Y9. GEH2.3: FREEDM Cost Benefit Analysis based on Detailed Utility Circuit Models

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I. Project Goals

The goal of this task is to enhance the Cost-Benefit Analysis for the FREEDM System based on the feedback from Y8 SVT. The efforts in the following:

i. Identify the technologies/approaches that are alternative to FREEDM system, especially from the capability of integrating high penetration DER on a distribution system.

ii. Conduct a Cost-Benefit Analysis for the FREEDM system by comparing the alternative technology/ approach to FREEDM system.

II. Role in Support of Strategic Plan

This Task is part of the cost-benefit analysis project. It has been undertaken by the engineering analysis group which focuses on the system analysis to determine system benefits. The other group -economic analysis group- aims to monetize the benefits and thus make an economics assessment of the system.

III. Fundamental Research, Technological Barriers and Methodologies

The main challenge in this task involves estimation of capabilities and the benefits of the new alternative technologies considered. To address these challenges we solicited help from industry members and worked collaboratively with the other team which focused on the economic assessment of the cases considered.

IV. Achievements

This is the third year of this project, and this year the work has focused on the two main sub-tasks that have been identified based on the feedback from NSF SVT. The work builds on the accomplishments made during the last year. Main accomplishments made this year include the following:

4.1 Unreported Work: FREEDM System benefits using representative feeders from industry

Three actual distribution feeders have been obtained from a member utility in order to demonstrate the capabilities of the FREEDM system and quantify the benefits. These circuits are 12.47kV circuits and Table 1 shows their main characteristics. By using the circuit models and the yearly load data (15 min resolution) provided by the utility, quasi-static time series power flow analysis has been performed in OpenDSS [1]. All the following results were obtained through these yearly simulations. First, PV hosting capacities for these circuits are estimated. These cases define our base cases. Then the full FREEDM deployment case and the partial FREEDM deployment case are analyzed to determine and quantify the benefits of the FREEDM system.

Table 1 Characteristics of Three Utility Circuits

	Circuit A	Circuit B	Circuit C
Circuit Length (Backbone)	3 miles	4.3 miles	3.8 miles
Number of Voltage Regulators	0	0	**2**
Number of Capacitors	4	4	4
Number of transformers (Total)	309	298	456
Number of Customers (Total)	1240	1511	1448
Efficiency	99%	99%	98%
Peak kW	6800 kW	7427 kW	7900 kW

PV hosting capacity

PV hosting capacity is evaluated for two cases: partial PV deployment where PVs are clustered at certain parts of the feeder, and the full PV deployment where each node has PV installation. The main impact that limited the PV deployment on these circuits were voltage limit violations, especially the overvoltage violation during light load conditions. PV penetration levels are increased to see when the circuits are having overvoltage issues. The results are shown in Table 2. It can be seen from the table that Circuit C starts having overvoltage issues in lower penetration levels than the others. Also, note that the partial deployment case has a lower PV hosting capacity than full deployment case.

Table 2 PV Hosting Capacity

Circuit #	Full PV deployment		Partial PV deployment	
	PV penetration	% Duration (yr.)	PV penetration	% Duration (yr.)
Circuit A	70%	0.23%	32%	0.14%
Circuit B	70%	0.24%	46%	0.32%
Circuit C	45%	0.15%	33%	0.15%

Benefits of FREEDM System Deployment

As the results in Table indices, the circuits considered have good PV hosting capability, and hence a full FREEDM deployment on these circuits offers only marginal benefits. Indeed our simulations indicate that due to the relatively larger loss of solid state transformer (SST), the system loss actually increases by deploying SST at every node. Furthermore the early FREEDM deployment will be more likely on circuits with partial PV deployment. Hence, we focused on this case – partial FREEDM system deployment.

The study involved increasing the PV penetration to around 50% for each circuit and then SSTs are added to fix overvoltage issues. The energy and peak demand savings are used to calculate system benefits due to higher penetration of PV. Then, more SSTs are added to allow for more effective conservation voltage reduction (CVR) on the circuits. The additional energy and peak demand savings by CVR is counted as FREEDM benefits. Table 3 summarizes these benefits. It can be seen from the table that the increased PV penetration leads to reduction in energy and line losses. However, it does not reduce the peak demand as much, as in this case the peak demand usually happens during the early morning or night when there is not too much PV output. As the table shows, there is small increase in transformer losses due to mainly relatively larger SST loss compared to the traditional transformer. The results also show the effectiveness of CVR, as there is a considerable drop in system peak kW and energy losses. CVR also help lower the total yearly energy demand.

These results clearly illustrate that: (i) FREEDM systems facilitates higher PV penetration on these circuits by mitigating the overvoltage issues, and (ii) FREEDM system improves system efficiency by lowering both the peak demand as well as the power loss on these circuits.

Table 3 Partial FREEDM Deployment Results

	#SST Added	Overvoltage reduction (% time/yr.)	CVR ΔV	Diff Δ	Energy MWh-yr.	Peak kW	Losses MWh-yr.		
							Line	XFMR	Total
Circuit A	32	2.70%	3.8V	DER	-1187	-2	-1	16	15
				CVR	-534	-146	1	-32	-32
				Total%	-1,721	-147	0	-17	-17
Circuit B	16	0.40%	4V	DER	-969	0	-4	0	-5
				CVR	-483	-92	0	-21	-20
				Total %	-1,452	-92	-4	-21	-25
Circuit C	58	1.32%	4V	DER	-1344	-16	-18	16	-2
				CVR	-559	-149	3	-36	-33
				Total %	-1,903	-165	-15	-20	-35

4.2 Accomplishments in Year 9

1) Alternative Technologies to FREEDM System

Our search on the technologies that can be alternative to FREEDM system indicated that there are two technologies that can be adopted for partial PV deployment cases: Edge-of-grid devices and smart inverters. These technologies are selected because they have the capability to provide voltage mitigation on partial PV deployment cases, similar to that of a FREEDM deployment considered last year and reported above. Basic comparison of these technologies is as follow:

- In FREEDM system, the SST is the main device that provides voltage mitigation on a distribution stem. The key functionalities of SST are voltage regulation on load side and reactive power compensation on the source side. SST also has a DC port which facilitates DER connection (like PV, battery), and serving DC loads directly.
- Edge-of-grid device is a power electronics based equipment which is designed to be connected to the low voltage side of the traditional transformer. These devices provides services like voltage regulation and reactive power compensation.
- Smart inverter is the inverter designed to connect PV to the utility on the low voltage side. The newly emerging smart inverters have Volt-Var control capability by adjusting the reactive power at the point of interconnection.

There are only a few products that are currently available with these functionalities. In our study, we have selected the GRIDCOSYSTEM's In-line power regulator (IPR) as the sample edge-of-grid device, and SMA Sunny Tripower inverter (STI) as the smart inverter. IPR is a low voltage, single phase device that combines utility-scale power electronics and advanced control algorithms [4]. IPR can be used for residential, commercial utility scale renewable integration, and/or for Conservation Voltage Reduction (CVR) to improve energy efficiency and for fault detection, isolation, and restoration (FDIR) [4]. Table 5 summarizes the comparison of SST, IPR and STI. The information for IPR and SMA smart inverter are based on the published product datasheet [4, 5] that are available online. In order to do the comparison, Gridco IPR is assumed to have the same power rating ranges as SST.

Table 4: Comparison of FREEDM SST, Gridco System IPR and SMA STI

Product	Power Rating	Input Voltage	Output Voltage	Voltage Regulation	VAR Compensation	Efficiency	DC Port
FREEDM ***SST***	0-100 kVA	3.6 kV Vac	120Vac 200Vdc	± 10%	20% of Rating (lead. or lag.)	95%	Yes
Gridco Systems ***IPR-50***	50 kVA	240 Vac	240 Vac	± 10%	10% of Rating (lead. or lag.)	≥ 99%	No
SMA ***Smart Inverter***	12 kW - 30 kW	1000 Vdc (max)	480/277 Vac	244V-305V	0-1 power factor (ind. or cap.)	98.3%	No

2) Estimating the benefits of alternative technologies

In order to determine the capabilities and to quantify the benefits that IPR and SMA inverter, simulations similar to the ones performed for the FREEDM system have been repeated for the two technologies considered. The case used is the partial deployment scenario on Circuit A. Table 6 shows the three cases simulated.

Table 5: Test Cases

(a) Base Case	**Circuit A + 32% PV**
(b) Higher PV	Circuit A + 43% PV + Devices
(c) Higher PV plus CVR	Circuit A + 43% PV + Devices +CVR

The PV deployment for the base case is the same as in FREEDM base case. For IPR alternative, simulations indicated that 32 IPRs are needed to accommodate the same level of PV penetration and same level of conservation voltage reduction benefits on the test feeder. For the SMA smart inverter case, it is assumed all the PVs in the cluster are equipped with the smart inverters. In this case, 133 STIs are used to accommodate 43% PV penetration. In this case, STIs allows for only 1V voltage reduction for CVR.

For simulations, IPR and STI were modeled in OpenDSS. Models are setup based on the datasheets [4, 5] published online by the vendors. Figure 3 shows the modelling structures for each type of device. IPR is modeled using the voltage regulator block in OpenDSS. The losses are adjusted based on data the datasheet. STI is simulated using volt-var mode for PV inverters in OpenDSS. This model adjusts the reactive power to maintain the voltage within range of 0.95 to 1.05 per unit. As the figure shows both IPR and STI are connected to the traditional transformer (XFMR). Note also that PVs need inverter to connect to IPR.

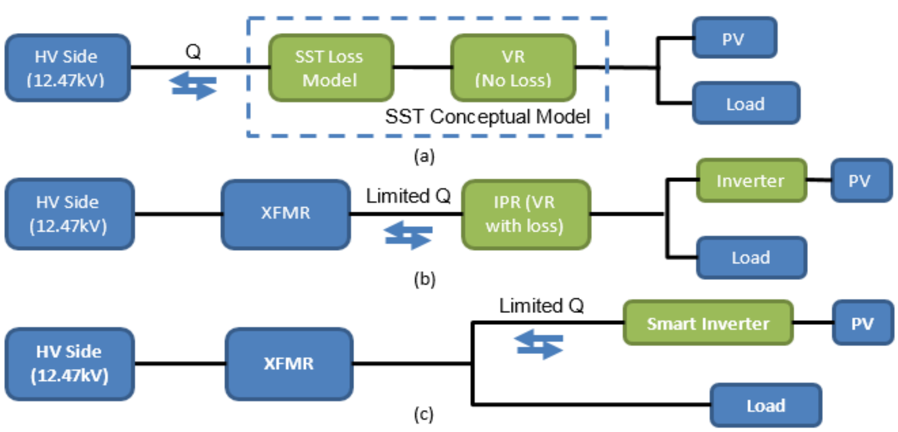

Figure 1 OpenDSS Modeling Structure for Three Technologies (a) SST (b) Gridco IPR (c) Smart Inverter

Table 7 shows the simulation results for three technologies considered as compared to the base case. In the table, DER savings indicate the difference between case (b) and the base case (a), and CVR savings is the difference between case (c) and case (b). It can be seen from the table that SST (FREEDM system) provides the highest benefits in energy reduction and peak demand savings. The result for IPR is quite close to that of the SST. SMA offers smaller savings in energy and peak demand. This is mainly due to the way STI provides voltage support, and also because of its limited ability in reducing voltages for CVR - it can only allow for 1V reduction, whereas both SST and IPR can do about 4V reduction.

Table 6 Simulation Results for SST and Alternatives

#	Diff Δ	Energy MWh-yr.	Peak kW	Losses MWh-yr		
				Line	XFMR	Total
SST to Base	DER	-1,187	-2	-1	16	15
	CVR	-534	-146	1	-32	-32
	Total	-1,721	-147	0	-17	-17
	Total %	-8.7%	-2.2%	0.00%	-0.08%	-0.09%
IPR to Base	DER	-1,110	-3	-1	1	0
	CVR	-534	-146	1	-32	-32
	Total	-1,644	-149	0	-31	-31
	Total %	-8.3%	-2.2%	0.00%	-0.16%	-0.16%
STI to Base	DER	-1,082	-11	5	25	30
	CVR	-153	-36	-3	-19	-22
	Total	-1,236	-46	2	6	8
	Total %	-6.2%	-0.7%	0.01%	0.03%	0.04%

3) FREEDM Benefits through DC port of SST

SST is designed to have a DC port to facilitate the direct connection of customer PV system to the utility. DC port also facilitates future residential homes with DC load, storage and electrical vehicle. The benefits through this additional feature have been investigated in this task as well.

One of the main benefits is due to the potential energy that could be saved by switching the traditional AC residential house to a DC/AC hybrid house or a purely DC house. Some earlier work has done by Lawrence Berkeley National Laboratory (LBNL) [6]. The report estimates that a net-metered PV residence could save 5% energy if the house has no storage, and 14% if the house has storage.

Our initial work involved setting up a spread sheet tool in order to calculate the net energy savings for different residential house scenarios. Figure 4 shows different power delivery systems considered: conventional AC house, DC house, FREEDM hybrid house, and FREEDM DC house. The voltage level in the DC house is 380V for high power DC load like cooling or heating load and 24V DC for the low power DC load. The voltage levels of 380V and 24V are based on the emerging standards for data center or commercial DC systems developed by Emerge Alliance [7]. The load data used in the analysis are the residential hourly load profile for Raleigh/Durham area published by US department of Energy on OpenEI [8]. The irradiance data from solar prospector by National Renewable Energy Laboratory (NREL) [9] is used to calculate the rooftop PV power output for a year. The spreadsheet tool developed based on the used provided results similar to that of LBNL's report.

By using these prototype house models, total savings have been estimated for the partial FREEDM deployment case on circuit A where 32 SST are deployed. The total energy savings for the total load connected through the 32 SST is around 160 MWh for a year (using 5% savings per house). The total avoided energy cost from these savings is around $5000. More detailed analysis will be conducted to further estimate the benefits for different cases considered.

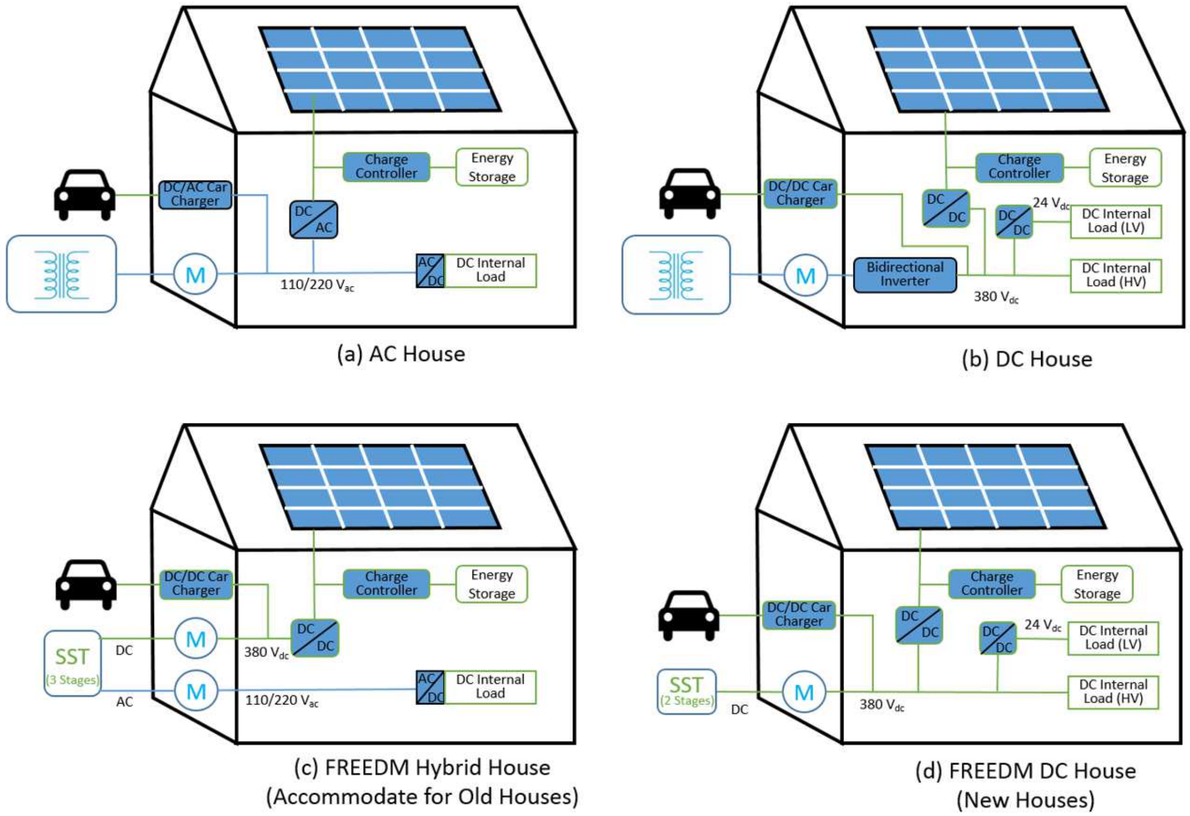

Figure 2. House Structures (a) Ac House (b) DC House (c) FREEDM Hybrid House (d) FREEDM ALL DC House

Some of the benefits that will be considered are the following:

- Customer benefits from energy saving by switching from AC to DC appliance.
- Customer saving by avoiding the cost of DC/AC power conversion equipment for DC appliances.
- Utility may have a tariff for providing DC service since customer gets benefits.
- Utility may offer SST+PV/Battery service package.
- Benefits in using SST to serve electric vehicles (EV) in case the EV get more and more popular.
- New Zero Energy Green House with FREEDM all DC structure

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