Cost-Benefit Assessment Challenges for a Smart Distribution System: A Case Study

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***Abstract*—The FREEDM system is a technology for a smarter and resilient distribution system that facilitates a higher level of distributed energy resource (DER) integration by offering effective voltage regulation, reactive power compensation and real time monitoring and control. This paper provides a framework for conducting a cost-benefit analysis for such a smart distribution system. The method first identifies the benefits, and then quantifies and monetizes them. OpenDSS time-series based power flow simulation is used to quantify the benefits accurately. The costs associated with the new components of the system are estimated based on prototype units. A cost-benefit analysis is adopted to identify the scenarios where employing such a system by a utility becomes economically attractive.**

***Index Terms*—Cost-benefit analysis, FREEDM system, DER, OpenDSS, net present value.**

I. INTRODUCTION

Over the last two decades, technologies have been developed towards increased level of automation for the distribution system monitoring and operation/control [1]. One of the challenges has been economic assessment of these technologies. With the recent efforts on smart distribution systems to accommodate higher level of DERs on the system, the economic assessment of the new technologies/systems becomes a critical task [2]-[5]. Although there are standard approaches for economic assessment of a given technology, the system-level assessment becomes more challenging, as estimating the benefits can be difficult and they cannot be easily converted to payments (revenues) [3]. As [6] points out, the usual practice considers only the costs and benefits of individual technology investments in smart grids, and only the economic values that can be captured by the utility deploying the technology are considered. A recent example which provides a cost-benefit analysis assessment for a smart distribution system with capability to perform electric vehicle charging is presented in [7].

In this paper, challenges of cost-benefit assessment for a new smart distribution system have been demonstrated through a case study - FREEDM system [8].

To facilitate seamless integration of distributed energy resources (DER) at high penetration levels, the FREEDM system uses power electronics technology to replace the conventional distribution transformers with Solid State Transformers (SSTs) [8]. The system uses a feeder level communication backbone to implement an intelligent power and energy management system –DGI. The system also employs solid state fault isolation Devices –FIDs, to facilitate fast fault interruption. Hence this system not only increases DER hosting capacity of a distribution system considerably, above 100% penetration, it also offers other significant benefits. Table I show the main features of the system and also the benefits the system offers through these features. In a cost-benefit analysis, these benefits need to be identified and quantified.

This paper focuses on conducting a comprehensive cost benefit analysis of a smart distribution system – FREEDM system. The analysis includes identifying and quantifying the benefits on actual circuits with high renewable penetration using time-series simulation, monetizing the benefits and estimating the realistic cost. Net present value based approach is used to determine economic feasibility of the smart distribution system considered.

The remainder of the paper is organized as follows. Section II introduces the cost-benefit method. The benefits of the FREEDM system is identified and quantified by conducting a time series simulation for a year using OpenDSS. The cost of the FREEDM system cost is estimated in Section II as well. Section III presents the cost-benefit analysis and the results for the three actual feeders. Net present value and discounted payback period are calculated. Section IV concludes the paper.

II. COST-BENEFIT METHOD

This paper adopts the cost-benefit assessment approach developed through an EPRI project, which was developed to provide guide for assessment of smart grid projects [5]. The process has the following major steps:

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- Identify the functions of the project that will provide new and/or additional benefits (that has value to the utility, customer, society). And develop a mapping between the functions the project will provide and the benefits identified.
- Quantify the benefits and costs.
- Perform a cost-benefit analysis.

For the analysis, we first need to identify the "base system" and then identify the additional benefits that the base system FREEDM Features-Benefits Matrix does not offer. The cost-benefit analysis will then be based on the additional cost and benefits the FREEDM system will offer with respect to the base case.

The base system considered is the conventional distribution system with high penetration of new DERs. Note that with such high level of DER penetration, the system usually needs upgrades in order to host these DERs.

TABLE I. FREEDM FEATURES-BENEFITS MATRIX

FREEDM System Features/Functions	**Benefits**
Accommodate High DER Penetration • Effective Volt/Var Control • Plug and Play • ES + DGI	• Reduced peak demand and energy demand • Mitigate voltage issues • Reduce power loss • Simplify DER integration • Mitigate variability of power
High Reliability and PQ • Looped Primary • Automated Fault Isolation and service restoration • Fast Protection with FID • Regulated Service voltage	• Very high reliability • Minimize fault impact on system • Very high PQ
Real Time Mon and Control • Enhanced DEMS • CVR	• Reduced operation and maintenance • Optimal capacity use • Load management: peak demand and energy reduction
Resiliency • Microgrid at Node, Feeder Section, Whole Feeder	• High resiliency

A. *System Features and Benefits*

This step involves identifying the main features and functions which the new system provides and the base system cannot support. Table I lists the new functions for the FREEDM, grouped under the desirable features of a "smart distribution" system. The next step is to identify the benefits these functions will provide. Table I shows these benefits also and the corresponding function-benefit mapping. The benefits in the table are adapted from the EPRI report, and they fall under three categories: economic, reliability, societal. The next step in the assessment process involves quantifying the benefits associated with each function.

As Table I shows, the FREEDM system not only offers a comprehensive set of functions that facilitates high penetration of DERs, it also offers other sets of smart grid features, such as very high reliability, advanced real-time monitoring and control which enables customer participation, and others listed in the table. However, it is expected that the early adoption of this system will be for the main benefit the system offers – to accommodate high penetration DER on a system. We call such a deployment case a partial deployment scenario, as in this case only the components needed to mitigate the issues DER introduces will be deployed. In this paper, such a scenario is considered. Hence, we will focus only on the benefits related to this function/feature.

Benefits of DERs has been studied and illustrated in many cases [2], [9]. The main benefits of DERs will be: (i) Reduced demand and energy from conventional power plants, and (ii) Demand reduction during peak load conditions. Energy savings provides savings mainly for the customers, and the peak demand reduction allows for deferment of new generation build/purchase.

B. *Quantifying FREEDM System Benefits*

Benefits of the new FREEDM system is quantified with respect to the base case. The base case corresponds to the system before any mitigation measure is implemented.

To help illustrate the process, three actual residential feeders have been used. These are 12 KV residential feeders with 270-440 distribution transformers and peak load of 6800 – 7900 KW. To quantify the benefits, operation of these feeders have been simulated over a year, for both the base system and the new system with FREEDM system components. Actual feeder load and PV profiles for a year with a 15 min resolution are used in the study. Time-series based power flow simulations have been conducted, for both the base system and the new system. OpenDSS was used as the main simulation tool [10].

From these simulations the following benefits have been quantified: high DER hosting capacity, demand and energy reduction due to real time load monitoring and management. These benefits are discussed in more detail below.

1) *High DER Hosting Capacity*

Conventional distribution systems need upgrades when the DER penetration approaches 30% or higher [2]-[4]. We envision that in the near future some new feeders will have penetration levels of 70% or higher and such high levels of penetration will need substantial upgrading in order to enable the full benefit from DERs.

To assess the DER hosting capacity of the sample feeders, a high PV penetration scenario is considered where PVs are assumed at all load points. The PV penetration is adjusted to 100% (penetration is defined as the total size of PV systems divided by the peak load for a year). Fig. 1 shows the voltage heat map of one of the three feeders under both heavy loading and light loading conditions. Fig. 1(a) and (c) show the voltage profile when there is no PV; Fig. 1(b) and (d) show the voltage profile with distributed PV at all residential nodes. Fig. 1 shows that the voltage levels increase with PV integration. During the heavy loading condition with high penetration of PV, the voltage profile is in the green zone (around 124V) as shown in Fig. 1(b) and the voltages are within the 0.95 to 1.05 per unit ANSI limits. However, during the light loading condition, since the voltage is already high when there is no PV as shown in Fig. 1(c), power injection from PVs pushes the voltage even higher into the red zone (around 126V) which is above 1.05 per unit. Overvoltages occur towards the end of the feeder. Through these simulations, hosting capacity of the feeder A, B and C was

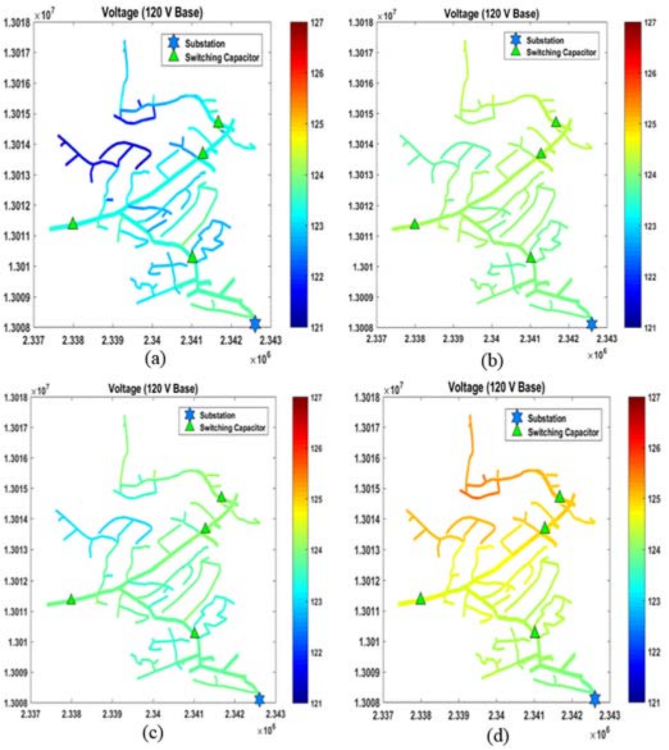
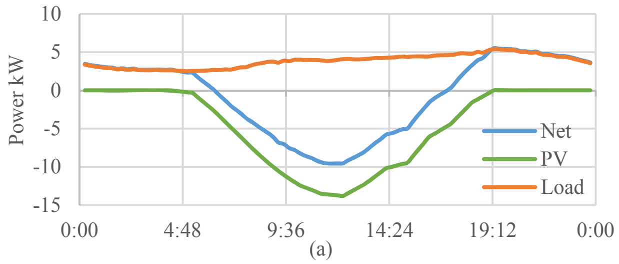


Figure 1. Voltage heat map (a) Heavy loading with no PV (b) Heavy loading with high PV penetration (c) Light loading with no PV (d) Light loading with high PV penetration

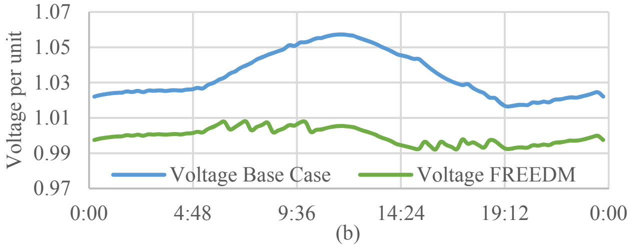
determined to be 70%, 70% and 45% respectively.

2) *Partial FREEDM Deployment*

To assess the conditions for a more likely scenario of PV penetration, a moderate level of PV penetration in the form of clusters located towards the ends of the feeders was simulated. The hosting capacities of the three feeders for this scenario are estimated to be 32%, 46% and 33%. Note: this is lower than the hosting capacity determined above in subsection B. 1) because each node in the cluster has a higher PV penetration. This scenario forms the base case for the following FREEDM deployment case studies where the PV penetration is increased to 43%, 54% and 43% for the three feeders. A partial FREEDM deployment scenario was constructed by adding SSTs to fix the overvoltage issues caused by PV. SSTs are also added at low voltage nodes to allow for effective conservation voltage reduction (CVR). This resulted in deploying 36, 16 and 58 SSTs on feeders A, B and C respectively. These partial FREEDM system deployments helped to mitigate the overvoltage violations on the feeder, and allow a 4V conservation voltage reduction.



(a)



(b)

Figure 2. (a) Light-loading day load and PV curves (b) Voltage profiles

Fig. 2 shows the load and voltage profiles at the secondary of a distribution transformer during light loading conditions. As the figure shows, the voltage goes above 1.05 per unit due to the relatively large power backfeeding. With the FREEDM system, these voltage violations are eliminated. This illustrates that indeed FREEDM system can accommodate high levels of PV systems on a distribution system.

3) *Demand and Energy Reduction*

From these simulations we also determined the benefits in terms of energy saving, peak demand reduction and loss reduction. To get a detailed power loss estimation, the distribution transformers on the base case and the SSTs on the FREEDM case have been represented. A model for SST has been developed to incorporate the load dependent power loss characteristics of the SST. The SST loss model is based on the lab experimental data which fits a quadratic function of $y = ax^2 + b$, with $a = 0.0141$, $b = 0.0052$. In OpenDSS, it is modeled as a transformer with no load loss corresponding to coefficient b and the series resistance using coefficient a.

The simulation results are shown in Table II. As expected, PV penetration in the circuit reduces the energy consumption. However, PVs do not help in reducing peak demand too much because the peak usually happens in the early morning or late afternoon when there is not too much PV output. Also, there is a small increase in transformer losses due to the relatively larger SST losses compared to the traditional transformer and the large PV backfeeding.

Note that these energy benefits are accrued mainly to the customer, and thus they will not be included in the cost-benefit analysis here as the analysis is from the utility perspective. Reduced energy and peak demand however helps the utility at the generation and transmission level. We refer to these benefits as the system benefits and the approach used to estimate them is given later in the cost-benefit analysis step.

4) *Real Time Load Monitoring and Management*

SSTs also offers tight voltage regulation at every customer load point [8]. This capability can be used to achieve effective Conservation Voltage Reduction (CVR) which has recently been adopted by many utilities as part of their energy efficiency efforts. The effectiveness of the CVR scheme is measured by the CVR factor, which indicates % reduction in demand ΔPd for a given % reduction in voltage ΔV. In a conventional system the secondary voltage can normally only be reduced by a maximum of 3V in order to avoid the low voltages at the end of feeder segments. However, in a FREEDM system, since we control the voltage at each SST, we can normally lower the voltage by up to 6V to get the maximum benefits of CVR.

For the sample feeders simulated in OpenDSS, an exponential load model is used with a CVR factor of 0.7, as this load model is typically used for conservation voltage reduction studies [11]. Low voltage nodes are examined to determine how much the voltage can be lowered before load voltage drops below the lowest limit. The limit is set to be 117 V to leave enough margin for other additional secondary voltage drop on service lines up to the meter. CVR is simulated in the test feeders for both the base case and the FREEDM case, with the results given in Table II. It can be seen from Table II that CVR provides energy conservation and reduction on peak demand and transformer losses.

TABLE II. PARTIAL FREEDM DEPLOYMENT RESULTS

#	**Diff Δ**	**Energy MWh-yr.**	**Peak kW**	**Losses MWh-yr.**		
				Circuit	***XFMR***	***Total***
Feeder A	PV	-1,227	4	-1	18	16
	CVR	-540	-169	1	-31	-31
	Total%	-2.3%	-2.4%	-0.002%	-0.06%	-0.1%
Feeder B	PV	-969	0	-4	0	-5
	CVR	-483	-92	0	-21	-20
	Total %	-1.4%	-1.2%	-0.01%	-0.06%	-0.1%
Feeder C	PV	-1,344	-16	-18	16	-2
	CVR	-559	-149	3	-36	-33
	Total %	-1.7%	-2.0%	-0.05%	-0.06%	-0.1%

C. *FREEDM System – Cost Estimation*

The main component in partial FREEDM deployment is the SST which is the new power electronics based device that is under development [8] for smart distribution applications. Hence, the starting point for a cost analysis is the actual production cost of the prototype SST [12].

For a single SST with an 'Optimized Design' the prototype cost is estimated to be around $455/kVA and this is based on 7.2 kV, 25 KVA design. When extended to larger production quantities, the cost falls to $300/kVA for single phase units up to 75 kVA; the price for larger three-phase units is in the $200/kVA range. The amount of the reduction is approximated by reviewing several other product development cycles. The price further decreases as the product matures. One example of such maturation can be seen in the projected cost of automotive Lithium-ion battery packs [13]. The conclusion to be drawn from these projected data is that the overall price decrease ratio is around 3.5:1 from introduction to full maturation. Hence, we will assume that the manufactured price, after the technology matures, will be in the ratio of 3:1 as based on the present large scale production cost. When applied to SST, the final production cost is estimated to be the following:

Single phase units up to 75 kVA: $90/kVA; Three phase units: $70/kVA

In partial deployment scenario, it is assumed that the utility will replace the existing transformers with SSTs at selected locations. The replaced transformers will be considered 100% depreciated and have no book value, which will make the cost benefit analysis more conservative. Hence, the cost differential between the SST and the distribution transformer to be replaced is defined as the cost of the SST.

III. COST-BENEFIT ANALYSIS AND RESULTS

A cost-benefit analysis (CBA) was performed to estimate the benefits and costs accrued to the utility. The analysis estimates the net present value (NPV) and the discounted payback period (DPBP) associated with upgrading a conventional feeder to the partial FREEDM deployments considered. Each benefit category is monetized by utilizing a variety of methods, including literature review, industry surveys, and by using the benefits quantified through system simulations presented above.

A. *High DER Hosting Capacity*

This is the main benefit FREEDM system offers. As noted in sectionII.B.1), PV penetration above 30% may require grid upgrades before additional capacity can be added, due to voltage violations. Hence, the economic benefits of increasing PV above the hosting capacity of the original feeder can be attributed to an investment in FREEDM system.

Existing literature has attempted to quantify the marginal economic value of PV as a function of increasing penetration. Net benefits to utilities include avoided energy costs, deferred investment in capacity expansion, and forecast errors associated with PV uncertainty (+ or -) [14], [15]. Fig. 3 presents a summary of these findings from Arizona, California, and Hawaii. Note that the PV penetration definition is the percentage of PV energy generated divided by the total load energy consumption of the feeder [14], [16], [17]. We used this curve to estimate the associated system benefits: the area under the curve between the two penetration levels – the level corresponding to the hosting capacity and the new level achieved by the FREEDM deployment – represents the additional economic benefit that can be attributed to FREEDM. The increase in PV penetration level the FREEDM system enables is determined from system simulations as indicated in previous section.

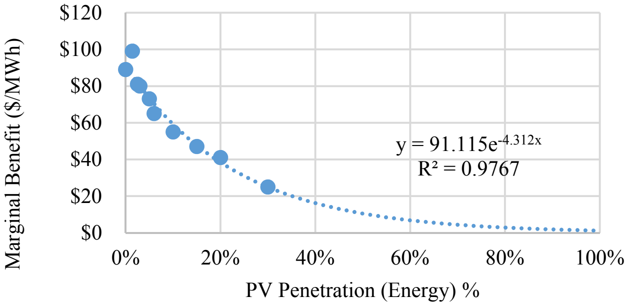


Figure 3. Marginal Benefit of PV

B. *Real Time Monitoring and Control*

SSTs have embedded real-time monitoring and control capability which can be used to improve system operation and efficiency. The main benefit that is quantified and monetized is the Conservation Voltage Reduction (CVR). CVR helps reducing the energy consumption and peak demand which incurs avoided electric energy and capacity costs to electric utility. The avoided cost of energy includes both fixed and variable cost that can be avoided as electricity usage decreases;

the avoided capacity cost consists mainly of the costs associated with purchasing/building peak generation facilities [18].

C. CBA Results

A spreadsheet tool was developed to evaluate the annualized benefits and costs in order to calculate the NPV and discounted payback period (DPBP) for different FREEDM deployment scenarios. Table III presents the results for the three feeders considered. The benefits shown in the table are calculated as follows: the system benefits of DER is calculated by using the marginal benefit of PV curve. The DER avoided capital cost is due to the peak reduction caused by PV. The reduction in energy and peak caused by CVR is considered as feeder benefits. A 10% discount rate was used, which represents the weighted average cost of capital (WACC) used by utilities [19]. Annual cash flows were assumed constant over the lifetime of the SSTs, currently estimated at 25 years. The avoided energy cost used in the calculation is 0.051$/kWh and the avoided capital cost is 55$/kW. These costs are obtained from [18] for seven electric distribution companies.

Sensitivity analysis has also been conducted. In Fig. 4, eight parameters are varied, first by +25%, then by -25%. The impact on NPV is recorded and the corresponding importance of each parameter is ranked. This confirms that the price of the SST and the discount rate are the most influential factors on the NPV.

These results indicate the following:

- The FREEDM system is likely to be deployed first in niche markets where a combination of economics and policy require it.
- The economic feasibility of the partial deployment scenarios considered indicates that early adoption of FREEDM systems is likely in near feature.

TABLE III. NPV AND DISCOUNTED PAYBACK PERIOD RESULTS

#	**Cost**	**DER Benefits (yr.)**		**Feeder Benefits (yr.)**		**NPV**	**DPBP (yrs.)**
	SST	***System***	***Avoided Capital***	***Avoided Energy***	***Avoided Capital***		
A	$145k	$53k	$0	$27k	$9k	$669k	2.9
B	$41k	$42k	$0	$25k	$5k	$606k	1.6
C	$244k	$62k	$872	$29k	$8k	$657k	4

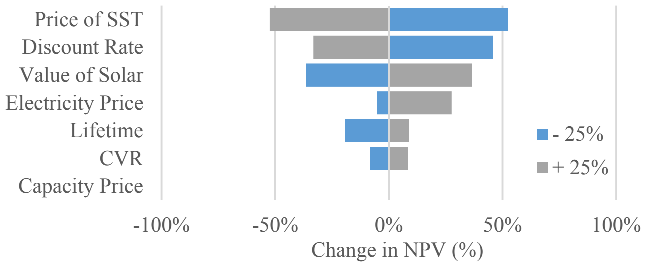


Figure 4. Sensitivity Analysis

IV. CONCLUSIONS

In this paper, a cost-benefit analysis case study for the FREEDM system deployment has been presented using three sample feeders from a utility. The simulations on these feeders also clearly demonstrate that FREEDM system increases DER hosting capacity considerably. These benefits are quantified and monetized from the utility perspective that includes avoided energy costs and deferred investment in capacity expansion. Other benefits are due to more effective real time monitoring and control which is monetized as CVR benefits.

The cost-benefit analysis results presented a positive net present value for a partial deployment case with less than 5 years payback period for the sample feeders. The above results indicate that the partial FREEDM deployment is likely to be utilized on feeders with moderate DER penetration in near future.

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