

Identifying Techniques, Topologies and Features for Maximizing the Efficiency of a Distribution Grid with Solid State Power Devices

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Abstract— The FREEDM grid utilizes solid state transformers (SST) and solid state fault interruption devices (FID) which may lead to unfavorable operating losses as compared to a conventional grid. Various SST topologies and switching techniques are identified for minimizing losses and a performance evaluation is made to determine the efficiency of the FREEDM distribution network to improve the overall efficiency. Losses include conductors, SSTs, FIDs, and conventional distribution transformers tested under various loading levels. Compared to a conventional distribution network, the FREEDM grid has a slight reduction in losses. By choosing the proper distribution line configuration, conductor type, switching devices and switching techniques, the power losses on the system may be minimized further.

Index Terms—FREEDM, Solid state transformer, solid state fault interruption device, microgrid, renewable energy.

I. INTRODUCTION

THE Future Renewable Electric Energy Delivery Management (FREEDM) Systems Center is developing an AC/DC microgrid, dubbed the Green Hub that utilizes distributed renewable power sources in addition to newly developed topologies for a multi-purpose solid state transformer (SST) that will provide bidirectional power flow between the system and the renewable energy sources. The system also includes solid state fault interruption devices (SSFID). The addition of these new devices creates more parameters imposed on a conventional distribution system, and it is important to compare the overall efficiency with other distribution networks.

The SST is particularly important for efficiency consideration since it is a pervasive device functioning as an interface for every distributed energy resource available including distributed generation and distributed energy storage devices (DESD) on the grid. Replacing conventional transformers with SSTs may dramatically reduce the overall system efficiency mainly because of the additional conduction and switching losses incurred in the SST. The basic configuration of the proposed 20kVA SST interfaced to 12kV_{LL} distribution

voltage, with center-tapped 120V single-phase output is shown in Fig. 1 [1]. The SST consists of a cascaded high voltage high frequency AC/DC rectifier that converts 60Hz, 7.2 kV AC to three 3.8 kV DC buses, three high voltage high frequency DC-DC bi-directional converters that convert 3.8 kV to 400V DC bus and a voltage source inverter (VSI) that inverts 400V DC to 60Hz, 240/120 V, single-phase/3 wires. The switching devices in high voltage H-bridge and low voltage H-bridges in Fig. 1 are 6.5kV silicon IGBT and 600V silicon IGBT respectively. The switching frequency of the high voltage silicon IGBT devices is 1 kHz, and the low voltage IGBT in the VSI switches is 15 kHz.

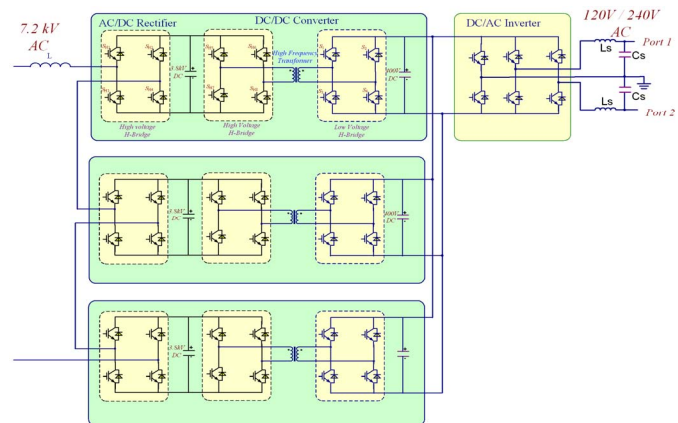


Fig. 1. Solid state transformer [1]

The proposed SSFID will have 3 modules of IGBT-diode pairs [2]. Each module will consist of two pairs, IGBT-diode in anti-parallel, connected in the common emitter configuration. Each module is to be protected by a metal oxide varistor. The SSFID design is shown in Fig. 1.

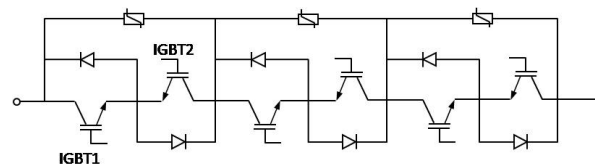


Fig. 1. The Solid State Fault Interruption Device.

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For the SSFID, an IGBT module 5SNA 0400J650100 from [3] with forward breakdown voltage $V_{ce} = 6.5$ kV and continuous rated current $I_c = 400$ A has been selected. See the Appendix for loss calculations for the SSFID.

A conceptual three-phase diagram of the proposed FREEDM Green Hub microgrid is shown in Fig. 3. The model is a 3-phase loop system connected to the legacy grid through three single-phase SSTs. Two 25kW_p photovoltaic (PV) arrays and one 10kW_p distributed generator (DG) are planned for connection to one of the phases within the loop through individual SSTs. The PV arrays are connected to the 400V DC bus and the DG is connected to the $120/240\text{V}$ AC bus. The microgrid will be allowed to operate in islanded mode provided adequate generation is available.

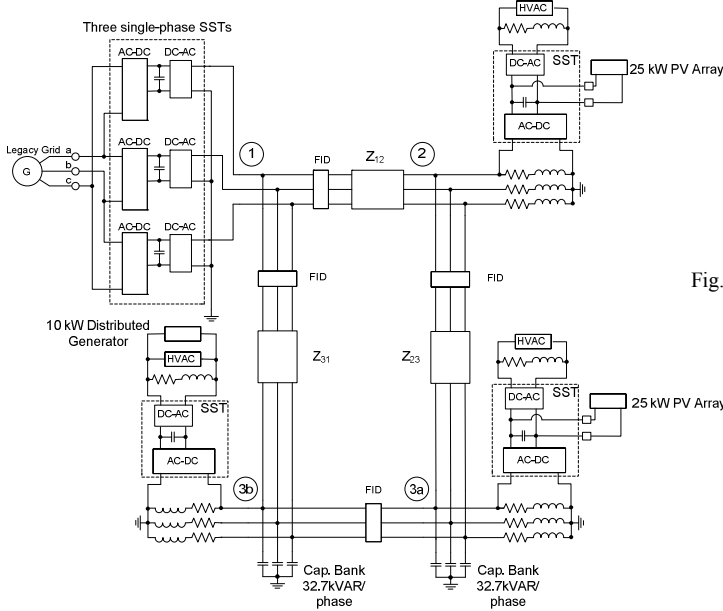


Fig. 3. FREEDM Green Hub [4]

II. EFFICIENCY OF THE SOLID STATE TRANSFORMER

Four SST topologies were investigated: (1) a back-to-back voltage source converter (VSC) with a conventional 60 Hz transformer (SST1), shown in Fig. 4; (2) a three-stage SST with three two-level front end rectifiers in series connection (SST2) [5], shown in Fig. 5; (3) a three-stage SST with a four-level flying capacitor front end rectifier (SST3), shown in Fig. 6; and (4) a single-stage ac-ac dual active bridge converter-based SST (SST4) [6], shown in Fig. 7.

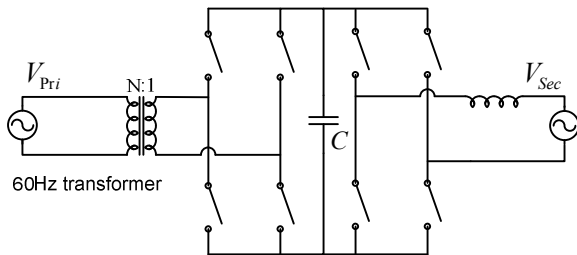


Fig. 4. Back-to-back ac-dc-ac

A. Power Losses

Power losses in power converter circuits consist of conduction loss and switching loss. Conduction loss is evaluated using device forward voltage, on-time resistor, load power factor and load current. Losses in the SST also include copper loss and core loss in the transformer.

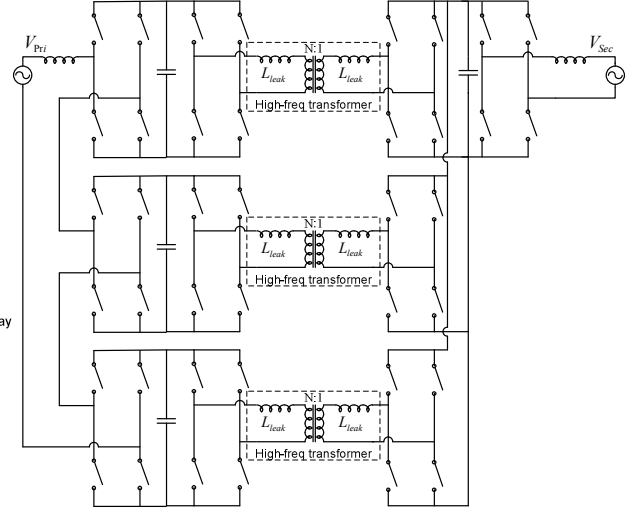


Fig. 5. Multi-stage SST

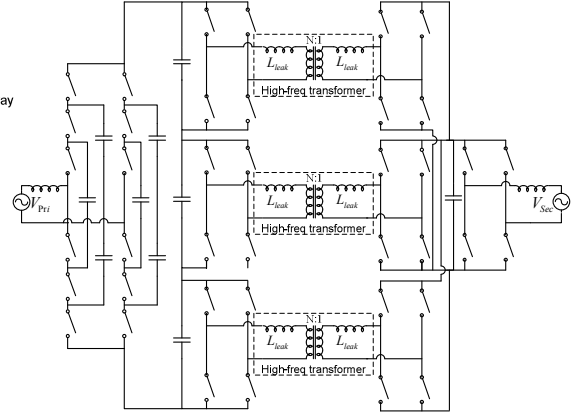


Fig. 6. SST with Multi-level flying capacitor front-end

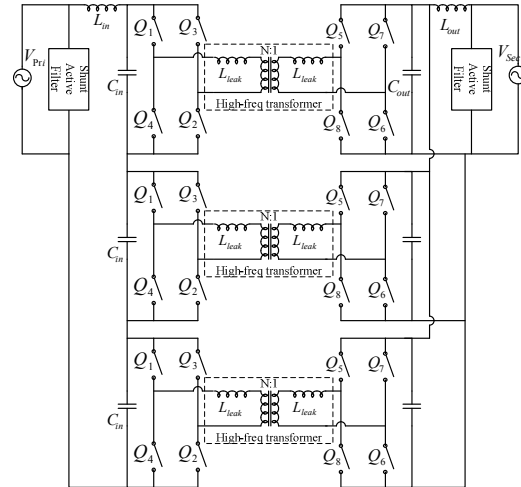


Fig. 7. Ac-Ac DAB

A one-dimensional method is used to calculate the ac resistance of the multilayer windings. The transformer core loss is calculated using the manufacture datasheets, the

operating frequency and the calculated magnetic flux density. The relevant equations for loss determination are as follows:

Conduction losses of rectifiers and inverters:

Transistors

$$P_{cond,T} = \left(\frac{1}{2} + \frac{4}{3} m \cos \varphi\right) \frac{I_m^2 R_{on,t}}{4\pi} + \left(2 + \frac{\pi}{2} \cos \varphi\right) \frac{V_{ce} I_m}{4\pi} \quad (1)$$

Diodes:

$$P_{cond,D} = \left(\frac{1}{2} - \frac{4}{3} m \cos \varphi\right) \frac{I_m^2 R_{on,d}}{4\pi} + \left(2 + \frac{\pi}{2} \cos \varphi\right) \frac{V_f I_m}{4\pi} \quad (2)$$

Conduction loss of DAB converters

Leading bridge:

$$P_{cond,lead} = 2 \left(i_0 v_f d_1 + i_\varphi v_{ce} \left(d_2 + \frac{\pi - \varphi}{\pi} \right) \right) \quad (3)$$

Lagging bridge:

$$P_{cond,lag} = 2 \left(i_0 v_f \left(d_1 + \frac{\pi - \varphi}{\pi} \right)_1 + i_\varphi v_{ce} d_2 \right) \quad (4)$$

Switching losses:

Hard switching loss

$$P_{sw} = \frac{f_{sw}}{\pi} (E_{on} + E_{off} + E_{rr}) \quad (5)$$

Soft switching loss of DAB

$$P_{sw} = f_{sw} \frac{t_f^2 i^2}{6C_r} \quad (6)$$

Transformer losses:

Copper loss

$$P_{cu} = I_{pri}^2 R_{pri} + I_{sec}^2 R_{sec} \quad (7)$$

Core loss

$$P_{core} = k f^m B_{ac}^n \quad (8)$$

(k, m, and n are from manufacture datasheets).

B. Comparisons

The four topologies were subjected to hard or soft switching at varying load levels resulting in seven cases. The results of efficiency analysis are: (1) the efficiency of all four SST topologies is lower than that of conventional magnetic transformer due to the addition of power electronic converters. SST1 is the most efficient topology; however, it lacks the size advantage of a high-frequency transformer. Efficiency decreases as the power converters become more complex. The efficiency of SST3 is slightly better than that of SST2 due to the reduction of switching frequency by using a multilevel front-end rectifier. Although SST4 has higher conduction loss, it benefits from less energy circulation and reduced number of power conversion stages. (2) ARCP, which utilizes soft switching, increases efficiency, particularly under light-load conditions, at the expense of increasing circuit complexity even further. (3) Efficiency at light load conditions is low, as shown in Fig. 8, which is a disadvantage of an SST. It is necessary to develop a novel technique to make SSTs more efficient at light loads.

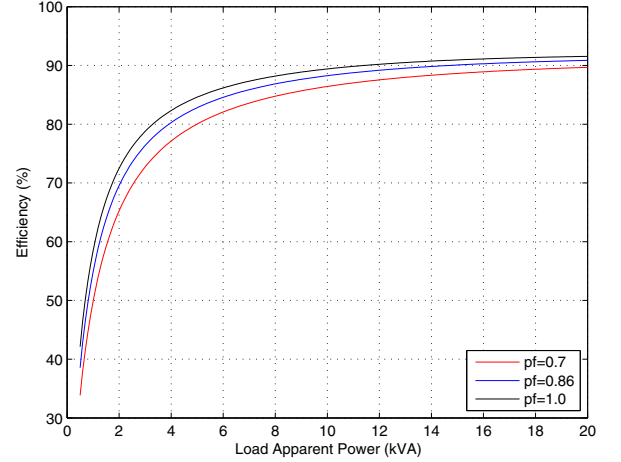


Fig. 8. Efficiency vs. load for different input power factors

III. SYSTEM STUDIES

The FREEDM system model shown in Fig. 3 contains three buses with unbalanced three phase loads. Phase-A across these buses contains the distributed voltage sources comprised of the two PV panels and the DG connected by an SST. The unbalanced three-phase loads at the three buses are not properly represented in the current model since the loads are at 12kV L-L. A good representation would take into account the distribution lines and transformers. Typical single phase distribution transformers rated at 50 kVA were placed along a feeder starting from the existing three-phased loads in Fig. 3. The original loads are shown in Table I, and they were divided amongst 25 distribution transformers ensuring that the total loads seen by each phase on each bus on the original system remained unchanged. After this adjustment, the error was calculated to be about 0.05% or less. The new transformers are not shown in Fig. 3, but shown in Fig. A.1 of the Appendix. See Appendix A for more information on this procedure.

Table I. Original 3-Phase Loads

	Phase A				Phase B				Phase C			
	P	Q	S	pf	P	Q	S	pf	P	Q	S	pf
Bus-2	99.71	59.67	116.20	0.86	171.90	89.05	193.60	0.89	90.14	47.59	101.93	0.88
Bus-3a	106.51	54.39	119.59	0.89	28.07	13.09	30.98	0.91	16.37	9.32	18.83	0.87
Bus-3b	126.75	54.75	138.07	0.92	168.90	76.30	185.34	0.91	153.23	64.29	166.17	0.92

A. Conductor Impedances

The FREEDM green hub is a loop distribution system with three line sections with lengths defined at 7.141, 2.939, and 2.261 km. The conductor used in this system is an ACSR 2/0 that has a GMR of 0.0051 ft and a resistance of 0.556 Ω /km (0.894797 Ω /mi) [4]. The phase conductors are defined as being in a triangular configuration with one meter spacing in the current model. This model does not give a specific location of the neutral conductor which is the same type as the phase conductors. In a test radial distribution system available through IEEE, the neutral is 4' below the crossarm where the outer most conductors are spaced 7' apart [7]. This 4/7 ratio is used to place the neutral 1.8742' below the crossarm in the FREEDM system. Shown below are the conductor spacings

where phase-c is the highest conductor.

$$D_{ab} = D_{ac} = D_{bc} = 3.281 \text{ ft.} = 1 \text{ m}$$

$$D_{an} = D_{bn} = 2.490 \text{ ft.}, D_{cn} = 4.481 \text{ ft.}$$

From this information the sequence impedances can be calculated [8], [9].

$$Z_1 = 0.5563 + j0.4871 \ \Omega/\text{km}$$

$$Z_0 = 0.9526 + j1.3616 \ \Omega/\text{km}$$

With a power base of 1 MVA and a voltage base of 12kV, an impedance base of 144 Ω was obtained. With the impedance base, the sequence values can be converted into per unit quantities. These can be multiplied by the line lengths which gives the per unit impedance for each branch given in Table II. The augmented distribution portion of the FREEDM system uses the same conductors as the original part of the system.

Table II. Branch Impedance

	Section Length (km)	R_1 pu	X_1 pu	R_0 pu	X_0 pu
1 to 2	7.141	0.0276	0.0242	0.0472	0.0675
2 to 3	2.939	0.0114	0.0099	0.0194	0.0278
3 to 1	2.261	0.0087	0.0076	0.0150	0.0214

B. Efficiency of the Modified FREEDM grid

Assuming typical conductor configurations found on distribution wires, the positive and zero sequence impedances were calculated for the additional conductors in the modified Green Hub and used in unbalanced power flow simulation tests. The power flow was simulated using ASPEN DistriView [10]. Power losses occurring on the conductors were found for varying load conditions.

ASPEN DistriView has only a conventional transformer model. Therefore to model an SST in DistriView, two conventional transformers were used. One transformer is connected to the 6.928kV L-N across phase-A and is transformed into 400V (representing the DC bus), and the second transformer takes this voltage and transforms it into 120/240V. The reason for splitting up the transformers in this fashion is to allow a connection point for the PV panels.

The SST has optimum points at which it operates based on the power factor and loading level. Therefore, an equivalent SST resistance may be determined for power loss calculations. Since the different represented parts of the SST could be loaded differently because of the bidirectional power flow capabilities, the resistance might be different on either side of the SST. The SST has much higher resistance than a conventional transformer due to the high frequency switching losses of the device. At lower loading levels, the SST is less efficient. Figs. 9 and 10 show the variation of the SST resistance under different system loads and power factor. For the given SST loading levels (about 3.5kW) [4] and assuming that the distributed generation sources are operating at their rated outputs, the SSTs with PV panels attached to them have much less of a power loss compared to the SSTs with the DG because 6.5 kW out of the 10 kW generated flows backward through the SST to serve other loads in the FREEDM system. At 6.5 kW, the SST is only about 35% loaded which makes the resistance on the 12 kV L-L:400V DC side of the transformer approximately 0.6 pu (this quantity uses an impedance base calculated from the voltage and the power rating of the SST and not the system base).

The SST's resistance affects the FREEDM system as a whole. If the value of the downstream loads change, the efficiency of the system also changes. As the downstream loads decrease and the SST secondary loading remains constant, the efficiency of the SSTs barely change; this is because the distributed sources are generating the same amount of power and it has to be put back into the system. Since the SST loading levels do not change, the resistances were assumed to be constant through the different load level cases. Fig. 11 compares the FREEDM system efficiency with and without SSTs and FIDs under various loading conditions. See Appendix C for FID losses.

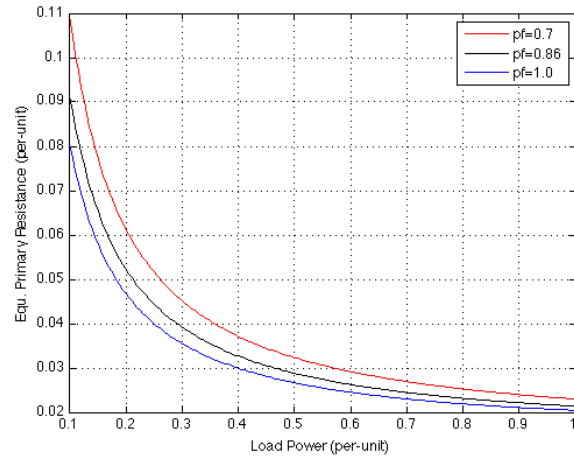


Fig. 9. Resistance from 12kV L-L:400Vdc Transformer [11].

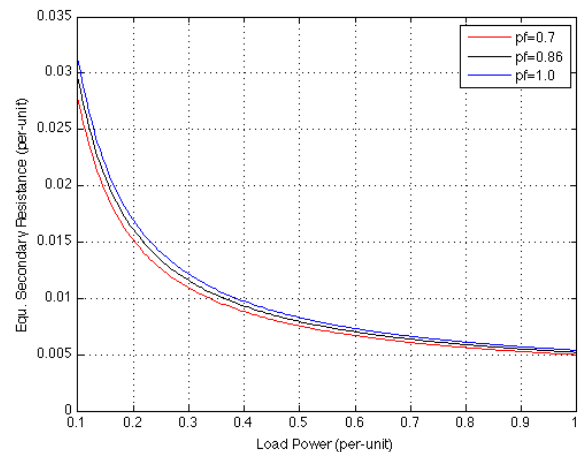


Fig. 10. Resistance from 400Vdc:120/240V Transformer [11].

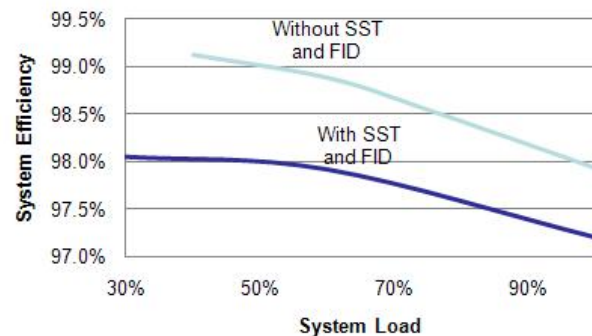


Fig. 11. System efficiency vs. loading.

The power factor of the downstream loads also affects system efficiency, and Fig. 8 illustrates this. Under low loading levels a lower power factor has less of an effect than high loading levels on system efficiency.

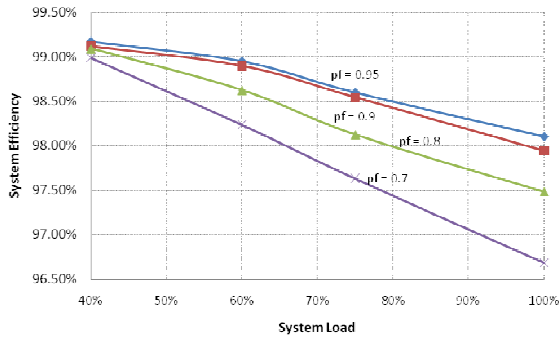


Fig. 12. Efficiency vs. System Loads at Various Power Factors (Without SSTs and FIDs).

A voltage analysis of the augmented FREEDM system reveals that in some cases, the voltage dropped to nearly 0.94 pu on the secondary side on some of the transformers, as shown in Fig. 13. Capacitive compensation can improve this profile and slightly improve the system efficiency.

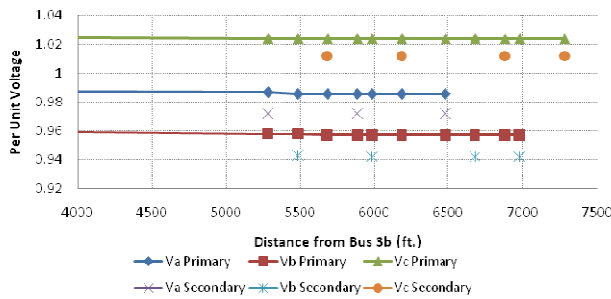


Fig. 13. Feeder voltage profile from Bus 3b.

Table III provides a summary of losses in the FREEDM grid for three different power levels after all components are added in.

Table III. Summary of losses for different power levels (with short circuit capacity = 10 MVA at the legacy grid)

Per cent loading	30%	60%	100%*
Total Load (kVA)	281.4+j140.7	562.8+281.35	938+j468.92
Total Losses (kW)	5.62	12.03	27.06
In all conductors (kW)	0.60	2.70	8.60
In dist. Transformers	0.20	3.70	11.40
In 3 SSTs (kW)	4.30	4.30	4.30
In 4 SSFIDs (kW)	0.52	1.33	2.76
Efficiency (%)	98.04%	97.91%	97.20%
Efficiency (%) without dist trans.	98.11%	98.54%	98.36%

The assumption is that the SST loading remains constant even though the bus loading changes. The resulting efficiency is about 97.20% at rated load. If, however, the SST at the main substation is included as part of the FREEDM system, then the efficiency would be lower. The same would be true if the three tested SSTs had different loading or PV and DG outputs. Fig. 14 illustrates the losses.

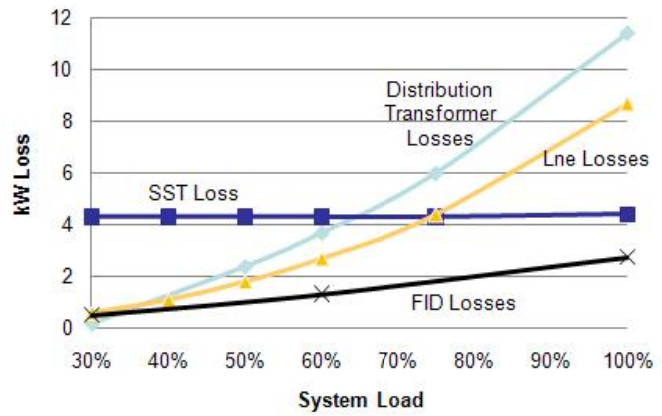


Fig. 14. kW Loss vs. System Load

C. Comparing the FREEDM grid with an IEEE system

An IEEE 13-bus system was compared with the FREEDM system in order to observe the efficiency of each one while noting the different voltages, currents, and load levels [7]. The IEEE system has significantly more losses in the lines than the FREEDM system, and the impedances per unit length are also slightly higher than in the FREEDM system. Fig. 14 shows the efficiencies of the two systems compared to another case where the SST and FID losses were not included.

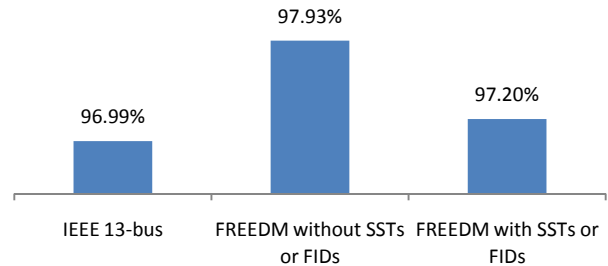


Fig. 14. Comparison of FREEDM system efficiency with an IEEE test system.

IV. CONCLUSION

The FREEDM grid will enable alternate and renewable energy resources, such as PV and other distributed energy resources to work seamlessly with the SST. With a significant number of solid state devices (SST and SSFID) operating on the grid at varying levels of loading, it will become important to manage the efficiency levels to be at least similar to what exists in the present power distribution systems. This study provides a basic understanding of how the FREEDM system efficiency may be impacted by the various devices. A comparison is also made to a published IEEE test system. The results indicated that the proposed FREEDM green hub, as it stands now, is just as efficient as a typical small distribution system provided measures are taken to manage the efficiency of the SST. Currently, there are different SST topologies being investigated. Loss models for the 3-phase 100kVA SST topologies are also being developed.

V. APPENDIX

A. Adding downstream distribution transformers

In order to account for the downstream losses, a P and Q ratio was obtained, as shown in Eqs. (A.1) - (A.3), by using the original 3-phase load values and the power flow from buses 2, 3a, and 3b going downstream by using the values from Table A1 as the distributed load values. The values in Table A1 were then multiplied by the P and Q ratios and a voltage ratio to account for any significant voltage drops.

$$P_{ratio} = \frac{P_{orig}}{P_{new}}, \quad Q_{ratio} = \frac{Q_{orig}}{Q_{new}} \quad (A.1)$$

$$P_{new,xfrm} = P_{ratio} \left[1 - \left(\frac{V_1 - V_2}{V_1} \right) \right] P_{old,xfrm} \quad (A.2)$$

$$Q_{new,xfrm} = Q_{ratio} \left[1 - \left(\frac{V_1 - V_2}{V_1} \right) \right] Q_{old,xfrm} \quad (A.3)$$

Where V_1 = voltage at bus2, 3a, 3b

V_2 = downstream bus voltage

The number of transformers in this model was determined by dividing each phase of the original loads such that the calculated values were less than 50 kVA (with the exception of phase-C off of bus 2). The integer values corresponding to bus 2 in vector format are, [phase-a; phase-b; phase-c] = [3; 4; 2], for bus 3a, they are [3; 1; 1], and [3; 4; 4] for bus 3b. The "Transformer" column in Table A.1 shows the order in which the distribution transformers appear on the feeder as they move further away from the corresponding bus (i.e. Bus 2, Bus 3a, or Bus 3b). The values in Table A.1 are not the adjusted values. The new augmented FREEDM system is shown in Fig. A.1.

B. The IEEE 13-bus test system

The IEEE 13-bus system is rated at 4.16 kV; the total active load on the system is 3,577 kW and the reactive load is 1,725 kW. The branch data is shown in Table B.1.

Table B.1. The IEEE 13-Bus test system.

	Node A	Node B	km	Ia	Ib	Ic	Loss kW
Conductors	632	645	0.1524		143.02	65.21	2.76
	632	633	0.1524	81.33	61.12	62.70	0.81
	645	646	0.0914		65.21	65.21	0.54
	650	632	0.6096	558.35	414.87	586.60	59.72
	684	652	0.2438	63.02		71.15	0.90
	632	671	0.6096	478.24	215.12	475.50	35.89
	671	684	0.0914	63.02		71.15	0.58
	671	680	0.3048	0.00	0.00	0.00	0.00
	671	692	0.0000	229.10	69.61	178.38	0.00
	684	611	0.0914			71.15	0.38
	692	675	0.1524	205.33	69.61	124.07	4.14
	Transformer	633	634	-	81.33	61.12	62.70
Switch	671	692	-	229.10	69.61	178.38	0.00
	Total		2.4994			Total	111.14

Table A.1. Dist. transformer loading for the modified FREEDM grid.

BUS 2									
# of Conductors	Phase	Transformer	Branch Length (ft)	Distance from BUS 2 (ft)	P (kW)	Q (kVAR)	S (kVA)	pf	
Double*	A	1	900	900	33.236	19.891	38.734	0.8581	
	B	2	200	1100	42.976	22.262	48.399	0.8879	
	C	3	200	1300	45.070	23.794	50.966	0.8843	
	A	4	150	1450	33.236	19.891	38.734	0.8581	
	B	5	350	1800	42.976	22.262	48.399	0.8879	
	C	6	200	2000	45.070	23.794	50.966	0.8843	
	Double	A	7	300	2300	33.236	19.891	38.734	0.8581
	Double	B	8	350	2650	42.976	22.262	48.399	0.8879
	Single	B	9	200	2850	42.976	22.262	48.399	0.8879

BUS 3a									
# of Conductors	Phase	Transformer	Branch Length (ft)	Distance from BUS 3a (ft)	P	Q	S	pf	
Double*	A	1	1000	1000	35.502	18.129	39.863	0.8906	
	B	2	500	1500	28.075	13.093	30.978	0.9693	
	C	3	300	1800	16.366	9.316	18.832	0.8691	
	Single	A	4	150	1950	35.502	18.129	39.863	0.8906
	Single	A	5	200	2150	35.502	18.129	39.863	0.8906

BUS 3b									
# of Conductors	Phase	Transformer	Branch Length (ft)	Distance from BUS 3b (ft)	P	Q	S	pf	
Double*	A	1	5280	5280	42.250	18.251	46.024	0.9180	
	B	2	200	5480	42.225	19.076	46.334	0.9113	
	C	3	200	5680	38.307	16.074	41.542	0.9221	
	A	4	200	5880	42.250	18.251	46.024	0.9180	
	B	5	100	5980	42.225	19.076	46.334	0.9113	
	C	6	200	6180	38.307	16.074	41.542	0.9221	
	A	7	300	6480	42.250	18.251	46.024	0.9180	
	Double	B	8	200	6680	42.225	19.076	46.334	0.9113
	Double	C	9	200	6880	38.307	16.074	41.542	0.9221
	Double	B	10	100	6980	42.225	19.076	46.334	0.9113
	Single	C	11	300	7280	38.307	16.074	41.542	0.9221

*Indicates how many phases are present on primary side of transformer. Nothing means 3-phase

C. SSFID losses

The SSFID efficiency can be estimated by the following method [3]:

$P_{conduction\ losses}$ for 1 IGBT+1Diode =

$$\frac{1}{T_0} \int_0^{T_0/2} [V_{CEO} \times I \times \sin \omega t + r_{CE} \times I^2 \times \sin^2 \omega t + V_F \times I \times \sin \omega t] dt$$

$$= \frac{V_{CEO} \times I}{\pi} + \frac{r_{CE} \times I^2}{4} + \frac{V_F \times I}{\pi}$$

$$P_{switching\ losses} = 6.8 \times 10^{-6} \times I_C^2 + 8.5 \times 10^{-3} \times I_C + 0.451$$

Where

I_{rms} = Rated rms line current of the system

I = Peak amplitude

V_{CEO} = On-state collector-emitter voltage drop of IGBT at $I_{rms} = 46.2$ A

r_{CE} = Internal collector-emitter resistance of IGBT

V_F = On-state forward voltage of diode

Conduction and switching losses will occur in the three SSFID modules where each module has two pairs of IGBTs.

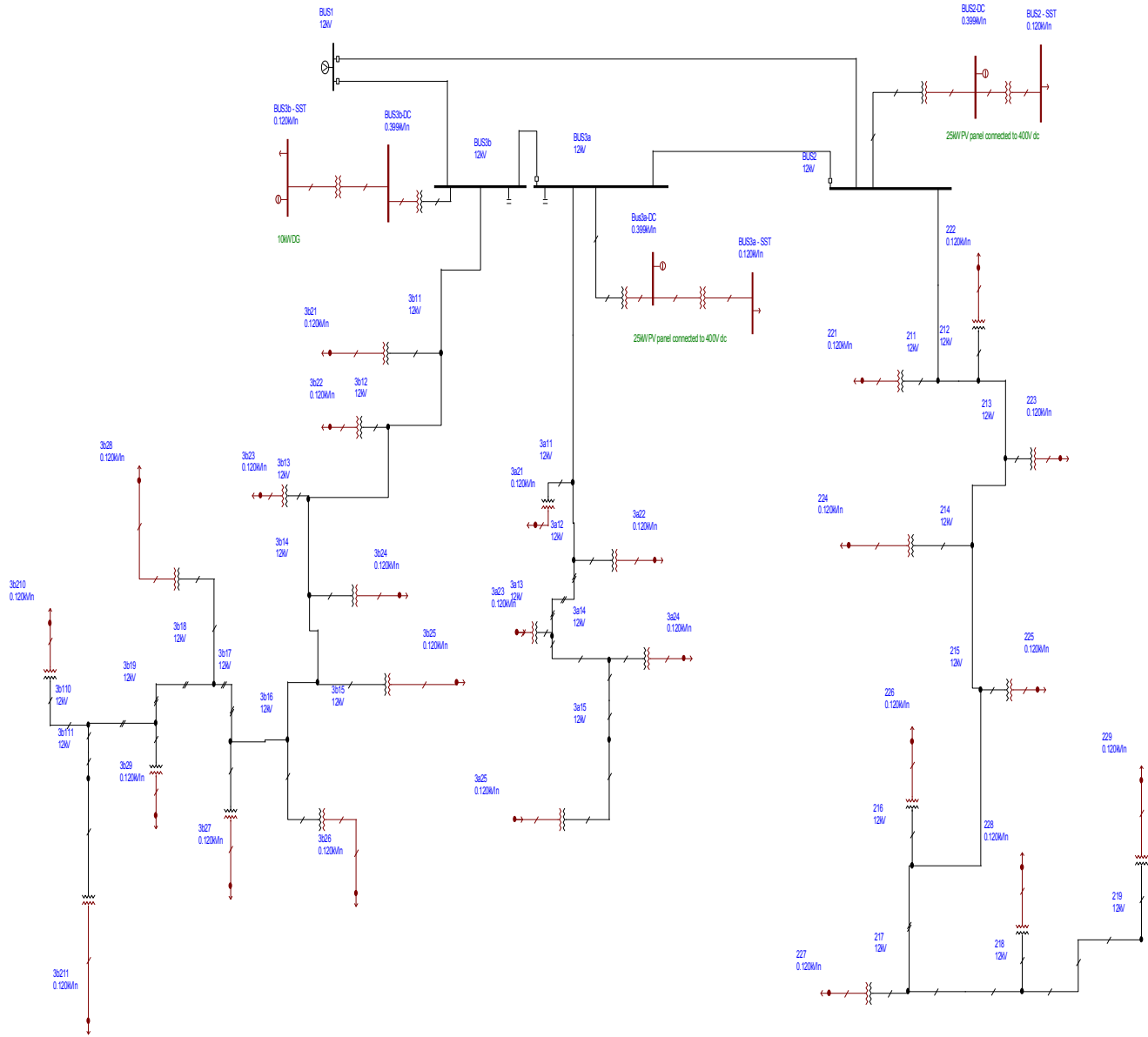


Fig. A1. The modified FREEDM System

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