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Optimal Placement and Sizing of Distributed Generation in Distribution System using Analytical Method

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Abstract: ***The reliability of distribution network can be improved with the penetration of small scale distributed generation (DG) unit to the distribution grid. Nevertheless, the location and sizing of the DG in the distribution network have always become a topic of debate. This problem arises as different capacity of DG at various location can affect the performance of the entire system. The main objective of this study is to recommend a suitable size of DG to be placed at the most appropriate location for better voltage profile and minimum power loss. Therefore, this paper presents an analytical approach with a fixed DG step size of 500 kW up to 4500 kW DG to analyses the effect of a single P-type DG in IEEE 33 bus system with consideration of system power loss and voltage profile. Four scenarios have been selected for discussions where Scenario 1: 3500 kW DG placed at node 3; Scenario 2: 2500 kW DG placed at node 6; Scenario 3: 1000 kW DG placed at node 18 and Scenario 4: 3000 kW DG placed at node 7. Results show that all the four scenarios are able to reduce the power loss and improve the voltage profile however Scenario 4 has better performance where it complies with minimum voltage requirement and minimizing the system power loss.***

Keywords: ***Distribution Generation, Distribution System and Power losses***

I. INTRODUCTION

It can't be denied that the electricity is the basic need in both urban and rural area in view of exponential development of economic and social. The electricity in the urban area will be commonly supplied by the utility companies, equipped with substation and transmission line infrastructure.

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The power utilities are currently facing great challenges as the consumer demand is growing exponentially in addition to face different economical, technical and environmental limitation considering expansion of existing power plant and transmission line. Instead of upgrading the transmission facilities, study has been conducted to utilize modular power generation dispersed throughout the utility grid to reduce the transmission loading hence achieving power losses reduction and power quality improvement [1].

The rural area on the other hand is usually having small grid which is not attached to the utilities and very dependent to diesel generator as the source of electricity. The major concern for the rural electricity is on power quality and reliability issue where the supply is frequently being interrupted. The power interruption is even worse if the grid system is solely depending on a single unit generator. Research is currently on going to study the technical and financial viability for a more sustainable rural electrification [2].

Distributed Generation (DG) can be a feasible solution where it is defined as small-scale generating units installed at distribution system. With the advantage of DG generation near to load center, transmitting bulk power via transmission line can be minimized therefore upgrading of existing transmission facility is no longer required. As for rural electrification, it can prevent the small grid from solely dependent to a single source hence minimize the breakdown of the grid.

II. REVIEW OF DG TECHNOLOGIES AND PLACEMENT

DG can be categorized into traditional technology based generating unit and renewable energy based generating unit. While traditional technology based DG is utilizing conventional fossil fuel as source of generation, the industry is moving towards prevailing renewable energy based DG where the clean and sustainable resources such as solar, wind, hydro, biomass etc. are utilized. There are drawbacks of utilizing renewable energy based DG. Solar PV for instance, the output generation is the function of solar irradiation and temperature which vary and lead to the output power is not constant at time [3]. DG can be generally categorized into three types: Type I named as P-type DG, injecting active power only to the grid; Type II named as Q-type DG, injecting only reactive power to the grid; Type III named as PQ-type DG, injecting both active and reactive power to the grid [1, 3].

The major challenges on the placement of DG in the distribution network are the location and DG sizing selection. Optimal placement of DG is able to improve the system performance specifically on system loss reduction, voltage profile and voltage stability improvement as well as enhancement of system loadability and reliability [4-7]. Since DG is usually relatively small, research has been conducted to consider multiple DG to be placed in the network. However, if the DG(s) is not installed optimally, it may lead to stability problems, protection problems and islanding difficulties [8].

Therefore, DG placement need to be carefully studied to ensure the system achieving overall performance and efficiency improvement at the same time meeting the consumer demand.

Numerous studies are conducted for optimal allocation of DG. The process of finding a near global solution of DG allocation is difficult as it has non-linear and highly constrained complex conditions. The optimization is generally be categorized into two major approaches: Classic Algorithm and Artificial Intelligent Algorithm.

Classical approaches are using derivative from mathematical equation hence perform basic search method for further achievement. It is relatively simple but large computing time is required. Some example of classical techniques is analytical method, linear programming, mixed integer linear programming, optimal power flow, index method, sensitivity method etc. Analytical method illustrates the system by mathematical model hence obtaining the solution by performing direct numerical computation. The solution via linear programming can be obtained based on the linearization of objective function along with the constraints. Mixed integer linear programming involves both continuous and discrete constraints for the computation of objection function. Optimal power flow is a non-linear programming technique manipulating the control variables to meet the desired optimal solution. The index method can be conducted via evaluating and comparing the deviation of any parameters from its actual value, while the sensitivity method achieves optimal solution by applying the variation of variables into the target variables [1, 6-9].

Artificial Intelligent techniques ride on the soft computing expertise developing evolutionary optimization algorithm to achieve optimal allocation of DG in the distribution system. Artificial Intelligent algorithm can handle more complex problem particularly managing multiple objective functions. However, the algorithm is relatively hard to be developed and it may provide premature solution. Among the notable algorithm are particle swarm optimization (PSO), genetic algorithm (GA), and artificial bee colony (ABC), and artificial neural network (ANN), fuzzy logic (FZ) and so on. PSO is utilizing new position updating strategy to generate a set of solutions moving toward the best solution [3]. Inspiring by natural evolution, GA applies selection, crossover, mutation and inheritance to compute repetitive calculation of the objective function. Based on honey bee swarm intelligent behavior, ABC registers three control parameter, which are colony size, iteration and variable limits to adjust the position towards the global solution. ANN is a brain-inspired system, consisting layers that transform the inputs into useful output. FZ aggregates data and generate a number of partial truths for further higher truths development hence approaching desired solution [6-10].

An analysis on optimal placement and sizing of DG using analytical method is presented in this paper. A 500 kW step sizing of P-type DG is placed at specific nodal point or bus in IEEE 33 bus system and analysis is made to the system power loss and voltage profile. In this study, four scenarios are selected to be compared with the conventional IEEE 33 bus system, namely Scenario 1: 3500 kW DG placed at node 3; Scenario 2: 2500 kW DG placed at node 6; Scenario 3: 1000 kW DG placed at node 18 and Scenario 4: 3000 kW DG placed at node 7. Results show that all four scenarios are able to improve the voltage profile and reduce the system power loss.

III. DG PLACEMENT AND SIZING

Bus Model Concept for Distributed System Analysis

In this study, a radial distribution system has been selected for the performance analysis of the distribution system before and after the implementation of DG. In general, the radial system is developed from the basic two bus model. Fig. 1 shows the two bus model of radial distribution system.

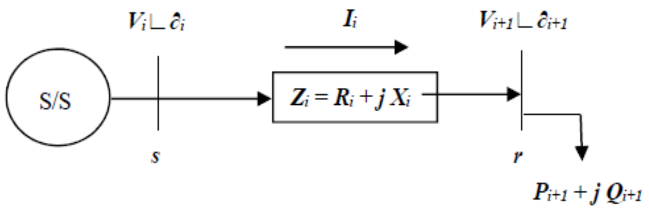

Fig. 1 Two bus model

The sending end voltage, V_i, receiving end voltage, V_{i+1}, branch current, I_i and branch impedance, Z_i can be illustrated in (1) to (4) respectively.

$$V_i = |V_i| \llcorner \partial_i \quad (1)$$

$$V_{i+1} = |V_{i+1}| \llcorner \partial_{i+1} \quad (2)$$

$$I_i = |I_i| \llcorner \Theta_i \quad (3)$$

$$Z_i = |Z_i| \llcorner \Phi_i \quad (4)$$

From Fig. 1, the relationship of sending end voltage, V_i, receiving end voltage, V_{i+1}, branch current, I_i and branch impedance, Z_i can be presented in (5).

$$V_{i+1} = V_i - I_i Z_i \quad (5)$$

It shows that the receiving end voltage will suffer voltage drop where the voltage drop is affected by the branch current and the branch impedance. The real power loss, P_{loss} and reactive power loss, Q_{loss} can be illustrated in (6) and (7) respectively [13].

$$P_{loss}(i, i+1) = \frac{{P_{i+1}}^2 + {Q_{i+1}}^2}{|V_{i+1}|^2} * R_i \quad (6)$$

$$Q_{loss}(i, i+1) = \frac{{P_{i+1}}^2 + {Q_{i+1}}^2}{|V_{i+1}|^2} * X_i \quad (7)$$

DG Integration into the Distributed System

DG can be integrated into the distribution system by interconnecting the DG system to a specific bus. The DG integration into the distributed system can be presented in Fig. 2.

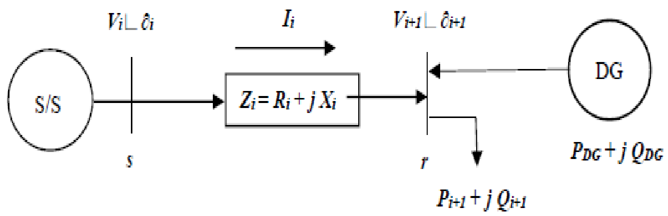

Fig. 2 Integration of DG into two bus model

With the integration of DG, the net injected real power, P_{inj} and the net injected reactive power, Q_{inj} at bus $i + 1$ can be shown in (8) and (9). The real power loss, $P^{DG}{}_{loss}$ and reactive power loss, $Q^{DG}{}_{loss}$ at bus $i + 1$ can be extended to (10) and (11) correspondingly.

$$P_{inj} = P_{i+1} - P_{DG} \quad (8)$$

$$Q_{inj} = Q_{i+1} - Q_{DG} \quad (9)$$

$$P^{DG}{}_{loss}(i, i+1) = \frac{(P_{i+1} - P_{DG})^2 + (Q_{i+1} - Q_{DG})^2}{|V_{i+1}|^2} * R_i \quad (10)$$

$$Q^{DG}{}_{loss}(i, i+1) = \frac{(P_{i+1} - P_{DG})^2 + (Q_{i+1} - Q_{DG})^2}{|V_{i+1}|^2} * X_i \quad (11)$$

Where, P_{DG} is real power supplied by DG, and Q_{DG} is the reactive power supplied by DG.

Analytical Method Application

The load flow of the radial distribution system with and without DG is performed using MATLAB simulation. Reference is made to the software package developed by RM Saloman Danaraj, Shankarappa F. Kodad and Tulsi Tam Das specifically for IEEE 12 bus, IEEE 28 bus and IEEE 69 bus load flow simulation [12]. Nevertheless, IEEE 33 bus system is selected for this study hence the input data shall be amended and made to suit the characteristic of the IEEE 33 bus system. The data of IEEE 33 bus system in [13] and [14] with total system active and reactive power of 3,715 kW and 2,300 kVar is referred and the respective single line diagram is shown in Fig. 3. An analytical method is performed by applying DG into the bus system. The content of this paper however is limited to the following constraints:

Quantity of DG

The study is made with consideration of a single DG only. The effect of single DG to the entire distribution system is studied.

Type of DG

Although there are three types of DG categories as discussed in the earlier section, only type I is considered. P-type DG will be integrated into the distribution system for system performance evaluation.

Step size of DG

The DG is fixed at step size of 500 kW and restricted to the maximum of 4,500 kW. DG which is more than 4,500 kW is generally not to be taken into consideration as the demand of the IEEE 33 bus system is 4,369.35 kVA only.

Steady state voltage requirement

Reference is made to Distribution Code for Peninsular Malaysia, Sabah & F.T. Labuan 2017 by Energy Commission, Malaysia, which this document is commonly applied for the Electricity Supply Industry in Malaysia. The Distribution Code mentions that under normal conditions, when all circuit elements are in service, the voltage at all points in the Distributor's Distribution System including the points before the Users Connection Point shall be planned to be maintained within ±5% of nominal voltage for medium voltage system. Therefore, the steady sate voltage requirement under this study is defined to be within ±5%.

Minimization of power loss

Prevailing fulfilling steady state voltage requirement, an analytical analysis is made to compare a few scenarios where DG integrated system with the least power loss to be identified. The location and sizing of DG for the system with minimum power loss shall be the recommended solution.

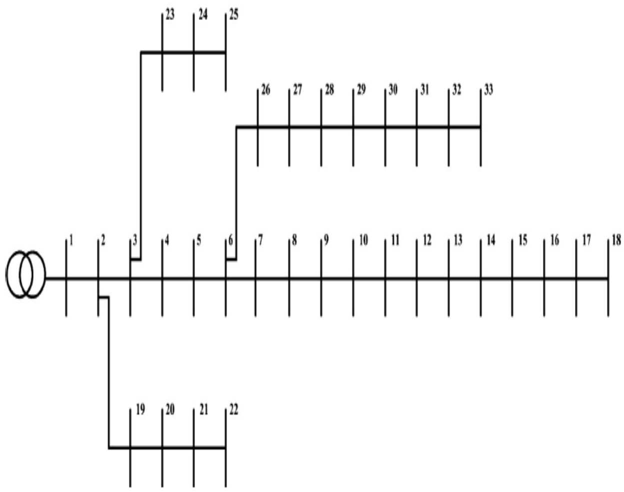

Fig. 3 Single line diagram of IEEE 33 bus system

IV. RESULTS

The branch power loss and voltage profile of IEEE 33 bus system without DG integration is presented in Fig. 4. The voltage profile shows that there are significant amount of voltage loss in the entire system due to system impedances. The voltage drop at node 18 is extremely high as node 18 is the end node having substantial impedances aggregated from node 1 to node 18. The total power loss of the system is 210.98 kW.

A fixed step size of 500 kW P-type DG is applied into a specific bus or nodal point of IEEE 33 bus system up to a maximum of 4,500 kW. The system power loss data in respective DG application is recorded in Table 1 where a more detail analysis will be discussed in the discussion section later.

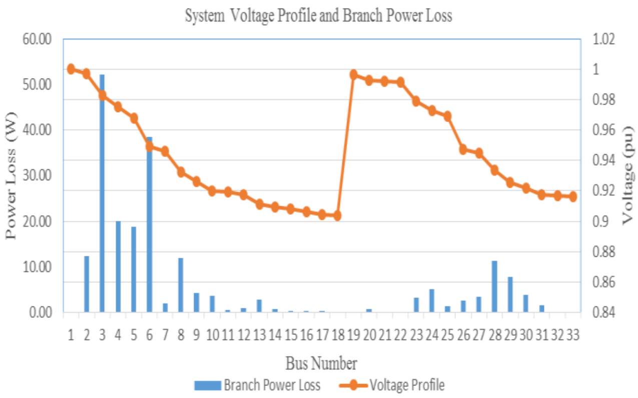

Fig. 4 Branch power loss and voltage profile of IEEE 33 bus system

Table. 1 Power loss for system with fixed step size of DG integrated at a specific bus

Specific Nodal Point at IEEE 33 bus system	Capacity of P-type DG (kW)								
	500	1,000	1,500	2,000	2,500	3,000	3,500	4,000	4,500
2	208.72	206.75	205.07	203.69	202.59	201.79	201.27	201.04	201.10
3	197.95	186.91	177.82	170.66	165.42	162.08	160.60	160.98	163.18
4	192.40	177.14	165.14	156.33	150.66	148.08	148.51	151.92	158.25
5	186.89	167.60	152.98	142.90	137.25	135.90	138.76	145.71	156.67
6	175.11	147.56	127.94	115.91	111.13	113.31	122.17	137.45	158.91
7	173.72	145.63	126.26	115.19	112.02	116.41	128.03	146.59	171.80
8	164.96	135.21	120.37	119.25	130.84	154.25	188.72	233.56	288.17
9	161.33	132.22	121.52	127.46	148.59	183.65	231.58	291.48	362.55
10	158.19	130.24	124.10	137.32	167.96	214.39	275.28	349.47	436.00
11	157.71	130.06	124.81	139.41	171.79	220.28	283.46	360.16	449.38
12	156.92	129.96	126.51	143.77	179.50	231.88	299.41	380.83	475.06
13	154.49	130.91	135.11	163.26	212.44	280.32	365.03	465.06	579.13
14	153.84	131.78	139.04	171.42	225.73	299.49	390.74	497.87	619.58
15	153.74	133.72	144.53	181.55	241.35	321.28	419.26	533.62	662.98
16	153.97	136.76	152.11	194.93	261.48	348.90	454.98	577.96	716.38
17	155.04	143.29	167.07	220.51	299.41	400.68	521.94	661.36	817.47
18	155.96	147.38	175.76	234.82	320.11	428.37	557.16	704.56	869.09
19	208.61	207.04	206.28	206.31	207.15	208.78	211.20	214.41	218.40
20	208.41	211.32	219.56	232.96	251.36	274.61	302.58	335.15	372.18
21	208.58	212.93	223.76	240.83	263.93	292.83	327.34	367.29	412.50
22	209.30	216.47	232.05	255.66	286.91	325.50	371.11	423.48	482.35
23	195.85	184.24	176.08	171.30	169.83	171.61	176.59	184.69	195.86
24	192.21	180.08	174.36	174.81	181.21	193.36	211.08	234.17	262.46

25	191.16	181.02	180.05	187.79	203.80	227.71	259.14	297.77	343.31
26	174.01	146.16	126.97	116.03	112.96	117.40	129.04	147.56	172.70
27	172.59	144.46	126.00	116.72	116.12	123.80	139.35	162.42	192.68
28	167.73	139.13	124.04	121.48	130.60	150.64	180.92	220.85	269.90
29	164.45	135.99	123.91	126.79	143.42	172.78	213.96	266.17	328.72
30	162.94	135.04	125.21	131.74	153.20	188.37	236.20	295.80	366.37
31	161.55	136.20	132.04	146.77	178.51	225.71	287.08	361.50	448.04
32	161.50	137.30	135.23	152.79	187.98	239.14	304.90	384.11	475.77
33	162.06	139.68	140.39	161.52	200.91	256.83	327.84	412.72	510.47

Four scenarios have been selected for discussion. The voltage profile of the scenarios has been simulated and compared with the conventional IEEE 33 bus system and the results are shown in Fig. 5. The application of DG in the system has improved the voltage profile however different scenarios of DG application has different implications. Table 2 shows that compilation of the system performance particularly the minimum voltage, V_{min} achieved in the system and system loss of both the conventional IEEE 33 bus system and DG integrated system (the selected four scenarios). In table 2, the system performance of system with DG application has improved compared with the conventional IEEE 33 bus, where the minimum voltage is better while the system loss is reduced. The different impact of four scenario will be further detailed in discussion section.

The simulation result is also compared with other literatures which were applying the same study to IEEE 33 bus system. In [15], the author implemented Analytical Method proposing 2.49 MW DG applied to Node 6 while in [16], the author conducted Grid Search Method proposing 2.60 MW DG applied to Node 7. The summary of the proposed method and the respective research outcome by other literatures is quoted in Table 3.

Table. 2 Summary of system performance of IEEE 33 bus system with and without DG application

Scenario	Proposed DG		System Performance	
	Sizing (kW)	Location (No. of Bus)	V_{min} (pu)	System Loss (kW)
Conventional IEEE 33 bus system	Not Applicable		0.9038	210.98
Scenario 1	3,500	3	0.9180	160.60
Scenario 2	2,500	6	0.9411	111.13
Scenario 3	1,000	18	0.9315	147.38
Scenario 4	3,000	7	0.9517	116.41

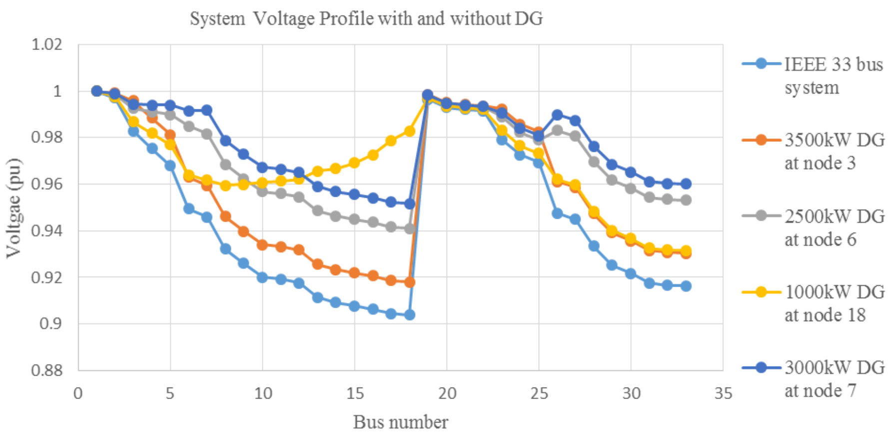

Fig. 5 Voltage profile of four selected scenarios and the conventional IEEE 33 bus system

Table. 3 System performance of IEEE 33 bus system integrated with proposed DG solution

Ref.	Proposed Method	Proposed DG	System Performance		
		Sizing (MW)	Location (No. of Bus)	V_{min} (pu)	System Loss (kW)
[15]	Analytical Method	2.49	6	0.9410	111.24
[16]	Grid Search Method	2.60	7	0.9425	111

V. DISCUSSION

Although minimization of system losses is important, the voltage stability cannot be disregarded. The voltage limit for the system under this study is predefined to be ±5%. Table 2 shows that the conventional IEEE 33 bus system suffers system loss of 210.98 kW with voltage V_{min} of 0.9038 pu.

Table 1 presented the system power loss data when DG is applied into IEEE 33 bus system. It can be detected that different capacity of DG at various placements affects the performance of the system. It is not necessary that higher capacity of DG could compensate the system losses; nevertheless it may cause the reverse effect of having higher system loss. For instance, the system loss is improving when a larger DG applied in node 6. However, it is observed that the system loss increased from 111.13 kW to 113.31 kW when DG sizing is increased from 2,500 kW to 3,000 kW. In addition, placement of DG is fairly important as at a fixed DG capacity, different system performance is observed. For example, when a 2,500 kW DG is applied at node 3 and node 6, different value of system loss is identified where in this case, 165.42 kW and 111.13 kW are observed respectively.

It can be noticed that Scenario 1, Scenario 2, Scenario 3 and Scenario 4 with DG application are able to enhance the performance of system with better voltage profile and reduction of system loss. Scenario 1 is selected to be explored as referring to the conventional IEEE 33 bus system, bus 3 is suffering the highest branch power loss. By considering DG application at bus 3 only, the minimum power loss of 160.60 kW can be achieved by integrating a 3,500 kW DG into the system.

As for Scenario 2, the least system loss of 111.13 kW is discovered when a 2,500 kW DG is applied into bus 6. This is the lease system loss for the application of DG ranges from 500 kW to 4,500 kW and DG placement from node 2 to node 33.

Fig. 4 demonstrated bus 18 of conventional IEEE 33 bus system is experiencing extreme voltage drop. Hence, by considering DG application at bus 18 only, the minimum power loss can be achieved by integrating 1,000 kW DG.

All the Scenario 1, Scenario 2 and Scenario 3 proved that system loss can be improved when a DG is applied into the system. However, the application is not able to comply with the steady sate voltage requirement of ±5% which the V_{min} recorded is 0.9180pu, 0.9411pu and 0.9315pu respectively for Scenario 1, Scenario 2 and Scenario 3. The minimum voltage to be achieved shall be 0.95 pu.

To select the most effective solution, the system loss recorded in Table 1 is arranged in acceding order followed by investigating the system V_{min} of each solution. It is observed that with a 3,000 kW DG applied into bus 7 (Scenario 4), the system can achieve minimum power loss of 116.41 kW and at the same time complying with ±5% voltage requirement. With this solution, the system is achieving 44.82% loss reduction with an enhancement of voltage profile to V_{min} 0.9517 pu than the conventional IEEE 33 bus system.

A comparison is made to other solutions proposed by literature. Referring to Table 3, both solutions proposed by [15] and [16] are very close to Scenario 2 but the drawback of this solution is having a higher limit of voltage drop. It is recommended that for DG planning purposes, the system shall comply with ±5% steady state voltage requirement as practically the load might vary to higher demand. Therefore, the system would be placed at higher risk of experiencing voltage instability and eventually disastrous voltage collapsed of the entire system might be happening.

VI. CONCLUSIONS

An analytical approach has been performed to study the effect the single P-type DG to IEEE 33 bus system. DG is applied into the distribution system with a fixed step size of 500 kW and to the maximum of 4,500 kW. The performance of the system is investigated with various DG capacity to be placed at different locations.

Four scenarios have been selected for examination. The scenarios have also been compared with the solutions proposed by other literature. Result shows that 3,000 kW DG applied into bus 7 outperform other solutions where this recommended solution is demonstrating optimal performance, fulfilling voltage requirement of ±5% with minimum system losses.

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