Evaluating the Application of BESS for Peak Load Management of a Distribution Transformer

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***Abstract*—**
The Indian electricity sector is undergoing a significant transition with increasing share of variable renewable energy (VRE) in the system. This, coupled with an annual increase in peak demand could put significant stress on the distribution network. The role of battery energy storage systems (BESS) thus becomes important for distribution network applications such as voltage regulation and peak shaving. With high summer peaks, distribution networks with high penetration of solar rooftop PV systems (SRPV) tend to have a low load factor. This has an impact on rate of loss-of-life of equipment, especially distribution transformers (DTs) and thus for such feeders, the non-reduction in augmentation/replacement costs on these components offsets the benefits of load reduction through SRPV. There are certain factors which affect the health/life of DTs (1) Overloading (2) Non-linear load operation (3) Poor maintenance are among the prominent ones. Overloading is a major cause of DT failure (failure rate in India is around 12 to 15 %) particularly in urban areas where the population growth is high. The overloading of a DT can be prevented by deployment of BESS at its secondary side, thus preventing DT augmentation. This study tries to evaluate the need for BESS at the distribution level to defer investments on DT augmentation and reduce DT failure while increasing the DT life. This application along with energy arbitrate could make BESS viable at the distribution level. A control logic developed for the battery monitoring system along with detailed cost benefit analysis under various scenarios has been reported in this study.

***Keywords*— Battery energy storage system, Distribution transformer, Cost Benefit Analysis**

I. INTRODUCTION

The power sector in India is under a transition stage towards clean technologies coupled with measures to improve grid discipline. Rising demand with increasing variability of net load with advent of solar rooftop PV and EVs could result in changing demand pattern with increasing peak-demand. Meeting the periods of peak power demand puts an additional financial burden on the distribution utilities apart from the technical up-grades required at distribution level. The process of distribution network up-gradation becomes even more difficult and expensive in congested areas and in the case of an under-ground cable network.

A number of measures are being adopted by utilities to reduce or shift the peak power consumption and manage the system overload. Demand Response (DR) programs are being run to encourage customers to shift their consumption to off-peak periods by incentivizing them since a Time-of-Use (ToU) tariff structure exists in many countries. Even though DR improves the utilization ratio of a DT, it may lead to shifting of the overload to a new period [1], if not planned and executed optimally.

BESS could provide a reliable solution to this problem of overloading by integrating with the distribution network. It has wide range of applications in power systems, for example; peak shaving, load balancing, voltage regulation [2], frequency control, uninterrupted power supply and facilitating smoother integration of distributed energy resources [3]. BESS installed at secondary side of a DT can charge during its under-loading instances and discharge during over-loading instances. This application can be termed as peak-shaving at DT level. Such an application can result in additional savings on the costly peak –power purchase (subject to coincidence with utility load-curve) along with savings in terms of investment deferral in replacing or augmenting the DT. Optimal BESS sizing for peak shaving application and assessment of utility side cost savings from battery energy storage has been addressed in [4], [5] and [6]. For the overload management and peak shaving application at a DT, it is desirable to mitigate all the overload instances in order to defer the investments in replacement or augmentation of the DT. However, this merits a detailed analysis from the techno-economic BESS sizing point of view.

This paper assesses the viability of installing BESS at the secondary side of a DT to defer investments on its augmentation and reduce the failure by managing the overload. A comprehensive detailing of BESS sizing, development of operational logic and corresponding cost-benefit analysis under various scenarios has been explained in this paper.

II. PROPOSED METHODOLOYGY

A. Characteristics of the DT Selected

The distribution utility considered under this study operates at 6 kV level as well as at 11 kV-level in the Eastern part of India. The local LT consumer supply is fed through 6 kV/420 V and 11 kV/420 V DTs.

The initial step was to identify a suitable DT which is overloaded so as to establish the feasibility of installing a BESS to manage the over-loading. A site-survey was conducted in the utility licensee area and a particular DT was shortlisted based on its overloading status.

The DT is a part of a 6.6 kV feeder that passes through a congested locality of a major metropolitan area in Eastern

India. The 315 kVA (6 kV /420 V) DT supplies residential premises and a few commercial buildings. The peak demand on the feeder occurs in the summer months. The load curve of the DT for a typical peak load day i.e. June 18 is shown in Fig. 1. Also shown on the same figure is the utility load curve. It can be seen that the DT load curve follows the same pattern as the utility load curve as seen on June 18, 2018, the peak day of the year.

This distribution utility identifies a transformer to be overloaded if its loading is greater than or equal to 120% of the rated capacity for consecutive two hours for any 7 days in a month. As a measure, the utility traditionally adopts the following steps to resolve the persistent overloading on any of the existing DTs:

(i) Load shifting through LT network: Shifting a certain amount of load to other existing DTs on the feeder.

(ii) Capacity addition by installing new DT: If the load cannot be transferred to the nearby DTs due to LT network congestion, then a strategic location is identified to install a new DT near a common load center of the overloaded DT. The new transformer will not only relieve the concerned overloaded DT but will also provide better load management during an outage condition by supplying some part of the area.

In case the above two options stand to be infeasible, the utility has to resort to augmentation of the existing overloaded DT. This results in replacing the existing DT with another one of higher capacity. In the case presented in this study, the utility had planned for a 500 kVA (680 A) DT to replace the existing overloaded 315 kVA DT. The loading on this DT was analyzed to find whether it qualifies to be overloaded as per the utility's criteria.

B. Analysis of overloading on the selected DT

Overloading of the DT was analyzed as per the criterion followed by the utility. However, a threshold of 80% of the rated capacity was taken as the change in demand pattern of DT in future years was not assessed under this study. The threshold of 80% of rated capacity was decided in consultation with utility.

As per the overloading condition criteria adopted for the study, the DT was found to be operating in overloaded conditions continuously for two or more than two hours for a total of 7 days in the month of June (26% of the time in a year, in the month of June). Later, in the results section, an analysis has been presented that shows when, after the installation of BESS based on present year loading, the DT would be overloaded again if different trajectories of Compound annual growth rate (CAGR) in load-growth are followed.

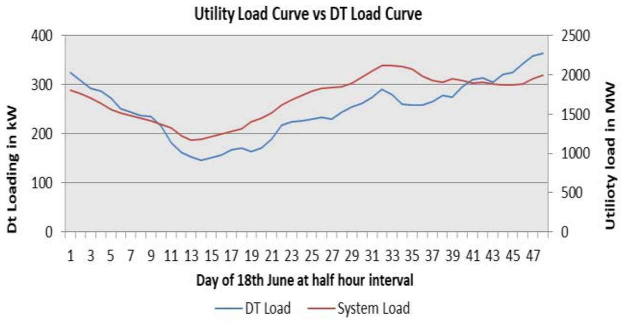


Fig. 1. DT and utility load curve for June 18

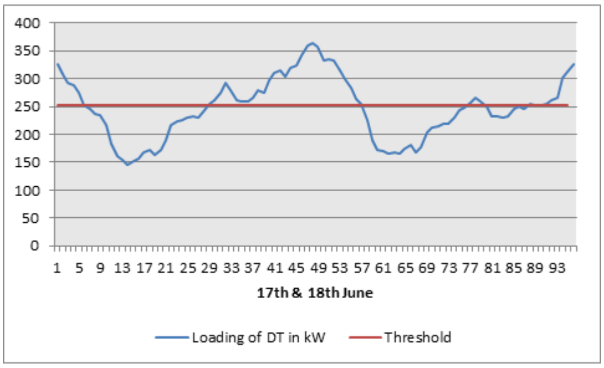


Fig. 2. DT loading curve for June 17 and 18

The maximum continuous overloading duration was found to be 14.5 hours on the 17th & 18h day of the month of June as shown in Fig.2. It can be seen again that the DT has been operating under overloaded conditions.

III. BESS SIZING

The sizing of the BESS for the DT overload management application involved determining two quantities: Battery size in kWh and the inverter/power converter unit rating in kVA. The sizing of these two invariably depends upon the level of peak-shaving required at the DT. The sizing was done in two steps to arrive at the final rating of the BESS:

1) Preliminary sizing: Based on the total energy contained in the overload instances throughout the year to estimate the energy capacity as the rough size

2) Detailed sizing: To rank all the overload instances according to their peak over-shoots and identify whether the size obtained in step 1 is sufficient to completely meet all instances of overload i.e. sufficient charging time is available to bring the battery to a SoC level sufficient to meet the next duration of overload. The following sub-sections explain each step.

A. Preliminary Sizing

The basic sizing was done based on the loading data of the DT provided by the utility. Time-series loading, as recorded from the DT meter, for 1 year at 30-minute time interval was made available. Hence, a total of 17520 (8760 × 2 values) rows of kVA values sampled at 30 minutes interval were analyzed in a spreadsheet for pre-processing. Since no solar PV generation was present, these 17520 values of DT loading corresponded to the gross load P_{Gross}. Linear interpolation was used to refine the sheet with any inconsistent recordings. Accordingly, the gross load for the present situation was calculated for use in the study.

An over-load check flag K(t) was set up to check for the instances of overload P_{OL} = Loading - P_{shave}. K(t) was set up for each loading instant t such that K(t) =1 whenever P_{OL} = 1 else it is zero. A parameter *TOL(j)* defines the total number of overload instances in a year when j=1which corresponds to the sum of continuous overload instances), and which has other values for overload periods that correspond to *j*=2,3,4 etc. This parameter is calculated as in (1) for an overload period *j*

$$TOL(j) = \sum_t^N K(t) \tag{1}$$

which holds true for t=17520, K(t)=1, K(t+1)=1, K(t-1)=0 and t=1. For every overload period *j*, the overload duration is calculated as in (2)

$$OLD(j) = TOL(j) - TOL(j+1) \tag{2}$$

This formulation makes it very clear that the amount of energy E_{OLj} contained in an overload period starting from instance *t* can be calculated as in (3)

$$E_{OLj} = \sum_t^{OLD(j)} P_{OLt} \times T \tag{3}$$

Here, T equals 0.5 h as duration of a period starting from each instance. The initial battery size was thus calculated by considering the DoD and overall system efficiency η for a Lithium-ion based BESS and was derived from (3) using (4) as

$$E_{initial} = \frac{max.(E_{OLj})}{DoD \times \eta} \tag{4}$$

B. Detailed Sizing

It is not techno-economically feasible to cater to all instances of overload by a BESS. Also, the number of loading instances must be categorized based on the loading of the DT and the charging rate so that BESS charging does not overload the DT. Based on the sum of the instantaneous charging rate $C_{kW}(i)$ and DT loading, a loading instance can define the operation whether to charge, discharge or remain idle. A comparison with the P_{shave} can always help in categorizing. Accordingly, the state of charge remaining in the battery and the unmet demand for each instance $E_u(t)$ was considered in the calculations to determine the optimal battery size so that an optimum number of overload instances are met. However, for the same, the instances were ranked based on the most prominent peak-overshoots among the overload instances. Considering all these parameters, the C_{kW} was adjusted in an iterative process until the E_u over the year reaches a set predefined value, based on the allowable hours of demand un-served. Utilizing this iterative process, the optimal BESS size for the present year calculations was obtained to be 231 kWh and the maximum power required during an overload period was taken as the PCU size which was found to be 157 kW.

IV. BESS CONTROL METHODOLOGY

The proposed methodology aims to reduce the stress on the DT by placement of BESS at the LT side. The selected DT for this particular study is rated at *315 kVA* and placed in licensee area of a privately owned distribution utility. It has been recommended by the state electricity regulatory commission to operate these DTs below 105% of the rated capacity to restrict the thermal loading. BESS can play an important role in ensuring that the aforementioned criteria are met for reducing the thermal stress of a Tithe operation of BESS for overload management will depend on the shave level of DT. A shave level is defined (*105%* of *315 kVA*) for battery to discharge and support the DT so that thermal stress can be reduced up to certain extent. The charge and discharge operation of BESS shall depend on the energy remaining in the battery and net loading of DT. It is therefore essential to monitor these parameters (SoC and net loading of DT) in real-time in order to evaluate the reference values (C-rate) for charge/discharge of the battery pack. BESS will be discharged when net loading of the transformer exceeds the 80% of the rated capacity as depicted in Fig.2. To prevent the battery from deep discharge, it is suggested to interrupt the discharging process when SoC of battery pack drops below 20%. Rate of discharge will be determined based on the real-time power flow from DT and the defined shave level as shown in (3). Battery SoC is evaluated based on coulomb counting method as expressed in (4).

$$P_{shave} = 105\%\ of\ 315\ kVA = 330.75\ kVA \tag{3}$$

$$P_{net} = (P_L - P_{solar}) \tag{4}$$

$$I_{discharge} = \frac{P_{net} - P_{shave}}{V_b} * 1000 \tag{5}$$

Where, $I_{discharge}$ is current flowing from battery in ampere, P_L is the load power in *kVA*, P_{solar} is solar PV output power in *kW*, P_{shave} is shave level at DT level in *kVA* and V_b is the battery voltage in *volts*.

SOC is expressed as in (6),

$$\%\,SOC = \left(1 - \frac{\int I(t) * dt}{Q}\right) * 100 \tag{6}$$

I(t) is battery current in ampere and *Q* is battery rated capacity in ampere-hour.

BESS will be charged when the loading of DT is lower than its rated capacity and the rate of charge is expressed in (7). There are two modes of charging that are suggested to prolong the battery life and these are as follows; (I) Constant current (CC) mode till 80% SOC and (II) Constant voltage mode from 80% to 95% of SOC. The charging rate in constant voltage (CV) mode is generally much lower than the C-rate in constant current (CC) mode. Hence, charging time in CV mode will be comparatively higher than the CC mode of charging.

$$I_{charge} = \frac{P_{shave} - P_{net}}{V_b} * 1000 \tag{7}$$

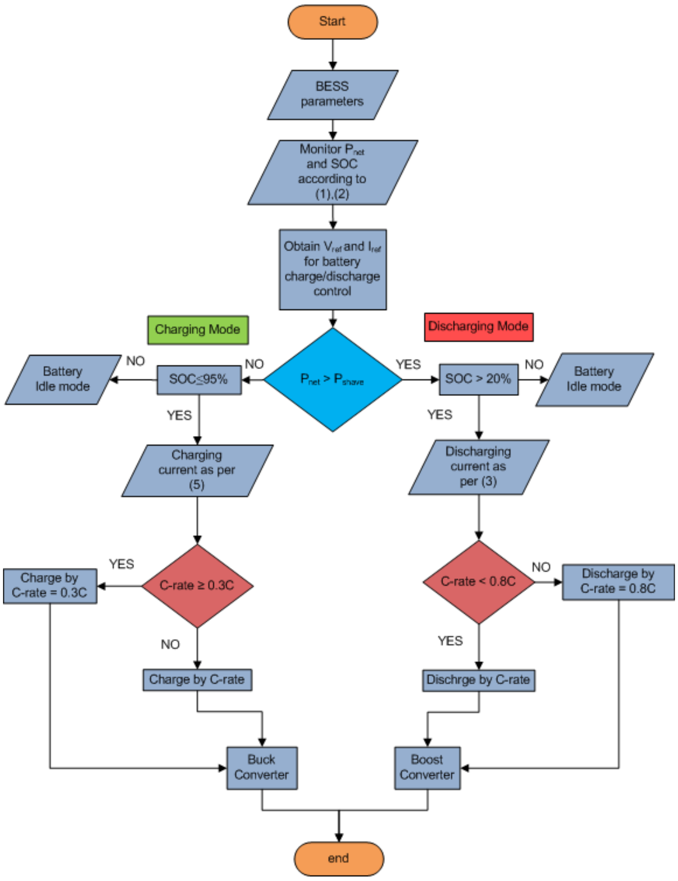


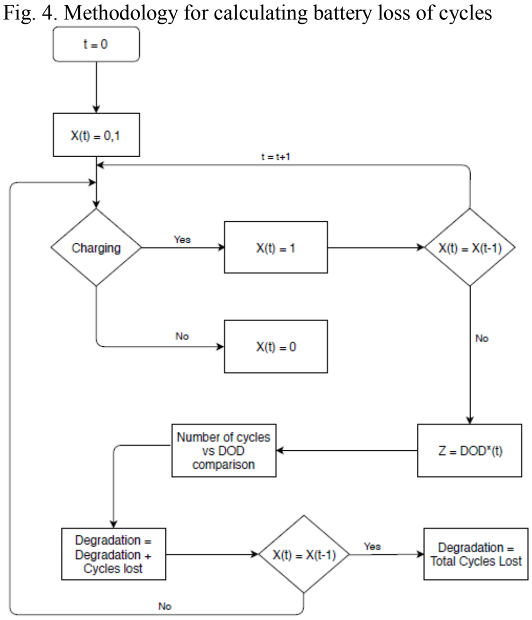
Fig. 3. Flow chart for battery charge/discharge control methodology

Charge/discharge rate limitations have also been proposed in this study for safe operation of the battery pack as high rate of charge or discharge may lead to hazardous impact on the overall system as battery state of health depends on the rate of charge/discharge. It is therefore proposed to limit these values and if it exceeds the limiting value then the rate will be fixed at those limiting values (0.3 C in charging mode and 0.8 C during discharging as depicted in flow diagram).

Battery DoD at every instance was calculated and thus actual loss in BESS cycles as a result of the desired application was calculated as shown in flow chart in Fig. 4. Considering the cumulative loss in cycles, battery was found to operate for a life of more than 15 years. Since battery operated only 6% of total annual instances. The Cost-Benefit Analysis (CBA) was performed for a life of 10 years, considering the life of inverters and other associated equipment.

The BESS sizing was done for the present or the base-year

Fig. 4. Methodology for calculating battery loss of cycles



(2018) loading curve considering a load CAGR of 1% in consultation with the utility officials to ensure sufficient battery capacity to defer augmentation of the DT by 10 years.

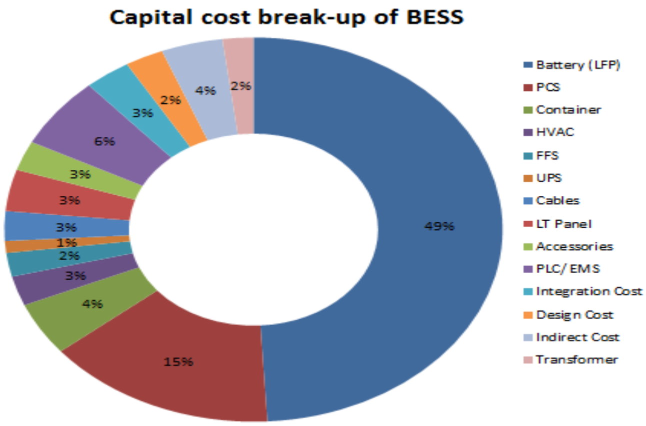
The next section describes the methodology adopted for performing the cost-benefit analysis for the BESS in view of the DT overload management application. A detailed 4quantification of benefits in terms of financial performance indices is presented in section VI.

V. Cost-Benefit Analysis

Despite batteries' falling prices, their high upfront cost is looked at as an impediment to large-scale deployment. However, life cycle economic assessment of any battery storage system is important before arriving at any conclusion. A prima facie cost-benefit analysis is performed investigating plausible revenue streams against levelised cost of battery storage.

The approach for cost and benefit analysis can be explained in the following steps:

1. Capital cost is segregated under various segments such as Battery packs cost, safety container cost, integration cost, cables cost, O&M cost etc. The capital cost can be broken as under:



2. Each cost segment was divided into power and energy cost. Energy cost changes with kWh rating of the BESS and power cost changes with power rating. For example, battery packs cost is an energy cost and PCS/UPS cost is a power cost. Some cost such as Fire-fighting system cost is proportionally allotted under both heads. Hence, total capital cost becomes the function of both power and energy rating of BESS.
3. Plausible revenue streams such as investment deferral, savings in terms of peak power purchase, savings in terms of reduced deviation penalties etc. were identified
4. All revenue streams are analyzed to understand their applicability in the distribution system. All revenue streams may not be added together as one revenue stream has to be selected on the expense of not considering other. Thus, a decision to add specified revenue streams may differ on case to case basis. Revenue streams and costs considered are shown in Table I.

Table I: Cost-Revenue stream matrix

Costs	Revenue streams	Quantified
ROE	Investment deferral	Yes
Interest on loan	Savings in peak power purchase	Yes
Depreciation	Reliability Improvement	No
O&M	Increased life of DT	Yes
Interest on WC	Avoiding DSM penalties	No

Additional benefits such as residual value of 20%, accelerated depreciation of 40% and funding support of 20% has also been assumed.

5. Selected revenue streams are stacked together and evaluated against cost on year to year basis under a set of financial and technical assumptions such as discount factor, capital structure, roundtrip efficiency, auxiliary consumption of the application i.e. peak-shaving in this case etc. as shown in Table II

Table II: Set of technical and financial assumptions

Project Parameters	Values	Units
Energy output required	230	kWh
Designed Energy capacity	302	kWh
Designed Power capacity	157	kW
Plant Life	10	Years
Battery Cost	250	USD/kWh
Total capital investments	24,462,122	INR
After VGF capital investments	17,123,485	INR

Technical Parameters	Values	Units
Depth of discharge	90%	
System efficiency	90%	
Auxiliary Consumption	1%	%
SOH	95%	%
Life in number of cycles	3000	
Number of cycles per day	1	
Energy required to charge the BESS annually	165,298	kWh
Energy output from the BESS annually	125,925	kWh
Peak and Off-peak price difference	3.5	INR/kWh
BESS Degradation Factor	0.5%	%
End of the Project Value	20%	%

Financial Parameters	Values	Units
Current exchange rate	66.40	INR/USD
Debt	70%	%
Equity	30%	%
Interest Rate	12%	%
ROE	14%	%
Tax	33%	%
Interest on Working Capital	13.5	%

Net present value can be calculated using the formula below.

$$NPV = \sum Capital\ (p) + \sum Capital\ (e) + \sum_{0}^{t} \frac{Revenue\ Streams}{(1+r)^\wedge t} + \sum_{0}^{t} \frac{Additional\ Savings}{(1+r)^\wedge t} - \sum_{0}^{t} \frac{O\&M}{(1+r)^\wedge t}$$

Here,
Capital (p) = Capital cost associated with power rating of Inverter (INR)
Capital (e) = Capital cost associated with Energy rating of BESS (INR)
r = Discount rate (%)
t = Life time of the project in years

The cost-benefit analysis of BESS depends on various factors such as BESS application, technology, government support towards technology implementation (through viability gap funding and associated funds), land availability (whether taken on lease or purchased) and other location-specific factors. Hence, a case based approach should be adopted to perform (CBA) for more accurate results. Battery prices are continuously falling; therefore, it is essential to compute results under present and envisaged future cost after two to three years. Therefore, appropriate time to invest in BESS should be selected.

VI. Results

The size of the BESS for the present loading conditions and the associated benefit to cost weightage was calculated and described in the respective sections above. However, taking into consideration the estimated number of cycles that a BESS will last for the presented application, it is important to project when the DT may get overloaded again, even after installation of a BESS and what would be the number of years of deferring the DT's augmentation. Accordingly, the size required to manage the overload and the associated benefits (and costs) will change and must be projected for different CAGR of loading on the DT. This would depend on the CAGR in load and hence different scenarios of CAGR trajectory are important to study.

Fig. 6 shows the CAGR based loading analysis of the DT and what year will the threshold be crossed if different growth trajectories are followed. The number of instance shown on the y-axis represents the number of days in a month where overloading is observed. This relates to the overloading criteria of the utility which says that any 7 days of above 80% loading for 2 consecutive months qualifies a DT to be overloaded. Accordingly, the threshold of 7 days has been marked as a red colored horizontal line on the curve. It can be seen that at a CGAR of 5%, the DT becomes overloaded in the 7th year and the number of such instances increase in a linear fashion.

Fig. 7 shows the required BESS size for meeting the overload instances and the corresponding cost-benefit ratio and the project NPV to quantify the anticipated benefits for different scenarios of CAGR.

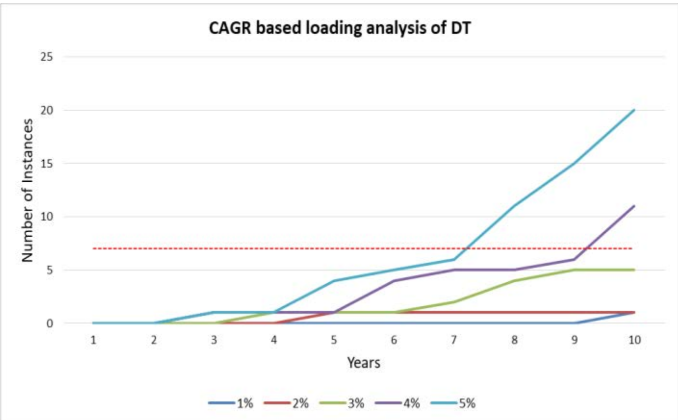


Fig. 6. DT overloading for base-case BESS for different CAGRs over a horizon of 10 years

												@250 $/kWh	
CAGR/ Year	1	2	3	4	5	6	7	8	9	10	BESS Rating kWh*/kW*	NPV	Cost to Benefit Ratio
1%											231/71	(7,852,244)	0.57
2%											231/112	(9,821,100)	0.53
3%											231/157	(11,922,117)	0.49
4%											300/208	(15,383,420)	0.49
5%											860/262	(24,580,202)	0.57
estimated as per the present loading conditions i.e. 230 kWh/ 157 kW											*BESS Capacity required to suffice all overloading instances for 10 years		

Fig. 7. BESS size, NPV and cost-benefit ratio for different CAGR for different years over the base year

VII. . Conclusions

This paper presented an application of BESS for overload management of a DT supplying a congested area in a major metro city in India. A detailed sizing methodology, operational control scheme and cost benefit analysis for the mentioned application was showcased in this paper.

CAGR of DT load is observed to be a significant parameter to justify the investment in BESS at LT side of DT. Installation of BESS is a justifiable solution in congested areas and preferably in areas of saturated load growth.

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