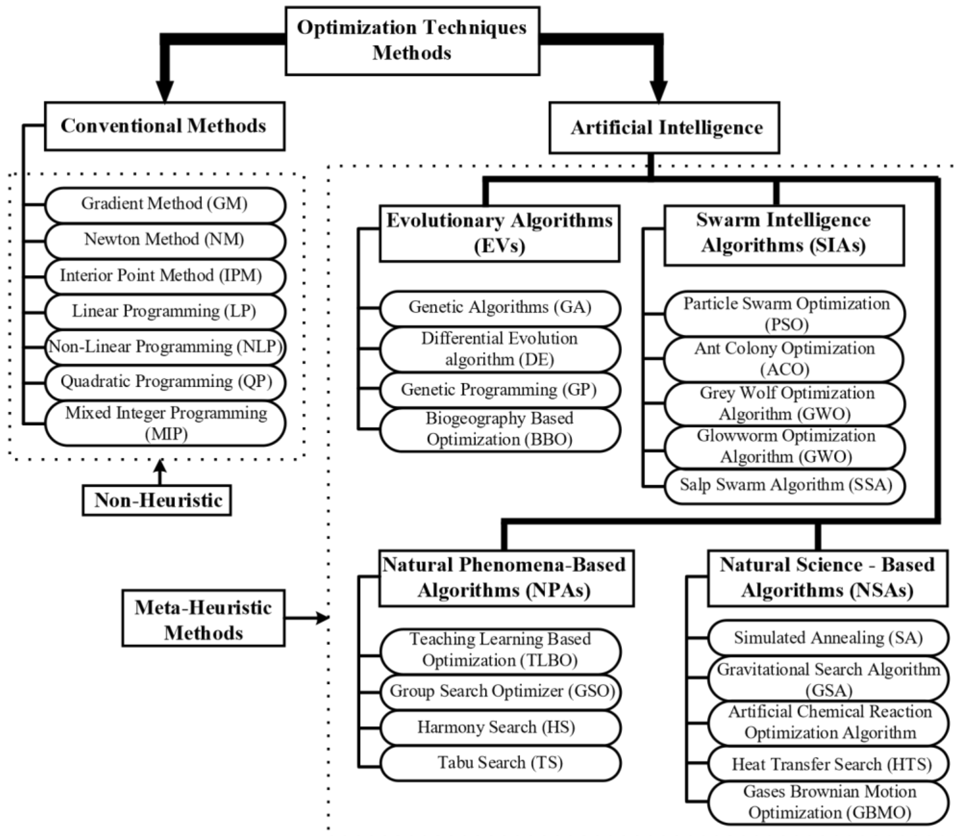


Figure 2. 1 Classification of optimization methods.

2.2. Mathematical Model

The main aim of applied single- and multi-objective OPF in power systems is to optimize the objective functions of single and multiple objectives (Bi, Tri, Quad, and Quinta) through setting optimal control variables (active power output of generators except for active power output of slack bus, voltage magnitude of PV bus, Source VAR compensator, and tap setting regulating of transformers) with satisfying equality and inequality constraints, simultaneously. The mathematical model can be formulated as follows:

$$\begin{aligned} &\text{Optimize} \quad f(x,u) = f_1(x,u), f_2(x,u), \ldots, f_{Nobj}(x,u) \\ &\text{subjected to} \quad g(x,u) = 0 \\ &\qquad\qquad\qquad h(x,u) \leq 0 \end{aligned} \tag{2.1}$$

2.2.1. Objective Functions

In this paper, the five most common objective functions were optimized to solve OPF problems, which are fuel cost, losses, emission, voltage deviation, and the voltage stability index .

- *Total Fuel Cost [$/h]* - *Active power losses [MW]* - *Total emission [ton/h]* - *Voltage deviation [p.u.]* - *Voltage stability index*

CHAPTER 3 THE MATHEMATICAL MODEL OF MODERN METAHEURISTIC OPTIMIZATION TECHNIQUES

In this thesis, we propose four new meta-heuristic algorithms: Grey Wolf Optimizer (GWO), Harris Hawks optimization, Hunger Games Search (HGS), and Slime Mould Algorithm (SMA).

3.1. Grey Wolf Optimizer (GWO)

Grey wolf optimizer (GWO) is a recent heuristic optimization inspired by the social behavior of grey wolves belonging to the Canidae family. The grey wolves classified into four levels according to leadership are alpha (α), beta (β), delta (δ) and omega (ω). The main step of grey wolf hunting as follows:

3.1.1. Encircling Prey

3.1.2. Hunting

3.1.3. Attacking

3.1.4. Searching

3.2. Harries Hawks Optimizer (HHO)

Harris hawk's optimizer (HHO) is a newly discovered population-based optimization technique proposed by A. Heidari et al. [5]. The two main process of MOHHO, exploration and exploitation, is essential process. The HHO algorithm can be briefly described:

3.2.1. Exploration phase

3.2.2. Transformation from exploration to exploitation

3.2.3. Exploitation phase

3.3. Hunger Games Search (HGS)

Hunger games search (HGS) is a new optimization technique inspired on behavior of social animals' cooperative which is proportional to their level of hunger. It can be summarized the processes that characterized this algorithm into two stages as follows:

3.3.1. Approach food

3.3.2. Hunger role

3.4. Slime Mould Algorithm (SMA)

The slime mould algorithm (SMA) is a new optimization algorithm inspired by the diffusion and behavior conduct of slime mould in nature and proposed by S. Li et al. in 2021 [6]. The processes of SMA by approaching food, wrapping food, and oscillating can be summarized as follows:

3.4.1. Approach food

3.4.2. Wrap food

3.4.3. Oscillation

CHAPTER 4 MULTI-OBJECTIVE OPTIMAL POWER FLOW (MOOPF)

New approaches have been proposed to solve MOOPF problems (two or more objective functions) and optimized simultaneously, are multi-objective grey wolf optimizer (MOGWO), multi-objective Harries Hawks optimizer (MOHHO), multi-objective hunger games search (MOHGS), and multi-objective Slime mould Algorithm (MOSMA). Based on the number of objective functions, the Pareto concept (PC) is the proposed approach to find out the dominant and non-dominated solutions. The decision maker is responsible for determining the best compromise solution (BCS) from non-dominated solutions (NDS). In this thesis, the fuzzy membership function (FMF) is the equation used to extract the BCS from NDS. Finally, the specific strategy that is employed to reduce and arrange the NDPF is the crowding distance (CD).

4.1. Multi-Objective Grey Wolf optimizer (MOGWO)

In this thesis, Grey Wolf Optimizer (GWO) has been developed into a multi-objective Grey Wolf Optimizer (MOGWO) to solve multi-objective optimal power flow problems. The two main MOGWO procedures, as previously mentioned —encircling and hunting— are the crucial stages.

4.2. Multi-Objective Harries Hawks Optimizer (MOHHO)

The second framework that has been developed to solve MOOPF is a multi-objective harries hawks optimizer (MOHHO).

4.3. Multi-Objective Hunger Games Search (MOHGS)

The third approach has been proposed to solve MOOPF problems (two or more objective functions) and optimized simultaneously, named multi-objective hunger games search (MOHGS).

4.4. Multi - Objective Slime Mould Algorithm (MOSMA)

The last method of this thesis is the multi-objective slime mould algorithm (MOSMA). These motions serve as a heuristic in the first iteration. To address the MOPs' limitations, a simple method is defined in MOSMA.

CHAPTER 5

APPLICATION OF MODERN METAHEURISTIC OPTIMIZATION ALGORITHMS TO SOLVE SINGLE AND MULTI OBJECTIVE OPTIMAL POWER FLOW PROBLEMS

5.1. Generalities

To demonstrate the effectiveness and performance of the proposed algorithms (GWO, HHO, HGS, and SMA) and the developed approaches (MOGWO, MOHHO, MOHGS, and MOSMA) to solve OPF problems, two standard systems (IEEE-30 bus system and IEEE 57-bus test system) and one real system (Iraqi Super Grid High Voltage ISGHV 28-bus) were used with 46 cases for various objective functions. **Table 5.1** describes the various case studies that have been applied. The simulation results have been carried out on Intel Core (TM) i5-2540 2.6GHz and 6.00 (64 bit) GB RAM.

Table 5. 1 Various case studies.

Type of System	**Type of OF(s)**	**Case #**	**FC**	**Em**	**Loss**	**VD**	**VSI**
IEEE 30-bus	Single OF(s)	Case #1	□				
		Case #2			□		
		Case #3		□			
		Case #4				□	
		Case #5					□
	Bi-OF(s)	Case #6	□	□			
		Case #7	□		□		
		Case #8	□		□		
		Case #9	□				□
		Case #10		□		□	
		Case #11			□	□	
		Case #12				□	□
	Triple-OF(s)	Case #13	□	□	□		
		Case #14	□	□		□	
		Case #15	□		□	□	
		Case #16	□		□		□
		Case #17	□	□			□
		Case #18	□			□	□
		Case #19		□	□	□	
	Quad-OF(s)	Case #20	□	□	□	□	
		Case #21	□	□	□		□
	Quinta-OF(s)	Case #22	□	□	□	□	□
IEEE 57-bus	Single OF(s)	Case #23	□				
		Case #24		□			
		Case #25			□		
		Case #26				□	
		Case #27					□
	Bi-OF(s)	Case #28	□	□			
		Case #29	□		□		
		Case #30		□	□		
		Case #31	□			□	

		Case #32	□				□
		Case #33	□		□	□	
		Case #34		□		□	
	Triple-OF(s)	Case #35	□	□	□		
		Case #36	□	□		□	
		Case #37	□		□	□	
		Case #38		□	□	□	
		Case #39	□			□	□
	Quad-OF(s)	Case #40	□	□	□	□	
		Case #41	□	□	□		□
	Quinta-OF(s)	Case #42	□	□	□	□	□
ISGHV 28-bus	Single OF(s)	Case #43	□				
		Case #44			□		
		Case #45				□	
		Case #46					□

5.2. Standard study Cases

In this study, two bus power systems have been tested, IEEE 30 and IEEE 57 bus, with fortyfour studies cases are investigated to prove the viability and efficiency of the proposed approaches.

5.2.1 Study case on IEEE 30 bus power system

A) Single-Objective OPF on IEEE 30-Bus Power System

Five objective functions were optimized to solve OPF problem— the generational fuel cost (GFC), real power loss (RPL), emission (Em), voltage deviation (VD), and voltage stability index (VSI)—by setting the parameters of the control variables (active power output of generators except for the slack bus, the voltage of PV bus, tap ratio of transformers, and shunt VAR compensator).

Five cases of different objective functions have been considered to demonstrate the effectiveness of the proposed algorithms GWO, HHO, HGS, and SMS. These cases are as follows:
Case 1: The total fuel costs minimization for generation units.

Case 2: Minimization of total emission issued by fossil-fueled thermal units.

Case 3: Reduction of active power losses in transmission lines.

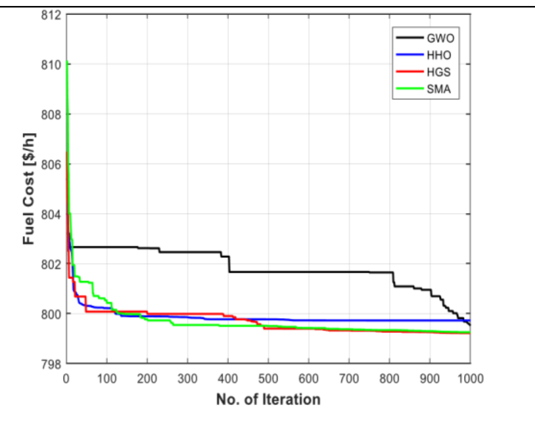
Case 4: Voltage profiles improvement.

Case 5: Voltage stability enhancement.

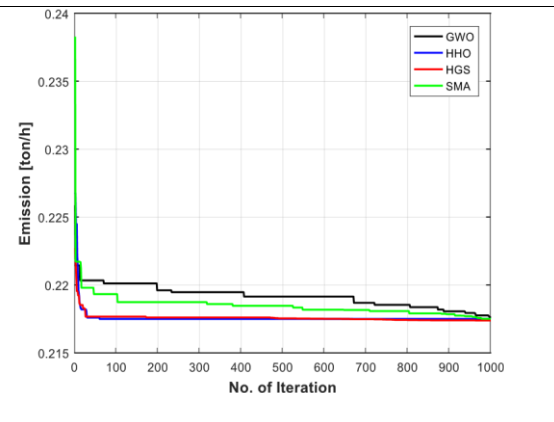
Table 5.2 The optimal result for single-objective function on IEEE 30 bus system

Objective function	**Initial**	**Case 1**				**Case 2**			
		GWO	HHO	HGS	SMA	GWO	HHO	HGS	SMA
FC [$/h]	901.6391	**799.5214**	**799.7265**	**799.2202**	**799.2557**	938.30	934.13	933.70	936.12
Em [ton/h]	0.2253	0.364	0.369	0.367	0.368	**0.2176**	**0.2175**	**0.2174**	**0.2175**
loss [MW]	5.6891	8.638	8.817	8.642	8.669	3.673	3.496	3.352	3.594

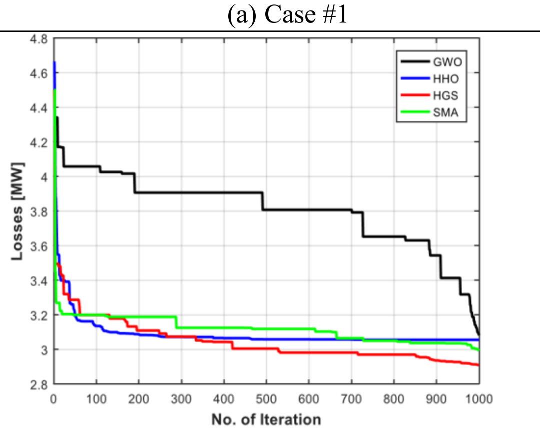
VD [p.u.]	1.1747	1.324	0.493	1.567	1.419	0.413	0.644	0.797	0.475
VSI	0.1727	0.126	0.136	0.120	0.124	0.143	0.139	0.131	0.148
Red. Rate	-	11.326%	11.303%	**11.359%**	11.355%	3.42%	3.48%	**3.51%**	3.46%
Objective function	**Initial**	**Case 3**				**Case 4**			
		GWO	HHO	HGS	SMA	GWO	HHO	HGS	SMA
FC [$/h]	901.6391	966.19	967.50	966.84	964.57	839.20	816.141	889.278	868.051
Em [ton/h]	0.2253	0.221	0.2216	0.2216	0.2213	7.6644	8.1454	5.1253	6.2099
loss [MW]	5.6891	**3.082**	**3.056**	**2.911**	**2.993**	0.297	0.2964	0.2343	0.2569
VD [p.u.]	1.1747	1.129	0.7621	1.71	1.47	**0.1413**	**0.1281**	**0.1195**	**0.1100**
VSI	0.1727	0.134	0.1331	0.119	0.123	0.1385	0.1358	0.1375	0.1371
Red. Rate	-	45.83%	46.28%	**48.83%**	47.38%	87.97%	89.09%	89.83%	**90.63%**
Objective function	**Initial**	**Case 5**							
		GWO	HHO	HGS	SMA				
FC [$/h]	901.6391	811.18	931.86	920.183	834.02				
Em [ton/h]	0.2253	6.721	3.5918	3.5803	6.3446				
loss [MW]	5.6891	0.293	0.2208	0.2204	0.31				
VD [p.u.]	1.1747	1.644	1.3991	1.9699	1.7545				
VSI	0.1727	**0.1172**	**0.1150**	**0.1119**	**0.1157**				
Red. Rate	-	32.16%	33.44%	**35.20%**	32.98%				

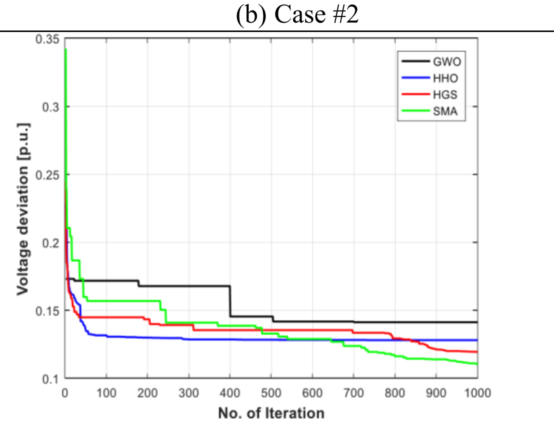


(a) Case #1



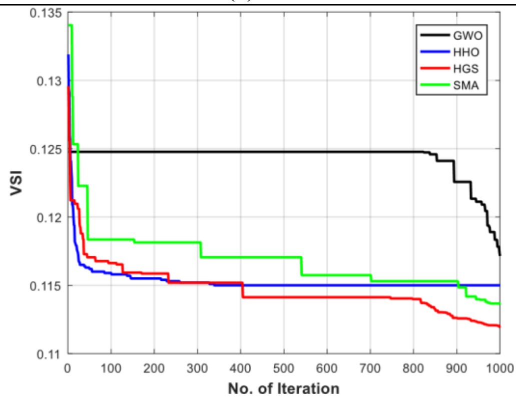
(b) Case #2





(c) Case #3

(d) Case #4



(e) Case #5

Figure 5. 4 The convergence speed for Cases (1-5) (FC &Em &RPL&VD & VSI Separately).

B) Multiple-Objective OPF on IEEE 30-Bus Power System

In this subsection, two, three, four, and five objective functions have been optimized simultaneously to achieve the best compromise solution (BCS) from non-dominated solutions (NDS).

a) Bi-objective OPF

In this subsection, two objective functions have been optimized simultaneously to achieve the best compromise solution (BCS) from non-dominated solutions (NDS). In this subsection, seven case studies have been suggested to prove the efficiency and superiority of the (MOGWO, MOHHO, MOHGS, and MOSMA). These cases can be summarized as follows: Case 6: Minimization of fuel cost and emission simultaneously

Case 7: Minimization of fuel cost and real power losses simultaneously

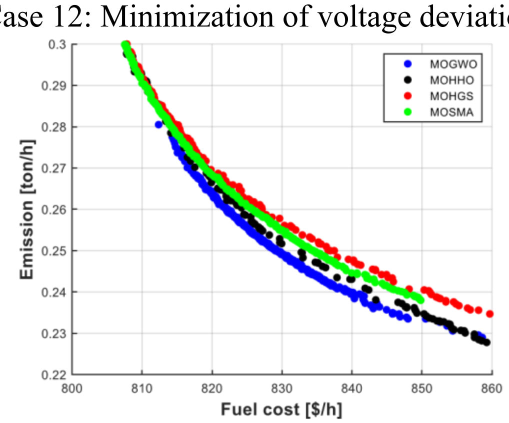
Case 8: Minimization of fuel cost and voltage deviation simultaneously

Case 9: Minimization of fuel cost and voltage stability index simultaneously

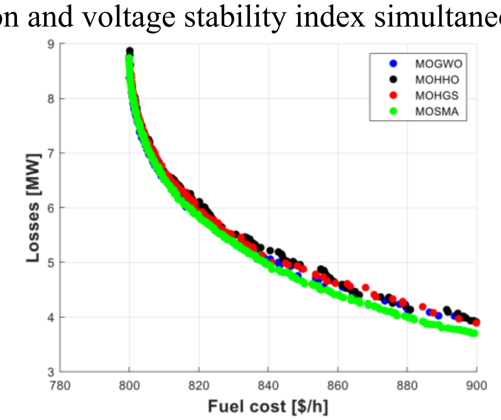
Case 10: Minimization of emission and voltage deviation simultaneously

Case 11: Minimization of real power losses and voltage deviation simultaneously

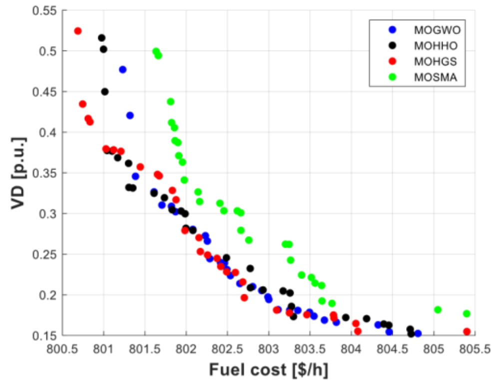
Case 12: Minimization of voltage deviation and voltage stability index simultaneously



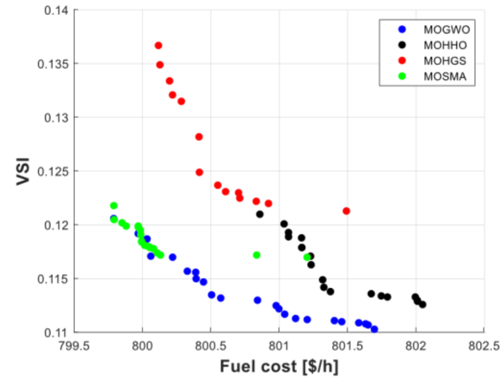
(a) Case #6 (FC &Em)



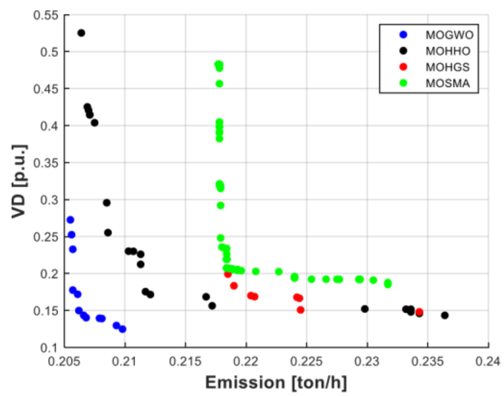
(b) Case #7 (FC & Loss)



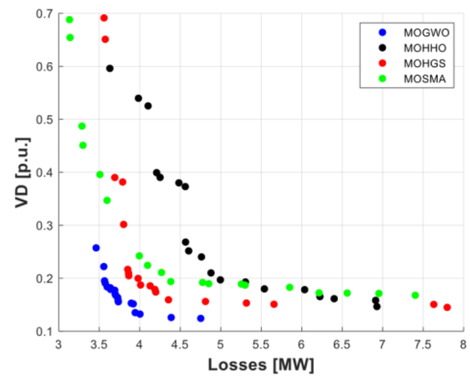
(c) Case #8 (FC & VD)



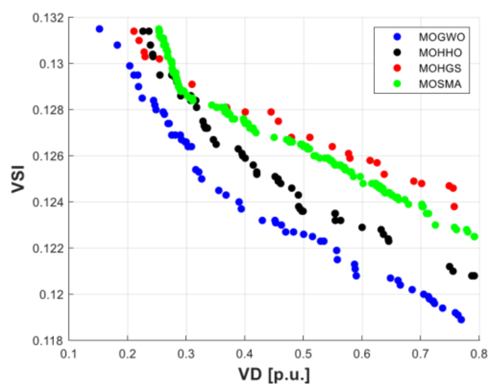
(d) Case #9 (FC & VSI)



(e) Case #10 (Em & VD)



(f) Case #11 (Loss & VD)



(g) Case #12 (VD & VSI)

Figure 5.5 Pareto Front non-dominated solution for Cases (6-12).

b) Triple-objective OPF

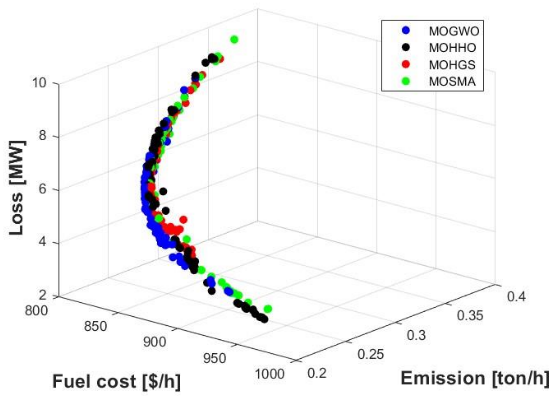
In this type, three objective functions have been considered simultaneously to obtain the best compromise solution (BCS) from non-dominated solutions (NDS) in the non-dominated set. Seven case studies have been suggested. These cases can be summarized as follows:

Case 13: Minimization of fuel cost, emission, and real power losses simultaneously

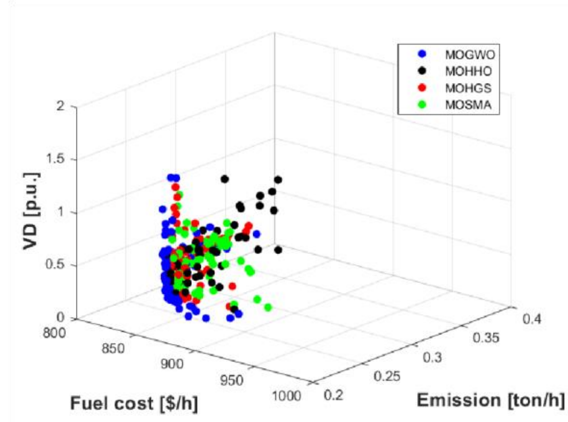
Case 14: Minimization of fuel cost, emission, and voltage deviation simultaneously

Case 15: Minimization of fuel cost, real power losses, voltage deviation simultaneously

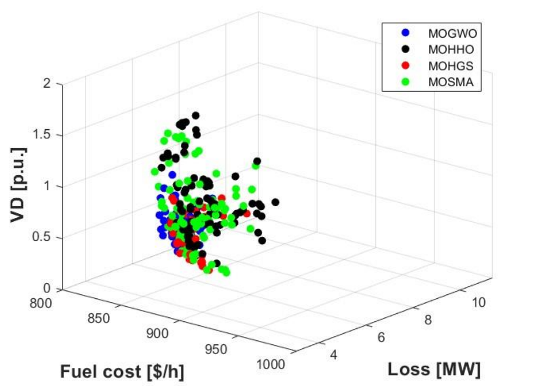
Case 16: Minimization of real power losses, emission, and voltage deviation
Case 17: Minimization of fuel cost, real power losses, voltage stability index
Case 18: Minimization of fuel cost, emission, and voltage stability index simultaneously Case 19: Minimization of fuel cost, voltage deviation and voltage stability index



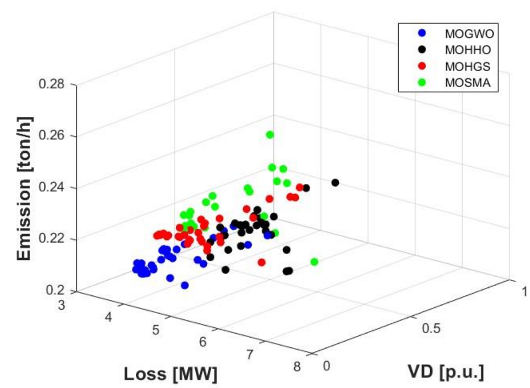
(a) Case #13 (FC & Loss & Em)



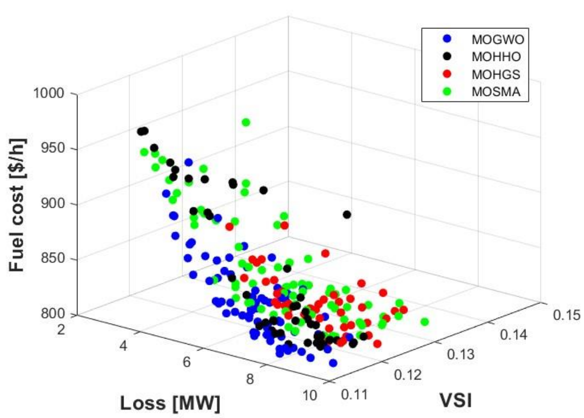
(b) Case #14 (FC & VD & Em)



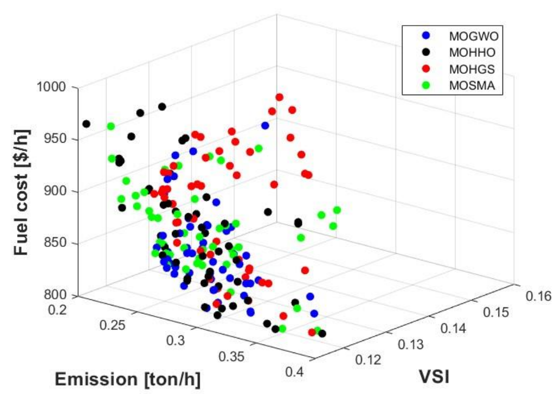
(c) Case #15 (FC & VD & Loss)



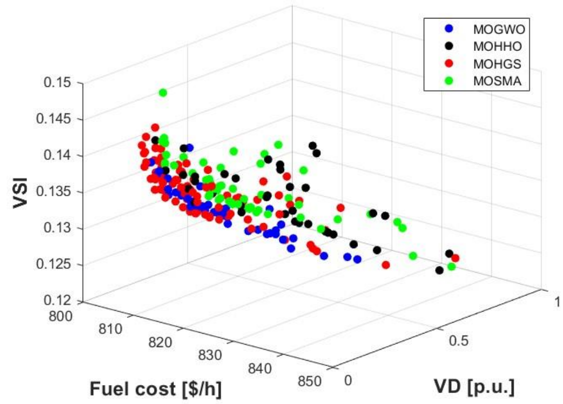
(d) Case #16 (Loss & Em & VD)



(e) Case #17 (Loss & FC & VSI)



(f) Case #18 (Em & FC & VSI)



(g) Case #19 (FC &VD & VSI)

Figure 5.6 Pareto Front non-dominated solution for Cases (13-19).

c) Quad and Quinta objective OPF

Case 20: Minimization of fuel cost, emission, losses, and voltage deviation.

Case 21: Minimization of fuel cost, emission, losses, and voltage stability index.

Case 22: Minimization of fuel cost, emission, losses, voltage deviation, and voltage stability index.

Table 5.3 The optimal result for Quad and Quinta-objective function on IEEE 30 bus system

Objective function	Case 20				Case 21			
	GWO	HHO	HGS	SMA	GWO	HHO	HGS	SMA
FC [$/h]	**836.5049**	**863.4444**	**845.4721**	**832.3665**	**819.2675**	**861.4731**	**819.4061**	**847.723**
loss [MW]	**5.9222**	**5.2679**	**5.7458**	**6.4495**	**6.6427**	**4.8018**	**7.4137**	**5.1423**
Em [ton/h]	**0.2460**	**0.2320**	**0.2507**	**0.2675**	**0.2692**	**0.2324**	**0.2898**	**0.2466**
VD [p.u.]	**0.2264**	**0.7258**	**0.1400**	**0.2189**	1.4733	1.4139	0.3514	1.6979
VSI	0.1417	0.1317	0.1456	0.1408	**0.1143**	**0.1193**	**0.1389**	**0.1183**
Objective function	Case 22							
	GWO	HHO	HGS	SMA				
FC [$/h]	**827.746**	**844.3225**	**818.7575**	**824.7751**				
loss [MW]	**6.5865**	**6.1965**	**7.4471**	**6.3599**				
Em [ton/h]	**0.2625**	**0.2485**	**0.2912**	**0.2753**				
VD [p.u.]	**0.2575**	**0.3369**	**0.3272**	**0.5111**				
VSI	**0.1421**	**0.1342**	**0.1399**	**0.1290**				

5.2.2 Study cases on the IEEE 57-bus power system

In this subsection, the IEEE 57- bus power system is applied to validate of performance of proposed approaches GWO, HHO, HGS, and SMA. The total generation capacity of this system is 1975.9 MW [7].

A) Single-objective OPF on IEEE 57-bus power system

To demonstrate the superiority and performance of the proposed method on IEEE 57- bus power system, five single objective functions (Case 23 to Case 27) have been considered. The convergence speed of the proposed method is illustrated in **Fig. 5.7**. Five cases of different objective functions have been considered to demonstrate the effectiveness of the proposed algorithms GWO, HHO, HGS, and SMS. These cases are as follows:

Case 23: The total fuel costs minimization for generation units.

Case 24: Minimization of total emission issued by fossil-fueled thermal units.

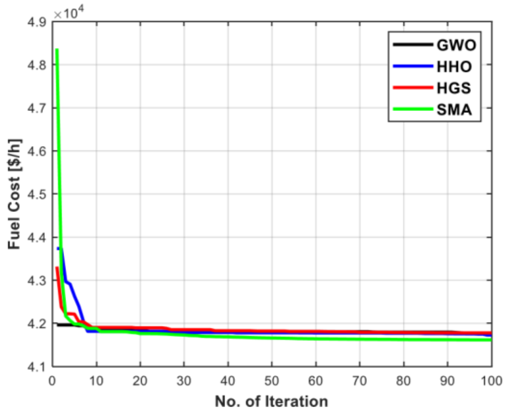
Case 25: Reduction of active power losses in transmission lines.

Case 26: Voltage profiles improvement.

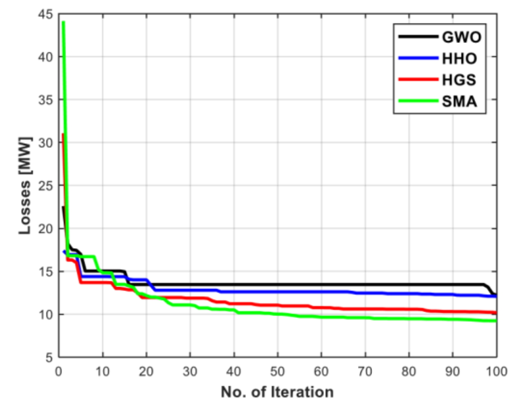
Case 27: Voltage stability enhancement.

Table 5.4 The optimal result for single-objective function on IEEE 57 bus system

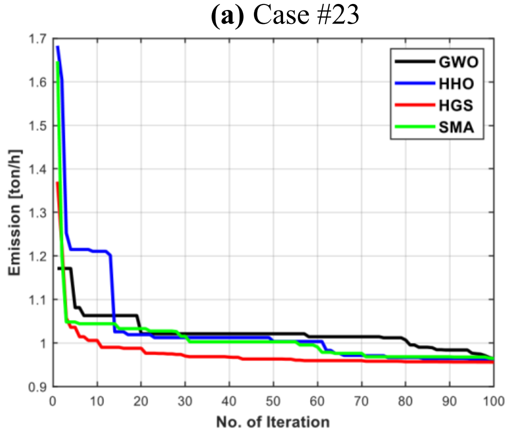
Objective function	**Initial**	**Case 23**				**Case 24**			
		GWO	HHO	HGS	SMA	GWO	HHO	HGS	SMA
FC [$/h]	51353	**41766.97**	**41728.48**	**41778.24**	**41617.33**	45310	45313	45093	45092
Em [ton/h]	2.413	1.505	1.3913	1.3679	1.3589	**0.9645**	**0.9626**	**0.9565**	**0.9645**
loss [MW]	27.868	32.371	16.271	17.355	14.003	16.627	15.192	13.798	16.699
VD [p.u.]	1.126	4.0191	3.0688	3.0544	4.0085	4.0169	2.8481	2.5322	3.7026
VSI	0.28	0.3349	0.2775	0.2732	0.2223	0.4093	0.2912	0.2838	0.3600
Red. Rate	-	18.67%	18.74%	18.64%	**18.96%**	60.03%	60.10%	**60.36%**	60.03%
Objective function	**Initial**	**Case 25**				**Case 26**			
		GWO	HHO	HGS	SMA	GWO	HHO	HGS	SMA
FC [$/h]	51353	42848	44310	44558	44343	52679	56932	96339	97896
Em [ton/h]	2.413	1.3724	1.0334	1.0943	1.1069	2.3937	2.3162	4.9997	5.3157
loss [MW]	27.868	**12.201**	**12.082**	**10.184**	**9.240**	33.12	42.849	106.477	110.01
VD [p.u.]	1.126	1.637	2.255	1.937	3.744	**0.8283**	**0.7416**	**0.7016**	**0.7151**
VSI	0.28	0.2425	0.2631	0.2330	0.2513	0.2477	0.2467	0.2369	0.2699
Red. Rate	-	56.22%	56.65%	63.45%	**66.84%**	26.44%	34.2%	**37.71%**	36.52%
Objective function	**Initial**	**Case 27**							
		GWO	HHO	HGS	SMA				
FC [$/h]	51353	59448	56694	56692	82082				
Em [ton/h]	2.413	2.3328	2.5001	2.1099	4.1188				
loss [MW]	27.868	42.6415	50.080	41.125	91.261				
VD [p.u.]	1.126	3.6066	2.646	6.139	1.930				
VSI	0.28	**0.21678**	**0.2033**	**0.1804**	**0.2141**				
Red. Rate		22.58%	27.32%	**35.52%**	23.50%				



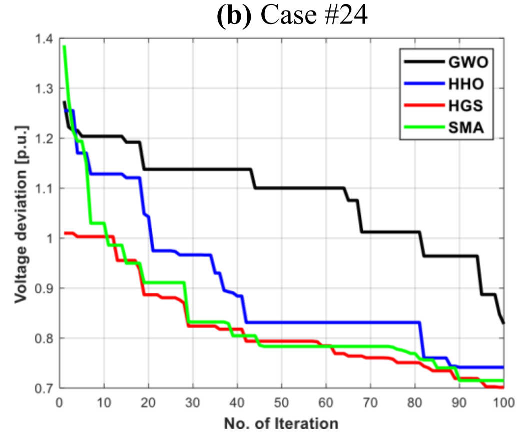
(a) Case #23



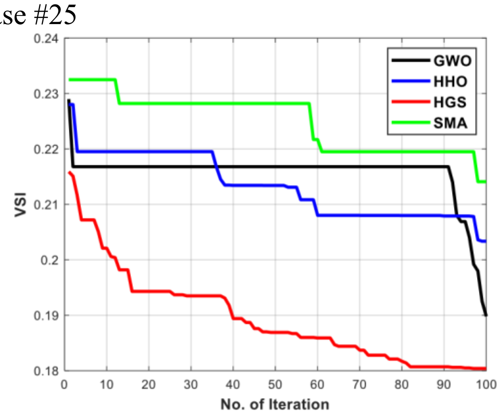
(b) Case #24



(c) Case #25



(d) Case #26



(e) Case #27

Figure 5.7 The convergence characteristics of the proposed algorithms for Cases (23-27).

B) Multiple-Objective OPF on IEEE 57-Bus Power System

In this subsection, two, three, four, and five objective functions have been optimized simultaneously to achieve the best compromise solution (BCS) from non-dominated solutions (NDS).

a) Bi-objective OPF

These cases can be summarized as follows:

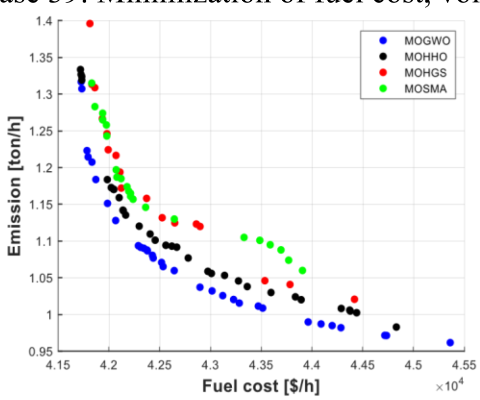
Case 28: Minimization of fuel cost and emission simultaneously on IEEE 57-bus.

Case 29: Minimization of fuel cost and real power losses on IEEE 57-bus.
Case 30: Minimization of real power losses and emission on IEEE 57-bus.
Case 31: Minimization of fuel cost and voltage deviation on IEEE 57-bus.
Case 32: Minimization of fuel cost and voltage stability index on IEEE 57-bus.
Case 33: Minimization of real power losses and voltage deviation on IEEE 57-bus. Case 34: Minimization of emission and voltage deviation on IEEE 57-bus.

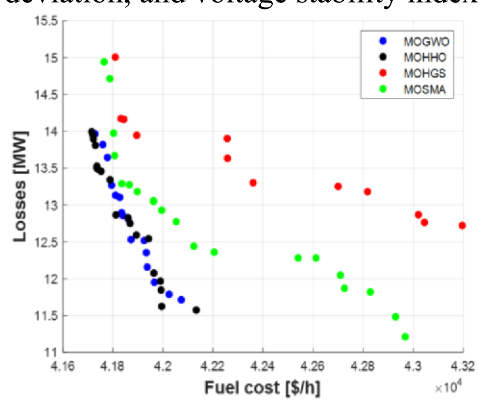
b) Triple-objective OPF on IEEE 57-bus

In this type, three objective functions have been considered simultaneously to obtain the best compromise solution (BCS) from non-dominated solutions (NDS) in the non-dominated set. Five case studies have been suggested. These cases can be summarized as follows:

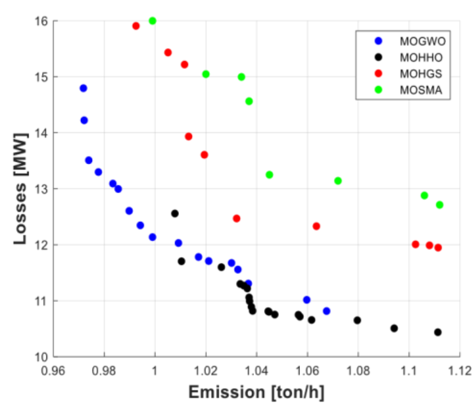
Case 35: Minimization of fuel cost, emission, and real power losses simultaneously.
Case 36: Minimization of fuel cost, emission, and voltage deviation simultaneously.
Case 37: Minimization of fuel cost, real power losses, voltage deviation simultaneously.
Case 38: Minimization of emission, losses, and voltage deviation simultaneously.
Case 39: Minimization of fuel cost, voltage deviation, and voltage stability index.



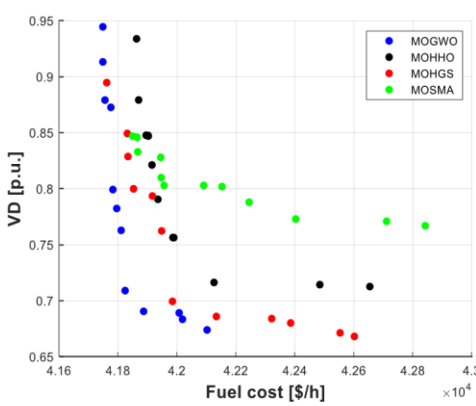
(a) Case #28 (FC &Em)



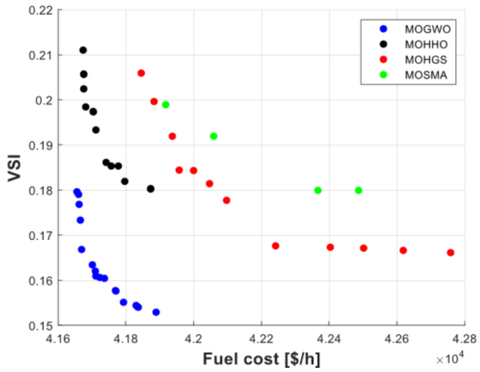
(b) Case #29 (FC & Loss)



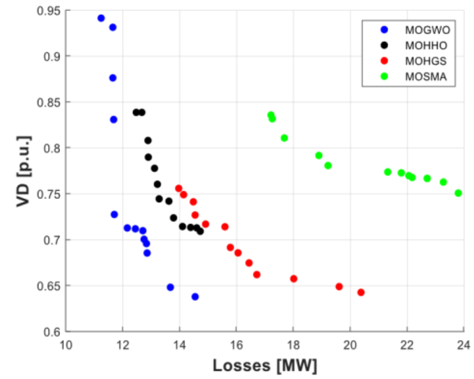
(c) Case #30 (Loss & Em)



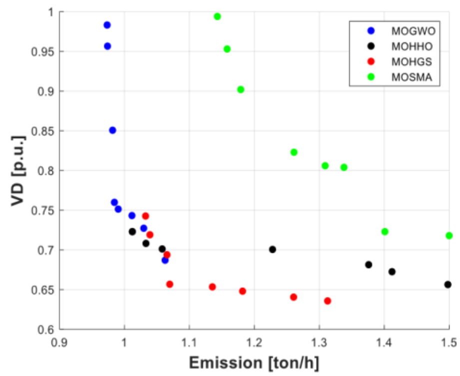
(d) Case #31 (FC & VD)



(e) Case #32 (FC & VSI)



(f) Case #33 (Loss & VD)

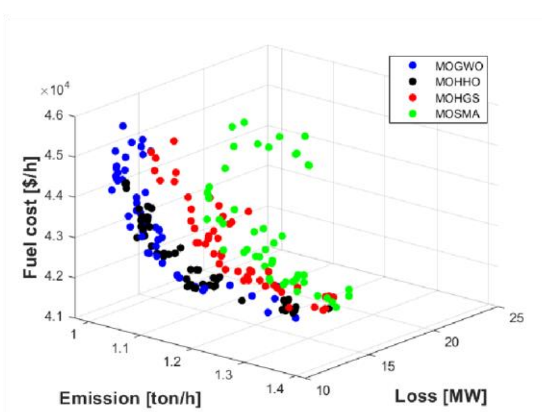


(g) Case #34 (Em & VD)

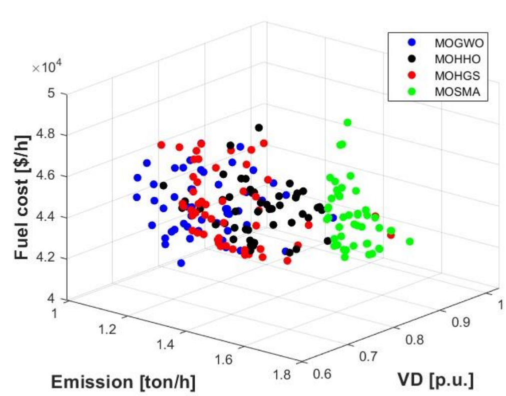
Figure 5.8 Pareto Front non-dominated solution for Cases (28-34).

c) Quad and Quinta objective OPF on IEEE 57-bus

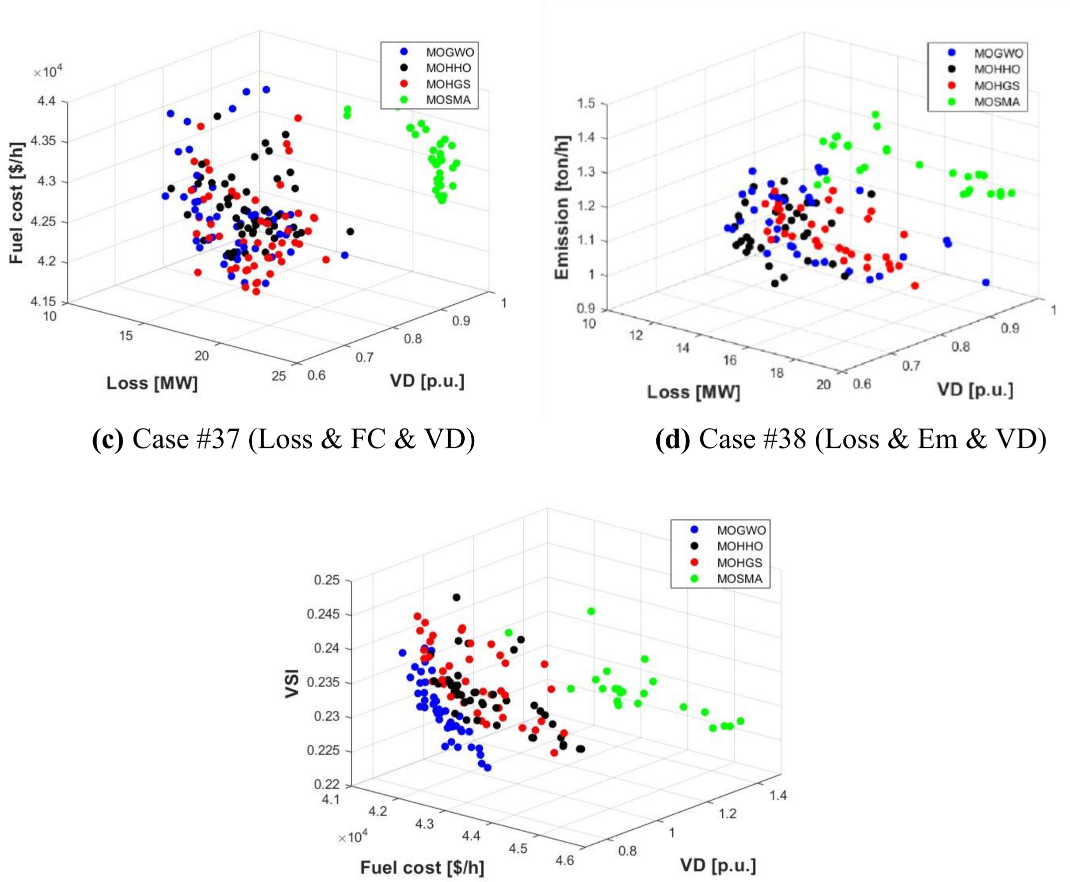
The last type of objective function in IEEE 57-bus test represents the Quad and Quinta objective functions as shown in **Table 5.1**. Two case studies Quad objective functions and one case study of Quinta objective function are the cases that have been suggested to solve MOOPF in this type. It can be summarized as follows:



(a) Case #35 (Em & FC & Loss)



(b) Case #36 (Em & FC & VD)



(c) Case #37 (Loss & FC & VD)

(d) Case #38 (Loss & Em & VD)

(e) Case #39 (FC &VSI & VD)

Figure 5.6 Pareto Front non-dominated solution for Cases (35-39).

Case 40: Minimization of fuel cost, emission, real power losses, and voltage deviation

Case 41: Minimization of fuel cost, emission, losses, and voltage stability index

Case 42: Minimization of fuel cost, emission, losses, voltage deviation, and voltage stability index.

Table 5.5 The optimal result for Quad and Quinta-objective function on IEEE 57 bus system

Objective function	**Case 40**				**Case 41**			
	GWO	HHO	HGS	SMA	GWO	HHO	HGS	SMA
FC [$/h]	**42876.63**	**42241.61**	**43535.32**	**44410.01**	**42144.44**	**43252.14**	**43069.32**	**43018.98**
loss [MW]	**1.0801**	**1.2809**	**1.1547**	**1.3665**	**1.1595**	**1.0406**	**1.0722**	**1.1899**
Em [ton/h]	**11.8224**	**16.2366**	**15.2100**	**23.5669**	**11.652**	**11.639**	**14.753**	**12.948**
VD [p.u.]	**0.8300**	**0.8384**	**0.7338**	**1.0149**	4.9898	4.3952	5.7594	2.6095
VSI	0.2631	0.2485	0.2723	0.2509	**0.1863**	**0.1902**	**0.1805**	**0.2236**
Objective function	**Case 42**							
	GWO	HHO	HGS	SMA				
FC [$/h]	**47750.98**	**48389**	**43996.96**	**44665**				
loss [MW]	**1.7452**	**1.4185**	**1.2241**	**1.2741**				

Em [ton/h]	**33.746**	**38.040**	**22.862**	**20.957**
VD [p.u.]	**1.0092**	**1.4185**	**1.3421**	**1.0216**
VSI	**0.2361**	**0.2210**	**0.2260**	**0.2347**

5.3. Practical Case Study: Iraqi Super Grid High Voltage (ISGHV) 400 kV

The power generation facilities, transmission network, and distribution network make up the Iraqi super grid high voltage. There are two voltage level of transmission networks—one with a 400 kV voltage (the ISGHV) and the other with a 132 kV voltage (the IGHV). The Iraqi super high voltage grid consists of power generation stations, transmission, and distribution. Transportation stations often operate at two voltage levels (400 kV and 132 kV), hence there are two transmission networks, one with a 400 kV voltage (the ISHV grid) and the other with a 132 kV voltage (the IHV grid). Due to lower summertime temperatures for 2020, Iraq saw an increase in its electricity generation capacity from 16.25 to 18.6 GW. The last statistics related to the ISGHV reported by National Control Center Iraqi of the Ministry of Electricity (NCCIME) of 2022 have been shown in **Table. 5.6** and **Fig. 5.7.**

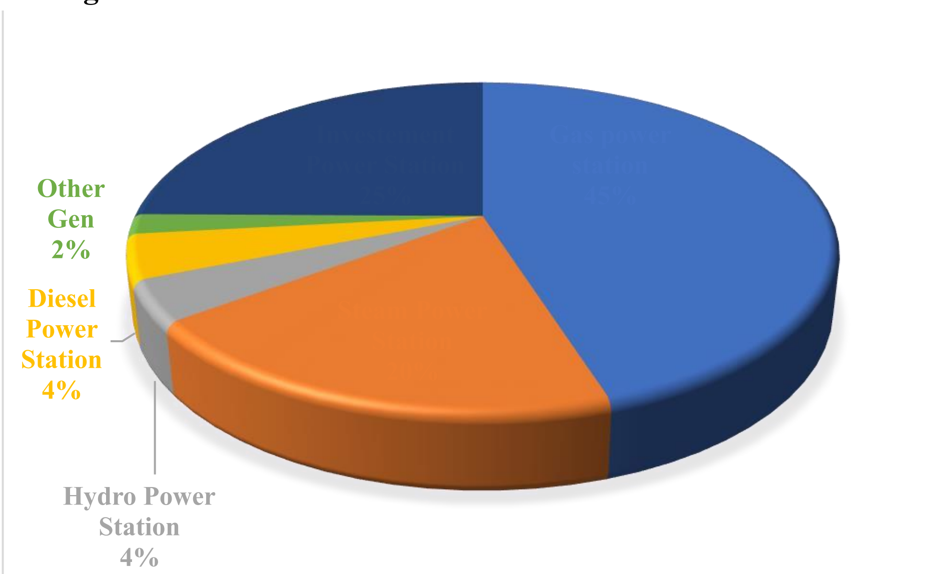


Figure 5. 7 Current generation facilities of Iraqi power system.

Table 5. 6 Power plant units in the Iraqi power system.

No.	Types of Power Plant	Installed Capacity (MW)
1	Gas power station	16433
2	Steam Power Station	7183
3	Hydro Power Station	1477
4	Diesel Power Station	1594
5	Other Gen	710
6	Investment Power Station	9038
Total		36435

5.3.1. Application of proposed algorithms to solve OPF problems on ISGHV 28 bus

In 2013, ISGHV400 kV, contained 14 generators, 28 buses, and 43 transmission lines. The bus number 01 (MUSP) represents the swing bus, and the total load demand is 5994 MW [8]. In this subsection, four single objective functions (fuel cost, real power losses, voltage deviation, and voltage stability index) have been considered. The convergence speed of the proposed method is illustrated in **Fig. 5.8.**

Case 43: Minimization of generation fuel cost on ISGHV 28-bus

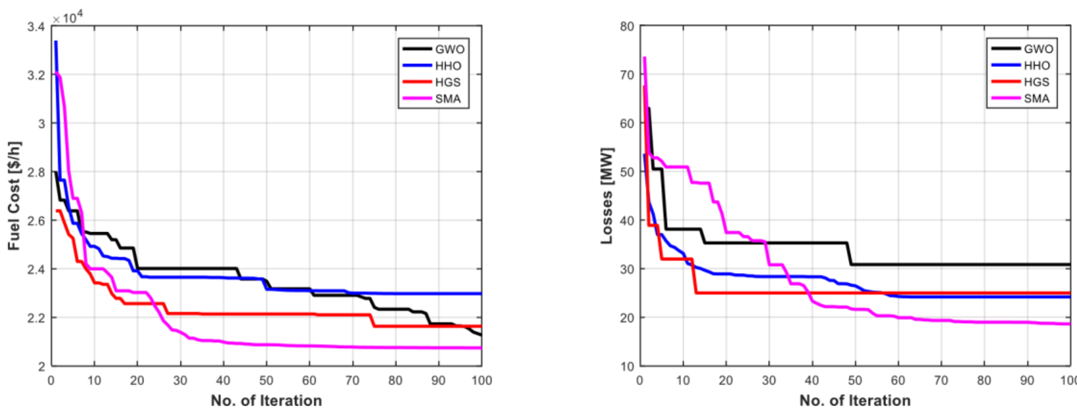
Case 44: Minimization of real power losses on ISGHV 28-bus

Case 45: Minimization of voltage deviation on ISGHV 28-bus

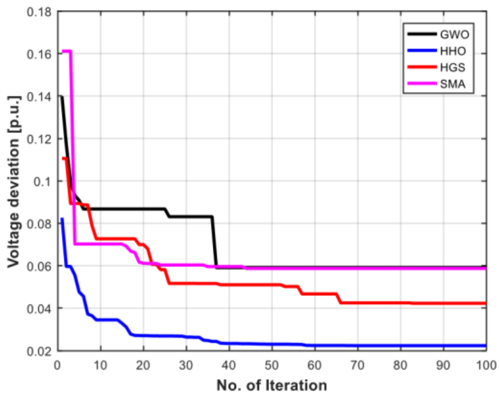
Case 46: Minimization of voltage stability index on ISGHV 28-bus

Table 5.7 The optimal result for single-objective function on ISGHV 28 bus system

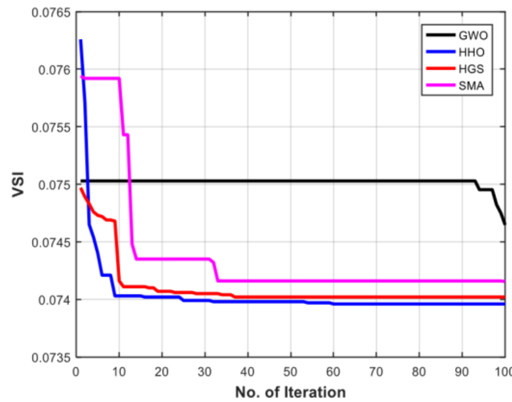
Objective function	**Initial**	**Case 43**				**Case 44**			
		GWO	HHO	HGS	SMA	GWO	HHO	HGS	SMA
FC [$/h]	39565	**21729**	**22974**	**21631**	**20740**	49536	47224	36533	36784
loss [MW]	42.383	73.15	111.60	45.238	45.225	**30.82**	**24.18**	**24.984**	**18.61**
VD [p.u.]	0.2013	0.4404	0.6043	0.528	0.4678	0.5721	1.3504	1.301	0.7725
VSI	0.0886	0.0777	0.0996	0.084	0.0826	0.0892	0.0747	0.075	0.0815
Red. Rate	-	45.08%	41.93%	45.33%	47.58%	27.28%	42.96%	41.05%	56.09%
Objective function	**Initial**	**Case 45**				**Case 46**			
		GWO	HHO	HGS	SMA	GWO	HHO	HGS	SMA
FC [$/h]	39565	72230	66099	48550	49843	39565	55559	46396	46396
loss [MW]	42.383	94.49	86.979	120.98	54.843	81.88	116	118.0	117.99
VD [p.u.]	0.2013	**0.0591**	**0.022**	**0.042**	**0.0625**	0.7167	0.499	0.514	0.514
VSI	0.0886	0.0906	0.089	0.089	0.0917	**0.075**	**0.074**	**0.074**	**0.074**
Red. Rate	-	70.64%	88.90%	78.99%	68.95%	15.40%	16.52%	16.52%	16.46%



(a) Case #43 **(b)** Case #44



(c) Case #45



(d) Case #46

5.4. Performance comparison

This subsection presents the performance and efficiency of the proposed algorithms (GWO, HHO, HGS, and SMA) and developed approaches (MOGWO, MOHHO, MOHGS, and MOSMA) to solve single and multi-objective optimal power flow problems. The standards and all their variants are evaluated to solve real-world problems. The proposed algorithms (GWO, HHO, HGS, and SMA) and developed (MOGWO, MOHHO, MOHGS, and MOSMA) have been carried out on all cases to achieve the optimal solution and good convergence for single objective optimal power flow and best compromise solution with well-distribution in Pareto front set for multiobjective optimal power flow. The researchers have faced two main challenges to solve single and multi-OPF problems, the speed convergence toward the global optimum (single and multiobjective function) and the good distribution of the Pareto front (multi objective function). In other words, the balance between convergence and coverage should be found to determine the effectiveness of the algorithm. For example, the results obtained by the proposed algorithms (GWO, HHO, HGS, and SMA) from cases (1-5 and 23-27) and developed (MOGWO, MOHHO, MOHGS, and MOSMA) for Cases (6-8, 13, 28-29 and 35) have been compared with other recent algorithms. These results confirmed the efficiency and superiority of the proposed algorithms. It's worth mentioning that none of the meta-heuristics algorithms can be superior to all optimization algorithms in solving all optimization problems, according to the no free lunch theorem (NFL) [9]. This is the main reason leading to no superior algorithm on all sides (coverage and convergence). This is very clear when applying the proposed approach to multi-objective functions. Therefore, it is difficult to compare the proposed approaches (MOGWO, MOHHO, MOHGS, and MOSMA) with other methods in terms of the results.

Based on the above, the simulation results obtained by proposed algorithms (GWO, HHO, HGS, SMA) and developed approaches (MOGWO, MOHHO, MOHGS, and MOSMA) for both single- and multi-objective have a high performance and provide high-quality solutions to solve OPF problems. The computational times of proposed algorithms and developed approached are competitive from other recent algorithms. In multi objective function and based on high-quality random search property of MOGWO, MOHHO, MOHGS, and MOSMA, the objective functions (even though conflict with each other) provide the trade-off solutions among of each objective function. In Pareto fronts, the MOGWO, MOHHO, MOHGS, and MOSMA provide good convergence, high efficiency, and well-distribution of two- and three-dimensions.

5.5. Summary

In this chapter, two standard test systems have been proposed to solve single and multiobjective optimal power flow problems using four meta heuristics algorithms (GWO, HHO, HGS, and SMA). Forty-six cases have been studied with various objective functions (single, bi, tri, quad, and Quinta). The author can be concluding the best choose from these algorithms as follows:

- IEEE 30-bus system: the results obtained by the HGS algorithm in a single objective function represent the best results compared with other algorithms (GWO, HHO, and SMA) because of it have the best four results of objective functions including fuel cost, real power losses, emission, and voltage stability index. In multiple objective functions (Bi, Tri, Quad, and Quinta), the results obtained by MOGWO method represent the best results compared with other algorithms (MOHHO, MOHGS, and MOSMA) because of the results obtained by MOGWO do not dominate by other methods (MOHHO, MOHGS, and MOSMA).
- IEEE 57-bus system: the results obtained by the HGS algorithm in a single objective function represent the best results compared with other algorithms (GWO, HHO, and SMA) because of it have the best two results of objective functions including fuel cost and voltage stability index. In multiple objective functions (Bi, Tri, Quad, and Quinta), the results obtained by MOGWO method represent the best results compared with other algorithms (MOHHO, MOHGS, and MOSMA) because of the results obtained by MOGWO do not dominate by other methods (MOHHO, MOHGS, and MOSMA).
- ISGHV 28-bus: the results obtained by the HHO and SMA algorithms in a single objective function represent the best results compared with other algorithms (GWO and HGS) because of it have the best two results of objective functions for each one including fuel cost, real power losses of SMA algorithm and voltage deviation and voltage stability index of HHO algorithm.

Also, the author confirmed the voltage magnitude of the load bus can be controlled in the boundary values ([0.95-1.05 p.u.] of IEEE 30-bus and [0.94-1.06 p.u.] of IEEE 57-bus power systems) when the voltage deviation is considered an objective function such as Cases (4, 8, 10, 11, 12, 14, 15, 16, 19, 20, and 22) of IEEE 30-bus, Cases (26, 31, 33, 34, 36, 37, 38, 39, 40, and 42) of IEEE 57-bus systems.

CHAPTER 6 CONCLUSIONS, CONTRIBUTIONS, AND PERSPECTIVES

6.1. Conclusions

First of all, I summarized the conclusions according to the chapters mentioned above and as follows:

- A general survey of optimal power flow problem, the main objectives of this thesis, the main structure of the whole thesis, and a comprehensive survey of the literature review related to the study of optimal power flow using meta-heuristic optimization methods are concluded in *chapter one*.
- A comprehensive survey of conventional and intelligent optimization methods is presented in *chapter two*. The mathematical model of optimal power flow (OPF) has been described in this chapter. Then, the author presented the most popular objective functions that have been used in the application of optimal power flow, which are total fuel cost of generation units, total emission issues by the thermal and gas generation units, real power losses on transmission lines, voltage deviation at load bus, and voltage stability index of the whole system. Also, the constraints that must be considered, such as equality and equality constraints were presented. Finally, the author describes the equation of the multi-objective function that will be used in the next chapters.
- Four modern meta-heuristic optimization techniques have been explained in *chapter three*. These original algorithms, selected from the literature, are Grey Wolf Optimizer (GWO), Harris Hawks Optimization (HHO), Games Search (HGS), and Slime Mould Algorithm (SMA). Also, the mathematical formulas of these algorithms were explained in this chapter. The main reasons to choose these algorithms from literature include simplicity, fewer parameters used, and their modernity – they were written in 2014, 2019, 2021, and 2020, respectively.
- Due to the fact that the selected algorithms (GWO, HHO, HGS, and SMA) are not suitable to solve multi objective optimization (MOOP) problems, in *chapter four* these algorithms were modified for solving multi objective optimal power flow (MOOPF) problems. The modified algorithms were named Multi-Objective Grey Wolf Optimizer (MOGWO), Multi-Objective Harries Hawks Optimization (MOHHO), Multi-Objective Hunger Games Search (MOHGS), and Multi-Objective Slime Mould Algorithm (MOSMA). The modified algorithms were created by the author integrating the original selected algorithms with Pareto concept optimization (PCO), which is used to determine the set of nondominated solutions from all solutions (nondominated and dominated). The fuzzy membership theory is used to extract the best compromise solution from nondominated solutions. The crowding distance is the strategy applied to select the best nondominated solutions (according on the distance between them) from Pareto front set. The modified algorithms (MOGWO, MOHHO, MOHGS, and MOSMA) have been used to find the best solutions for multiple conflicting objective functions simultaneously (Bi, Tri, Quad, and Quinta).

- To validate the performance and efficiency of original selected algorithms (GWO, HHO, HGS, and SMA) - that used to solve the single objective optimal power flow (SOOPF), and the modified algorithms (MOGWO, MOHHO, MOHGS, and MOSMA) - that used to solve multi objective optimal power flow (MOOPF), in *chapter five* have been applied two standard power systems, IEEE 30-bus and IEEE 57- bus, and real power system, Iraqi Super Grid High Voltage 28-bus. The number of cases used in my thesis is 46 studies cases (14 for single objective OPF and 32 cases for multi-objective OPF). The numerical and simulation results obtained by original selected algorithms (GWO, HHO, HGS, and SMA) and the modified algorithm (MOGWO, MOHHO, MOHGS, and MOSMA) demonstrated that these algorithms give good convergence speed, high efficiency, and well distribution of Pareto front set. In comparison with other recent metaheuristics optimization methods, the original selected algorithms (GWO, HHO, HGS, and SMA) and the modified approaches (MOGWO, MOHHO, MOHGS, and MOSMA) provide a favorable performance and competitive optimizer to solve single and multi OPF problems in power systems.

6.2. Thesis Contributions

My main contributions in this thesis can be summarized as follows:

1- The literature review presented in Section 1.4 of the thesis consists in a large number of publications in the field of OPF. The author studied many articles to achieve new information about the state of the art of OPF and solve it by new metaheuristic optimization techniques. – Contribution 1

2- In this thesis, the mathematical model of five objective functions has been optimized to solve single and multi-objective functions. These objective functions are total fuel cost of generation units, emission issued by fossil fueled, real power losses on transmission lines, voltage profiles at load bus, and voltage stability index on whole system — Contribution 2

3- Four metaheuristics optimization techniques were used in this this thesis, Grey Wolf optimizer (GWO), Harris hawk's optimizer (HHO), Hunger Games Search (HGS), and Slime Mould Algorithm, to solve single objective optimal power flow and achieve the economic, environmental, and technical benefits of power systems – Contribution 3

4- The original selected algorithms (GWO, HHO, HGS, and SMA) have been adapted to solve multi-objective optimal power flow (MOOPF) problems in power systems named MultiObjective Grey Wolf Optimizer (MOGWO), Multi-Objective Harries Hawks Optimization (MOHHO), Multi-Objective Hunger Games Search (MOHGS), and Multi-Objective Slime Mould Algorithm (MOSMA). – Contribution 4

5- Pareto concept optimization (PCO) is the method used to obtain the solution for the nondominant Pareto front. Crowding distance is the strategy applied to select the best solutions from the non-dominant Pareto front. Fuzzy set theory represents the technique selected for extract the best compromise solution (BCS) from the non-dominant Pareto front. – Contribution 5

6- These algorithms were applied on three power systems to solve single and multiple (Bi, Triple, Quad, and Quinta) objective functions. Two power systems standard, IEEE 30-bus and IEEE 57-bus test systems, and a real electrical network, Iraqi Super Grid High Voltage 400 kV– Contribution 6

7- The values of objective functions (fuel cost, emission, real power losses, voltage deviation, and voltage stability index) obtained by used selected algorithms (GWO, HHO, HGS, and SMS) and the adaptive approaches (MOHGS, MOHHO, MOHGS, and MOSMA) are better than other metaheuristics optimization techniques reported in the literature. These comparisons prove the ability and efficiency the selected algorithms (GWO, HHO, HGS, and SMS) and the developed approaches (MOHGS, MOHHO, MOHGS, and MOSMA) to solve single and multi-objective functions optimal power flow (OPF) in power systems with satisfied equality and inequality constrains – Contribution 7

6.3. Perspectives

In future work, the proposed algorithms (GWO, HHO, HGS, and SMA) and the developed methods (MOGWO, MOHHO, MOHGS, and MOSMA) can be used with can be used to solve single and multi-objective optimal power flow problems with more difficult power systems and more control variables, such as the IEEE 118-bus, IEEE 300-bus systems, and most recent real power system network in my country (Iraq). In addition, it can be applied the proposed algorithms and developed methods to solve other optimization problems such as economic dispatch, optimal location, and sizing to incorporate the FACTS devices, distributed generation, and renewable energy sources in power systems.

References

[1] D. Çelik and M. E. Meral, "Current control based power management strategy for distributed power generation system," *Control Eng. Pract.*, vol. 82, pp. 72–85, 2019.

[2] J. Carpentier, "Contribution to the economic dispatch problem," *Bull. la Soc. Fr. des Electr.*, vol. 3, no. 8, pp. 431–447, 1962.

[3] N. Mo, Z. Y. Zou, K. W. Chan, and T. Y. G. Pong, "Transient stability constrained optimal power flow using particle swarm optimisation," *IET Gener. Transm. Distrib.*, vol. 1, no. 3, pp. 476–483, 2007.

[4] P. E. O. Yumbla, J. M. Ramirez, and C. A. C. Coello, "Optimal power flow subject to security constraints solved with a particle swarm optimizer," *IEEE Trans. Power Syst.*, vol. 23, no. 1, pp. 33–40, 2008.

[5] A. A. Heidari, S. Mirjalili, H. Faris, I. Aljarah, M. Mafarja, and H. Chen, "Harris hawks optimization: Algorithm and applications," *Futur. Gener. Comput. Syst.*, vol. 97, pp. 849–872, 2019.

[6] S. Li, H. Chen, M. Wang, A. A. Heidari, and S. Mirjalili, "Slime mould algorithm: A new method for stochastic optimization," *Futur. Gener. Comput. Syst.*, vol. 111, pp. 300–323, 2020.

[7] I. power systems test Case., "http://www.ee.washington.edu/ research/pstca/".

[8] A.-B. L. T. A. Ali, “Optimal Power Flow (OPF) with different Objective Function based on modern heuristic optimization techniques.” Politehnica University of Bucharest, Bucharest, Romania, 2015.
[9] D. H. Wolpert and W. G. Macready, “No free lunch theorems for search,” Technical Report SFI-TR-95-02-010, Santa Fe Institute, 1995.