

DYNAMIC FEEDER ROUTING IN SMART GRID DISTRIBUTION

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Abstract

The increment of reactive power is one of the most practical problems in power system. The increment of reactive power in distribution system causing low power factor or PF. The impacts of this problem are higher current in distribution line, higher power generation at the power plant, overloading current in devices, etc. Smart Grid can face the impact that found in the traditional grid. However, this problem of reactive power can be solved with the smart technology. This research proposed the dynamic feeder routing method to improve the maximum PF in the feeder of Smart Grid distribution. A modified version of Dijkstra's algorithm applied to this research in order to decide and select a power route for each load cluster. New parameters included with the factor of impedance (FoI), the angle between active load and apparent power created as major factors for using in the method. The results of the proposed methods effectively reduced the variance of load fluctuation (FoS Variance) of all feeders as much as 51.16%. Moreover, the PF was higher base on reactive power that measured by the totality index in PF correction (PFAI Totality) of all feeders could be reduced as much as 38.42% with no exceeding in power rating of each feeder.

Keywords: Smart grid distribution system, power factor, dijkstra's algorithm, feeder routing

Introduction

Electrical energy is the main crucial importance for supporting the business sectors operation including the appliance in the household. The effect of electrical power availability causes to the demand for electricity to rise steadily. Therefore, the power system is developed by integrated Information and Communications Technology (ICT) to the traditional grid. The integration of ICT supports the generation, transmission,

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distribution and consumption (Bichlien, 2013). Moreover, the Smart Grid feature able to support Distributed Generation (DG) penetration as well (James, 2012).

Improvement the PF, a key part of the Smart Grid distribution from the obligation to supply the power in transmission through consumption that operated by converting the medium voltage to low voltage (Paulo *et al.*, 2011). The aforementioned operation, the distribution loss in Smart Grid was a problem as the traditional grid. The distribution loss arose by the case of the reactive load that generated from the impedance of electric devices coupled with active power (Youjie *et al.*, 2014). The distribution loss, from the case of reactive load (Jame, 2012), occurred by the lagging voltage of electric current in magnetic flux devices (Eaton, 2014) such as electric devices that assembled with the coil part. The distribution loss led to increasing of supply power that affects improvement cost in distribution line and distribution transformer. Moreover, the mentioned problem has been increasing the cost of substation building for accommodating the electricity consumption (Xiang-min *et al.*, 2014). The consequence from distribution loss, the PF was reduced (Zhang *et al.*, 2014) in Smart Grid distribution.

The objective of research aimed to solve the problem in the scope of electric energy services organizations. The solution achieved by routing the power in each feeder both radial and loop distribution system. The objective of routing power was defined to improve the maximum PF under the terms of reactive load occurred (Glover, 2002).

In addition, the demand fluctuation depends on the consumption time. The fluctuation caused by the daily demand or seasonal demand changing on load types (Ozturk *et al.*, 2013), such as the factory production planning as the result of the potential demand led to exceeds supply ability. The process of research solved the problems by analyzing the variables to develop the feeder routing (William, 2002; Xiang-min *et al.*, 2014) in the Smart Grid distribution. The solution was defined by the routing algorithm from the source of supply power, in the constraint of the feeder supply capacity doesn't exceed ability in each feeder (Chiumarulo, 2015).

In related research, the radial distribution feeder was routed by Dijkstra's algorithm that could reduce the fixed cost, energy cost and interruption cost (Priya *et al.*, 2013). Moreover, a few work set the objective to determine the routing factors to measure the feeder routing performance about the power sufficiency and the PF improvement. The significant technique used the graph theory to search the shortest paths with Dijkstra's algorithm because of simple and lower complexity implementation (David *et al.*, 2011; Kocay *et al.*, 2004; Priya *et al.*, 2013). After finding the shortest path, the next step developed the routing algorithms for selected and adjusted the feeder routing with variables and routing factors (Raju *et al.*, 2014).

Materials and Methods

In order to obtain this goal, the researchers determined the steps to carry out in three parts; input section, process section and output section, that show in Figure 1.

The first part was input section that analyzed relevant information on the statistics for process simulation data for experiments in Figure 1(i). The data were the key variables in Figure 1(ii) for mapping to graph theory in Figure 1(iii). The second part was the process section the defined the routing factors in Figure 1(iv) and development routing algorithms in Figure 1(v). The routing factors and routing algorithms conducted to routing experiments in any situation in Figure 1(vi). The last part was output section that involved the results of feeder routing from an experiment and comparison of results in Figure 1(vii).

Analyze and Simulate Data

The information of electricity consumption is daily load, both terms of active load and reactive load (PEA, 2015). The process of preparing the data shown in Figure 2.

In the analysis process, load pattern in each load type in Figure 2(i) are combined to the group of electricity demand that call load types that consist of 5 categories; department stores, factory, hotel, household and office. After the process defines the load curve in a

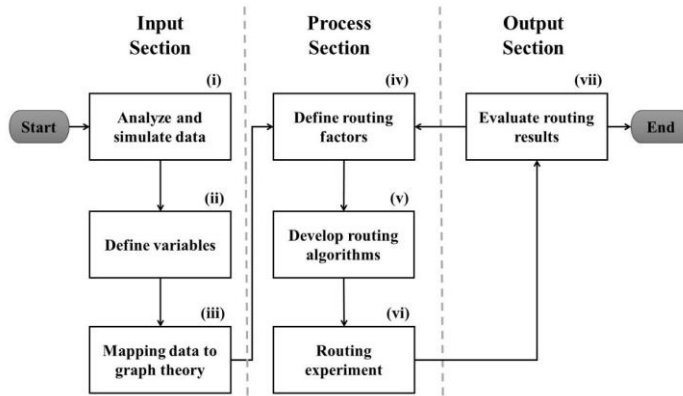


Figure 1. The section of the experiment

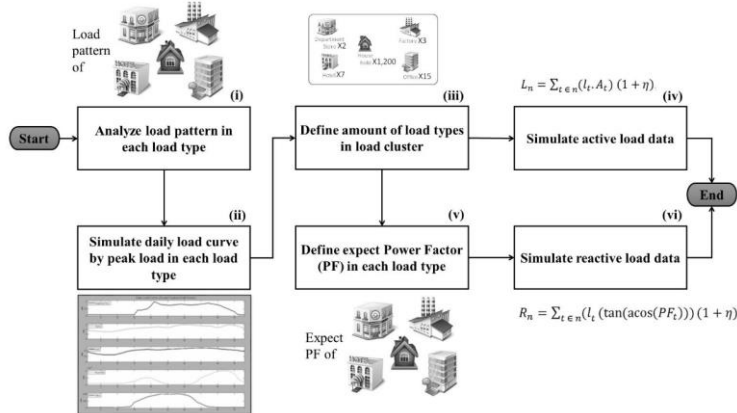


Figure 2. The process of analysis and simulation data

day. The daily load curve is calculated from load pattern with peak load in Figure 2(ii) (CEATI, 2010) and defines a number of load types in load clusters in Figure 2(iii), that groups load cluster from various load types.

The load clusters are determined by simulation data that could divide into 2 parts consisting of the active load and reactive load. The first part is the step of simulation active load data in Figure 2(iv) from the summation of the electricity consumption in each load type in half-hourly intervals of the day. After that, the result is multiplied by consumption in peak time and add the random variable with probability distribution function. The variables are composed of; L_t is active load (watt) and A_t

is the number of consumption (unit) in load type t . The active load is defined as

$$L_n = \sum_{t \in n} (l_t \cdot A_t) (1 + \eta), \quad (1)$$

where L_n is active load (watt) in load cluster n that computed from the summation of $l_t \cdot A_t$ that t is the member of load cluster n and added with random variable with probability distribution function, in the term of $1 + \eta$.

The second part is the reactive load (volt-ampere reactive) simulation by replicating data from the sum of the electricity consumption of each load type to calculation with expected PF in each load type in Figure 2(v). The load

types comprise department stores, factory, hotel, household and office by expected PF are respectively by 0.85, 0.80, 0.85, 0.90 and 0.85 (Norman Disney & Young, 2002). After that, the next phase simulates reactive load data in Figure 2(vi). The random variable with probability distribution function by PF_t is expect PF in load type t and the reactive load define as

$$R_n = \sum_{t \in n} (l_t (\tan(\cos(PF_t))) (1 + \eta)), \quad (2)$$

where R_n is reactive load (volt-ampere reactive) in load cluster n that compute from the summation of l_t multiply by reactive in each load type t , in term of $\tan(\cos(PF_t))$, and add the random variable with probability distribution function.

The simulation data generated the matrix format of active load and reactive load. The matrix contained 48 rows by half-hourly periods of a day and the number of columns followed by load clusters. By the results, the simulation data of load clusters are grouped that each group comprising load types in Table 1.

The load clusters were set the load types amount and classified as 3 classes. The first class comprised the high consumption as the factory that conducted by the load clusters 1-4. The second class comprised the medium consumption that scheduled in working time as a department store, hotel, and office that the group of load clusters 10-14. The third class

comprised the low consumption class that tentatively scheduled of use as the group of the household in load clusters 5-9. Notwithstanding in three class, load types were combined with the real characteristics of consumption. After simulation the data, daily load curve could find the power consumption activity varied and still highest power consumption at the peak time. Finally, in the terms of feeder supply from substations, the capable of supply power were equal 15 MW in each feeder.

Define Variables

The variables are determined by calculated the important variables. Let M is set of supply, N is the set of load cluster and f is number feeder. The supply variables are consist of;

$$S_{all} = \sum_{m \in M} S_m, \quad (3)$$

$$S_f = \sum_{m \in f} S_m, \quad (4)$$

where S_{all} is all supply (watt) that computed by the summation of S_m , supply (watt) number m which member of supply set M . The S_f is feeder supply (watt) that computed by summation of S_m in feeder f .

The active load and reactive load variables are consists of;

$$L_{all} = \sum_{n \in N} L_n, \quad (5)$$

$$L_f = \sum_{n \in f} L_n, \quad (6)$$

Table 1. The number of load types in load cluster

Load Cluster No. (L_n)	Load Type Units (L_t)				
	Department Store	Factory	Hotel	Household	Office
1	1	5	1	100	1
2	1	6	0	200	2
3	0	4	0	150	2
4	1	3	2	100	3
5	1	0	1	900	4
6	0	0	1	1,000	2
7	1	0	3	800	2
8	2	0	2	1,000	5
9	1	0	1	1,100	1
10	4	0	6	200	2
11	2	0	5	300	7
12	3	0	4	100	8
13	3	0	4	200	5
14	1	2	1	700	15

$$R_{all} = \sum_{n \in N} R_n, \quad (7)$$

$$R_f = \sum_{n \in f} R_n, \quad (8)$$

where L_{all} is all active load (watt) and R_{all} is all reactive load (volt-ampere reactive). Let L_n is active load (watt) and R_n is reactive load in load cluster number n . Both L_{all} and R_{all} are computed by summation of L_n and R_n in the set of N . In the scope of the feeder, L_f is feeder active load (watt) and R_f is feeder reactive load (volt-ampere reactive). Also, L_f and R_f are computed by summation of L_n and R_n is the member of f .

In the same notion, the capacity reserve variables are capable of supplying and computing by supply subtraction with the active load. The capacity reserve variables are consist of

$$C_{all} = \sum_{m \in M} S_m - \sum_{n \in N} L_n, \quad (9)$$

$$C_f = \sum_{m \in f} S_m - \sum_{n \in f} L_n, \quad (10)$$

where C_{all} is all capacity reserve (watt) and C_f is feeder capacity reserve(watt).

cluster 5-9 and the third feeder was connected to load cluster 10-14 as shown in Figure 3.

The one-line diagram transformed base on graph theory. The nodes assigned by the source of feeder and load clusters were connecting supply power with edges. Graph topology was directed graph in which direction from efficacy the power flow by edges and configuration from the data obtained in simulation. Each simulation data group consisting of active load and reactive load that was calculated the weights for use in experiments to the next step as shown in Figure 4.

From the graph topology, the nodes were assigned by the rectangle symbol presented the Source of Feeder Node (SN) and a symbol of the circle presented Load Cluster Node (LN). In the case of the edges were bi-directional that meant the connection between nodes had an alternative to change the flow as well. Graph topology implemented with MATLAB by import active load and reactive load inclusive feeder topology of each connected load clusters to the feeder (PEA, 2015), which shown in Figure 5.

Mapping Data to Graph Theory

The experiment chose the distribution loop system topology. The features of the load clusters abled to connecting in any feeder. The path topology an association was the first feeder that connected with load cluster 1-4, the second feeder was connected with the load

Routing Factors

The routing factors defined under the conditions and circumstances (Vineetha *et al.*, 2014), the active load and reactive are designated consists of; Factor of Sufficiency (FoS), Factor of Prioritize (FoP), Factor of Impedance (FoI),

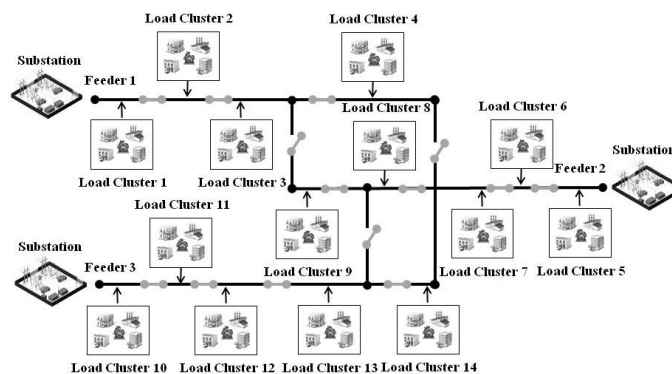


Figure 3. One-line diagram of the experiment

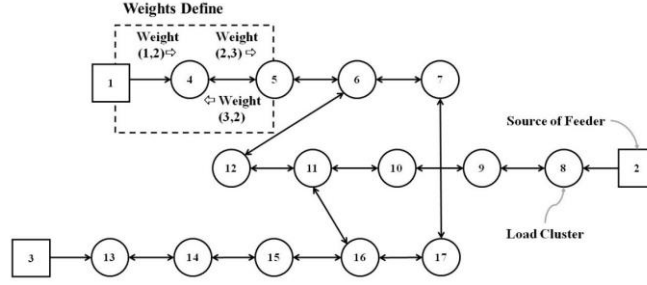


Figure 4. Graph topology

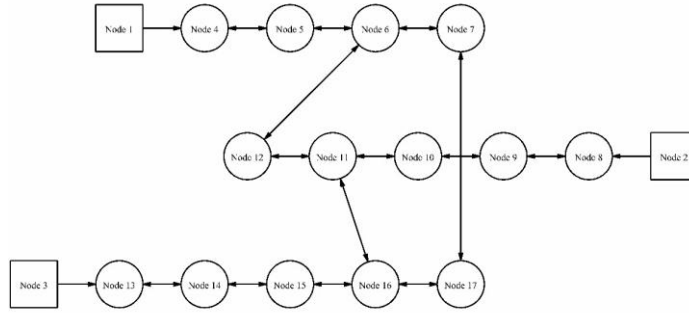


Figure 5. Implement graph topology with MATLAB

Power Factor (PF) and Power Factor Adjustment Index (PFAI).

i) **The Factor of Sufficiency (FoS)** as a factor that determines the adequacy proportion that calculated from active load divided by feeder supply. The objective of the FoS is applied to measure the adequacy of the supply power of each feeder. The FoS is defined by

$$\beta_f = \frac{\sum_{n \in f} L_n}{\sum_{m \in f} S_m}, \quad (11)$$

where β_f is FoS in feeder f that real number between 0 and ∞ . The case of the FoS less than or equal 1 shows the active load is under feeder supply ability, but if the FoS is over than 1 means active load exceeds feeder supply. In the truth conditions, FoS is over than 1 the power is continues supplied under the risk of damage to the electrical devices.

ii) **Factor of Prioritize (FoP)** is a factor for determining load cluster prioritize. The FoP calculated by a ratio between the active load in load cluster and all active load. The FoP is the real number between 0 and 1, the more value will be the high priority. The FoP is defined as

$$\gamma_n = \frac{L_n}{\sum_{n \in N} L_n}, \quad (12)$$

where γ_n is FoP of load cluster n . The objective of the FoP aimed to the decision to opt for feeder routing with the active load prioritize.

iii) **The Factor of Impedance (FoI)** is the factor of load cluster that the angle (Radian) between active load and appearance power on the impedance triangle (William, 1982). The FoI value is real number between 0 and 1 that define by

$$\theta_n = \tan^{-1} \frac{R_n}{L_n}, \quad (13)$$

where θ_n is FoI in load cluster n . The FoI will varies according to the reactive load. The case of FoI lower incurs the PF is higher.

iv) Power Factor (PF) is the main factor that measures the performance of the feeder efficiency. The PF is computed by

$$PF_f = \cos \left(\tan^{-1} \frac{\sum_{n \in f} R_n}{\sum_{n \in f} L_n} \right), \quad (14)$$

where PF_f is the PF of feeder f , that is the real number have ranged between 0 and 1. Consequently, the highly PF value effect to the feeder efficacy (Bhatia, 2012).

v) Power Factor Adjustment Index (PFAI) is a factor reflect of PF that calculate by subtraction 1 with PF and multiply by the amount of reactive load in the feeder. The PFAI value is real number, which ranges between 0 and 1 that calculate in two conditions as

$$\varphi_n = R_n \left(1 - \cos \left(\tan^{-1} \frac{\sum_{n \in f} R_n}{\sum_{n \in f} L_n} \right) \right), \quad (15)$$

$$\psi_f = \sum_{n \in f} \varphi_n, \quad (16)$$

where φ_n is PFAI of load cluster n and α_f is PFAI of feeder f . The result of the low PFAI has an impact on the low PF correction cost base on the amount of reactive load. If PFAI is lower the base value of previous routing, it effects to PF is higher.

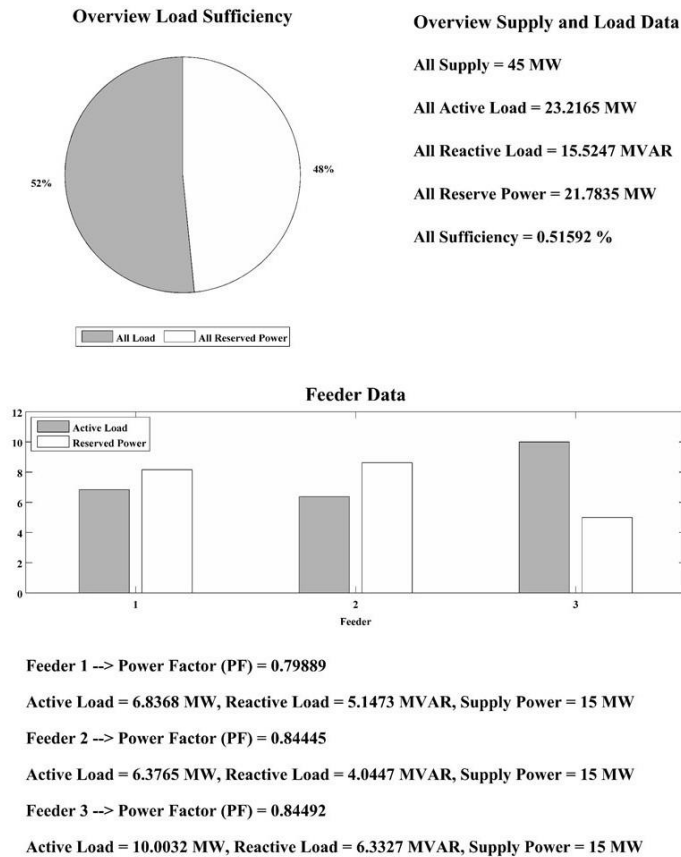


Figure 6. Overview original path variable

After defined the routing factors, in next step prescribed the original routing path. The measure in the unit of the active load is MW and the reactive load unit is MVAR. The sources of the feeder are SNs, which replaced with a node that square symbol and set in the order of nodes 1-3. The circle symbols are LNs that the sequence of nodes 4-7, 8-12 and 13-17 respectively, that shown in Figure 4.

The variables and routing factors conclude from the preliminary experiment of routing that compost of; all supplies (S_{all}), all active load (L_{all}), all reactive load (R_{all}), all reserve power ($S_{all} - L_{all}$) and the all sufficiency (L_{all}/S_{all}). In addition, the variables of the feeder that comprise feeder PF (PF_f), feeder active load (L_f), feeder reactive load (R_f), feeder supply power (S_f) and feeder reserve power ($S_f - L_f$) as shown in Figure 6. The variables and routing factors are take place and change when the amount of power consumption alter each half-hourly and the topology each feeder remodel.

Develop Routing Algorithms

The algorithm constraint provided with two criteria's. The first criteria were the supply power brought to the limit of the supply ability (C_f). The second criteria were the purpose of path choosing by minimum PFAI in the situation of reactive load occurred. The algorithm of feeder routing was experimented in the scenarios below.

Scenario 1: In the first scenario, the algorithm determined to search the shortest path from each LNs to all SNs by using the weight of the edge, that calculated by FoI, and selected the maximum PF path to define the first path. The next step, the algorithm chose residual LNs to perform the next iteration until all LNs were connected. Then, the LNs were grouped by checked the conjoint SNs After that cut overlapping LNs in maximum FoS path.

The result of scenario 1: the routing method was determined by one source to one-sink and incorporated overlapping routes later

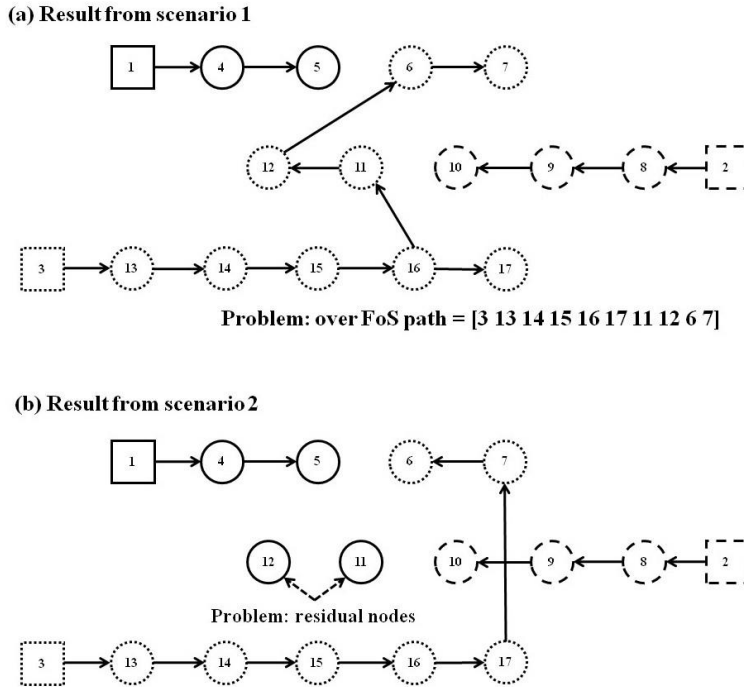


Figure 7. Routing result from experiment scenario 1 and 2

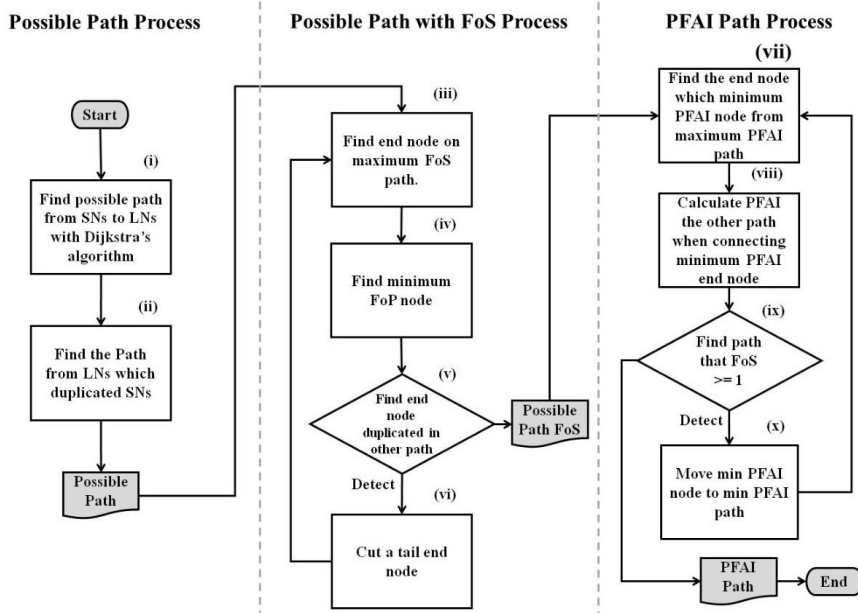


Figure 8. Flowchart of routing algorithms in scenario 3

in the term of maximum PF. Therefore, the results of feeder routing in Figure 7(a) brought FoS to over sufficiency (FoS over than 1). In the practice of result mean, the feeder has electricity consumption exceeds the supply of feeder.

Scenario 2: the second scenario, the algorithm routed in the scope of the FoS. The algorithm searched the shortest path by Dijkstra's algorithm from SNs to all LNs (reverse from scenario 1). The weights of edges were defined with FoI and selected the maximum PF path in the constraint of FoS no more than feeder supply (FoS less than or equal 1). The result kept as the first path. And then the new path was chosen from residual LNs. After that, the algorithm continued to loop from the first step until LNs didn't leave. In the last step, grouped the LNs that connected in the conjoin of SNs and cut the overlapping minimum FoS LNs from maximum FoS path.

The result of scenario 2: the algorithm had determined by one source to one- sink when the junction decided the route to find the problem by minimum PF. The cause of problem occurred from the remaining LNs, that shown in Figure 7(b). In the practice of the

problem meant to the consumers didn't get the power supply.

Scenario 3: in this scenario, the algorithm has solved the problem from the first and second scenarios, in the case of the routing from one source to one sink. Moreover, the feeder routing constraint contained with the feeder sufficiency by FoS less than or equal 1. The process of algorithm separated into three stages as shown in Figure 8 that consist of; Possible Path Process, Possible Path with FoS Process and PFAI Path Process.

The Possible Path Process was the routed for the feasible path by routing factors. Initiation step, the process searched the shortest path with Dijkstra's algorithm from all SNs to all LNs with the weights of edges by FoI in Figure 8(i). Next step, the process searched the path from LNs that duplicated SNs in Figure 8(ii). The obtained result was defined as Possible Path that shown in Figure 9.

The next process was Possible Path with FoS that used the Possible Path to find the end nodes of LNs from maximum FoS path in Figure 8(iii). Therefrom, the process searched the minimum FoP in Figure 8(iv) and cut-a-tail if it connected to another path in Figure 8(v)

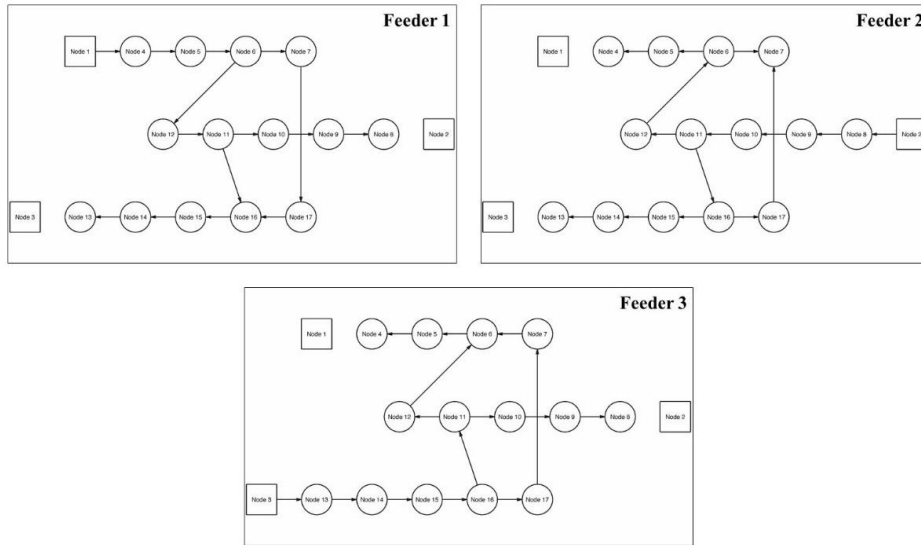


Figure 9. Possible path

and vi). Finally, the algorithm looped until each LN connected to any SNs. The result in this process as shown in Figure 10 which the active power in all feeder balanced (Glover, 2002).

The PFAI Paths Process was a process of calculating the minimum PFAI end node from the maximum PFAI path in Figure 8(vii). Thereafter, the algorithm calculated PFAI of the other path that connecting maximum PFAI end node from the previous process in Figure 8(viii). If the destination path decreased PFAI and provided the FoS less than or equal 1 in Figure 8(ix), the algorithm will migrate the minimum PFAI to lowest PFAI path in Figure 8(x). Then the loop operation from the first step iterated until couldn't reduce PFAI in any path. The results obtained from the routing that all LNs connected to feeder supply as shown in Figure 11. In proposed condition, the process controlled the FoS less than or equal 1 and reduced the PFAI.

In the final result, the algorithm of feeder routing had improved the PFAI that have been calling the adjusted path as in Figure 12. The critical routing factors of the adjusted path will be evaluated to precisely before performing change the physical accordance feeder routing result.

Define Routing Decision

In the routing decision process specified to change the physical feeder topology. The decision took place the new routing path under the criteria's below.

i) First Decision Criteria, the path was changed by compared FoS variance and PFAI totality from the adjusted path. If the result of the FoS variance and PFAI totality in the adjusted path lower than the base path, the process will be altered the path as shown in Figure 13.

ii) Second Decision Criteria, the process modified the path that maximum FoS is greater than 1. That in the real situation, the active load in any feeder was over sufficiency. If the adjusted path could reduce FoS down, the path will be changed following the result from routing algorithm.

In the case of the transition path in first decision criteria, it wasn't checked the terms of the second criteria. When the decision condition had changed the path, the routing factors were kept as the base path for use in the next session. On the other hand, when the state feeder routing had processed without modification, the base path's routing factors were kept to determine the path in next period.

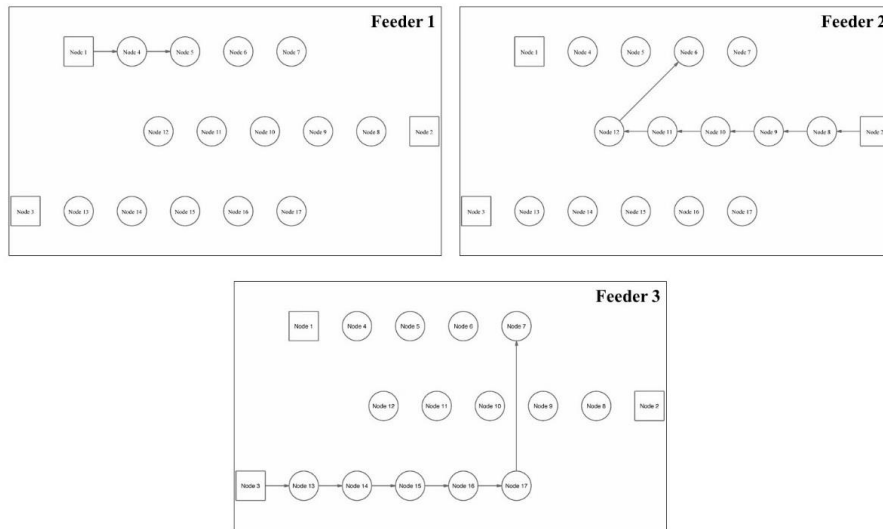


Figure 10. Possible path with FoS

Routing Experiment

In the experiment with the half-hourly periods, the random variables of active load and reactive load were set as 0.1 and 0.05, respectively. The routing results abled to adjust routing path according to the data variation in each period. The algorithm of feeders routing modified base path to adjusted path 15 times in the periods; 2, 3, 10, 13, 15, 27, 36, 37, 38, 40, 42, 44, 46, 47 and 48.

Evaluate Routing Results

The evaluation process compared the output of the automated feeder routing with different scenarios. Analytically, the relationships of routing factors in multi-condition that affects in each aspect arose following.

In terms of the reactive load in Figure 14 substantiated accordance the amount of active load. In addition, the total of the active load in each period was higher than feeder supply, the algorithm effected to minimize all active load. The algorithm was moved the load cluster to a feeder for lower FoS and reduced the characteristic of FoS variance. However, in the

peak time, between the period 38 and 44, all active load was over the all supply power. The algorithm could reduce the FoS variance and protect the risk conditions of supply beyond the feeder capability.

In terms of modification, the paths were changed 15 times as shown in Figure 15. The changing in the terms of the FoS variance and PFAI totality reduction was 6 times, at the period 2, 3, 10, 27, 46 and 48. In the field of modifying the path from FoS maximum over than 1, the paths were changed 9 times, at the period 13, 15, 36, 37, 38, 40, 42, 44 and 47. The reduction of FoS variance contributed to balance load in the feeder that meant to reduce the risk of the electrical overload.

In the reduction of PFAI totality could present the maximum PF. The algorithm could modify the path to reduce FoS maximum. In the real situation, the risk of damage was reduced from the distribution devices.

The comparison of FoS variance in Figure 16 presented the FoS variance declined from 0.0579 to 0.0283 at the path changed periods. In the mentioned period, the mean PFAI totality declined from 3.6986 to 2.2773. In addition, the feeder routing algorithm had improved the power supply by continuously reduced the PFAI totality at all period.

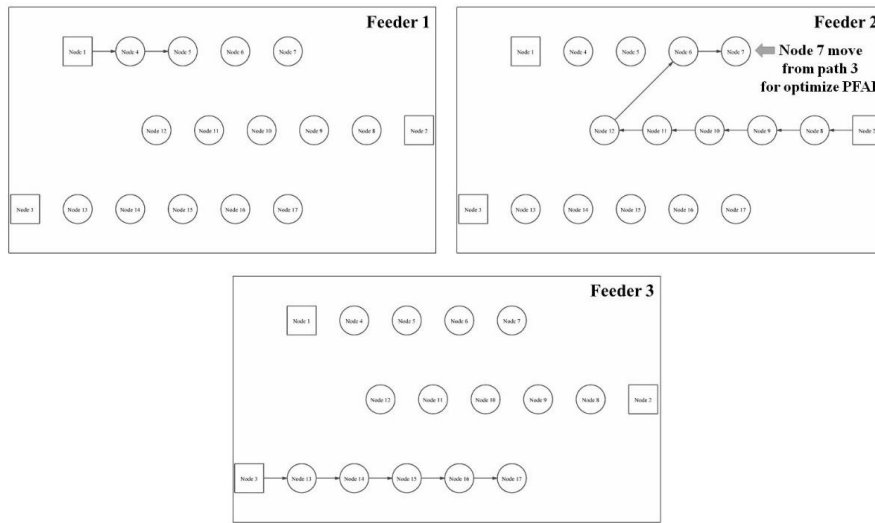


Figure 11. PFAI path

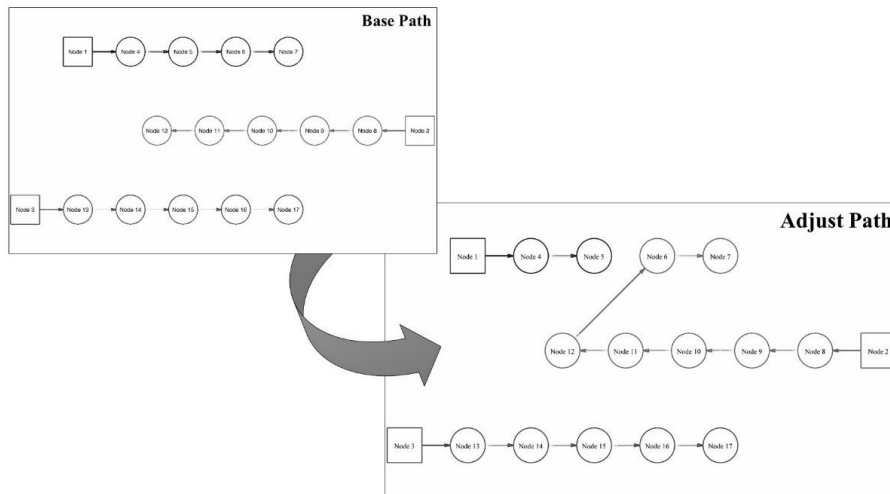


Figure 12. Comparison of feeder routing result

Results and Discussion

All of the above experiment, the algorithm had the capable to route the path automatically. The decision criterion had changed the path by comparing the routing performance both of FoS variance and PFAI totality reduction.

In the reality experiment, the result was compared to 30 days. It was found the adjusted path had better performance than original path (the path wasn't routing). In the mean values of a day, the feeder routing could reduce FoS

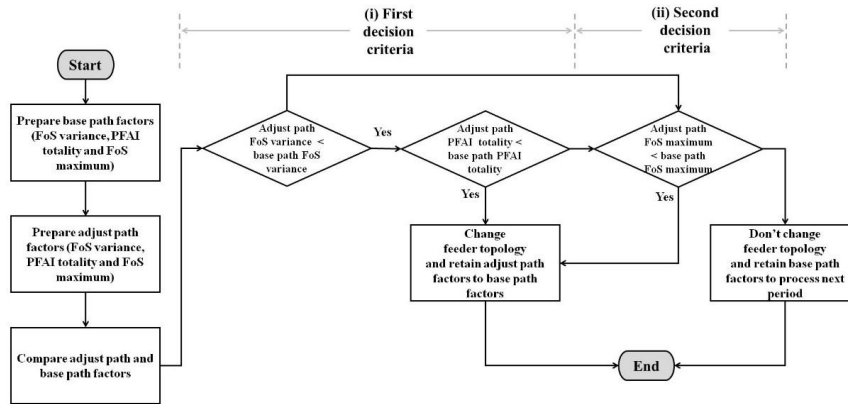


Figure 13. Routing decision criteria's

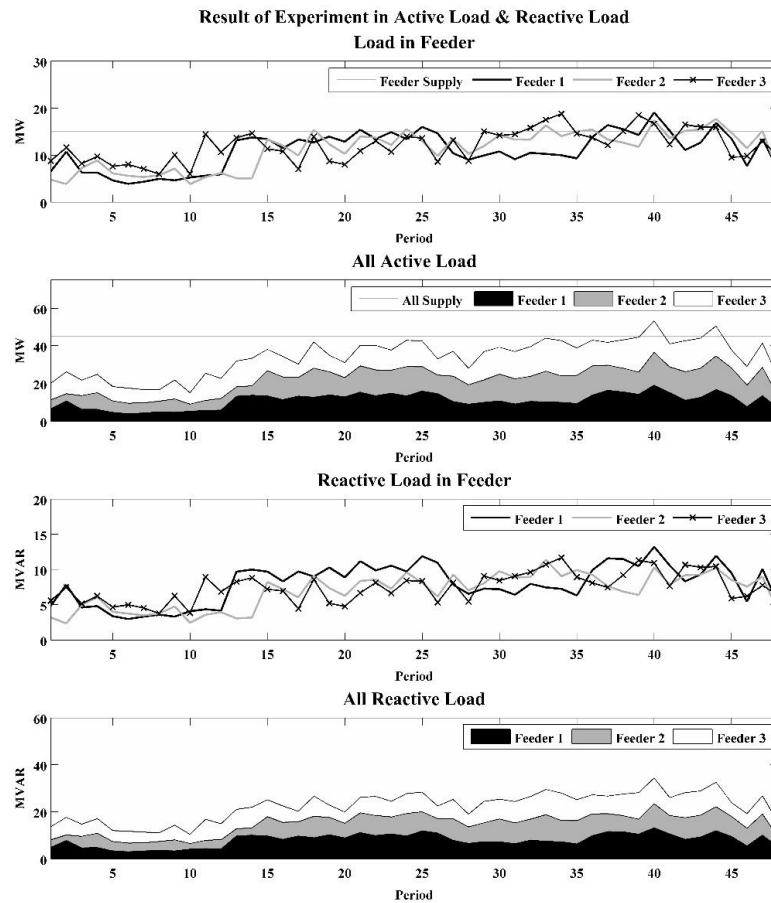


Figure 14. Active load and reactive load in the experiment

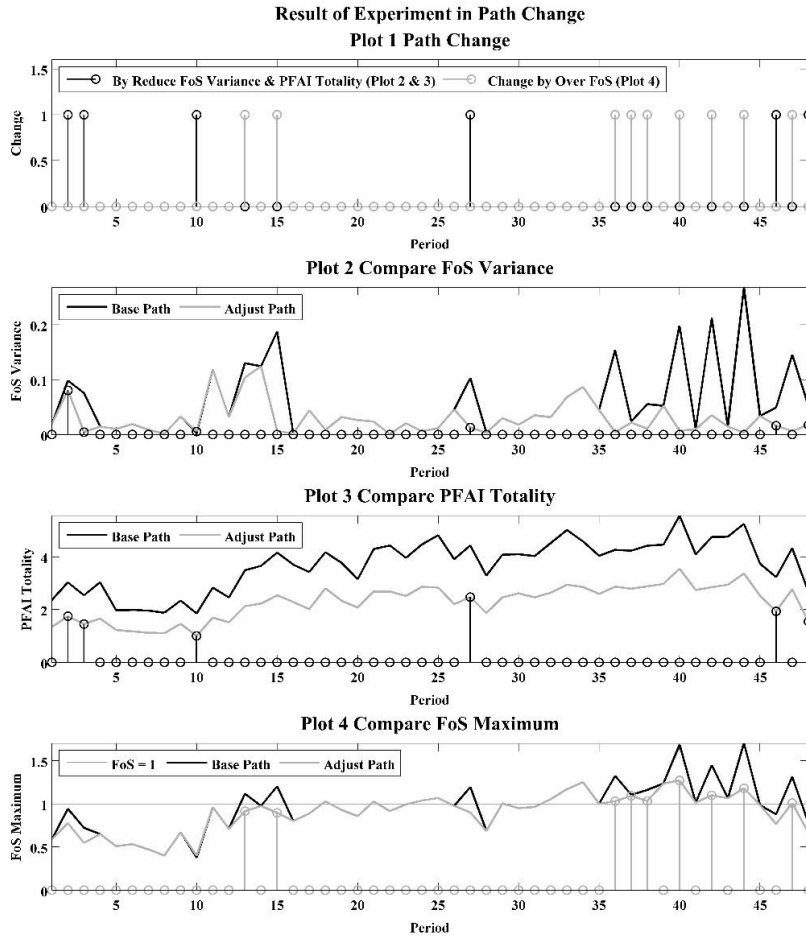


Figure 15. Routing experiment of path change

variance 0.0296 representing 51.16% and PFAI totality down 1.4213 representing 38.42%. Furthermore, the routing algorithm eliminated when the state of power had exceeded by balance load of each feeder as well.

The efficacy of proposed algorithm increased routing efficient that processed by Dijkstra's algorithm (Kocay *et al.*, 2004). In the routing result, the method optimized both FoS variance and PFAI totality in the terms of

the electrical consumption by given the node priority on the demand fluctuation.

Conclusions

The state of art in this research, the modified version of Dijkstra's algorithm applied to decide and select the direction power route. The contribution of this work is the feeder routing development in the conditions of

Distributed Generation (DG) penetration. The important features for research focus the conditions of feeder supply that support by the capabilities of DG. Also, there is a need to expand the automatically routing within the situation of the false incidents on the supply power sufficiency to support electrical demand.

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