Economic-emission load dispatch for power system operation using enhanced sunflower optimization

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Article Info

Article history:

Received Feb 18, 2022
Revised May 18, 2022
Accepted Jun 8, 2022

Keywords:

Economic dispatch
Economic-emission
Load dispatch
Power system
Sunflower optimization

ABSTRACT

Conventional thermal power plant uses limited sources of gas, fuel or coal which contributes to the rise of air pollution. Thus, it is crucial to efficiently use the natural sources and minimize the emissions of greenhouse gases and other pollutants. This paper presents an optimal economic dispatch considering three factors which are cost of generation, loss of power transmission and amount of emission for an efficient operation of power generation. Enhanced sunflower optimization (ESFO) algorithm is applied to determine the solution for three different cases: economic load dispatch, emission load dispatch and economic-emission load dispatch. The optimal solution based on the minimum generation cost and emission is obtained for the IEEE 6-unit test system using MATLAB software.

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1. INTRODUCTION

The power industry is very important currently because of its contribution to global economic growth and the urbanization movement. However, one of the most significant difficulties in the urbanisation process is the effective use of electrical energy [1]. To address this issue, generating units must be operated under optimal conditions to reduce power losses during transmission, thus lowering total generation costs [2]. In order to solve the issue of fossil fuel depletion and global warming, electrical energy must be managed effectively in order to lessen reliance on conventional power generations. Economic dispatch (ED) is an important technique in the operation of conventional power systems because it establishes the appropriate real power settings of generating units [3], [4]. It is often expressed as a mathematical optimization problem, with the goal of reducing the overall operating cost of dispatch solutions for a given load while meeting system limitations [5]. However, due to their high output emissions of greenhouse gases (GHG) and other pollutants such as nitrogen oxides (NOx), sulphur oxides (SOx), and carbon oxides (COx), traditional fossil-fuel power plants are responsible for air pollution [6]. As a result, the newly implemented clean air legislation and policies place a strong focus on utilities' responsibilities to maintain permitted emission levels from power generation in order to preserve a cleaner environment. As the total emission outputs in modern power generation systems have sparked global concern, the optimal ED problem must be reformulated by developing the combined economic emission dispatch (CEED) problem, which aims to accommodate both cost and emission minimization while taking into account system operational constraints [7], [8].

Many techniques have been presented to address various CEED issues. Ela *et al*. [9] presented the crow search algorithm (CSA) for resolving the CEED while limiting generating costs and pollution emissions. The CSA-based CEED approach was used in MATLAB software to four different test systems consisting of three, ten, and forty thermal generating units, as well as the typical IEEE 30-bus model system. The efficiency of the suggested approach in addressing the CEED issue was proved by a comparison of the CSA and other optimization techniques. The efficacy of CEED employing the internal search algorithm (ISA) was studied on five different test systems, which included a three-unit system, an IEEE 30-bus system, a 10-unit system, a 20-unit system, and a Taiwan 40-unit generating system [10]. In this work, a multi-objective dispatch function was developed, which included total pollution emissions and producing cost with valve point effect. [11] suggested another method for handling CEED-based problems in order to minimize overall generating costs, emission output, and active power losses. The viability of particle swarm optimization (PSO) was studied by taking four price penalty elements into account in order to establish the most ideal condition for the test system's generating units. Bhattacharya and Chattopadhyay [12], a biogeography-based optimization method was presented to tackle the CEED issue by taking into account the emission chemicals NOx, SOx, and COx, as well as the power demand equality constraint and the operational limit constraint.

Furthermore, hybrid approaches such as particle swarm optimization-based grey wolf optimization (PSGWO) and chaotic self-adaptive interior search algorithm (CSAISA) [13], [14] have been widely employed to handle CEED issues in the power system network. The optimum power flow (OPF)-based CEED issue was defined in [13] by combining fuel cost, fuel emission with a penalty function, actual power loss, and voltage variation. The PSO algorithm was included into the approach to retain the individual's best position information, preventing the process from slipping into a local optimum. Meanwhile, Rajagopalan *et al*. [14] presented a chaotic self-adaptive interior search algorithm (CSAISA) to handle CEED issues by taking into account generator nonlinear behaviour in terms of valve point effects, banned operating zones, and operational limits. To address the interior search algorithm (ISA) method's limitation, the chaotic variables technique was incorporated into the suggested algorithm.

Using enhanced sunflower optimization (ESFO), the goal of this study is to develop a multi-objective fitness function based on the operating cost and pollution emissions of conventional generating units. To validate the proposed multi-objective fitness function formulation, a test system comprised of six generating units will be used. In terms of convergence and consistency, the suggested technique will be validated further by comparison with sunflower optimization (SFO)-based CEED. It is expected that the approach will be capable of solving both least cost and emissions concurrently with improved accuracy and shorter computing time, while meeting the test system's equality and inequality criteria.

2. PROBLEM FORMULATION

In a test system comprised of six generating units, ESFO was used to identify the effective solution for generation costs and emission reduction. To validate the performance of the proposed technique, several case studies were studied based on economic load dispatch, emission load dispatch, and combined economic emission load dispatch. A comparison with SFO was also performed to assess the viability of ESFO in attaining the most ideal condition for generating units in the test system.

2.1. Economic load dispatch formulation

Economic load dispatch requires minimising the generation cost for a given load demand while taking into account different system and producing unit limitations [15], [16]. The generation cost of conventional power plants may be approximated as a quadratic function of the generating units' active power production, as shown in (1) [17]-[19]:

$$FC = \sum_{i=1}^{N_g} (a_i P_i^2 + b_i P_i + c_i) \quad (1)$$

where FC is the total generation cost, a_i, b_i, and c_i are the i^{th} unit's fuel cost coefficients, P_i is the i^{th} unit's output power, and N_g is the number of generating units. As presented in (2), the output power limitations are specified using a feasible range for the minimum and maximum limits of the active output power of each producing unit. [20], [21]. The load dispatching problem's power balance constraint is defined as:

$$P_i^{min} \leq P_i \leq P_i^{max} \tag{2}$$

$$\sum_{i=1}^{N_g} P_i = P_D + P_L \tag{3}$$

where P_D denotes total load demand and P_L denotes total power transmission losses, which may be written as a function of producing unit output power and *B-loss* coefficients shown in (4).

$$P_L = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} P_i B_{ij} P_j \tag{4}$$

Where B_{ij} is the ij^{th} element of the loss coefficients square matrix.

2.2. Emission load dispatch formulation

Emission load dispatch reduces emissions without taking into account economic factors. The total output emissions from conventional power plants may be approximated using a quadratic function of the producing units' active power output. The emission load dispatch problem may be represented as (5) to minimize total output emissions:

$$E = \sum_{i=1}^{N_g} 10^{-2}(\alpha_i P_i^2 + \beta_i P_i + \gamma_i) \tag{5}$$

where E is the total amount of emissions (lb/h), and α_i, β_i, and γ_i are the emission coefficients of the i^{th} unit.

2.3. Economic-emission load dispatch formulation

As demonstrated in (6), the objective function (*OF*) for combined economic emission dispatch simultaneously minimizes both generating cost functions, *C*, and pollutant emissions, *E*.

$$OF = C + z \times E \tag{6}$$

Using a modified price penalty factor, *z*, as shown in (7), the multi-objective dispatch formulation may be reduced to a single objective function [22]:

$$z = h_{i1} + \left(\frac{h_{i2} - h_{i1}}{P_{max\,2} - P_{max\,1}}\right) \times (P_D - P_{max\,1}) \tag{7}$$

where z is the price penalty factor in [\$/kg], h_{i1} is the last unit's price penalty factor in [\$/kg], h_{i2} is the current unit's price penalty factor in [\$/kg], P_{max1} is the maximum power of the last unit in [MW], and P_{max2} is the current unit's maximum power in [MW]. The penalty factor for a given load demand is calculated as:

- Step 1: as in (8), compute h_i for each unit:

$$h_i = \frac{FC(P_{max}^i())}{E(P_{max}^i());\quad i=1,2,\ldots,N_g} \tag{8}$$

- Step 2: sort the h_i values ascendingly.
- Step 3: add the maximum output power of each unit one at a time, beginning with the unit with the lowest h_i until $\sum P_i^{max} \geq P_D$.
- Step 4: the price penalty factor for the specified load demand is h_i of the final unit.

3. OPTIMIZATION ALGORITHM FOR SOLVING ECONOMIC-EMISSION LOAD DISPATCH

3.1. Sunflower optimization algorithm

The SFO method was initially presented by Gomes *et al*. [23] and has shown to be competitive with other well-known optimization strategies. SFO uses three strategies to refresh the population and update the solution: pollination, plant survival, and plant mortality. Initially, a population of random power generation, P_i, is formed, which symbolizes the plants [24]. In the pollination process, new plants are created by combining two successive plants, as in (9). This method assists the plants in exploring and exploiting the search space.

$$Plants_i = (Plants_i - Plants_{i+1}) \times rand(0,1) + Plants_{i+1};\ i = 1:(round(p * n)) \tag{9}$$

In the survival method, the next generation plant is selected by the plant's shortest distance from the best plant, as shown in (10). This method generates new plants in order to move to the best plant.

$$Plants_i = Plants_i + rand(0,1) \times \left(\frac{Plants_{best} - Plants_{i+1}}{\|Plants_{best} - Plants_i\|}\right); \quad i = (round(p * n) + 1): (round(n * (1 - m))) \tag{10}$$

In the mortality approach, mortality rates are determined by the number of dead plants that are replaced by new plants, as in (11). This strategy assists in furthering the exploration of the search space and preventing the solution from settling on the local optimum value.

$$Plants_i = (UB - LB) \times rand(0,1) + LB; \; i = 1: (round(p * n)) \tag{11}$$

Where p denotes the pollination rate, n is the number of sunflowers, m denotes the mortality rate, LB denotes the lower bounds of power limitations, and UB denotes the upper boundaries of power limits.

3.2. Enhanced sunflower optimization algorithm

Nguyen [25] propose a novel strategy for creating a new plant by modifying the best plant acquired by the three original SFO techniques. If the new mutant plant outperforms the best plant in terms of quality, it will acquire its position. The best plant's mutation, as stated in (12) and (13):

$$Plants_{new,j} = Plants_{best,j} + rand(0,1) \times \mu \times \rho(0,1); \; j = 1: d \tag{12}$$

$$\rho(0,1) = \begin{cases} 1; if \; rand(0,1) < round(r_m) \\ 0; \; otherwise \end{cases} \tag{13}$$

where μ is a constant used to establish the maximum change limit of the variable and r_m is the mutation rate, which was chosen as 0.2 to reflect 20% of the $Plants_{best}$ that is regenerated. **Error! Reference source not found.** depicts the implementation of the ESFO algorithm to address the economic-emission load dispatch problem.

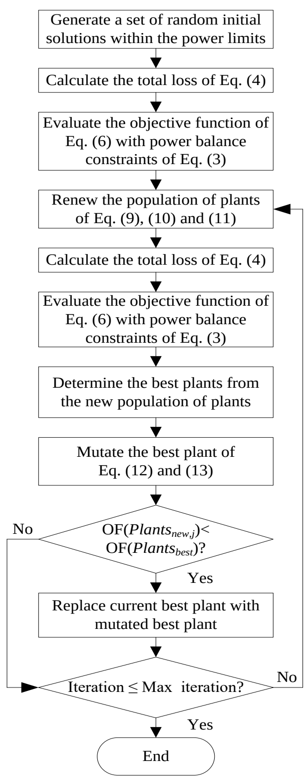

Figure 1. Flowchart of EFSO algorithm for economic-emission load dispatch

4. RESULTS AND DISCUSSION

The algorithms of SFO and ESFO are applied to IEEE 6-unit test system for the total load of 700 MW and 900 MW. Three cases are considered which are economic load dispatch, emission load dispatch and economic-emission load dispatch. To validate the performance of ESFO for economic-emission load dispatch, 30 different trials are carried out with 500 maximum iterations each trial. The data for fuel cost coefficients, NOx emission coefficients and power generation limits of the test system are shown in **Error! Reference source not found.** The results including the generation cost, the emission level and convergence time for economic-emission load dispatch are compared between SFO and ESFO.

Table 1. Data of generation cost coefficients, NOx emission coefficients and power generation limits

Generator	Cost coefficients			Emission coefficients			Generator limits	
	a	b	c	α	β	γ	P_{min}	P_{max}
1	756.7988	38.5397	0.15247	0.00419	0.32767	13.8593	10	125
2	451.3351	46.1591	0.10587	0.00419	0.32767	13.8593	10	150
3	1049.997	40.3965	0.02803	0.00683	-0.54551	40.2669	35	225
4	1243.531	38.3055	0.03546	0.00683	-0.54551	40.2669	35	210
5	1658.559	36.3278	0.02111	0.00461	-0.51116	42.8955	130	325
6	1356.659	38.2704	0.01799	0.00461	-0.51116	42.8955	125	315

4.1. Economic load dispatch

Error! Reference source not found. presents the optimal output power for the best generation cost obtained by SFO and ESFO for total load demand of 700 MW. The results obtained by the optimal solution presented in **Error! Reference source not found.** show that ESFO able to achieve lower generation cost as compared to SFO with a difference of 10,084 $/h. However, the emission level by ESFO is slightly higher with 545.05 [kg/h] as compared to SFO with 537.22 kg/h which is expected since only minimization of the cost is considered. The convergence time shows that ESFO converged faster as compared to SFO with a difference of 0.1335 s.

Error! Reference source not found. presents the optimal output power for the best generation cost obtained by SFO and ESFO for total load demand of 900 MW. The results obtained by the optimal solution presented in **Error! Reference source not found.** show that ESFO able to achieve lower generation cost as compared to SFO with a difference of 318 $/h. However, the emission level by ESFO is slightly higher as compared to SFO with a difference of 10.14 kg/h which is also expected due to only minimization of the cost is considered. The convergence time shows that ESFO converged faster as compared to SFO with a difference of 0.6762 s.

Table 2. Optimal solution for economic load dispatch with total demand of 700 MW

Generation unit	Output power [MW]	
	SFO	ESFO
P_1	114.00	120.55
P_2	150.00	134.65
P_3	71.22	132.26
P_4	147.09	141.34
P_5	141.60	130.00
P_6	147.12	131.35
P_{total}	771.02	790.15

Table 3. Results of minimum total cost for total demand of 700 MW

Output variables	SFO	ESFO
Fuel Cost [$/h]	1148675	1138591
NOx emission [kg/h]	537.22	545.05
Convergence time [s]	3.9008	3.7673

Table 4. Optimal solution for economic load dispatch with total demand of 900 MW

Generation unit	Output power [MW]	
	SFO	ESFO
P_1	122.58	125.00
P_2	150.00	150.00
P_3	134.42	149.96
P_4	172.86	167.12
P_5	209.59	203.29
P_6	217.40	220.12
P_{total}	1006.84	1015.49

Table 5. Results of minimum total cost for total demand of 900 MW

Output variables	SFO	ESFO
Fuel Cost [$/h]	2,146,727	2,146,409
NOx emission [kg/h]	802.59	812.73
Convergence time [s]	6.8775	6.2013

4.2. Emission load dispatch

Error! Reference source not found. presents the optimal output power for the best emission level obtained by SFO and ESFO for total load demand of 700 MW. The results obtained by the optimal solution presented in **Error! Reference source not found.** show that ESFO able to achieve lower emission level as compared to SFO with a small difference of 1.49 kg/h. However, the generation cost by ESFO is slightly higher with 1342067 $/h as compared to SFO with 1,338,617 $/h which is expected since only minimization of the emission level is considered. The convergence time shows that ESFO converged faster as compared to SFO with a difference of 2.3913 s.

Table 6. Optimal solution for emission load dispatch with total demand of 700 MW

Generation unit	Output power [MW]	
	SFO	ESFO
P_1	98.59	101.85
P_2	85.06	70.39
P_3	87.22	100.08
P_4	112.05	114.46
P_5	198.54	184.91
P_6	158.85	172.94
P_{total}	740.31	744.63

Table 7. Results of minimum emission level for total demand of 700 MW

Output variables	SFO	ESFO
Fuel Cost [$/h]	1,338,617	1,342,067
NOx emission [kg/h]	469.63	468.14
Convergence time [s]	6.4035	4.0122

Error! Reference source not found. presents the optimal output power for the best emission level obtained by SFO and ESFO for total load demand of 900 MW. The results obtained by the optimal solution presented in **Error! Reference source not found.** show that ESFO able to achieve lower emission level as compared to SFO with a difference of 10.89 kg/h. However, the generation cost by ESFO is slightly higher with 2,400,974 $/h as compared to SFO with 2,340,933 $/h which is expected since only minimization of the emission level is considered. The convergence time shows that ESFO converged faster as compared to SFO with a difference of 0.2068 s.

Table 8. Optimal solution for emission load dispatch with total demand of 900 MW

Generation unit	Output power [MW]	
	SFO	ESFO
P_1	116.36	125.00
P_2	119.04	109.39
P_3	138.38	96.45
P_4	140.72	130.87
P_5	263.12	267.31
P_6	206.51	232.37
P_{total}	984.13	961.39

Table 9. Results of minimum emission level for total demand of 900 MW

Output variables	SFO	ESFO
Fuel Cost [$/h]	2,340,933	2,400,974
NOx emission [kg/h]	776.77	765.88
Convergence time [s]	5.8852	5.6784

4.3. Economic-emission load dispatch

Error! Reference source not found. presents the optimal output power for the best economic-emission level obtained by SFO and ESFO for total load demand of 700 MW. The results obtained by the optimal solution presented in **Error! Reference source not found.** show that ESFO able to achieve lower objective function as compared to SFO. Minimum objective function achieved by ESFO provides slightly higher cost, but lower emission level as compared to SFO. However, the percentage of lower emission level is higher than percentage of higher generation cost with 3.26% and 0.70% respectively. Hence, the optimal power generation generated by ESFO yield better results as compared to SFO. **Error! Reference source not found.** presents the optimal output power for the best economic-emission level obtained by SFO and ESFO for total load demand of 900 MW. The results obtained by the optimal solution presented in **Error! Reference source not found.** show that ESFO able to achieve lower objective function as compared to SFO. Minimum objective function achieved by ESFO provides slightly higher emission level, but lower generation cost as compared to SFO. However, the percentage of lower generation cost is higher than percentage of higher emission level with 3.58% and 2.75% respectively. Hence, the optimal power generation generated by ESFO yield better results as compared to SFO

Table 10. Optimal solution for economic-emission load dispatch with total demand of 700 MW

Generation unit	Output power [MW]	
	SFO	ESFO
P_1	123.41	125.00
P_2	125.76	108.35
P_3	115.55	88.42
P_4	109.31	130.07
P_5	140.13	140.17
P_6	157.72	162.23
P_{total}	771.88	754.24

Table 11. Results of minimum economic-emission level for total demand of 700 MW

Output variables	SFO	ESFO
OF	2164450	2139055
Fuel Cost [$/h]	1138869	1146933
NOx emission [kg/h]	508.86	492.26
z [$/h]	2015.46	2015.46
Convergence time [s]	5.8229	5.2898

Table 12. Optimal solution for economic-emission load dispatch with total demand of 900 MW

Generation unit	Output power [MW]	
	SFO	ESFO
P_1	125.00	125.00
P_2	113.35	129.42
P_3	116.59	106.11
P_4	146.49	174.89
P_5	236.77	200.51
P_6	237.29	251.42
P_{total}	975.48	987.36

Table 13. Results of minimum economic-emission level for total demand of 900 MW

Output variables	SFO	ESFO
OF	3,922,615	3,920,968
Fuel Cost [$/h]	2,279,836	2,217,240
NOx emission [kg/h]	763.02	791.33
z [$/h]	2152.99	2152.99
Convergence time [s]	6.9978	6.5506

4.4. Convergence test

To validate the performance of ESFO, the best solution of each iteration for 500 iterations are plotted based on the case of economic-emission load dispatch. The algorithms of SFO and ESFO are applied to the IEEE 6-unit test system. Figure 2 shows the convergence characteristics of the 700 MW load demand using ESFO and SFO. Meanwhile, **Error! Reference source not found.** demosntrates the convergence characteristics for 900 MW total demand using both algorithms. The plots show that ESFO converges faster to achieve a better solution as compared to SFO.

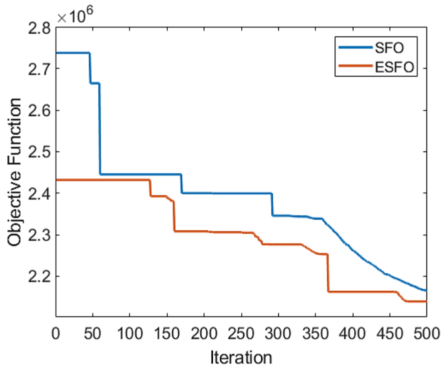

Figure 2. Convergence characteristic of SFO and ESFO for total demand of 700 MW

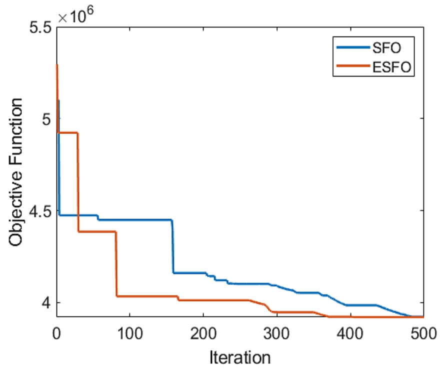

Figure 3. Convergence characteristic of SFO and ESFO for total demand of 900 MW

4.5. Consistency test

In order to show the consistency of the results obtained by ESFO, the best solution of each simulation run of 30 runs are plotted based on the case of economic-emission load dispatch as shown in **Error! Reference source not found.** and **Error! Reference source not found.** for 700 MW and 900 MW total demand respectively. To ease the analysis on the consistency plot, **Error! Reference source not found.** and **Error! Reference source not found.** show the summary of the plot. The results show that the minimum, maximum and standard deviation values of ESFO are lower than SFO. Hence, it is proven that ESFO is more robust than SFO as it is capable to produce more consistent result.

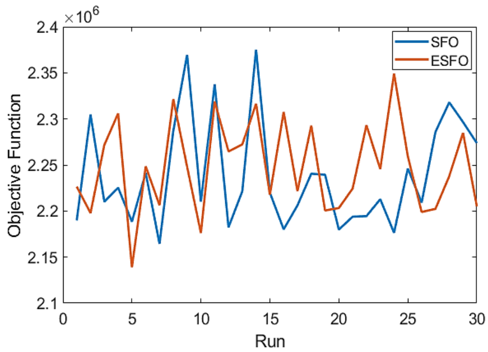

Figure 4. Consistency test of SFO and ESFO for total demand of 700 MW

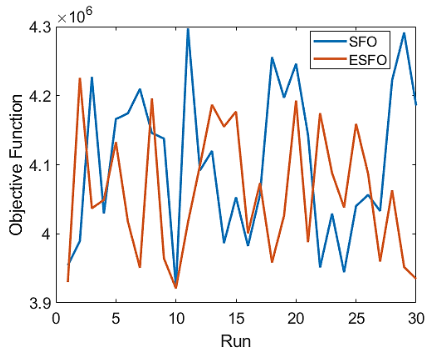

Figure 5. Consistency test of SFO and ESFO for total demand of 900 MW

Table 14. Summary of the consistency plot for 700 MW

Objective function	SFO	ESFO
Minimum	2,164,450	213,9055
Maximum	2,375,201	234,9073
Standard deviation	57,361	50,424

Table 15. Summary of the consistency plot for 900 MW

Objective function	SFO	ESFO
Minimum	3,922,615	3,920,968
Maximum	4,297,623	4,225,713
Standard deviation	118,653	91,912

5. CONCLUSION

In this paper, economic-emission load dispatch was performed based on SFO and ESFO with the objective to reduce the total generation cost and emission level. The simulation run on IEEE-6 Test System prove that ESFO has successfully obtained better optimal power generation as compared to SFO according to the minimum generation cost and minimum emission level. The ESFO also proven to demonstrated fast convergence characteristics and more robust for the combined economic emission dispatch problem.

ACKNOWLEDGEMENTS

The authors thank the Asia Pacific University of Technology and Innovation, Ministry of Education Malaysia (MOE) and National University of Malaysia (UKM) for supporting this work through FRGS research grant (FRGS/1/2018/TK04/UKM/02/12).

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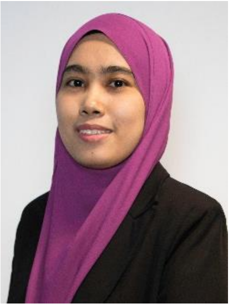

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