The Journal of CPRI,
Vol. 9, No. 4, December 2013 pp. 485-490

Energy Storage Sizing to Improve the Distribution Line Performance

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This paper presents a sizing methodology and optimal operating strategy for a battery energy storage system (BESS) to improve the operating efficiency of distributed networks. The alternate solution to network reinforcement is given by providing the optimal energy storage device. The targeted issues of loss reduction and possible local voltage control are investigated. The relation of feeder losses with requirements of the energy storage requirements are presented through mathematical modeling with actual distribution network parameters. This investigation is carried out with different types of the feeders viz. urban, rural and industrial. The case studies are presented with actual site data obtained from the Maharashtra State Distribution Company of India.

Keywords: *Energy storage, Modeling, Power distribution, Voltage control*

1.0 INTRODUCTION

The instantaneous supply of electricity must always meet the constantly changing demand. To meet this demand utilities involved from generation, transmission, & distribution sector are try to perform their task efficiently with full utilization of existing resources. Among the above sector, the distribution sector is more emphasize due to higher losses.

The distribution losses have been focused not only due to technical losses but also from environment and financial losses.

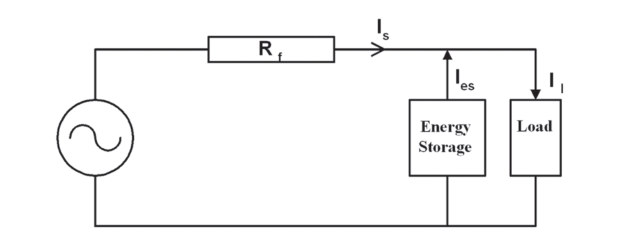

FIG. 1 DISTRIBUTION SYSTEM WITH ENERGY STORAGE

The reduction in distribution losses result in the reduction of CO_2 emission because "The saving of 1 unit at consumer end result in saving of 2 unit at generation". The recent area of research at distribution level is minimum loss configuration problem. A power loss in distribution feeder is also reducing rated capacity of electrical components because heat produce due to losses rise temperature and result in thermal overloading of feeder and electrical components. By reducing the power losses, the system becomes reliable and extend period of service. Therefore, loss minimization in distribution systems has become the subject of intensive research.

The distribution losses can be divided in real power loss & reactive power loss. These losses can be identified by performing load flow in distribution network. The loss reduction in distribution network by reconfiguring network can be done with optimal switching [1]. In distribution feeder total I^2R loss is reduce by reducing it's individual component i.e. real power loss is reduce by reconfiguration and reactive power

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loss is reduce by optimizing location of capacitor placement [2]. Energy storage can be use for peak shaving of load. The shifting of load from peak to off-peak period can reduce distribution loss [3]. The various energy storage devices are compared and among them batteries are more reliable & cost effective compare to other storage devices. The larger battery systems called Battery Energy Storage Systems (BESS) do not have the environmental challenges of other technologies. These systems can often be installed within a 12 month time frame. [4]. G. Koeppel has mentioned in [5] that a local storage device can be used to shave load peaks according to different objectives such as technical, economical and reliability. He has suggested peak shaving of load with storage device instead of network reinforcement. The storage device would be dimensioned in a way that it could supply the difference between the load demand and feeder capacity. The storage is dimensioned due to reliability requirement but can not motivate for loss reduction. Alexander Oudalov has mentioned in [6] a method to find the optimal battery energy storage capacity and power for a peak load shaving application. This method assess a customer load profile, finds the optimal battery size which provides an electricity bill reduction. M. A. Kashem & G. Ledwich has addressed voltage support in distribution system by energy injection from a battery storage distributed energy system. An operation strategy for an inverter interface battery energy storage DER has been developed for maximum improvement in feeder voltage with minimum energy injection from the DER [7].

The conventional method for loss minimization in distribution feeder is feeder reconfiguration but effectiveness of the method is restricted to reconfiguration of the load without consideration of the effective utilization of the feeder limits. Since these losses are proportional to square of the current flow, the part of current during overload period of feeder can be supplied through energy storage which is located near to the load. The under load condition can be use to charge energy storage. The integration of energy storage with feeder is result in rated current flow through the feeder.

2.0 MODELING OF DISTRIBUTION NETWORK

2.1 General Model of Distribution Network

A model shown in Figure 1 is a single line diagram of radial distribution system supplied by central generation. The loss in distribution feeder is

$$I^2_S R_f \qquad \text{....(1)}$$

Where

I_s = source current

R_f = feeder resistance

I_l = load current

I_{es} = Current supplied/drawn byenergy storage

2.2 Loading Trend of Distribution Feeder

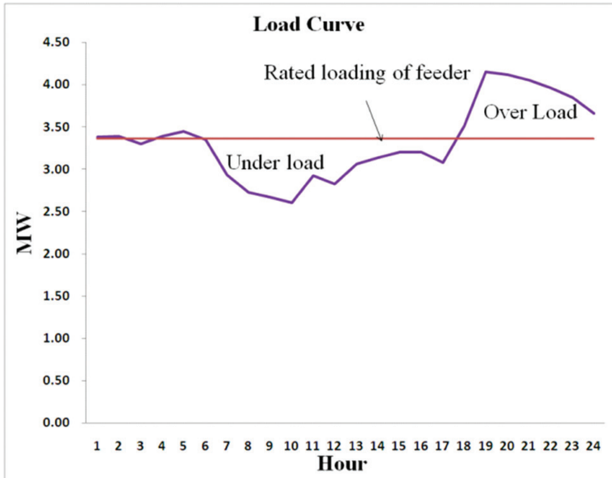

FIG. 2 LOADING PATTERN OF FEEDER

A daily load curve of a feeder is shown in Figure 2. The overload & under load condition of feeder with reference to rated loading capacity of feeder is indicated in load curve. It is observed from Figure 2 that feeder is overload from 4% to 23% in duration 18 hrs to 24 hrs and underload from 0.5% to 22% in duration 6 hrs to 17 hrs.

In overload condition energy storage supply the current to maintain feeder loading at rated capacity. The current supplied by energy storage is

$$I_{es} = I_l - I_s \qquad \text{....(2)}$$

In underload condition energy storage draws the current to charge storage device and maintain feeder loading at rated capacity. The current drawn by energy storage is

$$I_{es} = I_s - I_l \quad \text{....(3)}$$

3.0 PERFORMANCE INDICES FOR THE DISTRIBUTION NETWORK

The performance of distribution feeder by incorporating energy storage can be evaluated from loss reduction. The total feeder loss with and without energy storage during overload and underload condition can be consider as

$$L = I_o^2 R_o t_o + I_u^2 R_u t_u \quad \text{....(4)}$$

$$L_s = (I_o - I_{es})^2 R_o t_o + (I_o + I_{es})^2 R_u t_u \quad \text{....(5)}$$

Where

L = feeder loss without energy storage

L_S = feeder loss with energy storage

R_o, R_u = feeder resistance during overload and under load periods

I_o,I_u = load current during overload and under load periods

I_{es} = current supplied/drawn by energy storage

η = efficiency of storage system

t_o = discharge time of storage during overload

$t_u = t_o/\eta$ charge time of storage during underload

The loss reduction in feeder due to energy storage can be calculated from equation (4) and (5) is

$$L - L_s = R_o I_o I_{es} t_o \left\{2 - \left(\frac{R_u}{R_o}\right)\left(\frac{I_u}{I_o}\right)\left(\frac{1}{\eta}\right) - \left(\frac{R_u}{R_o}\right)\left(\frac{I_{es}}{I_o}\right)\left(\frac{1}{\eta}\right)\right\} \quad \text{....(6)}$$

Substituting

$a = I_{es}/I_o$

$b = R_u/R_o$

$c = I_u/I_o$

$$L - L_s = aR_o I_o^2 t_o \left\{2\left(1 - \frac{cb}{\eta}\right) - a\left(1 + \frac{b}{\eta}\right)\right\} \quad \text{....(7)}$$

The normalization of saved losses with respect to losses without storage is

$$\frac{L - L_s}{L} = a\frac{2\left(1 - \frac{cb}{\eta}\right) - a\left(1 + \frac{b}{\eta}\right)}{1 + \frac{c^2 b}{\eta}} \quad \text{... (8)}$$

The ratio of feeder loss without storage to the overload current is

$$d = \frac{L}{I_o} \quad \text{....(9)}$$

Rewriting equation (8) as saved losses to the overload current as

$$\frac{L - L_s}{I_o} = ad\frac{2\left(1 - \frac{cb}{\eta}\right) - a\left(1 + \frac{b}{\eta}\right)}{1 + \frac{c^2 b}{\eta}} \quad \text{....(10)}$$

It is observed from (10) that it is a parabolic function so saved in feeder loss will decrease after some peak value of storage size. This point of maximum storage size can be express with reference to difference in peak of overload and underload curve.

$$\frac{Max.Storage\ Size}{I_o - I_u} = \frac{\left(1 - \frac{cb}{\eta}\right)}{(1 - c)\left(1 + \frac{b}{\eta}\right)} \quad \text{....(11)}$$

To justify saved in feeder loss for size of energy storage, a (10) can be written as a function of energy storage size

$$\frac{L - L_s}{I_{es}} = d\frac{2\left(1 - \frac{cb}{\eta}\right) - a\left(1 + \frac{b}{\eta}\right)}{1 + \frac{c^2 b}{\eta}} \quad \text{....(12)}$$

The application of energy storage at multiple sites has considerable increment in saved feeder loss and equation for increase in saved losses with N no of sites is

$$\text{Increase in saved losses} = \frac{2\left(1-\frac{cb}{\eta}\right)-a\left(1+\frac{b}{\eta}\right)/N}{2\left(1-\frac{cb}{\eta}\right)-a\left(1+\frac{b}{\eta}\right)} \qquad ....(13)$$

4.0 CASE STUDY FOR DIFFERENT TYPES OF DISTRIBUTION FEEDER

Table 1 indicates hourly load variation and average loading on the rural, urban and industrial feeder. A column load in Table 1 is average loading of feeder for a week in specific hour. The rural feeder has minimum loading 2.60 MW & maximum loading 4.14 MW likewise urban feeders has minimum 0.80 MW & maximum 2.18 MW, industrial feeder has minimum 1.50 MW & maximum 2.03 MW. The ratio of minimum load to maximum load is indicated in last raw of Table 1.

The daily load curve for rural, urban and industrial feeder is shown in Figure 3. To maintain feeder loading profile constant over the period, average loading on the feeder is to be consider as a reference loading level. It is observed that overloading period on the urban feeder is larger than the rural and industrial feeder.

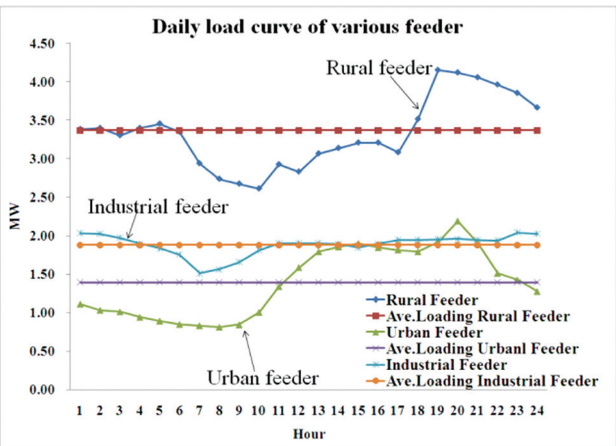

FIG. 3 LOADING PATTERN OF VARIOUS FEEDERS

TABLE 1

FEEDER DATA

11 Kv Feeder Hourly Data Nagpur Zone

Feeder Name	Kamptee I		Gokul Peth		MIDC I	
Type of feeder	Rural		Urban		Industrial	
Hour	Load (MW)	Ave. Load (MW)	Load (MW)	Ave. Load (MW)	Load (MW)	Ave. Load (MW)
1	3.38	3.36	1.11	1.39	2.03	1.87
2	3.39	3.36	1.02	1.39	2.02	1.87
3	3.30	3.36	1.00	1.39	1.96	1.87
4	3.39	3.36	0.93	1.39	1.89	1.87
5	3.45	3.36	0.88	1.39	1.83	1.87
6	3.34	3.36	0.84	1.39	1.75	1.87
7	2.93	3.36	0.82	1.39	1.50	1.87
8	2.73	3.36	0.80	1.39	1.56	1.87
9	2.67	3.36	0.84	1.39	1.65	1.87
10	2.60	3.36	1.00	1.39	1.80	1.87
11	2.92	3.36	1.33	1.39	1.89	1.87
12	2.82	3.36	1.58	1.39	1.89	1.87
13	3.06	3.36	1.78	1.39	1.89	1.87
14	3.13	3.36	1.85	1.39	1.88	1.87
15	3.20	3.36	1.89	1.39	1.84	1.87
16	3.20	3.36	1.84	1.39	1.89	1.87
17	3.08	3.36	1.81	1.39	1.94	1.87
18	3.51	3.36	1.78	1.39	1.94	1.87
19	4.14	3.36	1.91	1.39	1.95	1.87
20	4.11	3.36	2.18	1.39	1.95	1.87
21	4.05	3.36	1.89	1.39	1.94	1.87
22	3.96	3.36	1.50	1.39	1.93	1.87
23	3.85	3.36	1.42	1.39	2.03	1.87
24	3.66	3.36	1.27	1.39	2.02	1.87
Under load to over load ratio	0.6280		0.3694		0.7397	

To quantify saving in feeder loss following parameters are consider from [3].

i. Ratio of feeder resistance in under load to feeder resistance in overload is b = 0.9 & 0.8

ii. Ratio of feeder loss without storage to the peak overload current is d = 0.12

iii. Storage efficiency η = 85% & 79%

In Table 2 comparison of various feeders for overload and under load period is shown. It is observed that overloading period in industrial feeder is larger than other feeders but difference between peak of overload & under load period is less so the saved in feeder loss due to energy storage is less than other feeders.

TABLE 2

FEEDER ANALYSIS

Feeder	I_o-I_u	$t_{o(hr)}$	$t_{u(hr)}$	c= I_u/I_o
Rural	1.54	10	14	0.6280
Urban	1.37	12	12	0.3694
Industrial	0.53	17	7	0.7397

The saved in feeder loss with respect to peak of overload from (6) is plotted in Figure 4.

A Urban feeder

It is observed from Figure 4 that, %saved in feeder loss is maximum for storage size of 30% of peak overload value. The maximum saved losses is 1.9% of peak of overload value. If we further increase storage size than there is decrease in saved losses i.e losses increases.

B Rural feeder

It is observed from Figure 4 that, %saved in feeder loss is maximum for storage size of 16% of peak overload value. The maximum saved losses is 0.4% of peak of overload value. If we further increase storage size than there is decrease in saved losses i.e losses increases.

C Industrial feeder

It is observed from Figure 4 that, % saved in feeder loss is maximum for storage size of 10% of peak overload value. The maximum saved losses is 0.2% of peak of overload value. If we further increase storage size than there is decrease in saved losses i.e losses increases.

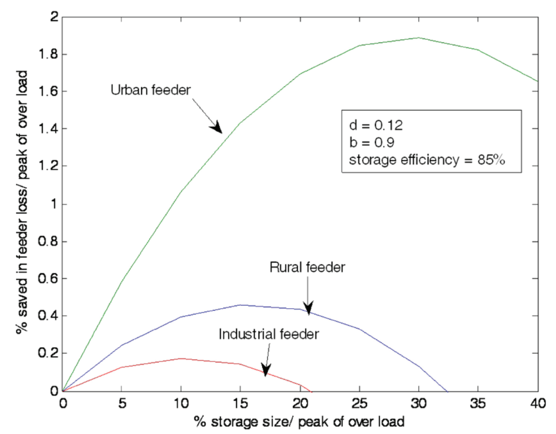

FIG. 4 SAVED IN FEEDER LOSS AS % OF PEAK OF OVER LOAD

5.0 ENERGY STORAGE LOCATION AND IT'S EFFECTIVENESS

The energy storage location has dominant role in feeder loss saving. A quantifying result of (9) for various feeders is shown in Figure 5. There are 10 sites consider for location of energy storage with equal capacity. It is observed that the overload compensating benefit is higher in initial stage.

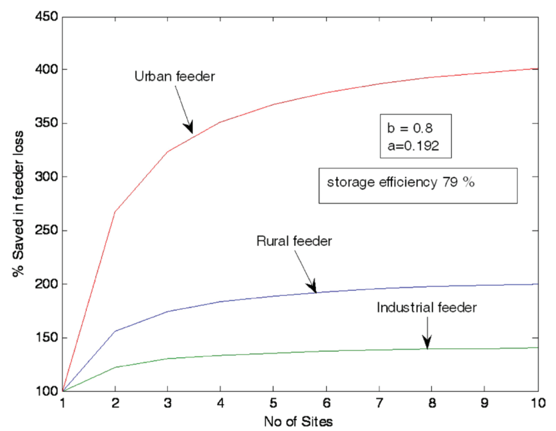

FIG. 5 INCREASE IN % SAVED FEEDER LOSSES FOR MULTIPLE SITES STORAGE

6.0 CONCLUSION

The energy storage using BES has been proved to be beneficial in the improvement of distribution performance. The storage size for which feeder loss occurs maximum is around 30%, 16 % and 10 % of the peak overload value for the urban, rural and industrial feeders respectively. The optimal storage size for the each type of the feeder is obtained from the given mathematical model. The estimates for the loss saved in the urban, rural and industrial feeder is 1.9%, 0.4% and 0.2 % respectively. The test data from the distribution network is used to identify the more realistic estimates.

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