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Overhead Conductor Efficiency Optimization using Steel Core

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SUMMARY

This paper examines the strategies for optimizing grid efficiency by selecting the optimal conductor size and conductor design. The efficiency benefits for composite cores and steel cores are compared.

A composite core is the compelling choice where the increased cost for the core can be offset by savings in the structures or right of way. A conductor with a steel core is the compelling choice when the savings in core costs can be used to increase the aluminum area and thereby provide the greatest efficiency at the lowest cost.

KEYWORDS

Grid efficiency, Overhead conductor, Steel core, Composite core, ACSS, ACSR

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INTRODUCTION

Improving the efficiency of the electrical grid is among actions to address climate change and rising energy costs. Conservative temperature limits for the earliest overhead lines made them efficient. By the mid-1970s, load growth - combined with the financial and political cost of new lines lead to thermal uprating of existing line; the downside is a corresponding increase in the line losses.

For the purpose of this paper, we define conductor efficiency as the point-to-point power delivery efficiency for each line section: the energy delivered at the load divided by the energy provided at the source. Grid efficiency is more difficult to define, but is a multi-factor weighted average of the efficiency of each point-to-point line section.

Many transmission lines are extremely efficient due to operation at low average capacity factor. Bundled EHV and UHV lines are typically highly efficient because bundling needed to suppress corona results in these lines operating at a small fraction of their thermal capacity. The suggestion has been made that replacing all ACSR with advanced conductors will make the grid efficient.

The US Congress is likely to impose new requirements designed to improve the efficiency of the grid: Senate Bill S2659 and the identical House Bill HR 4972 on grid efficiency will be approved, and regulatory agencies will be funded and tasked with writing regulations to limit energy loss, including losses in overhead lines. That will inevitably drive the purchasing decisions towards larger and more efficient conductors. What is the best use of money for improved grid efficiency? Smart grid (sensors for situational awareness, decision tools, and control devices) have their place. However, conductors dominate the loss. Therefore, larger (lower resistance) conductors and the associated structure changes will also receive careful attention.

ECONOMIC VALUE OF A 1% CONDUCTOR EFFICIENCY IMPROVEMENT

Power loss in a conductor is easily computed as the line current squared, multiplied by the AC or DC resistance of the conductor. Line current is highly variable over different seasons and times-of-day. It is therefore necessary to estimate an average annual current load to determine the annual loss. Once the engineers compute the energy loss in kWh, the economists place a dollar value on the line loss during the service life of the conductor. A more efficient conductor is justified by the value today for savings expected to accumulate over decades into the future.

Reference 1 in the Bibliography presents the method for computing the value of line losses. In addition to the cost of energy, the method addresses the utility specific owning costs for generation and transmission assets, demand charges, and other direct and indirect costs. A simple shortcut is to assume electricity is priced correctly and use the average selling price of electricity as the cost. A present value computation of the annual savings is used to justify an investment today that pays back over decades into the future.

Using 795 kcmil ACSR “Drake” conductor as the reference, and assuming a 200 A annual average line load (~20% of capacity), 25 °C average annual temperature, and 2 ft/s (0.61 m/s) average annual wind speed, the IEEE 738 method computes an average conductor temperature of 35.6 °C. The computation for a 1% efficiency improvement follows:

- AC resistance at 35.6 °C: 0.1215 Ω/mi (0.0755 Ω/km).
- Power loss: $(200\ \text{A})^2$*0.1215 Ω/mi/1000 W/kW: 4.860 kW/mi (3019 kW/km)
- Energy loss: 4.860 kW/mi*8760 hr/yr: 42,574 kWh/mi/yr (26,446 kWh/km/yr)
- Annual cost @USD 0.20/kWh: USD 8515/mi/yr (USD 5289/km/yr)

A 1% reduction in the AC resistance translates directly into a 1% loss reduction. The cost of losses is therefore reduced to USD 8430/mi/yr (USD 5236/km/yr). The annual savings for the 1% efficiency improvement is USD 85.15/mi/yr (USD 52.89 km/yr).

Assuming a 3.5% inflation rate, and 40-year service life, the Excel® PV function returns a present value of the future savings of USD 1,795.96/mi (USD 1115.50/km). If this present value of the future line loss is included in the cost of the conductor, the selling price for the 1% more efficient conductor could be increased by USD $1,795.96/mi (USD 1115.50/km), which is USD 0.34 per foot (USD 1.12/meter) of conductor. Assuming the conductor cost is USD 2/ft (USD 6.56/m), this justifies a 17% cost increase for each 1% efficiency improvement.

DESIGN AND MANUFACTURING OPTIONS FOR EFFICIENCY IMPROVEMENT

Numerous options exist for increasing the conductor efficiency at low to moderate cost. Options that effect interoperability within the existing system should be pursued only if all other options fail to meet the goal. For an example of interoperability, utilities maintain a supply of spare conductor and fittings for system restoration after storms and other events. It is unworkable to keep spares for special conductors needing special fittings. The fittings suppliers have a role in qualifying their special fittings to serve as storm spares for both legacy conductors and high-efficiency conductor. Similarly, the high-efficiency conductors should be suitable as storm reserves for similar legacy conductors in service.

In approximate order of cost effectiveness, these are some easily available options:

Design/Manufacturing Option	Efficiency Improvement	Cost[1]
ACSS Annealed Aluminum instead of ACSR Hard-drawn Aluminum	1% to 1.5%	<1% - 10%
Higher strength materials for the core to reduce core area and increase Aluminum area	3%	10% to 200%[2]
Larger conductor	0.1% - 10%	0.1% - 10%
1 not including effect on structure cost		
2 cost depends on steel vs composite core		

ECONOMIC OPTIMIZATION OF CONDUCTOR SIZE

It is well-understood that conductor characteristics, especially the sag, impact the structure cost, and that conductor cost should therefore not be considered independent of its effect on the structure cost. In this paper there is no attempt to quantify the structure cost implications, which, depending on the line design, can be a deciding factor. As a basic principle, the conductor and structure combined cost increases linearly with the conductor size.

Figure 1 shows a graphical presentation of Kelvin's law for conductor size optimization. The pink line shows the linear relationship between the conductor size and the conductor cost. The yellow line is an exponential curve, showing that the cost of losses increases exponentially as the conductor becomes too small. The benefit of increasing the conductor size reaches the point of diminishing returns, where it becomes uneconomical to further increase the conductor size. The green curve is total cost, which is the sum of the conductor/structure cost and cost of line loss. The size for the minimum total cost is the optimum size, located at the dashed black line. Note that the green total cost curve is relatively flat near the optimum. This means that picking a conductor one or two sizes above the optimum has a very small impact on the cost, if losses are considered.

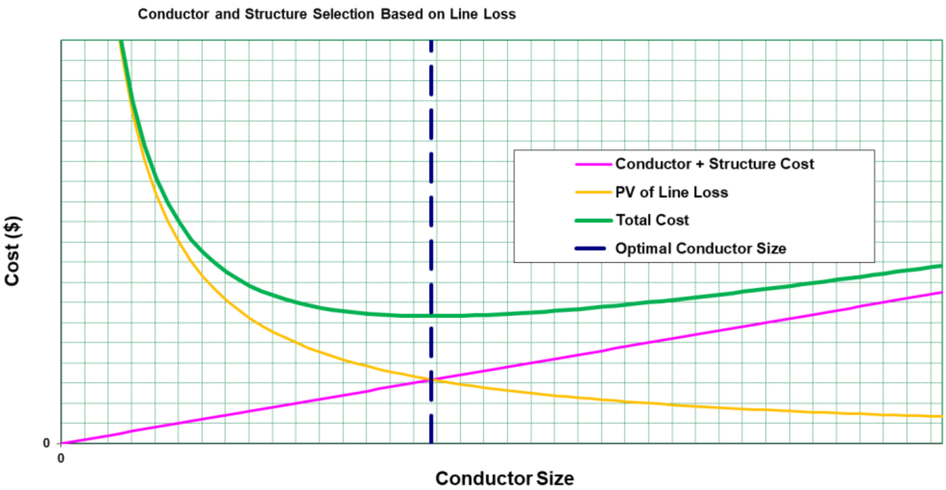

Figure 1: Kelvin's Law for Optimizing Conductor Size

CONDUCTOR CLASSIFICATION AND SELECTION

This paper proposes three conductor classifications for understanding efficiency and cost:

1) Equal <u>diameter</u>, which is a requirement for reconductor options when existing structure limitations require a conductor no larger than the conductor being replaced.
2) Equal <u>efficiency</u>, where the size and cost impacts are compared for any given efficiency target.
3) Equal <u>cost</u>, where the size and efficiency are compared on an equal-cost basis.

All conductor options considered in this paper use annealed aluminum, which offers lower resistance compared to hard-drawn aluminum used in ACSR and numerous other conductor designs. The proposed alternatives also use compact trapezoidal wire (TW) aluminum strands to increase the aluminum area or to reduce the conductor diameter for the same aluminum area. Annealed aluminum used in ACSS Conductors also offers a large capacity increase due to higher thermal limits compared to ACSR conductors.

Open-source data and industry-standard software were used to compute the temperature and corresponding AC resistance for conductors representing the three classification options. For simplicity, data for the alternate conductors are normalized by dividing the engineering value by the value for the "Drake" ACSR conductor. "Drake", accordingly, has a normalized value of one (1). The

AC resistance values for the ACSS/TW Bezinal® core options assume the efficiency benefit of the annealed aluminum.

An average line load of 500 A (50% of "Drake" capacity) is assumed to keep the comparisons on an equal basis. The larger conductors will run cooler at 500 A, resulting in an efficiency benefit from both lower resistance and lower operating temperature (aluminum resistance increases with increasing temperature at a rate of 0.4%/°C).

Conductors of Equal Diameter

Figure 2 shows two leading equal-diameter conductor choices for efficiency and cost:

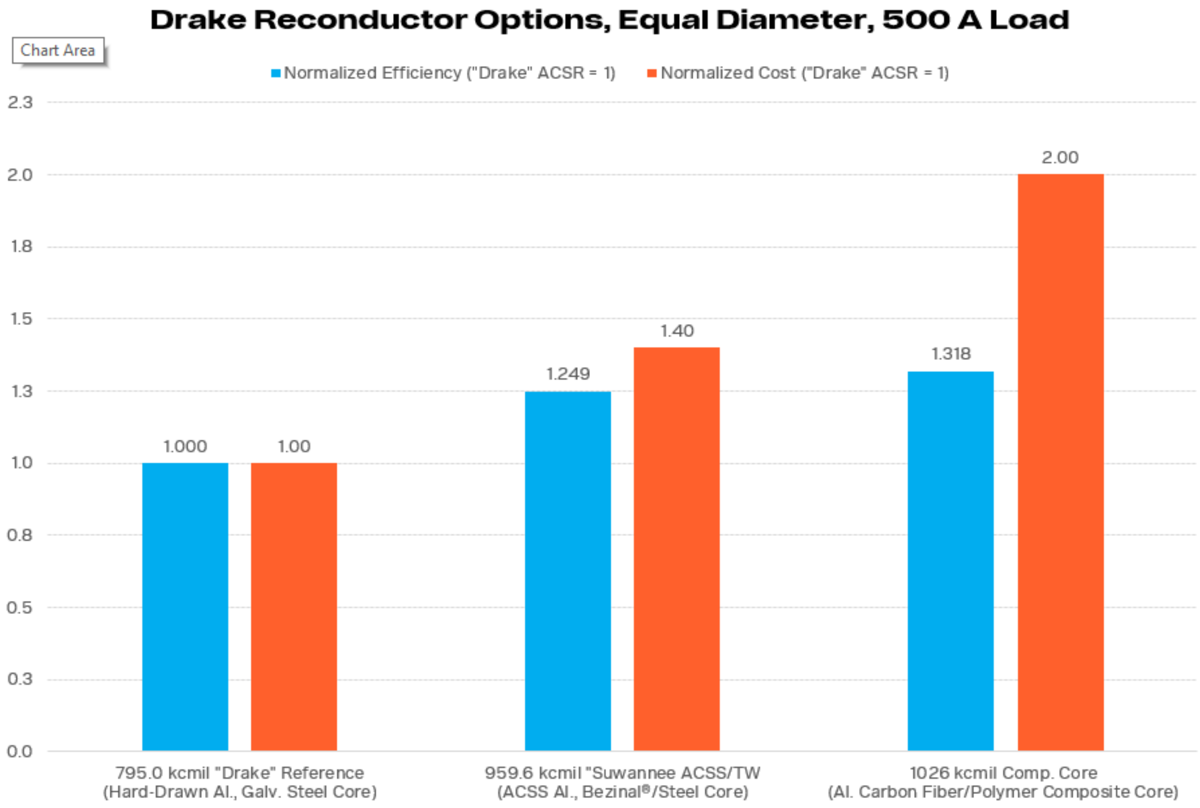

Figure 2: two equal-diameter reconductor options, values compared to same values for Drake ACSR

In this comparison, the leading "Drake" replacement candidates are equal-diameter 959.6 kcmil (486.7 sq mm) ACSS/TW "Suwannee" with a steel/Bezinal® core, and a proprietary equal-diameter 1026 kcmil (523.9 sq mm) conductor with a composite core. The ACSS/TW conductor offers 24.9% greater efficiency at a 40% greater cost versus "Drake" ACSR. The composite core option has a smaller core allowing an increase in the aluminum area to 1026 kcmil. This increases the efficiency by 31.8%, at a 200% greater cost versus "Drake" ACSR. Higher strength cores would close the competitive disadvantage for steel in the same diameter reconductor niche.

Not reflected in the chart is the capacity increase from the reconductor: 100% for the ACSS option, and 70% for the composite core option.

Conductors of Equal Efficiency

Figure 3 compares two conductors of approximately equal efficiency, where equal diameter is not the deciding factor. The grey bar is added to the chart to show the normalized diameter. The ACSS option has a 2% larger diameter and 30% greater aluminum area, compared to the reference "Drake" ACSR.

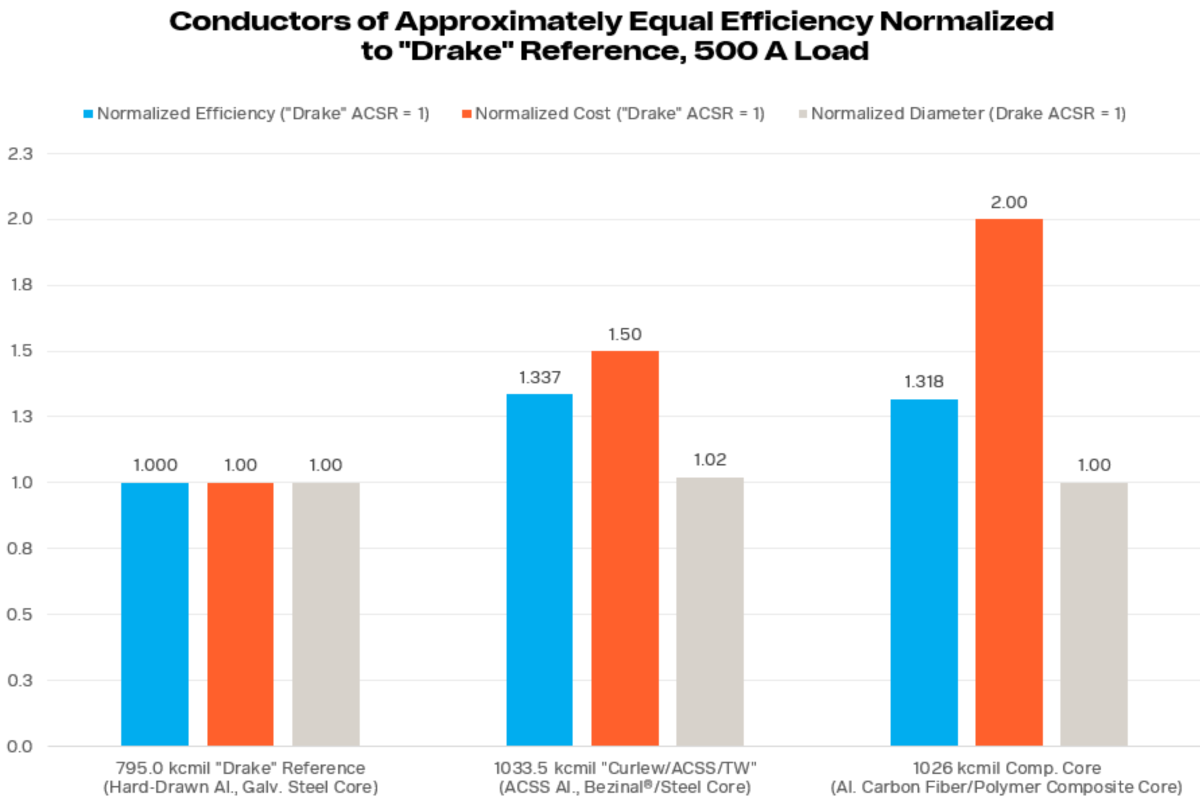

Figure 3: Equal-efficiency conductor options

Figure 3 shows that for a 2% diameter increase, the 1033.5 kcmil ACSS/TW option offers a 33.7% efficiency increase compared to “Drake” ACSR, and a 1.4% efficiency increase compared to the composite core option. In this comparison, the ACSS/TW option is both lower cost and higher efficiency.

Conductors of Equal Cost

The final comparison is the case of a fixed conductor budget, and a goal to increase the efficiency to the maximum for a given budget. Two options of approximately equal cost are illustrated in Figure 4. In this comparison, the 1622 kcmil (821.9 sq mm) ACSS/TW “Pecos” conductor offers a 104% increase in aluminum area compared to the “Drake” reference conductor. The “Pecos” diameter penalty is 28.2% compared to “Drake” and the same-diameter composite core conductor. The payoff is a 103.5% efficiency increase, compared to the “Drake” reference, and a 203.5%/131.8% - 100% = 54.4% efficiency increase compared to the same-cost composite-core conductor.

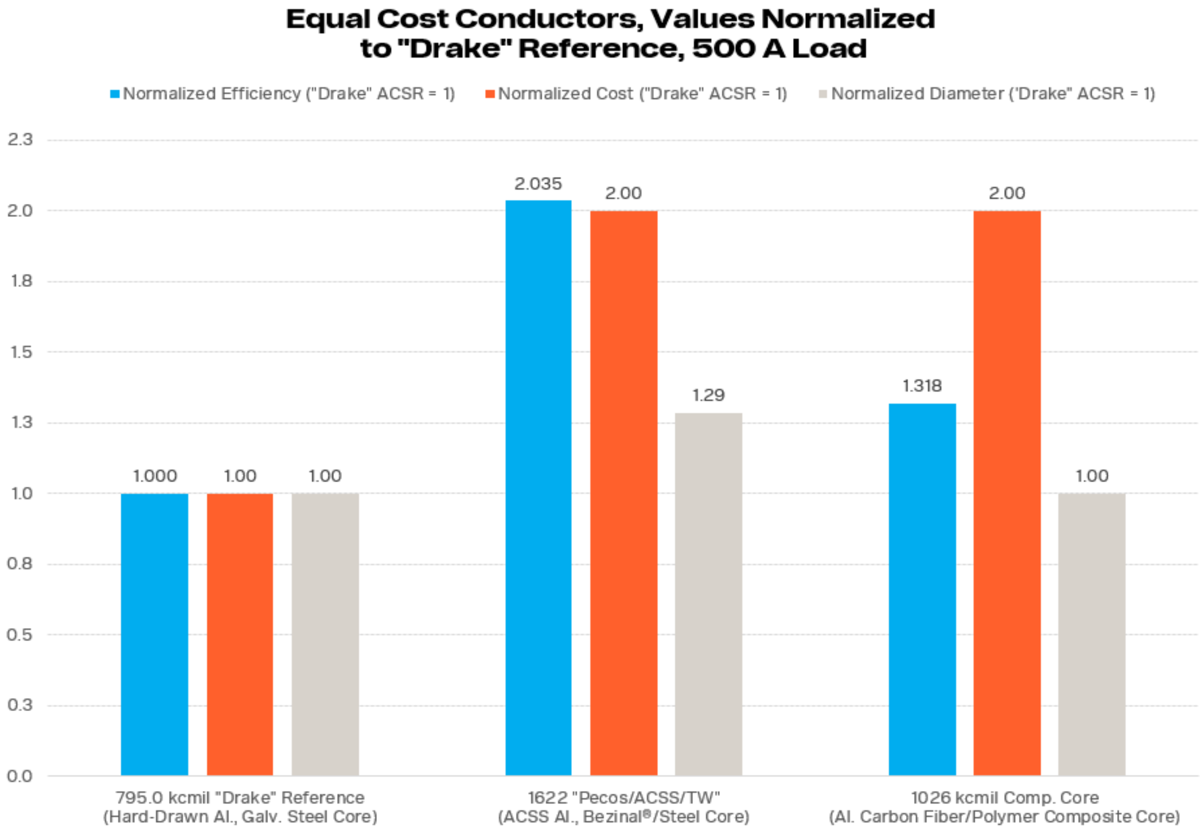

Figure 4: Comparison of conductors of approximately equal cost

CONCLUSION

The grid of the future will have higher efficiency due to increasing energy costs, public pressure, and policy directives that very likely will include a requirement to account for the cost of line losses in the line design. Steel cores are compelling for their excellent combination of low cost and high efficiency. Composite cores will fill a niche where the cost premium for a composite core can be justified by structure cost savings sufficient to justify the premium.

In this analysis, an ACSS conductor is shown to be 54.4% more efficient than the same-cost composite core conductor. An ACSS conductor with 1.4% greater efficiency than a composite core conductor is shown to cost 25% less. It is important that the policy makers and decision makers set rules that enable the selection of the most cost-effective and efficient conductor options. In most cases, the optimum conductor will have a steel core.

BIBLIOGRAPHY

[1] Aluminum Association Publication 54, "The evaluation of losses in conductors", Second Edition, 1998

[2] US Senate Bill S2659: Advanced Energy Technologies and Grid Efficiency Act of 2021

[3] US House Bill HR 4972 (identical to Senate bill): Advanced Energy Technologies and Grid Efficiency Act of 2021