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Discrete Evolutionary Programming for Network Splitting Strategy: Different Mutation Technique

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ABSTRACT

Network splitting is performed to prevent the power system network from blackout event during severe cascading failures. This action will split the power system network into few islands by disconnecting the proper transmission lines. It is very important to select the optimal splitting solution (transmission lines to be removed) to ensure that the implementation of network splitting does not cause the system to worsen. Therefore, this paper investigates two different mutation techniques; single-level and three-level mutation, utilized in Discrete Evolutionary Programming (DEP) optimization to find the optimal splitting solution following a critical line outage. Initial cutsets based heuristic technique is employed to help the convergence of the DEP optimization with minimal power flow disruptions as its fitness function. The techniques are validated using the IEEE 30 and IEEE 118-bus system. The results show that three-level mutation technique produces better optimal splitting solution as compared to single mutation technique.

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1. INTRODUCTION

Power System network splitting is one of the remedial actions taken to prevent the occurrence of system blackout during any severe cascading failures. Normally, when severe cascading failures occurs, the tendency of the system to split into few unbalance islands (automatic islanding) is very high and unavoidable. These unbalance islands will create many instability problems within the system that eventually lead to blackout phenomenon [1]. Based on the previous investigation, many major blackout phenomenon that had occurred in the world are caused by the severe cascading failures [2-3]. In order to avoid the occurrence of automatic islanding during severe cascading failures, intentional islanding or known as network splitting is more preferable. Network splitting is an action of splitting the power system network into few desired stand-alone islands by disconnecting the proper transmission line which meets certain criteria. Determining the optimal splitting solution (transmission line to be disconnected) is the toughest part in network splitting action since the search space of possible combination for splitting solution increases as the size of the network increases.

Numerous methods have been proposed by previous researchers on network splitting implementation. One of the former methods in network splitting implementation is using Ordered Binary Decision Diagrams (OBDDs) method [4-5]. Another method uses slow coherency based islanding which group the same dynamic characteristics of generators during network splitting is introduced in [6]. The method is then used in minimal cutsets with minimal power flow [7] and graph partitioning technique in [8].

Other methods such as linear programming methods [9-10], two- step spectral clustering [11], heuristic based ant search method [12], meta-heuristic methods [13-14] are introduced to determine the optimal splitting solution respectively.

This paper investigates two different mutation techniques; single-level mutation and three-level mutation techniques, applied in Discrete Evolutionary Programming (DEP) optimization technique for optimal network splitting determination following a critical line outage. The critical outage is determined based on N-1 contingency analysis using overloading criterion mentioned in [15]. The DEP optimization technique used in this study is different as compared to the Conventional Evolutionary Programming (CEP) in terms of mutation technique. In this work, the DEP optimization uses minimal power flow disruptions as the fitness function to determine the optimal network splitting solution.

2. PROPOSED APPROACH

This paper investigates two different approaches in the mutation part for Discrete Evolutionary Programming (DEP) optimization technique to solve network splitting problem. The two different techniques namely; single-level and three-level mutation technique are studied and evaluated on obtaining the best optimal network splitting with minimal fitness function.

The work began by conducting the N-1 contingency analysis to identify the critical line which can contribute to severe cascading problems. Critical line is the line if disconnected from network will cause other line to be tripped due to overloading issue. Criterion in [15] is used to evaluate and identify the critical lines for each test system studied in this work. Graph theory is used to model and represent the physical connection of power system network during network splitting implementation.

In this work, a good initial cutsets which obtained from heuristic technique is used in the initialization part of DEP optimization to assists the optimization algorithm to find the optimal solution and speed up the convergence process. The initial cutsets from heuristic technique is determined by taking into account two important constraints for successful network splitting which are desired number of islands and coherent groups of generators. The process started by grouping the coherent generators in each group of island using shortest path configuration [16]. Then, the nearest node (line) is assigned to the nearest groups of generators. The cutsets candidates (initial cutsets) are the lines that falls between two different groups of islands. Detail explanation on initial cutsets determination can be found in [17].

Then, two different techniques of mutation for DEP optimization is carried out to determine the optimal splitting solution. Appropriate load shedding scheme is performed if any imbalance between generation and load demand identified after network splitting execution. The transmission line capacity analysis is also verified to avoid any lines violates their maximum loading capacity after network splitting action. Figure 1 illustrates the flowchart of proposed approach.

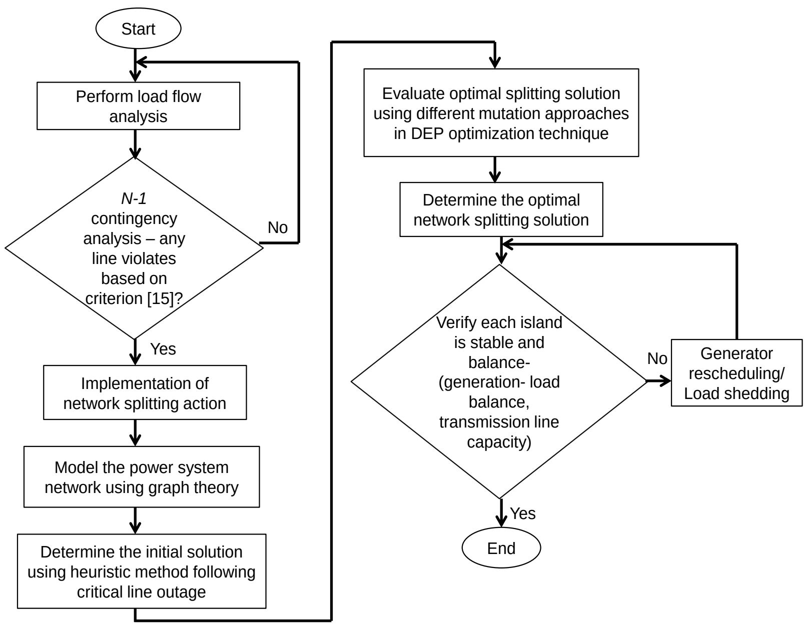

Figure 1. Flowchart of the proposed approach

3. METHODOLOGY

This section describes in detail the steps involved in the two mutation techniques which were investigated in this study. Besides, it also elaborates the analysis performed to determine the final optimal network splitting solution.

3.1. Different Mutation Techniques

Network splitting is a discrete problem in nature since the network splitting solution (transmission line to be removed) is represented by integers numbers (e.g., 2-4, 6-7, 8-12,…., etc). Therefore, CEP optimization technique is not feasible for network splitting problems. Compared to CEP optimization which uses random initialization for initial population [18], the DEP applied in this work uses initial population based on initial cutsets obtained from the heuristic technique as mentioned in the previous section. The flowchart of the DEP optimization utilized in work is shown in Figure 2.

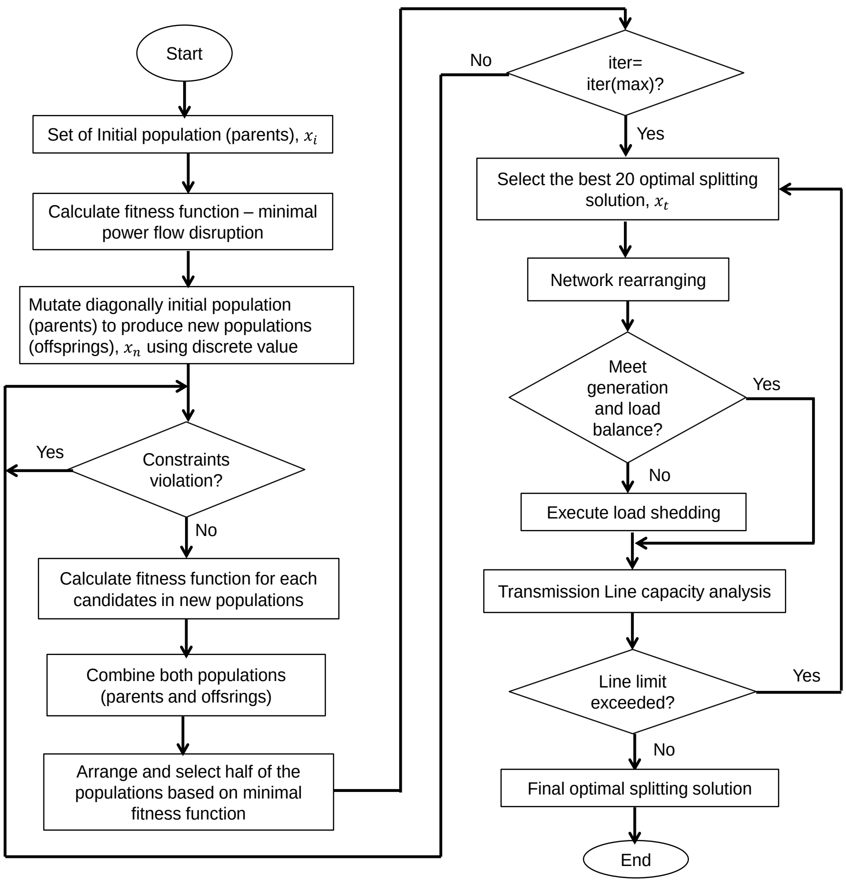

Figure 2. DEP optimization technique

Referring to Figure 2, the initial cutsets,xi obtained from heuristic technique is used as initial population in DEP optimization. Then, the fitness value is calculated based on the minimal power disruption as shown in Equation 1. Optimal splitting strategy based on this fitness function will produce better stable islands [11].

$$\min\left\{f(x) = \left(\sum_{d=1}^{d_{line}} |P_d|\right)\right\} \quad (1)$$

Pd is the active power flow in the transmission line (cutsets), d and dline is the total number of lines to be disconnected to forms the islands.

For each case evaluated in this paper, two different mutation approaches; single-level and three-level mutation are employed. In single-level mutation, the mutation process is carried out by mutating the initial population by replacing a random value, A1i in diagonal manner, from the search space, S to produce new populations (offspring), xn as shown in Table 1. The solution space, S is the number edges (transmission line), ED={EDp} in the system where p=1,2,3….total number of edges. The reason of performing such mutation process is to maintain certain level of heuristic based on the original initial cutsets obtained earlier. For each offsprings generated, the constraints will be checked and fitness function is calculated. The constraints considered in the optimization technique are the desired number of islands and coherent groups of generators.

Table 1. Single-level mutation process of DEP optimization

1	Example of initial cutsets from heuristics method	Y_1	Y_2	Y_3	Y_4	Y_5
2	1st cutset is randomly replaced	$\mathbf{A_{i1}}$	Y_2	Y_3	Y_4	Y_5
3	2nd cutset is randomly replaced	Y_1	$\mathbf{A_{i2}}$	Y_3	Y_4	Y_5
4	3rd cutset is randomly replaced	Y_1	Y_2	$\mathbf{A_{i3}}$	Y_4	Y_5
5	4th cutset is randomly replaced	Y_1	Y_2	Y_3	$\mathbf{A_{i4}}$	Y_5
6	5th cutset is randomly replaced	Y_1	Y_2	Y_3	Y_4	$\mathbf{A_{i5}}$

Then, the offsprings, xn will be combined with the parents for the selection process based on their minimum fitness function. The first half of the combined populations will be selected as the parents for the next iteration. The mutation process on the parents to produce offsprings continues until reached the preset number of iteration. Finally, the best 20 optimal splitting solutions, xt will be selected based on their minimum fitness function.

The length of final optimal cutsets obtained in single-level mutation technique will be same as the initial cutsets utilized. However, there is possibility that the total number of cutsets may be less or more than the initial cutsets obtained from the heuristic technique, with better fitness function. Therefore, three-level mutation technique is introduced in second mutation technique. The following steps are explained on the steps taken to perform the three-level mutation technique in DEP optimization:

1) Level 1: The first stage in three-level mutation technique is similar to mutation process executed in single-level mutation technique. The cutsets is randomly replaced diagonally from the search space, S to produce new populations (offspring), x_n.
2) Level 2: In the second stage, the number of initial cutsets is reduced by one and new populations (offsprings), x_n are produced based on the mutation process executed in step 1 (diagonal replacement). Mutation process in this stage is explained in Table 2.

Table 2. Mutation process of DEP optimization for level 2

1	Example of initial cutsets from heuristic technique	Y_1	Y_2	Y_3	Y_4	Y_5
2	1st cutset is randomly replaced	$\mathbf{B_{i1}}$	Y_2	Y_3	Y_4	0
3	2nd cutset is randomly replaced	Y_1	$\mathbf{B_{i2}}$	Y_3	Y_4	0
4	3rd cutset is randomly replaced	Y_1	Y_2	$\mathbf{B_{i3}}$	Y_4	0
5	4th cutset is randomly replaced	Y_1	Y_2	Y_3	$\mathbf{B_{i4}}$	0

3) Level 3: In this stage, the number of cutsets is added by another number and new populations (offsprings), x_n are produced following mutation in stage 1. Mutation process in this stage is shown in Table 3.

All the new populations (offsprings) obtained from the 3 stages of mutation above are combined and evaluated based on their minimal fitness function (minimal power disruption). The process executed to select the final optimal solution is similar to single-level mutation technique explained.

Table 3. Mutation process of DEP optimization for level 3

1	Example of initial cutsets from heuristic tehcnique	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
2	1st cutset is randomly replaced	$\mathbf{C_{i1}}$	Y_2	Y_3	Y_4	0	C_{16}
3	2nd cutset is randomly replaced	Y_1	$\mathbf{C_{i2}}$	Y_3	Y_4	0	C_{26}
4	3rd cutset is randomly replaced	Y_1	Y_2	$\mathbf{C_{i3}}$	Y_4	0	C_{36}
5	4th cutset is randomly replaced	Y_1	Y_2	Y_3	$\mathbf{C_{i4}}$	0	C_{46}
6	5th cutset is randomly replaced	Y_1	Y_2	Y_3	Y_4	$\mathbf{C_{15}}$	C_{56}
7	6th cutset is randomly replaced	Y_1	Y_2	Y_3	Y_4	Y_5	C_{66}

3.2. Network Rearranging, Load Shedding and Transmission Line Capacity Analysis

For each of the optimal splitting solution found, the network rearranging is carried out to allow load flow analysis to be performed. However, only one island has a slack bus when the system is split. The other islands contain only PV and load buses. Therefore, slack bus for other islands is determined based on the highest rating of generation capacity among the PV buses.

Then, the generation and load balance in each island are evaluated to avoid any imbalance scenarios during network splitting action. Equation 2 is used to calculate the power balance in each island.

$$P_{imb} = (\sum P_G - P_L) \quad (2)$$

Where PG is the generated power in the island and PL is the accumulation of all load and line losses in that particular island. If power imbalance is detected in the island after slack bus and other generators have been increased to their maximum limit, load shedding scheme are initiated. The load shedding scheme is executed by removing the best combination of loads based on the power imbalance noticed in this work.

Then, the transmission line capacity analysis is checked to avoid any violation of the loading limit in each line after network splitting action using Equation 3.

$$P_{c,line} < P_{c,max} \quad (3)$$

Where is the active power flow in line c, and Pc, max is the maximum permissible limit of active power flow in $P_{c,line}$ line c. If there is any violation on transmission line limit, the algorithm will search the next optimal solution for the evaluation. Otherwise, the current solution is considered the optimal splitting solution.

4. RESULTS AND ANALYSIS

The proposed network splitting algorithm is tested and validated on the IEEE 30 and IEEE 118-bus systems. The algorithm is coded using MATLAB R2015a on an Intel® Core™ i7-5500U CPU at 2.40GHz with 8GB of RAM.

4.1. Case Study I: IEEE 30-Bus System (Outage Line 3-4)

The IEEE 30-bus system consists of 30 bus and 41 transmission lines. Some modifications on the generator limits are executed in order to validate the effectiveness of the proposed approach. The system is modelled in the graph theory and initial cutsets is obtained using heuristic technique.

One of the critical lines identified from N-1 contingency analysis for this test system is line 3-4. Outage of line 3-4 due to any severe contingency, will cause other transmission lines to be overloaded and tripped; Line 1-2 (loading at 151.8055%), Line 2-4 (loading at 106.3733%) and Line 2-6 (loading at 111.9856%). These conditions will lead to partial or total system blackout. Therefore, the proposed splitting solution is carried out following this critical line outage.

In this case, network the splitting is performed out by splitting the network into two islands based on their coherent groups of generators; G1= {1, 2, 5, 13} and G2= {8, 11} [13]. The initial cutsets and its power flow disruptions are listed in Table 4. The utilization of heuristic technique in determining the initial cutsets helps to reduce the number of possible initial solution from 2no.of transmission line (240 ≈ 1.09951 x 1012) to 7 lines as an initial cutsets.

Table 4. Initial Cutsets for Case Study I

Initial Cutsets	$\sum P_D$ (MW)
2-6, 4-6, 6-7, 19-20,10-17,22-24, 24-25	128.8721

The initial cutsets is refined in the DEP optimization to produce an optimal splitting solution. Two different mutation methods are utilized in the DEP optimization in order to obtain the best optimal splitting solution with minimal total power flow disruption. Three-level mutation technique applied in the DEP optimization is able to produce splitting solution with lower total power flow disruption. Table 5 describes in detail the comparison between the two techniques.

Table 5. Comparison between Single-level and Three-level mutation technique– Case Study I

Methods	Optimal Cutsets	$\sum P_D$ (MW)	Number of cutsets
Single-level mutation	2-6, 4-6, 5-7, 16-17,18-19,22-24, 24-25	114.3996	7
Three-level mutation	2-6, 4-6, 5-7, 16-17,18-19,23-24	106.169	6

Since minimal total power flow disruption is the fitness function evaluated in determining the best optimal splitting solution, therefore optimal splitting solution using three-level mutation technique is selected during network splitting execution. Referring to the result as depicts in Table 6, the islands is split into two islands with 12 buses in Island 1 and 18 buses in Island 2. In Island 1, the total generation is more than the total load demand, therefore load shedding does not initiated. However, in Island 2, the total load demand is more than the maximum generator's supply (after all generators reached their maximum limit). Therefore load shedding is initiated by shedding the load at bus 7 (22.8MW) to ensure the generation and load balance is achieved. Finally, line capacity analysis is carried to ensure that maximum line capacity for each transmission line is not violated.

Table 6 Optimal Network Splitting information for IEEE 30-Bus System: Three-level mutation technique

Islands	Buses Info	Active Power				Load Shed
		Pre- splitting		Post- splitting		
		Total Pgen	Total Pload	Total Pgen	Total Pload	MW
Island 1	1~5, 12~16, 18, 23	165.363	161.40	165.363	161.40	-
Island 2	6~11, 17, 19~22, 24~30	110	122.0	100.316	99.2	22.8

4.2. Case Study II: IEEE 118-bus system (outage line 8-5)

The proposed algorithm is further tested on IEEE 118-bus system to evaluate the effectiveness of the proposed algorithm. IEEE 118-bus system consists of 118 bus and 186 transmission lines. Some modifications to the generator limits are performed to validate its effectiveness. The system is modelled using graph theory and initial cutsets is obtained from heuristic technique.

One of the critical lines identified for this test system is line 8-5. Failure of this line due to any severe contingency, will cause other transmission lines to be overloaded and tripped; line 8-30 (loading at 267.9248%), line 16-17 (loading at 152.9760%), line 12-16 (loading at 133.5864%), line 30-38 (loading at 125.4920%), line 14-15 (loading at 110.9481%) and line 17-18 (loading at 107.3589%). These conditions will lead to partial or total system blackout. Therefore, the proposed splitting solution is carried out following this critical line outage.

In this case, two islands are decided to be formed during network splitting based on their coherent groups of generators; G1= {10, 12, 25, 26, 31} and G2= {46, 49, 54, 59, 61, 65, 66, 69, 80, 87, 89, 100, 103, 111} [13]. The initial cutsets and its power flow disruptions obtained for this case study are listed in Table 7. The utilization of heuristic technique in finding the initial cutsets proves that the number of possible initial solution from 2no.of transmission line (2185 ≈ 4.903986 x 1055) can be reduced to 6 lines as an initial cutsets.

Table 7. Initial Cutsets for Case Study II

Initial Cutsets	$\sum P_D$ (MW)
37-40, 39-40, 34-43, 38-65,24-70,71-72	205.0499

The initial cutsets is used as initial population in the DEP optimization to help the algorithm to determine the optimal splitting solution. Two different mutation methods as applied in Case Study I are utilized in the DEP optimization in order to obtain the best optimal splitting solution with minimal total power flow disruption. Table 8 illustrates in detail the optimal splitting solution for both methods.

Table 8. Comparison between Single-level and Three-level mutation technique–Case Study II

Methods	Optimal Cutsets	$\sum P_D$ (MW)	Number of cutsets
Single-level mutation	23-24,37-40, 39-40, 34-43,38-65, 71-72	190.5757	6
Three-level mutation	23-24,37-40, 39-40, 34-43,38-65	190.5746	5

Referring to Table 8, three-level mutation technique is able to produce optimal splitting solution with minimal total power flow disruption as compared to single-level mutation technique. Furthermore, the number of cutsets for three-level mutation technique is less compared to single-level mutation technique. Therefore optimal splitting solution from three-level mutation technique is selected during network splitting execution. The information of optimal splitting solution is shown in Table 9 with 42 buses in Island 1 and 76 buses in Island 2. In Island 1, it is observed that the total load demand is more than the total generation supply (after all generators reached their maximum limit). Therefore load shedding is initiated by shedding the load at bus 11 and bus 14 (84MW) to ensure the generation and load balance is attained. While in Island 2, the total generation supply is more than the load demand, therefore load shedding does not initiated. Finally, line capacity analysis is carried to ensure that maximum line capacity for each transmission line is not violated.

Table 9. Optimal Network Splitting information for IEEE 118-Bus System: Method 2

Islands	Buses Info	Active Power				Load Shed MW
		Pre-splitting		Post- splitting		
		Total Pgen	Total Pload	Total Pgen	Total Pload	
Island 1	1~23, 25~39, 113~115, 117	1120	1136	1119.616	1052	84
Island 2	24, 40~112, 116, 118	3244.86	3106	3244.86	3106	-

4.3. Comparative Validation And Discussion

A comparative study is conducted to validate the effectiveness of the proposed network splitting algorithm. Since no previous published work performs similar case study for network splitting solution considering contingency analysis, the comparative study is carried out for cases without contingency scenarios. Table 5 illustrates the comparison of optimal splitting solution obtained from the proposed approach with other published work which has the same coherent group of generator and desired number of islands.

Table 10. Comparative Validation of Network Splitting Solution

Test System	Technique	Disconnected Lines	Total Power Flow Disruption, P_D (MW)
IEEE 30- bus	Reference [13]	2–6, 4–6, 6–7, 19–20,10–17, 22–24, 24–25	190.5051
	Proposed method	2–6, 4–6, 5–7, 16–17,18–19, 23–24	154.5361
IEEE 118-bus	Reference [13]	19–34, 21–22, 23–25,23–32, 30–38,33–37	381.2913
	Proposed method	37–40, 39–40,34–43, 38–35,23–24	199.7748

Referring to Table 10, the proposed algorithm can eventually find an optimal splitting solution with lower total power flow disruption of 154.5361 (improvement of 18.9%) as compared to the method in [13], for IEEE 30-bus system. Meanwhile, in IEEE 118-bus system, the proposed algorithm produces better optimal splitting solution with lower power flow disruption of 199.7748 (improved by 47.6%) as compared to the method in [13]. The results obtained prove that proposed algorithm (DEP optimization) has the ability to find better optimal splitting solution with lower fitness function than previously published work.

5. CONCLUSION

This paper presents on two different mutation techniques used in DEP optimization to determine the best optimal splitting solution. The proposed approaches are tested using IEEE 30 and IEEE 118-bus system and results shows that three- level mutation approach provide better optimal splitting solution with minimal power flow disruptions (fitness function). Furthermore, choosing splitting solution with lower fitness function will ensure the successful splitting implementation.

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REFERENCES

[1] A. B. M. Nasiruzzaman and H. R. Pota, "Measures of Impact Under Cascading Failure of Power Grid", *TELKOMNIKA Indones. J. Electr. Eng*., vol. 12, no. 2, pp. 1149–1161, 2014.

[2] S. Larsson and E. Ek, "The black-out in southern Sweden and eastern Denmark, September 23, 2003", *Power Engineering Society General Meeting*, 2004. IEEE, pp. 1–5, 2003.

[3] "Final Report System Disturbance on 4 November 2006 union for the co-ordination of transmission of electricity", 2006.

[4] Q. Zhao, K. Sun, D. Zheng, J. Ma, and Q. Lu, "A study of system splitting strategies for island operation of power system: a two-phase method based on OBDDs," *IEEE Trans. Power Syst*., vol. 18, no. 4, pp. 1556–1565, 2003.

[5] K. Sun, D. Z. Zheng, and Q. Lu, "Splitting strategies for islanding operation of large-scale power systems using OBDD-based methods," *IEEE Trans. Power Syst*., vol. 18, no. 2, pp. 912–923, 2003.

[6] H. You, S. Member, V. Vittal, X. Wang, and S. Member, "Slow Coherency-Based Islanding," *IEEE Trans. Power Syst*., vol. 19, no. 1, pp. 483–491, 2004.

[7] X. Wang, S. Member, and V. Vittal, "System Islanding Using Minimal Cutsets with Minimum Net Flow," *in Power System Conference and Exposition*, 2004, pp. 1–6.

[8] G. Xu, S. Member, and V. Vittal, "Slow Coherency Based Cutset Determination Algorithm for Large Power Systems," *IEEE Trans. POWER Syst*., vol. 25, no. 2, pp. 877–884, 2010.

[9] P. A. Trodden, W. A. Bukhsh, A. Grothey, and K. I. M. Mckinnon, "MILP Formulation for Islanding of Power Networks," *IEEE Trans. POWER Syst*., vol. 29, pp. 1–8, 2014.

[10] P. a Trodden, W. A. Bukhsh, A. Grothey, and K. I. M. McKinnon, "Optimization-Based Islanding of Power Networks Using Piecewise Linear AC Power Flow," *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1212–1220, 2014.

[11] L. Ding, F. M. Gonzalez-longatt, S. Member, P. Wall, V. Terzija, and S. Member, "Two-Step Spectral Clustering Controlled Islanding Algorithm," *IEEE Trans. POWER Syst*., vol. 28, no. 1, pp. 75–84, 2013.

[12] M. R. Aghamohammadi and A. Shahmohammadi, "Electrical Power and Energy Systems Intentional islanding using a new algorithm based on ant search mechanism," *Int. J. Electr. Power Energy Syst*., vol. 35, no. 1, pp. 138–147, 2012.

[13] W. Liu, "Binary Particle Swarm Optimization Based Defensive Islanding Of Large Scale Power Systems," *Int. J. Comput. Sci. Appl*., vol. 4, no. 3, pp. 69–83, 2007.

[14] W. Liu, L. Liu, and D. A. Cartes, "Slow Coherency and Angle Modulated Particle Swarm Optimization Based Islanding of Large Scale Power Systems," *in Proceedings of International Joint Conference on Neural Networks*, 2007, pp. 4–7.

[15] I. P. C. T. Force, "Initial review of methods for cascading failure analysis in electric power transmission systems," *IEEE POWER Eng. Soc. Gen. Meet., vol. PITTSBURGH*, no. July, pp. 1–8, 2008.

[16] S. Skiena, "Dijkstra's algorithm," *in Implementing Discrete Mathematics: Combinatorics and Graph Theory with Mathematica, Reading, MA: Addison-Wesley*, 1990, pp. 225–227.

[17] N. Saharuddin, I. Zainal Abidin, H. Mohklis, A. Abdullah, and K. Naidu, "A Power System Network Splitting Strategy Based on Contingency Analysis," *Energies*, vol. 11, no. 2, p. 434, 2018.

[18] S. A. S. Mustaffa, I. Musirin, M. M. Othman, and M. H. Mansor, "Chaotic mutation immune evolutionary programming for voltage security with the presence of DGPV," *Indones. J. Electr. Eng. Comput. Sci*., vol. 6, no. 3, pp. 721–729, 2017.