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Abstract: In a real-time electricity market, where the contribution of distributed resources is increasing, the utilization of fast and robust tools to compute locational prices becomes vital. This paper proposes a method for distributed resources based on linear programming to solve the direct current optimal power flow. In this manner, minimum generation cost, bus angles, line flows and locational marginal prices have been achieved subject to the system constrains and social welfare. To demonstrate the capability of the proposed method two scenarios have been studied on a 4-bus test system with and without considering grid congestion. It was found that the results converged precisely with a low computation time. The main feature of this method is its simplicity and robustness which allows the utilization of this method in a smart grid with a variety of customers.

Keywords: DC optimal power flow, Smart Grid, Locational Marginal Prices, Optimal Scheduling, Market Clearing Price

Nomenclature

P_{G_i}, Q_{G_i}	active and reactive power generation at bus *i*
P_{D_i}, Q_{D_i}	active and reactive power demand at bus *i*
$P_{G_i}{}^{min}, P_{G_i}{}^{max}$	minimum and maximum active power generation at generator *i*
$Q_{G_i}{}^{min}, Q_{G_i}{}^{max}$	minimum and maximum reactive power generation at generator *i*
I_i	current at bus *i*
V	vector of bus voltages
I	vector of currents at buses
Y	bus admittance matrix
V_i	i^{th} element of vector V
G_{ij}	conductance of *ij* bus
B_{ij}	susceptance of ij^{th} bus
N_B	number of buses
N_G	number of generators
N_D	number of load demands
f_{P_i}	cost function of active power
f_{Q_i}	cost function of reactive power
LMP	locational marginal price
B	$N \times N$ admittance matrix with R=0
P	$N \times 1$ vector of bus active power
P_B	$M \times 1$ vector of branch flows (M is the number of branches)
D	$M \times M$ matrix where b_{ii} is equal to the susceptance of line *i* and non-diagonal elements are zero
A	$M \times N$ bus-branch incidence matrix
P_i	active power of the system
Q_i	reactive power of the system
θ_i	Voltage angle at bus at bus *i*

1 INTRODUCTION

Optimal power flow, which determines power generation cost and transmission loss subject to practical constraints, is inherently nonlinear and non-convex. It has always been a challenging problem in power system operation. For simplicity, the majority of previous works use linearization and approximation methods such as small angle approximation and relaxation methods. In a smart grid, where intermittent energy such as photovoltaic plant supplies, direct current optimal power flow (DC-OPF) is practically important [1].

Locational marginal pricing (LMP) is an important method which can use AC-OPF and DC-OPF and has been utilized in most power markets ISOs such as PJM, New York, New England, California and Midwest. DC-OPF model is a linearized model of AC-OPF due to its simplicity, efficiency and fast response and is still preferred compared to AC-OPF [2], [3].

The authors of [4],[5] used decentralized DC-OPF method to solve the decentralized SC-OPF problem which is an iterative algorithm. The result of their studies demonstrated that DC-OPF has a fairly good result regarding congestion patterns compared to the full ac system model and they found that dc approach is substantially faster.

Reference [6] introduced a quadratic approximation of the OPF for power distribution system which is based on the linear power flow. The proposed method does not take into account PV nodes.

The authors of [7] used DC power flow to show the usefulness of this tool especially when power flow controlling devices such as phase shifting transformers are considered. In their study, they found a relatively small error between AC and DC-OPF which was caused by the approximation of a sine function.

Therefore, the focus of the present study is to investigate the effects of transmission lines constraint and congestions on the customers in the context of smart grid. To have an accurate and thorough investigation on payment to loads (customers) and generators a new formulation of LP-DC-OPF has been applied to a 4-bus test system with 2 different scenarios.

2 PROBLEM FORMULATION

2.1. AC Power Flow

The classical power flow (PF) problem can be formulated with considering four main decision variables for each bus of the power system. These variables are as follows [9]:

$$x = \begin{bmatrix} P_i \\ Q_i \\ V_i \\ \theta_i \end{bmatrix} \quad (1)$$

The active and reactive power of the system with respect to equality constraints can be calculated by the following formulation:

$$\sum_{i=1}^{N_B} P_i = \sum_{i=1}^{N_G} P_{G_i} - \sum_{i=1}^{N_D} P_{D_i} \quad (2)$$

$$\sum_{i=1}^{N_B} Q_i = \sum_{i=1}^{N_G} Q_{G_i} - \sum_{i=1}^{N_D} Q_{D_i} \quad (3)$$

Subject to inequality constraints

$$\begin{gathered} P_{G_i}^{min} \leq P_{G_i} \leq P_{G_i}^{max} \\ Q_{G_i}^{min} \leq Q_{G_i} \leq Q_{G_i}^{max} \end{gathered} \quad (4)$$

According to Kirchhoff's law for determination of the current at each bus [9]:

$$I = YV \quad (5)$$

subject to

$$I_i = \frac{(P_i - jQ_i)}{|V_i|} e^{j\theta_i} \quad (6)$$

$$V_i = |V_i| e^{j\theta_i}$$

$$Y_{ij} = |Y_{ij}| e^{j\delta_{ij}} = G_{ij} + jB_{ij} \quad (7)$$

Subsequently, the active and reactive power of the system can be expressed based on the equations [10]:

$$P_i = \sum_{j=1}^{N_B} |V_i||V_j|(G_{ij} \, cos(\theta_i - \theta_j) + B_{ij} sin(\theta_i - \theta_j)) \quad (8)$$

$$Q_i = \sum_{j=1}^{N_B} |V_i||V_j|(G_{ij} \, sin(\theta_i - \theta_j) - B_{ij} cos(\theta_i - \theta_j)) \quad (9)$$

Therefore, the objective function of AC-OPF can be simply proposed by summation of cost functions of active and reactive power injections for each generator [11]:

$$min_{P_i, Q_i, V_i, \theta_i} \sum_{i=1}^{N_G} f_{P_i}(P_{G_i}) + f_{Q_i}(Q_{G_i}) \quad (10)$$

2.2. DC Power Flow

The most frequently used solution for calculation of the power flows through the transmission lines and power grid injections is the ACPF, where the high level of analysis and detailed information of the power grid is carried out. The ACPF is a very time consuming method for the large scale of a power grid with *N* buses and *2N* resulting non-linear equations that have to be solved iteratively for each time step [12]. The main idea of DCPF is to simplify the task and reduce the calculation time of ACPF by considering several approximate assumptions. DCPF is non-iterative method and it is completely convergent but less accurate than ACPF. This non-iterative nature of DCPF causes to significant reduction in computation time which makes it a very useful method for the real time analysis of large systems.

The following assumptions are considered to formulate the DCPF [13]:

1) The resistance of transmission lines is significantly less than the reactance. Therefore, the resistance terms of the impedance will be ignored

$$Z = R + jX \quad (11.A)$$

$$Y = G + jB \quad (11.B)$$

$$Y = \frac{1}{Z} = Z^{-1} \quad (11.C)$$

$$R \ll X \quad (11.D)$$

The power flow equations can be rewritten:

$$P_i = \sum_{j=1}^{N_G} |V_i||V_j|(B_{ij} sin(\theta_i - \theta_j)) \quad (12)$$

$$Q_i = \sum_{j=1}^{N_G} |V_i||V_j|(-B_{ij} cos(\theta_i - \theta_j)) \quad (13)$$

2) Since the difference in angles of the voltage phasors at sending and receiving buses are less than 10-15 degrees, therefore we say that the angular separation across any transmissions lines are negligible $(sin(\theta) = \theta, cos(\theta) = 1)$.

$$P_i = \sum_{j=1}^{N_G} |V_i||V_j| \left(B_{ij}(\theta_i - \theta_j)\right) \quad (14)$$

$$Q_i = \sum_{j=1}^{N_G} |V_i||V_j|(-B_{ij}) \tag{15}$$

3) Ignoring the reactive power of the system ($P_i \gg Q_i$).

4) Ignoring the transmission line losses.

5) The tap settings of the transformers are neglected (means in-phase and phase-shifting transformers are considered like transmission lines).

6) Bus voltage magnitudes are fixed to 1.0 per unit.

According to aforementioned assumptions, only active powers of the system and voltage angles are the remaining variables of DCPF. Therefore, the power balance equation of DCPF will be converted to set of linear equations

$$P_i = \sum_{j=1, j\neq i}^{N} (B_{ij}(\theta_i - \theta_j)) \tag{16}$$

where the above equation as well as power of branch flows can be represented in the matrix notation as follows:

$$\theta = [B']^{-1} P \tag{17}$$

$$P_B = (D \times A) \times \theta \tag{18}$$

It should be noted, as in power flow the angle of slack bus is equal to zero therefore in B' matrix the first row and column must be removed. Consequently, the objective function of DCOPF by reducing the optimization variables can be derived as below

$$x = \begin{bmatrix} P_i \\ \theta_i \end{bmatrix} \tag{19}$$

$$min_{P_i,\theta_i} \sum_{i=1}^{N_G} f_{P_i}(P_{G_i}) \tag{20}$$

The DCPF estimates the approximate values of the system in comparison to ACPF which is able to carry out very detailed information of the power grid, but it has three main advantages over the classical Newton-Raphson PF [8]:

1) The admittance matrix (the system matrix, B) is almost half the size of the full problem.

2) Since the problem can be solved in a linear and non-iterative way, a single run is required to obtain the problem solution which has a significant reduction on the calculation time as well as real time analysis.

3) The admittance matrix of the system is totally independent from the system state, so it is required to be derived only once as long as the topology of the system has no changes.

It is worth noting that by considering the first and second advantages of DCPF, the calculations would be obtained 7 to 10 times faster than AC. Consideration of the third advantage which has a huge effect on the calculation time, the multiple solutions are required since the inverse of the admittance matrix has to be solved only for a single run.

2.3. DC-OPF Based on Linear Programming

While the DCPF attempts to find two variables; power flows in the transmission lines and the angles of bus voltages, DC-OPF gives this ability to user to have the optimal dispatch of the generating units at the same time. This feature is a handy tool for power system planners and operators which they tend to have a holistic overview of the system with respect to all of the load fluctuations in the real time systems. In this regard, the following section explains the principles of linear programming (LP) and then it illustrates how DCOPF can be embedded into LP concept.

LP has found many usages in the industry where system planners and operators want to utilize and optimally manage limited resources in a suitable way. The main application of linear programming is to find the maximum or minimum of some quantity such as cost or profit while the system is involved with different sets of linear equations. This mathematical approach of finding extremum values of a quantity is widely known as optimization. LP is a classical optimization method which deals with types of problem that are presented in forms of linear functions which subsequently they can be optimized with respect to a set of linear constraints where the functions are known as objective function. The basic principles of LP can be defined as [14], [15]:

$$min\, Z = \sum_{i=1}^{n} c_i x_i = c_1 x_1 + c_2 x_2 + \cdots + c_n x_n \tag{21}$$

subject to

$$\begin{gathered} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n (\leq, =, \geq) b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n (\leq, =, \geq) b_2 \\ \vdots \\ a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nm}x_n (\leq, =, \geq) b_n \\ x_1 + x_2 + \cdots + x_n \geq b_n \end{gathered} \tag{22}$$

where the set of LP constraints can be stated in terms of summation notation as below

$$\sum_{i=1}^{n} \sum_{j=1}^{m} a_{ij} x_j (\leq, =, \geq) \sum_{i=1}^{m} b_i \tag{23}$$

subject to

$$l_j \leq x_j \leq u_j \tag{24}$$

which can be simplified and rewritten in matrix notation

$$A_{eq} x (\leq, =, \geq) b_{eq} \tag{25}$$

Where Z is the objective function, c_i is per unit cost of i^{th} variable, x_i is i^{th} decision variable and $(\leq, =, \geq)$ defines the types of the constraints. The $\leq$ constraint indicates the upper limit of available resources, while the ≥ constraint defines a minimum value is targeted to be obtained in the final solution, where the = constraint strictly specifies a decision variable should be exactly equal to what desired amount. a_{ij} is the constraint coefficient of x_j in the ith main constraint, $b_i$is the right-hand side constant of main constraint *i*, n is number of the decision variables, *m* is number of the main constraints, $l_i$is the lower bound of ith decision variable, $u_i$is the upper bound of i^{th} decision variable, A_{eq} is the linear equality constraint matrix and b_{eq} is the linear inequality constraint vector.

The optimization process is highly dependent on the nature of problem, the study demonstrates how the DCOPF can be smoothly embedded into LP concept. The linear equality constraint matrix (A_{eq}) can be divided into six sub-matrices per below [17]:

1) $P_b = (D \times A)$ (26)

2) $form\ B'\ matrix$ (27)

subject to

$$\begin{cases} if\ i = j\ \rightarrow\ B_{ii}{}' = b_i + \sum_{j=1, j\neq i}^{N} b_{ij} \\ otherwise \qquad B_{ij}{}' = -b_{ij} \end{cases}$$

3) $E = (eye(N_B, N_B)) \times (-1)$ (28)

4) $Z_1 = zeros(N_{\theta,} N_B)$ (29)

5) $Z_2 = zeros(N_{B,} N_G)$ (30)

6) $G = zeros(N_{node}, N_G)$ (31)

subject to

$$\begin{cases} if\ N_{node_i} = N_{G_i}\ \rightarrow\ G = -1 \\ otherwise \qquad 0 \end{cases}$$

Where *D* is *M*×*M* susceptance matrix (where the B_{ii} is equal to the susceptance of line *i* and non-diagonal elements are zero), *A* is the node-arc incidence matrix, $b_{ij}$is susceptance between bus *i* and bus *j*, *E* is an eye matrix multiply by -1, $N_B$is the number of branches, Z_1 and Z_2 are the zeros matrix, *G* is a $N_{node} \times N_G$ matrix and N_{node} is the number of nodes (buses).

It is important to mention, that the size of A_{eq} is *M*×*N* where the *M* is equal to number of generators, branches and nodes (*means M* = $(N_G + N_B + N_{node})$) and *N* is equal to number of branches and nodes (means *N* = $(N_B + N_{node})$). Subsequently, A_{eq} can be formed in the following order:

$$A_{eq=}\begin{bmatrix} Z_2 & E & P_b \\ G & Z_1 & B' \end{bmatrix} \tag{32}$$

The vector dimensions of inequality constraint is *N*×*1* where *N* is equal to number of branches and nodes (means *N* = $(N_B + N_{node})$). In order to form b_{eq}, all the values which are assigned to number of branches are zero, while all the values which are assigned to number of nodes are equal to the corresponding load demand at that particular node. Also, it is required that all the values of load demand must be represented in the negative value to maintain the equality constraint of power flow. Therefore b_{eq} matrix can be represented as:

$$b_{eq} = \begin{bmatrix} N_{B_1} \\ N_{B_2} \\ \vdots \\ N_{B_i} \\ N_{node_1} \\ N_{node_2} \\ \vdots \\ N_{node_i} \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ P_{D_1} \\ P_{D_2} \\ \vdots \\ P_{D_i} \end{bmatrix} \tag{33}$$

By solving the LP-DCOPF values of *x* which are generators schedule, branch flows and bus angles will be calculated. The study has used inequality constrained minimization interior point method to solve the linear programming which can be found in [16].

3 RESULTS AND DISCUSSION

In order to demonstrate the procedure of problem formulation as well as the practicality of the proposed LP-DC-OPF, the methodology has been applied to a four bus test system [18]. Tables 1 and 2 illustrate the test system details where the single line diagram of the test system is depicted in Fig. 1. For simplicity of the calculation all the values of the test system are given in per unit. The considered test system has three generating units with total load 4.3075 p.u [18]. The directions of power flows through the branches are selected arbitrarily. To have an accurate investigation of proposed method, the study has considered two different scenarios to show the capability of the proposed method with respect to load fluctuation and transmission lines constraints in real time systems. The proposed method of the study has been implemented on MATLAB 2013a and executed on a personal computer with the following specifications, Intel® Core™ i7-3770 (3.40 GHz), 8.00 GB RAM (DDR5) and Windows 10 operating system. The study has indicated the procedure of the solution set up before analysis of the scenarios to have a better understanding about process of the proposed method.

Table. 1: Transmission lines characteristics

Branch No.	Nominal Flow		Admittance (p.u.)	Capacity (p.u.)
	From	To		
1	1	4	-j10	500
2	1	2	-j10	500
3	2	3	-j10	500
4	3	4	-j10	500
5	1	3	-j10	500

Table. 2: Generators' characteristics

Gen No.	Pmin (p.u.)	Pmax (p.u.)	Marginal Cost ($/MWh)
1	0.50	3.50	10.55
2	0.50	2.50	8.45
3	0.50	2.90	8.80

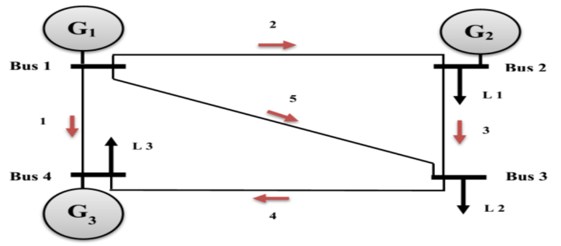

Figure. 1: 4-bus single line diagram

3.1. First Scenario

The LMP is one of the most effective analyses to evaluate the behaviour of the power grid in any electricity market especially for the day-ahead and real-time bases; therefore it is required to calculate the LMP of each bus of the network for every five minutes. In this situation, it is vital to have a quick and efficient tool like LP-DC-OPF to do the fast and optimal calculation. In the first scenario, the study assumed there is no transmission line constraint. The branch flows are strictly within the branch capacities, therefore the transmission lines has no effect on the economical dispatch of a lossless system in the proposed LP-DCOPF. To maintain the system security and adhere to this assumption, the study has assigned 500 p.u for the lower and upper bounds of all transmission lines which effectively makes the capacities equal to infinity in the per unit scale. The results of LP-DC-OPF are shown in the Table 3, where totals system demand is equal to 4.3075 p.u. The proposed method has successfully calculated the optimal scheduling of the generating units, branch flows, bus angles and LMPs. Also, by having the LMPs it is very easy to calculate the amount of payment to generators (PTG) as well as amount of payment to loads (PTL) or customers. The optimal and fast calculation of PTG and PTL has a key role in smart grid (SG) because the system operator is able to propose a suitable demand response program (DRP) for the consumer at each location of the system based on these values. As it can be seen from Table 3, all LMPs have the same value since the network has no transmission line constraint. Therefore, the marginal prices are equal at every node of the system, where the generators would be paid based on the market clearing price which is 8.8 $/p.u. It is important to mention, that PTG and PTL are equal to the total generation cost (37.906 $/h), it means the market has settled in the same price of PTG and PTL since the branch flows can vary in an infinite bound. To show the practicality of the proposed method, the study has considered another different load point at 4.6075 p.u to examine the efficiency of LP-DC-OPF where the results are shown in Table 4. By increasing the load demand in this case accordingly the schedule of generating units has been changed. The total cost of generation, PTG and PTL have increased to 40.546 $/h while LMPs are remained 8.8 $/p.u since the generator number 2 has cleared the market price. The evaluation Power balance violation (PBV) ensures that equality constraint of economic dispatch has been maintained intact, where in the both cases of this scenario the PBV is equal to -3.14×10^{-12} (which is small enough to be neglected). The elapsed time is less than 0.27 second for the both cases.

Table. 3: Results of LP-DCOPF without considering transmission lines constraints (load = 4.3075 p.u.)

No.	Gen Dispatch	Line Power Flows	Bus Angles	LMPs	PTG	PTL
1	0.5000	0.0034	0.0125	8.8000	4.4000	9.2400
2	2.5000	-0.3178	0.0443	8.8000	22.0000	24.2660
3	1.3075	1.1322	-0.0689	8.8000	11.5060	4.4000
4	0.0000	0.8109	0.0122	8.8000	0.0000	0.0000
5	0.0000	0.8144	0.0000	0.0000	0.0000	0.0000
Total Cost ($/h)	37.9060			Total	37.9060	37.9060

Table. 4: Results of LP-DCOPF without considering transmission lines constraints (load = 4.6075 p.u.)

No.	Gen Dispatch	Line Power Flows	Bus Angles	LMPs	PTG	PTL
1	0.5000	-0.1091	0.0125	8.8000	4.4000	9.2400
2	2.5000	-0.2803	0.0405	8.8000	22.0000	26.9060
3	1.6075	1.1697	-0.0764	8.8000	14.1460	4.4000
4	0.0000	0.9984	0.0234	8.8000	0.0000	0.0000
5	0.0000	0.8894	0.0000	0.0000	0.0000	0.0000
Total Cost ($/h)	40.5460			Total	40.5460	40.5460

3.2. Second Scenario

This scenario investigates the effects of transmission lines constraint and congestions on the customers in context of smart grid. The study has considered two test case studies to have a precise investigation on payment to loads (customers) while the capacity of the main transmission line of the system which accommodates the highest power flow within the system has been significantly limited. According to our calculation in the previous scenario, branch number three carries the highest power flow with 1.1322 and 1.1697 p.u for the first and second test case respectively. Therefore, to see the effect of congestion in transmission line the capacity of this line has been limited to 0.5 p.u which is less than 55% of its actual value. Thereafter, the results are shown in Tables 5 and 6 with respect to two different load points (4.3075 and 4.6075 p.u). It is observable by limiting the branch number three; LMPs are noticeably changed at each node with a specific marginal price. But the most important result is that, the amount of payments to generators and loads are less than total cost. The is due to the proposed method optimizing the system based on the bids that have been offered by the generators or power plant owners but the market has settled according to LMPs. This is based on the idea that most of the electricity markets around the world has adopted or adopting the principal of payment at market clearing price in order to discourage the market participants to offer their bids in the higher price.

Another noticeable fact that can be concluded by the results, the prices paid by loads are higher than by generators from 0.287 to 0.35 $/h respectively for case 1 and 2. This exceeding amount should be paid by customers due to transmission line congestion effect. The PBVs for case 1 and case 2 are 1.42×10^{-12} and -8.83×10^{-11} respectively. In the both cases of the second scenario the elapsed time has remained less than 0.27 second which indicates the fast convergence of the proposed method of the study.

Tab. 5: Results of LP-DCOPF with considering transmission lines constraints (load = 4.3075 p.u.)

No.	Gen Dispatch	Line Power Flows	Bus Angels	LMPs	PTG	PTL
1	0.5000	-0.6287	0.0125	8.7125	4.3563	8.8725
2	1.2356	0.3144	-0.0189	8.4500	10.4410	24.5073
3	2.5719	0.5000	-0.0689	8.8875	22.6325	4.4000
4	0.0000	1.4431	0.0754	8.8000	0.0000	0.0000
5	0.0000	0.8144	0.0000	0.0000	0.0000	0.0000
Total Cost ($/h)	38.3485			Total	37.4298	37.7798

Tab. 6: Results of LP-DCOPF with considering transmission lines constraints (load = 4.6075 p.u.)

No.	Gen Dispatch	Line Power Flows	Bus Angels	LMPs	PTG	PTL
1	0.5000	-0.6287	0.0125	8.7125	4.3563	11.4075
2	1.5356	0.3144	-0.0190	8.4500	12.9760	24.5073
3	2.5719	0.5000	-0.0690	8.8875	22.6325	4.4000
4	0.0000	1.4431	0.0753	8.8000	0.0000	0.0000
5	0.0000	0.8144	0.0000	0.0000	0.0000	0.0000
Total Cost ($/h)	40.8835			Total	39.9648	40.3148

4 CONCLUSION

In this paper, a new formulation of DC-OPF through the linear programming has been represented and successfully employed to solve the optimal power flow problem. The proposed method demonstrates the efficient and fast calculation of line power flows, bus angles, generators dispatch and LMPs with respect to system constraints and social welfare. The practicality of the LP-DC-OPF through to two scenarios was investigated; the first scenario with two base cases and second scenario with line congestion cases. It was found out that when the grid had congestion on the transmission line in the second scenario, market prices would be settled in the different amount at each node of the test system which results the significant changes in LMPs. Also, it has a direct effect on the payments that should be provided by the customer side, where the exceeding amount of market settlement that should be paid by the customers. Therefore, in the modern set up of power system or more specifically in context smart grid where the grid is more customer orientated, the efficient and fast calculation of system details and price transactions in market place is became absolutely vital. In order to facilitate this aim, the system operator needs an efficient tool in the real time systems to consider several scenarios of the demand response and substitute options to deal with these kinds of issues. It is believed that the proposed LP-DCOPF is a very fast and precise tool to handle the OPF problem in the smart grid context.

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