

AC vs. DC Distribution: A Loss Comparison

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Abstract--Environmentally friendly technologies such as photovoltaics and fuel cells are DC sources. In the current power infrastructure, this necessitates converting the power supplied by these devices into AC for transmission and distribution which adds losses and complexity. The amount of DC loads in our buildings is ever-increasing with computers, monitors, and other electronics entering our workplaces and homes. This forces another conversion of the AC power to DC, adding further losses and complexity. This paper proposes the use of a DC distribution system. In this study, an equivalent AC and DC distribution system are compared in terms of efficiency.

Index Terms--DC power systems, power system modeling, power distribution, losses

I. INTRODUCTION

I ncreasing demand and environmental concerns have forced engineers to focus on designing power systems with both high efficiency and green technologies. Green technologies are those that conserve natural resources such as fossil fuels while reducing the human impact on the environment through a reduction in pollution [1]. The most well-known green technologies include photovoltaics and wind turbines. Although fuel cells are not considered a green technology, fuel cells have low emissions compared to other forms of energy and are deemed more environmentally friendly. Unfortunately, the prevailing power system infrastructures are based on alternating current (AC) while two of the leading environmentally friendly energies, fuel cells and photovoltaics, produce direct current (DC).

Currently, power system infrastructures that wish to incorporate fuel cells and photovoltaics must first convert the DC power produced by these energy sources to AC. This adds complexity and reduces efficiency of the power system due to the need of a power converter. Furthermore, an ever increasing number of DC consuming devices such as computers, televisions, and monitors are being incorporated into our buildings. The power supplied to these devices must be converted again from AC back to DC adding further losses and complexity to the power system.

Instead of using multiple converters to convert DC to AC and then AC to DC, the power system could solely be based on DC. This would eliminate the need for two sets of converters for each DC load, reducing the cost, complexity, and possibly increasing the efficiency. However, a definitive analysis on a DC distribution system is needed to determine

the net benefits of eliminating the converters. In this paper, a large steady state analysis of an existing AC grid is constructed along with a DC counterpart. These models are compared in terms of efficiency.

II. BACKGROUND

Since the development of electricity, AC has been depicted as the better choice for power transmission and distribution. However, Thomas Edison one of the founders of electricity supported the use of DC. No method at that time existed for boosting and controlling DC voltage at the load, so that transmission of DC power from generation to load resulted in a large amount of losses and voltage variations at the different load locations. To resolve this issue, Westinghouse proposed AC distribution. Nikola Tesla had only recently at that time developed the transformer which had the capability of boosting voltage in AC. This allowed for efficient transmission of power from one location to another resulting in a complete transformation of the power systems to AC [2].

Although many things have changed since the invention of electricity, AC is still the fundamental power type of our power infrastructure. However, due to the development of power converters and DC energy sources, interest in DC has returned.

Several studies have investigated the use of a DC distribution system. In [3], a small-localized DC distribution system for building loads is investigated. This power system is supplied by a DC distributed energy source for the DC loads and has a separate AC grid connection for the AC loads. The author relates that this methodology leads to a higher efficiency compared to a system solely based on AC through avoiding the use of the rectifier. The author notes that power rectifiers have a relatively low efficiency compared to inverters and DC-DC converters.

In [4], a DC zonal distribution system for a Navy ship is investigated to provide electrical isolation, reduce cost, and increase stability. Essentially each zone has a separate distribution system providing protection to the overall ship power systems when an attack has occurred. Due to the need of multiple levels of DC voltage, a DC system was deemed superior to a AC system in terms of efficiency and cost. The AC system would need an inverter and then DC-DC converter for each DC bus voltage level, while a DC system would only implement DC-DC converters.

Nevertheless, several investigations in DC have suggested that DC distribution is not as efficient. In [5], the authors investigate DC distribution for a small-scale residential system. The authors note that although conduction losses in a DC system appear to be lower, the efficiency of power converters during partial loading is a concern and can ultimately lead to higher losses in DC. In [6], the author compares several AC and DC systems for data centers. Based on the results, the author concludes that a high voltage (HV) DC distribution system is more efficient than AC, but no components need this high voltage. The author constructed another DC system, coined a hybrid DC system, which contained multiple DC voltages. However, the author observed that the converter losses reduced the efficiency to that below what is found in an equivalent AC system.

In all of these cases, a DC distribution system was employed at systems below what is deemed the power distribution level of the utility. Furthermore, the loads were either assumed to be fully AC or DC. In this study, the utility level distribution is considered, and efficiencies of the AC and DC power systems are compared. The power system is also adjusted for partial loading of AC and DC components. The goal is to relate an AC power system to DC in terms of efficiency.

III. MODEL

To best represent the differences in AC and DC power infrastructures, two models were created, one implementing the actual AC devices and components of the grid and a second model implementing DC devices. The DC model adopts some of the AC components along with necessary DC components to represent a direct conversion from an AC system to a DC system.

The AC model is a representation of a large existing power distribution system with thousands of loads in a variety of sizes. The loads range in size from several watts to several hundred kW and come from industrial motors, lighting, computers, air conditioners, and other devices. Due to the sheer number, the loads are not measured for each device within the building, but instead are measured at the building level. This results in a power system consisting of 235 loads or buildings.

The loads employed have two sets of recorded data, a maximum and an average. During a one year span, daily maximum and average building loads of the power system in question were measured. At the end of the year, the daily averages were averaged and the maximum was found for the whole year. The average and maximum instantaneous power usage for the entire distribution system for the year are 31.9MVA/27.1MW and 42.6MVA/36.2MW, respectively.

The AC distribution power system under investigation is divided into three voltage divisions, two medium voltages(MV) and a low voltage(LV). For the AC power system the HV and MV are 13.8kV and 2.4kV. The LV magnitude is dependent on the building loads.

The DC model was constructed with the AC model in mind. Any location where voltage was increased or decreased with a transformer in AC, a DC/DC converter was

implemented in the DC model. AC components that are deemed applicable in DC power systems were implemented in the DC model and include the distribution lines and some fault interrupting devices.

Both of these models were inserted into the SKM power system analysis software package for analysis. This program is used extensively by the Oak Ridge National Laboratory (ORNL) for AC power system power flow verification. This software package accepts the input data from the user and implements several numerical analysis techniques to determine the voltage, current, and power levels at different locations in the power system. The following subsections describe the model in more detail.

A. AC Model

The components in the AC portion of the model that are implemented in the load flow analysis are the distribution line, transformer, AC load, and capacitor for Var compensation as seen in Fig. 1. These components account for more than 900 components in the model. Buses are also necessary for analysis of the data and are placed in between each load flow component. The total number of buses in the model were determined to be 714. The fault interruption devices in the model were ignored due to the negligible resistance these devices add to the overall power system.

The characteristic data used to determine the load flow and

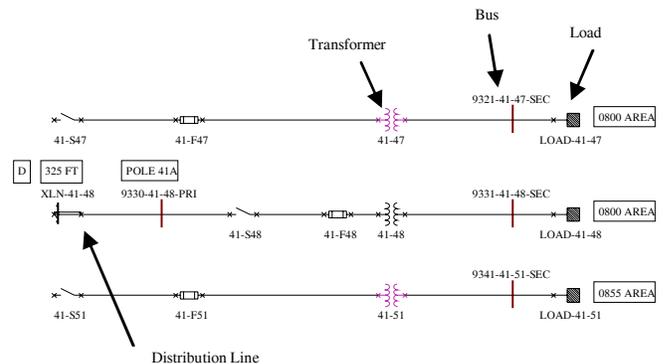


Fig. 1. Portion of AC distribution system.

losses for the different components is described in Table I. This data comes primarily from manufacturer-supplied data with missing information supplied by test data.

TABLE I
AC DISTRIBUTION SYSTEM CHARACTERISTIC COMPONENT DATA

Component	Characteristic Data
Distribution Line	Zero sequence impedance Positive sequence impedance
Load	Apparent Power Power Factor Voltage Rating
Transformer	Zero Sequence impedance Positive Sequence Impedance Power Rating Input/Output Voltage Rating
Capacitor Bank	Zero sequence capacitance Positive sequence capacitance

B. AC Model Equations

The basic methodology behind the SKM program is the use of Ohm's law. In matrix form this is:

$$[I] = [Y][V] \quad (1)$$

where I represents the currents, V the voltages, and Y the admittance matrix. The admittance matrix represents the different admittance values that interconnect the buses in the power system. These admittance values can come from a number of sources, line impedance, impedance within a transformer, or even shunt admittance from a capacitive source. Consider the three bus example provided in Fig. 2.

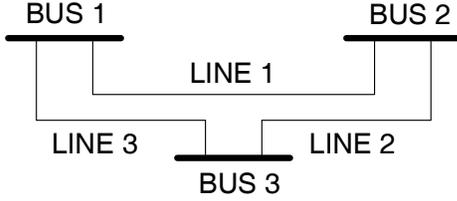


Fig. 2. Schematic of 3 bus example.

The three bus example is composed of 3 lines that could be considered as either a distribution line or a transformer. In either case, a characteristic series impedance is associated with these lines. Fig. 3 shows the admittance model.

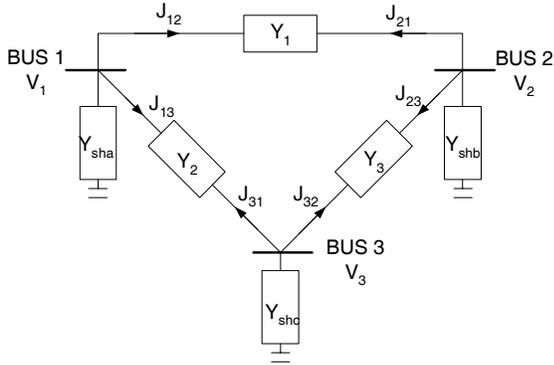


Fig. 3. Impedance schematic of 3 bus example

Using Fig. 3, equations for the injected current at each bus can be constructed in terms of the voltage and series and shunt admittance values. The following equations represent the injected current for the three different buses.

$$J_{13} + J_{12} = (Y_{sha} + Y_1 + Y_2) \times V_1 + (-Y_1) \times V_2 + (-Y_2) \times V_3 \quad (2)$$

$$J_{21} + J_{23} = (-Y_1) \times V_1 + (Y_{shb} + Y_1 + Y_3) \times V_2 + (-Y_3) \times V_3 \quad (3)$$

$$J_{31} + J_{32} = (-Y_2) \times V_1 + (-Y_3) \times V_2 + (Y_{shc} + Y_3 + Y_2) \times V_3 \quad (4)$$

Manipulation of these equations into matrix form results in the formation of the admittance matrix as shown below [7-8].

$$\begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} = \begin{bmatrix} Y_{sha} + Y_1 + Y_2 & -Y_1 & -Y_2 \\ -Y_1 & Y_{shb} + Y_1 + Y_3 & -Y_3 \\ -Y_2 & -Y_3 & Y_{shc} + Y_2 + Y_3 \end{bmatrix} * \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (5)$$

Since the voltages and current values are the unknown values in the system, another equation must be adopted to resolve the equations. The following equation relates the real and reactive power to current and voltage:

$$I_i = \frac{(P_i + jQ_i)}{V_i} \quad (6)$$

Combining equations 1 and 6 results in a nonlinear equation as shown:

$$[Y][V] = \left[\frac{(P + jQ)}{V^*} \right] \quad (7)$$

This equation contains the variables of real and reactive power, voltage (including magnitude and phasor angle), and the admittance. Depending on the unknown and known variables in this equation, the names swing bus, load bus, and voltage control bus are provided as descriptions of the bus type as shown in Table II.

TABLE II
AC BUS TYPES

	Specified	Free
Swing Bus	Pi, Qi V = 1 pu $\delta = 0^\circ$	Pg, Qg
Load Bus	Pg, Qg = 0 Pi, Qi	V, δ
Voltage Control Bus	Pg, Qg, Pi, V	Qg, δ

Pg = real power generated
Qg = reactive power generated
Pi = real power consumed
Qi = reactive power consumed
V = voltage magnitude
 δ = voltage angle

Since the base equation is nonlinear, an iterative numerical technique must be implemented to solve for the solution. The numerical analysis method implemented by SKM has been coined the "double current injection" method. In this method, the losses are originally assumed to be zero, and the current is determined through calculation from the load and nominal voltage values. The losses are then included and the voltage drop at each load and bus is determined. The new voltages lead to a recalculation of the current and another iteration is begun. This process is repeated to a minimum error has been reached.

C. DC Model

The components of the DC load model implemented in load flow include the distribution line, DC/DC converter, and DC load as seen in Fig. 4.

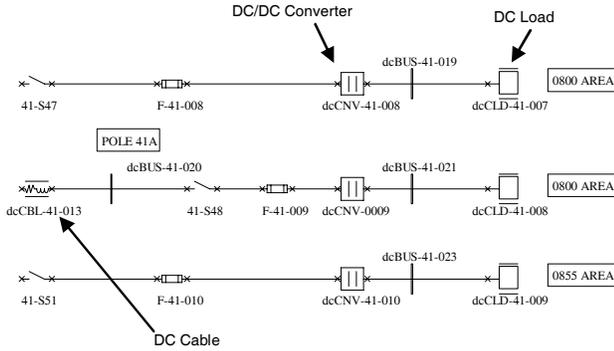


Fig. 4. Portion of DC distribution system.

For this model several assumptions had to be made:

- 1) As with AC, the fault interruption devices were deemed negligible in terms of losses and were ignored in the model.
- 2) One current problem with DC-DC converters is that the efficiency tends to fall when operated below the rating. In the model implemented, the DC-DC converter efficiency was assumed fixed for all operating conditions. A paralleling topology discussed in [9] describes a design that allows DC-DC converters to operate close to the maximum operating efficiency until as low as 10% of operation as seen in Fig. 5.

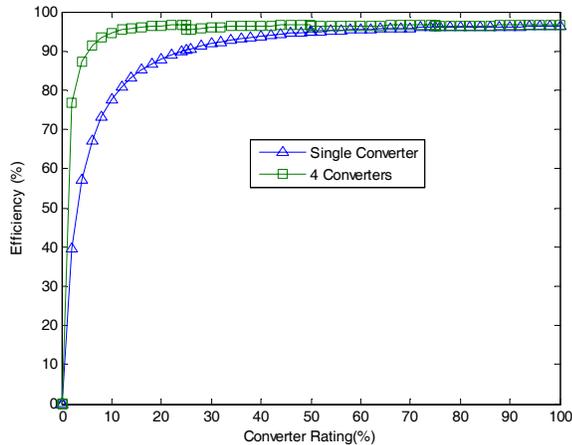


Fig. 5. Efficiency curves for DC-DC converter.

- 3) The distribution lines used in the DC model are the same as the AC model. Hence, the resistance values employed come from the manufacturer specifications of the AC distribution lines. The values used represent the DC resistance of the conductor at a temperature of 25°C.

- 4) Since DC is only composed of two cables instead of the three used in AC, an extra cable exists for DC. This extra cable is to be applied as a DC negative. This provides DC with a positive, neutral, and negative thereby doubling the apparent voltage [10].
- 5) Since no reactive power is produced or consumed in a DC power system, the loads modeled in DC were of the same real power magnitude. This power value was determined by multiplying the apparent power of the AC load by the power factor.

The characteristic data for the DC model involves purely resistive elements. SKM uses the equations in Table III to convert the data supplied to a DC resistance. Since the DC-DC converter model resistance is based on the rated power, the simulation results must be verified to ensure that the actual efficiency input was actually implemented.

TABLE III
DC COMPONENT CHARACTERISTIC EQUATIONS

Distribution Line	$r_{cable} \times l$
Load	$\frac{V^2}{P}$
DC-DC Converter	$(1-\eta) \frac{V^2}{P}$

r_{cable} – resistance/ft
 l – length of cable in ft
 V – rated voltage
 P – rated power
 η – rated efficiency

D. DC Model Equations

The DC load flow calculations are similar to those of the AC power system with a few differences. The DC power system uses a conductance matrix instead of an admittance matrix since no reactance exists in DC:

$$[I] = [Y][V] \quad (8)$$

This embodies the DC system with a much simpler overall equation and characterization of the buses. Table IV shows the distinct bus types of a DC type. Unlike the AC system, the DC system only has 2 bus types with 2 unknown variables. SKM implements Newton Raphson to solve for these variables.

TABLE IV
DC BUS TYPES

	Specified	Free
Swing Bus	P1 $V = 1$ pu	Pg
Load Bus	Pg, P1	V

E. Difference in AC and DC

In terms of the basic power system equations, AC and DC power systems have quite a contrast. In an AC system, power flow is often determined by the equation:

$$P_{3\phi} = 3 \times V_{RMS} \times I_{RMS} \times \cos(\theta) \quad (9)$$

where V_{RMS} , I_{RMS} , and θ are the respective voltage in RMS, current in RMS, and power factor angle. In DC, the power flow is calculated by:

$$P_{DC} = V \times I \quad (10)$$

Upon examination, these equations can have a substantial difference in power flow. Depending on the power factor, AC can have three times more power flow when the same RMS voltage and current are implemented in an AC and DC system as shown:

$$\frac{P_{3\phi}}{P_{DC}} = 3 \cos(\theta) \quad (11)$$

The voltage and currents in the DC system must be adjusted to overcome this difference. If we now consider the difference in losses for AC and DC:

$$P_{3\phi} = 3 \times I_{AC\ RMS}^2 \times R_{AC} \quad (12)$$

$$P_{DC} = 2 \times I_{DC}^2 \times R_{DC} \quad (13)$$

and if we wish the systems to have the same losses:

$$\frac{I_{AC\ RMS}}{I_{DC}} = \sqrt{\frac{2}{3}} \approx .82 \quad (14)$$

where the AC and DC resistance values are assumed to be the same, a noticeable gain in DC can be seen. This result shows that the DC current can be 1.22 times larger than the AC current and the system will have the same conduction losses.

If a DC neutral is implemented as previously discussed, and the equations (9),(10), and (14) are combined:

$$\frac{V_{AC\ RMS}}{2V_{DC}} = \frac{.82}{\cos(\theta)} \quad (15)$$

and if we convert the voltages from RMS to peak:

$$\frac{V_{AC}}{2V_{DC}} \approx \frac{1.15}{\cos(\theta)} \quad (16)$$

This illustrates that if the same peak voltages in both the AC and DC systems are implemented, DC should have a small advantage over AC in terms of transmission losses when implementing AC cables. Nevertheless, the transmission losses tend to only account for a small

percentage of the system losses. The power conversion devices have a more significant impact.

In AC, the power conversion devices employed are transformers. The efficiency of the transformer over the years has improved dramatically, particularly in upper level power systems. These devices now have efficiency upwards of 98%. Unfortunately to convert back to DC, AC power systems use rectifiers that are much lower in efficiency. In this study the rectifiers are assumed to be 90% efficient [3].

DC on the other hand employs DC-DC converters with overall efficiencies that tend to be below 95% and as mentioned, suffer from decreased efficiency when operated below rating unless special implementation of the converter is performed. To convert back to AC, inverters are necessary. In this study, the inverters are assumed to have efficiencies of 97%.

Based on the varying efficiencies of the power converting technologies, and the use of multiple converters in each system, it is difficult to distinguish one type of power over the other based on a simple calculation. Instead a power system must be analyzed to determine the system that has the better results.

The following section relates the outcome of the comparison of the power systems.

IV. RESULTS

For the comparative study, the efficiency rating of the DC-DC converters were assigned to three different efficiencies, 95%, 97%, and 99.5%. The voltages of the DC system were varied to represent the I^2R losses and the total losses are provided in kW. The data for a power system supplied by a DC source, with DC components, and DC loads based on maximum operation is shown in Fig. 6.

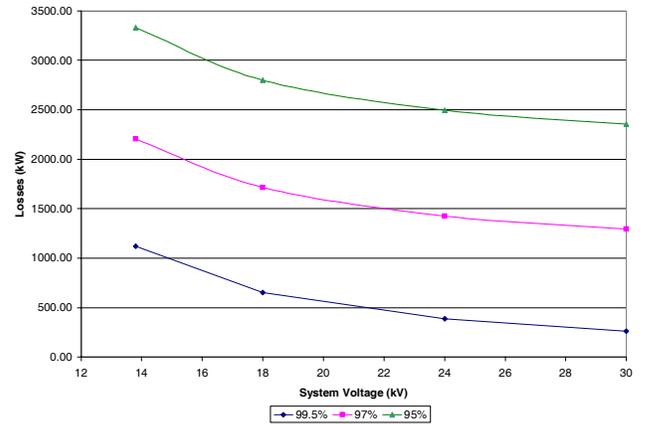


Fig 6. DC power system efficiency for maximum operation.

The equivalent AC system with an AC source, AC components, and AC loads resulted in 800 kW of losses. Table V shows the results. Based on a straight comparison of

a 100% AC system and a 100% DC system, AC would have fewer losses.

When adjusted to the average power, the AC power system again had fewer losses than the DC power system. Fig. 7 shows the losses of a 100% DC system. The equivalent AC system average system losses were determined to be 412 kW as shown in Table VI.

TABLE V
LOSSES BASED ON MAX LOADING OF PURE AC AND DC POWER SYSTEMS

System Type	System Voltage			
	13.8kV	18kV	24kV	30kV
AC	800	-	-	-
95% ¹ DC	3332	2799	2496	2354
97% ¹ DC	2204	1716	1427	1296
99.5% ¹ DC	1121	651	386	263

¹represents DC-DC converter efficiency

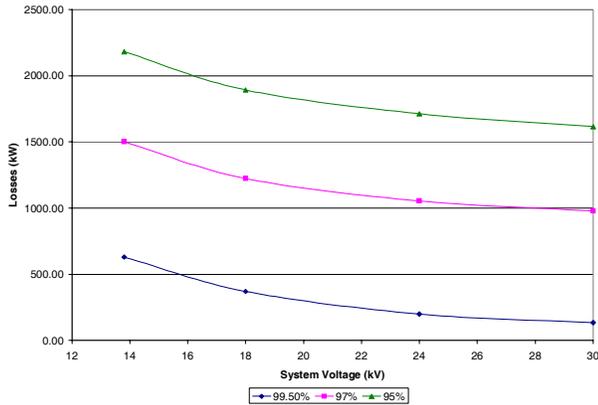


Fig 7. DC power system efficiency for average operation.

TABLE VI
LOSSES BASED ON AVG LOADING OF PURE AC AND DC POWER SYSTEMS

System Type	System Voltage			
	13.8kV	18kV	24kV	30kV
AC	412	-	-	-
95% ¹ DC	2181	1892	1712	1614
97% ¹ DC	1500	1223	1053	977
99.5% ¹ DC	630	370	198	133

¹represents DC-DC converter efficiency

Although this would seem detrimental to the application of a DC distribution system, another comparison is needed. To form a realistic study, the model of the power system should be composed of partial loads of both AC and DC components. Therefore, a partial loading of the different load types was examined based on the average model data, where the AC system is based on 13.8 kV and the DC system with 30 kV. This met with much better results in terms of the application of DC distribution as shown in Table VII.

Table 7 illustrates that when 50% of the loads are AC and 50% of the loads are DC, the difference in losses becomes relatively close with a 95% DC-DC converter. A better representation is shown in Fig. 8. DC distribution actually has lower losses when more than 50% of the loads are DC and DC-DC converters with efficiencies of 95% or higher are used.

TABLE VII
LOSSES BASED ON PARTIAL AC AND DC LOADING OF POWER SYSTEMS

Loads	AC(kw)	DC(kw)	DC(kw)	DC(kw)
AC%/DC%		95% ¹	97% ¹	99.5% ¹
100/0 ²	412	2317	1811	1119
50/50 ²	1679	1982	1313	583
0/100 ²	2872	1653	1008	329

¹represents DC-DC converter efficiency

²represents ratio of AC/DC loads

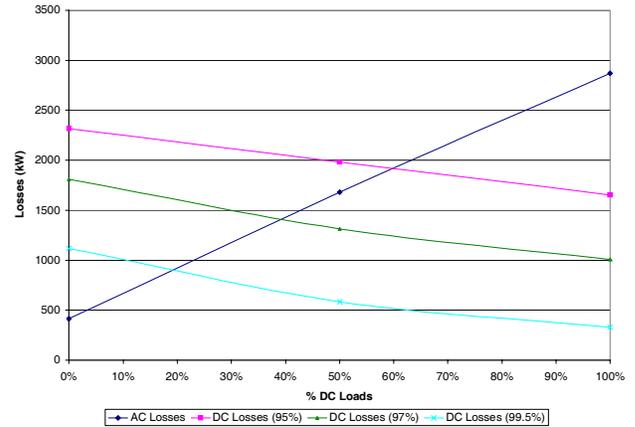


Fig 8 Partial AC and DC loading of power systems.

V. CONCLUSION

Under the current power system infrastructure, DC sources that supply DC loads must implement two converters, one that first converts the DC to AC and then another to return the AC back to DC. This type of power system can result in significant losses.

As this study shows, AC and DC distribution systems can have the same merit when the loads are equal in ratio, 50% AC loads and 50% DC loads. Nevertheless, this study assumed that AC power system was supplied by a AC source and DC through a DC source. If the AC power system is supplied by a DC source, further losses can be expected resulting in further benefits of a DC distribution system.

One other possibility in increasing the system benefits is offering two types of power for every load, AC and DC. As shown each has a substantial benefit in supplying their own loads and this can result in a significant reduction in power system losses.

Ultimately, the defining device in the possible application of a DC distribution system is the DC-DC converter. Although the data analyzed considered DC-DC converters with efficiencies with 95% or higher, actual DC-DC converters rarely meet 95% efficiency. To substantiate a DC distribution system, advancements in DC-DC converter technology are significantly needed.

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BIOGRAPHIES



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Dr. Tolbert is a registered Professional Engineer in the state of Tennessee. He is the recipient of a National Science Foundation CAREER Award and the 2001 IEEE Industry Applications Society Outstanding Young Member Award.



Burak Ozpineci (S'92–M'02–SM'05) received the B.S. degree in electrical engineering from the Middle East Technical University, Ankara, Turkey, in 1994, and the M.S. and Ph.D. degrees in electrical engineering from the University of Tennessee, Knoxville, in 1998 and 2002, respectively.

He joined the Post-Masters Program with the Power Electronics and Electric Machinery Research Center, Oak Ridge National Laboratory (ORNL), Knoxville, TN, in 2001 and became a Full-Time Research and Development Staff Member in 2002. He is also an Adjunct Faculty Member of the University of Arkansas, Fayetteville. He is currently doing research on the system-level impact of SiC power devices, multilevel inverters, power converters for distributed energy resources, and intelligent control applications to power converters.

Dr. Ozpineci was the Chair of the IEEE PELS Rectifiers and Inverters Technical Committee and Transactions Review Chairman of the IEEE Industry Applications Society Industrial Power Converter Committee. He was the recipient of the 2006 IEEE Industry Applications Society Outstanding Young Member Award, 2001 IEEE International Conference on Systems, Man, and Cybernetics Best Student Paper Award, and 2005 UT-Battelle (ORNL) Early Career Award for Engineering Accomplishment.