ARCHIVES OF ELECTRICAL ENGINEERING VOL. 68(2), pp. 265–277 (2019)

DOI 10.24425/aee.2019.128267

Optimal allocation of DG units in distribution system considering variation in active power load

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(Received: 20.03.2018, revised: 11.12.2018)

Abstract: High distribution system power-losses are predominantly due to lack of investments in R&D for improving the efficiency of the system and improper planning during installation. Outcomes of this are un-designed extensions of the distributing power lines, the burden on the system components like transformers and overhead (OH) lines/conductors and deficient reactive power supply leading to drop in a system voltage. Distributed generation affects the line power flow and voltage levels on the system equipment. These impacts of distributed generation (DG) may be to improve system efficiency or reduce it depending on the operating environment/conditions of the distribution system and allocation of capacitors. For this purpose, allocating of distributed generation optimally for a given radial distribution system can be useful for the system outlining and improve efficiency. In this paper, a new method is used for optimally allocating the DG units in the radial distribution system to curtail distribution system losses and improve voltage profile. Also, the variation in active power load in the system is considered for effective utilization of DG units. To evidence the effectiveness of the proposed algorithm, computer simulations are carried out in MATLAB software on the IEEE-33 bus system and Vastare practical 116 bus system.

Key words: exact loss formula, loss reduction, loss sensitivity formula, optimal DG placement, uncertainties in active power load, voltage profile

1. Introduction

The inclination with respect to distribution automation depends upon the utmost efficient operating scenario for economic feasibility variations. Hence distribution systems optimization is of greater importance so as to reduce losses and improve the voltage profile of the system.

As the generation cost is increasing gradually and depleting resources, it is necessary to have an efficient system. In electric power systems, 70% of overall losses correspond to power lost in distribution systems. The most efficient loss minimization techniques in distribution systems are feeder reconfiguration, distributed generation (DG), volt-amp reactive (VAR) compensation. DG units are installed on distribution primary feeders to provide adequate active power support for loss reduction which also improves voltage profile to some extent and increases available capacity of feeders. To obtain maximal benefits of DG implementation, it is important to find optimal location and the optimal size of DG units that are to be connected, for loss reduction. Various optimization algorithms/techniques are proposed in the past for optimal allocation of DG units.

T. Ackermann, G. Andersson and S. Lennart [1] have presented the related problems and directs at providing a general clarification for a dispersed generation in the competitive business of electricity. W. El-Khattam and M.M.A. Salama [2] in their paper have presented an overview of the revolutionary techniques of implementing DGs, which in turn change operation of electric power systems along with their types and operating technologies. N. Rugthaicharoencheep and S. Auchariyamet [3] have discussed the benefits and drawbacks of DG on distribution systems. Duong Quoc Hung and Nadarajah Mithulananthan [4] used a better analytical technique for recognition of the optimal location and best power factor for integrating multiple DGs to reduce system losses in wide-ranging primary distribution systems. Naresh Acharya, Pukar Mahat and N. Mithulananthan [5] proposed a detailed formulation to compute the optimum size and an efficient approach to recognize the correspondent optimal site for DG installation in primary distribution systems to reduce the total power losses. B. Venkatesh Reddy [6] in his paper discussed the two issues of the most suitable location and size of DG for loss reduction by using an exact loss formula and loss sensitivity factor. Mohammadreza Vatani, *et al.* [7] discussed the combination of analytical and genetic algorithm methods which are used for the optimal allocation of multiple DGs in a distribution network to minimize the system losses. Vadimgadu Roja, *et al.* [8] in their paper have presented the state of the art techniques for optimum placement and sizing of DG. The solution methodology implemented to solve the problem of optimal allocation and size of DG units are categorized as load flow based techniques, numerical methods, analytical methods, evolutionary algorithms such as GA, PSO etc.

In this paper, simple analytical expressions are applied to determine simultaneously the best position and optimum capacity of a DG unit to minimize system losses. The exact power loss formula [10], as well as the equation of a loss sensitivity factor [5], are used for obtaining optimal DG size and its location. The proposed method is evaluated on the IEEE-33 bus system and Vastare practical 116 bus system.

2. Formulation

The prime aim of DG integration in the distribution system is to minimize power losses. The 3Ø system is considered as balanced and variation in active power load is considered. In a distribution system load flow analysis is executed by the backward-forward sweep method [9]. The effective branch powers are calculated in backward propagation and in forward propagation voltage magnitudes at each and every node are calculated and updated. System losses are calculated after obtaining the all branches power and voltage.

2.1. Exact power loss formula

An exact transmission loss formula has been derived by using bus powers and system parameters [10]. The exact loss formula is represented as:

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right], \tag{1}$$

$$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos\left(\delta_i - \delta_j\right), \tag{2}$$

$$\beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right). \tag{3}$$

P_i, P_j and Q_i, Q_j are the real and reactive power injected at i^{th} and j^{th} bus, respectively.

$$\theta_i = \delta_i - \phi_i\,,$$

where δ_i is the voltage angle and

$$\phi_i = \tan^{-1}\frac{Q_i}{P_i}\,.$$

N is the number of buses, P_L is the real power loss of a system, V_i and V_j are the voltage at i^{th} and j^{th} bus, respectively,

$$Z_{ij} = r_{ij} + jx_{ij}$$

are the components of an impedance matrix wherein i and j are the different buses of the system. An explanatory technique was furnished based on an exact loss formula and was presented to discover an optimal size for the DG which is adequate of supplying only real power. At the DG located bus, the power added is formulated as the difference between the output power of DG and load demand. The active and reactive power injected at bus i^{th} is given as:

$$P_i = P_{DGi} - P_{Di}\,, \tag{4}$$

$$Q_i = Q_{DGi} - Q_{Di}\,, \tag{5}$$

assuming

$$a = (sign)\tan\left(\cos^{-1}\left(PF_{DG}\right)\right),$$

the reactive power output of the DG is expressed as:

$$Q_i = aP_{DGi} - Q_{Di}\,. \tag{6}$$

The power factor of DG depends on operating conditions and a type of the DG. The optimal size of the DG at each bus i for minimizing loss is obtained by taking the partial derivative of the exact loss formula with respect to injected power [11]. It can be written as:

$$P_{DGi} = \frac{\alpha_{ii}\left(P_{Di} + aQ_{Di}\right) + \beta_{ii}\left(aP_{Di} - Q_{Di}\right) - X_i - aY_i}{a^2\alpha_{ii} + \alpha_{ii}}, \tag{7}$$

where

$$X_i = \sum_{j=1, j\neq i}^{N} \left(\alpha_{ij} P_j - \beta_{ij} Q_j\right), \tag{8}$$

$$Y_i = \sum_{j=1, j\neq i}^{N} \left(\alpha_{ij} Q_j + \beta_{ij} P_j\right). \tag{9}$$

3. Loss sensitivity factor

Linearization of original non-linear equations about its initial operating point is the principle of loss sensitivity factor; it assists to decrease the number of solution space. The loss sensitivity factor method had been broadly accepted to figure out the capacitor allocation problem. Its application in DG location is new in the field and had been recorded. The sensitivity factor of real power loss in respect of real power injection from DG is expressed as [5]:

$$\frac{\partial P_L}{\partial P_i} = 2\sum_{j=1}^{N} \left(\alpha_{ij} P_j - \beta_{ij} Q_j\right). \tag{10}$$

4. Optimal allocation of DG units

In this paper, the optimal allocation of Type-I DG units is considered, i.e. DG, which can inject only active power whose power factor is 1 (unity power factor). The DG capacity and also DG location changes with a change in load demand, for optimal allocation of DG units. As load will not be constant over the year, maximum energy saving cannot be achieved only by considering the average value of load for DG allocation. Therefore to achieve maximum energy saving, variation in active power load is considered. The results change if the active load distribution in the network changes. Allocation of DG units is done using of Loss Sensitivity Factor, the optimal size of the DG unit obtained from Eq. (7) is rounded off to the nearer practically available DG sizes. DG units are considered to be operating at a unity power factor (UPF). The base voltage of both distribution systems considered for the test is 1.0 pu. The losses discussed in this paper are limited to only the losses that occur in distribution overhead lines.

a. Uncertainties in active power load

The IEEE-33 bus is a primary radial distribution system (RDS) operating at 11 kV voltage [16]. The base case losses of the system at different loading conditions are tabulated in Table 1. P_D refers to the total load in the system.

The variation in an optimal DG location and DG size with respect to variation in load is tabulated Table 2.

The power loss for the system without DG units are calculated for different loads and are tabulated in Table 1. Now, using the loss sensitive factor, for different load the optimal location and size of DG units are as shown in Table 2. Now for different loads, we have obtained their

Table 1. Losses of IEEE-33 bus system at different loading conditions

Losses without DG units		
Load	**Active power loss (kW)**	**Reactive power loss (kvar)**
Full load (P_D)	210.0756	142.5337
$0.966 \cdot P_D$	199.8448	135.5685
$0.806 \cdot P_D$	155.8165	105.6024
$0.721 \cdot P_D$	137.7264	93.2946
$0.612 \cdot P_D$	116.3751	78.7719
$0.506 \cdot P_D$	99.1465	67.0566

Table 2. Optimal allocation of DG units at different loads

Loads	**DG location (bus number)**	**Optimal DG size calculated (kW)**	**Rounded-off DG size (kW)**
Full load (P_D)	18	479.7337	500
	33	600.3487	600
	12	379.3485	400
$0.966 \cdot P_D$	18	463.5813	500
	33	575.7598	600
	11	374.2152	400
$0.806 \cdot P_D$	18	384.8999	400
	33	480.4842	500
	12	299.7766	300
$0.721 \cdot P_D$	18	346.5754	300
	33	443.3169	400
	13	258.1141	250
$0.612 \cdot P_D$	18	294.1742	300
	33	367.0459	400
	12	227.5465	250
$0.506 \cdot P_D$	18	243.0131	250
	33	302.0632	300
	12	192.2621	200

respective DG units allocation for minimum loss to occur in a system, i.e. at full load optimal DG units are located buses 18, 33 and 12 with a DG capacity of 500 kW, 600 kW, and 400 kW respectively and the power losses with DG units are tabulated in Table 3. At 0.966 of total load the optimal DG are allocated at buses 18, 33, and 11 with a DG unit capacity of 500, 600 and 400 respectively and the losses are calculated and tabulated in column 2 of Table 3. Similarly losses are calculated for other loads. We know that the equation for energy loss is expressed as:

$$\text{Energy Loss} = \text{Power Loss}(P_L) \times \text{Time}(T),$$

where P_L is the total active power loss in kilowatt and T is the time in hours.

$$\text{Annual time in hours} = 24\text{h} \times 365 \text{ days} = 8760 \text{ h}.$$

The total annual time in hours is divided into 6 duration each duration load is different from one another as tabulated in Table 3 ($8760 = 1401 + 1586 + 1822 + 1577 + 1034 + 1340$). The total annual energy losses in the system are calculated with and without DG and results are tabulated in Table 3. For example, energy loss occurred under full load in a year is calculated as:

[Annual energy loss under full load = (active power losses under full load × duration of full load in hours) = 210.0756 kW × 1401 h = 294315.92 kWh]

Table 3. Energy losses without DG units and with DG units

Loads	**Full load (P_D)**	**0.966 * P_D**	**0.806 * P_D**	**0.721 * P_D**	**0.612 * P_D**	**0.506 * P_D**
Time (hours)	1401	1586	1822	1577	1034	1340
Active power loss without DGs (kW)	210.0756	199.8448	155.8165	137.7264	116.3751	99.1465
Active power loss with DGs (kW)	93.5975	90.1506	81.9936	81.0322	72.9520	69.9767
Energy loss without DGs (kWh)	294315.92	316953.85	283897.66	217194.53	120331.85	132856.31
Energy loss with DGs (kWh)	131130.10	142979.17	149392.52	127787.78	75432.47	93768.78
Total energy saved with DGs (kWh)	163185.82	173974.68	134505.14	89406.75	44899.38	39087.53

It is impractical to displace DG units every time as load changes. To overcome this problem the DG units are placed where the energy saving is maximum. As it is evident from the Table 3, maximum energy can be saved if DG is placed in the locations obtained with respect to a load of 0.966*P_D. Thus the optimal allocation of the DGs is as shown in Table 4.

Table 4. Optimal allocation of DG units based on maximum energy savings

Optimal allocation of DG units	
DG location	**DG size (kW)**
18	500
33	600
11	400

The losses in the system for different loading condition are tabulated in Table 5 with the DG units at buses 18, 33 and 11with a size of 500 kW, 600 kW and 400 kW, respectively.

Table 5. Losses at different loading condition with DG units

Losses with DG units		
Load	**Active power loss (kW)**	**Reactive power loss (kvar)**
Full load (P_D)	93.2619	63.3918
$0.966 \cdot P_D$	90.1508	61.4913
$0.806 \cdot P_D$	79.4734	55.2474
$0.721 \cdot P_D$	76.8647	53.9498
$0.612 \cdot P_D$	75.9192	53.938
$0.506 \cdot P_D$	77.8068	55.8147

The total annual energy losses after optimally allocating the DG units are tabulated in Table 6. A total of 643133.3054 kWh of energy can be saved annually by the placement of the DG in the system. The voltage profile in the system is as shown in Figure 1. With the optimal allocation of DG units, the voltage profile of the network is also improved.

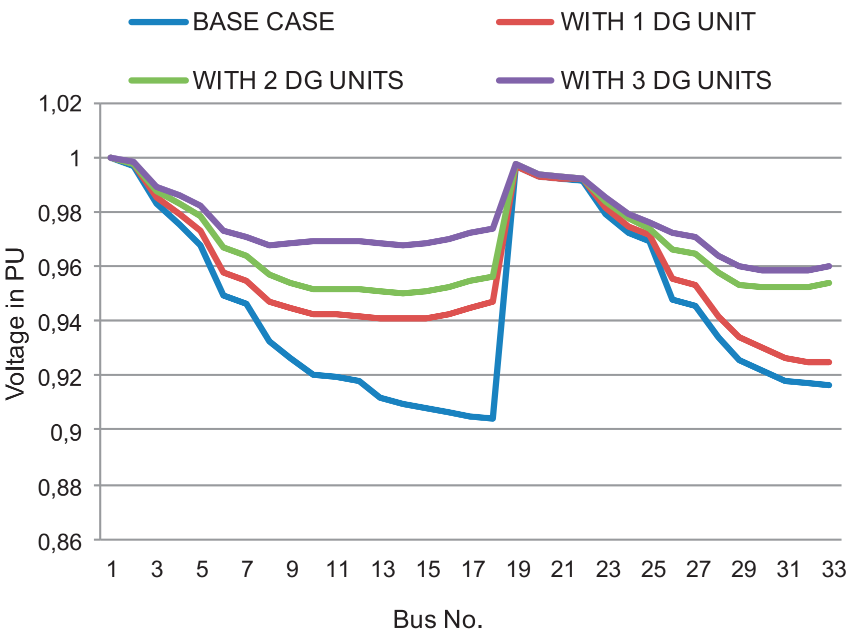

Fig. 1. Voltage profile of 33 bus system

Table 6. Energy losses and energy saving with DG units of 33 bus system

Loads	**Full load (P_D)**	**0.966 * P_D**	**0.806 * P_D**	**0.721 * P_D**	**0.612 * P_D**	**0.506 * P_D**
Time (hours)	1401	1586	1822	1577	1034	1340
Active power loss without DGs (kW)	210.0756	199.8448	155.8165	137.7264	116.3751	99.1465
Active power loss with DGs (kW)	93.2619	90.1508	79.4734	76.8647	75.9192	77.8068
Energy loss without DGs (kWh)	294315.92	316953.85	283897.66	217194.53	120331.85	132856.31
Energy loss with DGs (kWh)	130659.92	142979.17	144800.53	121215.63	78500.45	104261.11
Total energy saved with DGs (kWh)	163655.99	173974.68	139097.12	95978.90	41831.40	28595.20

b. Vastare practical 116 bus distribution system

The Vastare practical 116 bus is a primary radial distribution system (RDS) operating at 11 kV voltage. It has 116 buses and 115 lines [16]. The total active power load on the system is 2800 kW and reactive power load on the system is 1957 kvar. The base case losses of the system at different loading conditions are tabulated in Table 7.

Table 7. Losses of 116 bus system at different loading conditions

Losses without DG units		
Load	**Active power loss (kW)**	**Reactive power loss (kvar)**
Full load (P_D)	915.5021	707.3342
$0.966 \cdot P_D$	849.8834	656.6359
$0.806 \cdot P_D$	598.815	462.6557
$0.721 \cdot P_D$	499.4752	385.9039
$0.612 \cdot P_D$	398.6705	308.0203
$0.506 \cdot P_D$	323.5651	249.9925

The variation in an optimal location for the DG with respect to variation in load is tabulated in Table 8.

The energy losses after optimally allocating the DG units are tabulated in Table 9.

It is impractical to displace DG units every time as load changes. To overcome this problem the DG units are placed where the energy saving is maximum. As it is evident from the Table 9 maximum energy can be saved if DG is placed in the locations obtained with respect to a load of 0.966*P_D. Thus the optimal allocation of DGs is as shown in Table 10.

Table 8. Optimal allocation of DG units at different loads

Loads	**DG location (bus number)**	**Optimal DG size calculated (kW)**	**DG size (kW)**
Full load (P_D)	32	569.597	600
	108	465.0386	500
	73	293.0695	300
	113	216.0435	200
	99	184.2637	200
	54	173.2795	200
$0.966 \cdot P_D$	32	550.6565	600
	108	443.9087	400
	73	297.3492	300
	113	223.7434	200
	99	194.7273	200
	54	170.6132	200
$0.806 \cdot P_D$	32	461.5356	500
	108	370.3305	400
	73	233.0805	200
	113	178.8049	200
	99	140.7909	100
	54	145.0296	100
$0.721 \cdot P_D$	32	413.6863	400
	108	343.9129	300
	73	232.0463	200
	113	184.1138	200
	99	148.2553	100
	54	134.4292	100
$0.612 \cdot P_D$	32	351.6674	400
	108	274.5525	300
	73	173.0081	200
	113	118.091	100
	54	109.2327	100
	9	122.9139	100
$0.506 \cdot P_D$	32	290.6832	300
	108	234.5887	200
	73	160.808	200
	113	111.0759	100
	99	96.2467	100
	54	92.2367	100

Table 9. Energy losses without DG units and with DG units

Loads	**Full load (P_D)**	**0.966 * P_D**	**0.806 * P_D**	**0.721 * P_D**	**0.612 * P_D**	**0.506 * P_D**
Time (hours)	1401	1586	1822	1577	1034	1340
Active power loss without DGs (kW)	915. 5021	849.8834	598.815	499.4752	398.6705	323.5651
Active power loss with DGs (kW)	198.29	199.1039	193.252	190.7789	178.5169	177.5116
Energy loss without DGs (kWh)	1282618.44	1347915.072	1091040.93	787672.3904	412225.297	433577.234
Energy loss with DGs (kWh)	277809.19	315778.7854	352105.144	300855.0136	184586.474	237865.544
Total energy saved with DGs (kWh)	1004809.25	1103213.628	738935.786	486817.3768	227638.822	195711.69

Table 10. Optimal allocation of DG units based on maximum energy savings

Optimal allocation of DG units	
DG location	**DG size (kW)**
32	600
108	400
73	300
113	200
99	200
54	200

Table 11. Losses at different loading conditions with DG units

Losses with DG units		
Load	**Active power loss (kW)**	**Reactive power loss (kvar)**
Full load (P_D)	205.2218	158.5582
$0.966 \cdot P_D$	199.1039	153.8314
$0.806 \cdot P_D$	182.7962	141.2318
$0.721 \cdot P_D$	181.6599	140.3539
$0.612 \cdot P_D$	186.9341	144.4288
$0.506 \cdot P_D$	198.6376	153.4712

As it can be seen from Table 11 that at 60% and 50% loading conditions the losses are increasing, thus the last 2 allocated DGs are disconnected from the grid and used for charging purposes to use it later when needed. So the new losses when DGs are disconnected from the grid are tabulated in Table 12.

Table 12. Losses at different loading condition with DG units

Losses with 2 DG units used for charging		
Load	**Active power loss (kW)**	**Reactive power loss (kvar)**
Full load (P_D)	205.2218	158.5582
$0.966 \cdot P_D$	199.1039	153.8314
$0.806 \cdot P_D$	182.7962	141.2318
$0.721 \cdot P_D$	181.6599	140.3539
$0.612 \cdot P_D$	184.5968	142.6229
$0.506 \cdot P_D$	188.5376	145.6677

The total annual energy losses are calculated and tabulated in Table 13 after optimally allocating the DG units which are fixed and are not changed with the change in load.

Table 13. Energy losses and energy saving with DG units

Loads	**Full load (P_D)**	**$0.966 * P_D$**	**$0.806 * P_D$**	**$0.721 * P_D$**	**$0.612 * P_D$**	**$0.506 * P_D$**
Time (hours)	1401	1586	1822	1577	1034	1340
Active power loss without DGs (kW)	915.50	849.8834	598.815	499.4752	398.6705	323.5651
Active power loss with DGs (kW)	205.2218	199.1039	182.7962	181.6599	184.5968	188.5376
Energy loss without DGs (kWh)	1282618.44	1347915.07	1091040.93	787672.39	412225.29	433577.23
Energy loss with DGs (kWh)	287515.74	315778.78	333054.68	286477.66	190873.09	252640.38
Total energy saved with DGs (kWh)	995102.70	1032136.287	757986.25	501194.73	221352.20	180936.85

It can be seen from Table 13 that 3688709.025 kWh of energy can be saved annually.

Figure 2 shows the voltage profile of the system with and without DGs. It is clearly seen that on optimally allocating DG units there is considerable improvement in the voltage profile of the system.

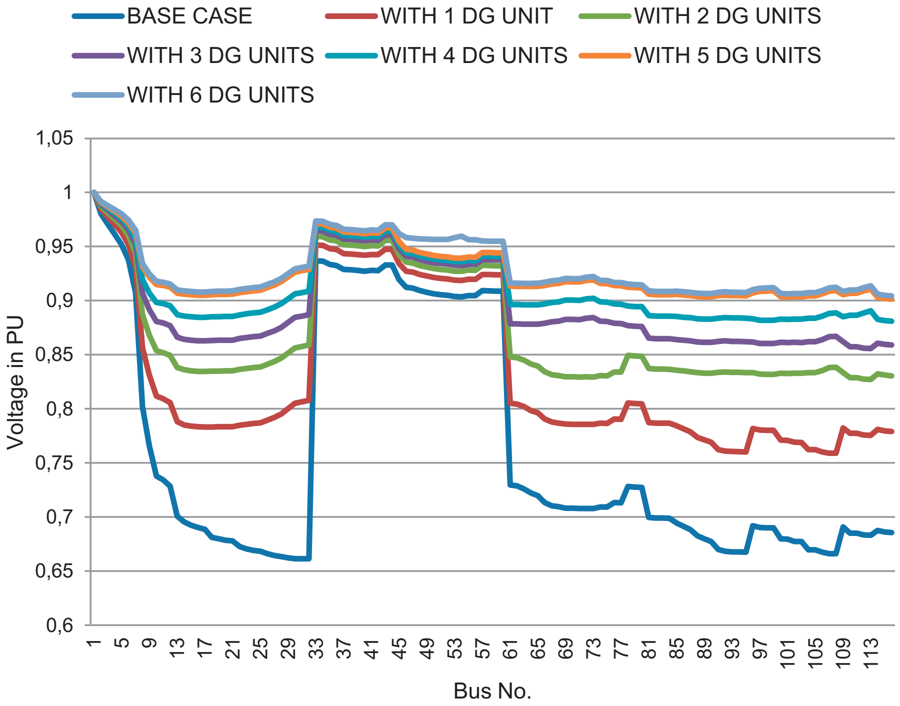

Fig. 2. Voltage profile of practical vastare 116 bus system

5. Conclusion

This paper introduces a methodology to reduce the system losses in distribution networks by optimum allotment of DG units considering the uncertainties in active power load. It is clearly presented that the optimal allocation of the DG unit considering only constant full load will not result in maximum energy saving. By considering the uncertainties in active power load, energy can be significantly saved. To validate the reduction in losses of the proposed method, simulation studies have been carried out on the IEEE-33 bus system and practical Vastare 116 bus system using MATLAB. The results show considerable energy saving when DG units are optimally allocated.

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