October 9, 2013

CTC GLOBAL

Conductor Performance
White Paper

Revision 0

PROJECT NUMBER:
131411

PROJECT CONTACT:
Larry Henriksen
EMAIL:
lhenriksen@powereng.com
PHONE:
208.788.3456

POWER
ENGINEERS

Conductor Performance White Paper

PREPARED FOR:
CTC GLOBAL

PREPARED BY:
LARRY HENRIKSEN, P.E. – 208.788.3456 – LHENRIKSEN@POWERENG.COM
JON LEMAN, P.E. – 509.758.6029 – JON.LEMAN@POWERENG.COM
SIVASIS PANIGRAHI, P.E. – 503.892.6742 – SPANIGRAHI@POWERENG.COM

REVISION HISTORY						
REV.	ISSUE DATE	ISSUED FOR	PREP BY	CHKD BY	APPD BY	NOTES
0	10/09/13	Impl	LLH	JTL	SP	For use

"Issued For" Definitions:
- "Prelim" means this document is issued for preliminary review, not for implementation
- "Appvl" means this document is issued for review and approval, not for implementation
- "Impl" means this document is issued for implementation
- "Record" means this document is issued after project completion for project file

TABLE OF CONTENTS

INTRODUCTION

This white paper was prepared for CTC Global by POWER Engineers, Inc. to address:

- Real (active) and reactive power concepts
- The creation and consumption of reactive power in electric transmission lines
- The effect of reactive power on system voltages
- Equipment for managing reactive power and system voltages
- Comparison of reactive power performance of different conductor designs
- A simple case study illustrating reactive power and voltage performance

EXECUTIVE SUMMARY

Replacing conventional conductors such as aluminum conductor steel reinforced (ACSR) with one of the high temperature conductors such as aluminum conductor composite core (ACCC) or aluminum conductor steel supported (ACSS) of the same diameter can be a cost effective way to increase the transfer capacity of transmission lines. Maintaining the same conductor diameter makes it likely that existing structures can be used and with proper conductor selection and application ground clearances can normally be maintained.

Increasing power transfer will impact reactive power consumption, and therefore voltage, as well as real power losses. Voltage drop and reactive power flow are related and interdependent. Reactive power flows from high voltage to low voltage. Adding shunt capacitors to increase the supply of reactive power will increase voltage.

The internal construction of conductors does not have a significant impact on the amount of reactive power supplied and consumed or voltage performance. So long as voltage remains constant the reactive power supply and consumption in an electric transmission line are primarily determined by the number of subconductors per phase, their diameter, and their spacing; along with the phase to phase spacing. Reactive power losses will be the same regardless of conductor type selected so long as the conductor diameters are the same.

Adding shunt capacitors or other reactive power sources can increase the ability to transfer power over transmission lines significantly, however reactive power losses vary with the square of current (or power transmitted) and this imposes practical upper limits on the ability to increase power transfer through the addition of shunt capacitors.

Real power losses vary directly with the resistance of the conductor, which is heavily influenced by the internal construction of the conductor as well as by the material used in the conductor. Conductors with relatively small cores using trapezoidal strands will have a larger cross sectional area of aluminum compared to other designs with the same overall diameter and will have significantly lower resistances and lower electrical losses as a result.

THEORY

Energy and Power

Energy is defined in IEEE 100, The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition (IEEE Dictionary), as "That which does work or is capable of doing work.". In the International System of Units (SI) the unit for energy is a Joule (J), which in usual electrical units can be defined as a Watt-second. (W-s). One J can also be defined as a Newton-meter (N-m) which is force times distance. In either definition energy is the ability to do a defined amount of work.

Power is defined in the IEEE Dictionary as "The rate of generating, transferring, or using energy.". In the SI system it is expressed in Joules/sec or Watts.

Energy is power summed over a period of time. In mathematical terms:

Equation 1) $$Energy = \int Power(t)dt$$

In the case where Power is constant over time:

Equation 2) $$Energy = Power \times Time$$

Real (Active) Power and Reactive Power

In alternating current (AC) electrical systems power is classified as real power (also referred to as active power) and reactive power.

Real power is power that is being generated, consumed, or transported that can be used to perform "real" work, for example heating a building or pumping water. Real power is expressed in units of Watts (W), kilowatts (kW) which is 1000 W, and megawatts (MW) which is 1,000,000 W. Real power is also referred to as active power. The symbol "P" is used for real power.

Reactive power can be present in alternating current (AC) power systems. Reactive power is power which is *stored* in or being transported *to be stored* in electric or magnetic fields. Reactive power is expressed in units of Volt-Ampere reactive (VAr), kilo Volt Ampere reactive (kVAr) or mega Volt Ampere reactive (MVAr) to differentiate it from real power. Please note that in terms of fundamental SI units W and VAr (or VA) are equivalent and can be used together in mathematical equations so long as proper mathematical accommodations are made. The symbol "Q" is used for reactive power.

Real power and reactive power are related by the equation:

Equation 3) $$\bar{S} = P + jQ$$

Where S is total power, P is real power, Q is reactive power and j is defined as the square root of -1. The bar above the symbol S indicates that in this formulation S is a vector, with both magnitude and angle. S is usually expressed in VA, kVA or MVA.

The magnitude of total power is:

Equation 4) $$S = \sqrt{P^2 + Q^2}$$

The magnitude of current flowing through a conductor in a balanced three phase system is:

Equation 5) $$I = \frac{S}{V_{ll} \times \sqrt{3}}$$

Where I is the magnitude of current in amperes (A), S is the magnitude of total power and V_{ll} is the line to line voltage of the system in Volts (V), or kV. S and V_{ll} need to be expressed in matching units (e.g. kVAr and kV).

It is important to note that reactive power flow results from the exchange of energy between electric and magnetic fields at system frequency, usually 50 or 60 times per second (50 or 60 Hz). Electric current results from this flow of energy. However in an ideal system (a system without resistance and therefore without real power losses) no real power is consumed in the transfer and temporary storage of the energy. Stated differently no fuel would have to be supplied to the electric generator prime mover to support the flow of reactive power in an ideal lossless system.

The energy transferred in reactive power flow would be capable of doing work, but is not accessible. It is either trapped in the capacitive (electric field) and inductive (magnetic field) elements of the AC electrical system, or is in transit between the capacitive and inductive elements of the system. Reactive power flow does affect system voltage and can be managed by application of equipment which will offset or supplement reactive power flow occurring in the electrical system.

Refer to Figure 1 for a graphical summary of this discussion.

Power = The rate of exchange of energy

Watts (P)
Conversion of electrical energy to <u>kinetic or thermal</u> energy ("useful work")

VARs (Q)
Exchange of electrical energy as <u>magnetic and electric fields</u> build up and collapse
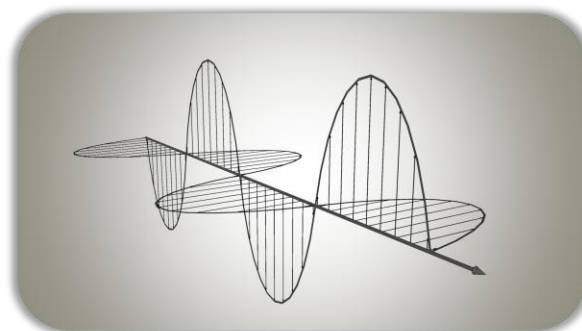
Figure 1 – Real Power (P) and Reactive Power (Q)

Reactive power is normally described as being:

- "consumed" or "lost" in inductive circuit elements, typically shunt (line to line or line to ground) connected inductors (usually referred to as shunt reactors) or the series inductive impedance in electric transmission lines. Inductive elements store energy in magnetic fields. An under excited synchronous generator will consume reactive power.
- "supplied" by capacitive circuit elements, typically shunt connected capacitors or the shunt capacitive impedance in electric transmission lines. Capacitive elements store energy in electric fields. An over excited synchronous generator will supply reactive power.

The phase angle of current into inductive circuit elements is 180 degrees out of phase with the current into capacitive elements. Consequently the current from inductive and capacitive elements cancel.

Reactive power supplied by capacitive circuit elements leads to a voltage rise on an electrical system, while reactive power consumed by inductive elements leads to reduced voltage.

In an electric transmission system reactive power flows from system buses that have higher voltage towards system buses that have lower voltage.

Reactive power consumed by an inductive element is often referred to as reactive power loss. In this report either term may be used and the reader should be aware that these terms are synonymous.

The use of the terms "supply", "consume" or "loss" as they apply to reactive power are not precise technical terms but are commonly used as a matter of convenience. In an ideal (no real power loss) system reactive power is not consumed, lost or supplied. Instead it is stored and released at system frequency (usually 50 or 60 times per second) as electric and magnetic fields build up and collapse.

Resistance, Inductance, and Capacitance

Resistor
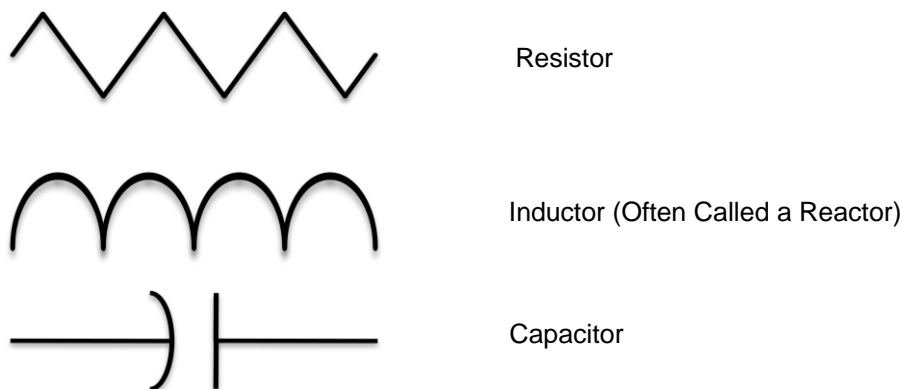
Inductor (Often Called a Reactor)

Capacitor

Figure 2 – Symbols for Resistors, Inductors, and Capacitors

Resistance, inductance and capacitance are properties used to mathematically describe behavior of electrical systems. The circuit elements for these properties are resistors, inductors and capacitors. See Figure 2 for the drawing symbols for these circuit elements.

Resistance and Real Power Conversion

This discussion applies to both AC and DC circuits.

Resistance is the property associated with real power consumption. Real power consumption can occur intentionally (as in the following space heater example) or unintentionally (as with real power losses in a transmission line). An everyday example of a resistor is the coil in an electric space heater. When the heater is turned on voltage is applied across coil of the heater, current flows, and the rate that electrical energy is converted to thermal energy is described by the following equation:

Equation 6) $$P = V \times I = I^2 \, x \, R = \frac{V^2}{R}$$

Where P is the electrical power converted to heat in W, I is the electrical current in A, V is the voltage across the resistor (heater coil in this case) in Volts (V) and R is the resistance of the heater coil in Ohms (Ω).

It is important to note that P is proportional to the square of the current (or alternatively with the voltage across the resistor), with the result that if the current is doubled the rate electrical energy is converted to heat quadruples.

Inductance and Reactive Power Consumed

This discussion applies only to AC circuits.

Inductance is the property associated with energy storage in magnetic fields. The reactive power consumed in an inductor, which is the rate that power is stored and released every power system cycle, is:

Equation 7) $$Q = V \times I = I^2 \times (2 \times \pi \times f \times L) = \frac{V^2}{(2 \times \pi \times f \times L)}$$

Where Q is the reactive power in VAr, I is the current through the inductor in A, π is the constant pi (3.14159 . . . .), f is the system frequency in Hertz (Hz), L is the inductance in Henries (H) and V is the voltage across the inductor in V.

Equation 7) can be simplified to:

Equation 8) $$Q = V \times I = I^2 \times X_L = \frac{V^2}{X_L}$$

Where X_L is the inductive reactance which is defined as $2\pi\ f\ L$ and has the units of Ω. The inductive reactance is a convenient and regularly used unit for expressing inductance for AC systems. Note the form of the equation is the same as equation 6).

The amount of reactive power consumed by an inductive element varies with the square of the electrical current passing through the element or alternatively with the voltage across the element. For example if the current doubles then the reactive power consumed will quadruple.

Capacitance and Reactive Power Supplied

Capacitance is the property associated with energy storage in electric fields. The reactive power supplied by a capacitor, which is the rate at which power stored and released every power system cycle, is:

Equation 9)
$$Q = V \times I = \frac{V^2}{\frac{1}{(2 \times \pi x f x C)}} = I^2 \times \frac{1}{(2 \times \pi \times f \times C)}$$

Where Q is the reactive power in VAr, V is the voltage across the capacitor in V, π is the constant pi (3.14159 . . . .), f is the system frequency in Hertz (Hz), C is the capacitance in Farads (F) and I is the current through the capacitor in A.

Equation 9) can be simplified to:

Equation 10)
$$Q = V \times I = \frac{V^2}{X_C} = I^2 \times X_C$$

Where X_C is the capacitive reactance which is defined as $1/(2\pi fC)$ and has the units of Ω. The capacitive reactance is a convenient and regularly used unit for expressing capacitance for AC systems. Note the form of this equation is the same as equations 6) and 8).

When transmission line shunt capacitance is involved equation 10) is often restated as:

Equation 11)
$$Q = V \times I = V^2 \times B_C = \frac{I^2}{B_C}$$

Where B_C is the capacitive susceptance (usually just called susceptance) and is usually expressed in Siemens (S) or microSiemens (μS); or alternatively in mhos (mhos is Ohms spelled backwards) or micromhos. Susceptance is the inverse of X_C or $2 \pi f C$. It is a convenient unit in transmission line performance analysis and will be used in subsequent discussions.

The amount of reactive power supplied by a capacitor varies with the square of the voltage energizing the capacitor (or alternatively with the square of the current flowing through the capacitor). For example if the voltage increases 10% then the amount of reactive power supplied by a capacitor will increase 21%.

Inductance Cancels Capacitance

It is important that the current through an inductor is most positive when the current through a capacitor is most negative (180 degrees out of phase). Consequently the current from a capacitor and inductor, when added together, will cancel one another.

Stated differently *a capacitor will supply the reactive power consumed in an inductor* (often referred to as a reactor in power systems).

ELECTRIC TRANSMISSION LINES

Electric transmission lines have resistance, inductance and capacitance. Figure 3 shows a simplified equivalent circuit for an overhead transmission line, including series (in line) resistance, series inductance, and shunt capacitance. Connecting one side of the capacitor symbol to ground, denoted by the ground ($\bar{\underline{\underline{}}}$) symbol, identifies this as a shunt (line to line or line to ground) capacitance. For illustration resistances, inductances and capacitances are shown as discrete elements, however in reality they are continuously distributed along the transmission line.
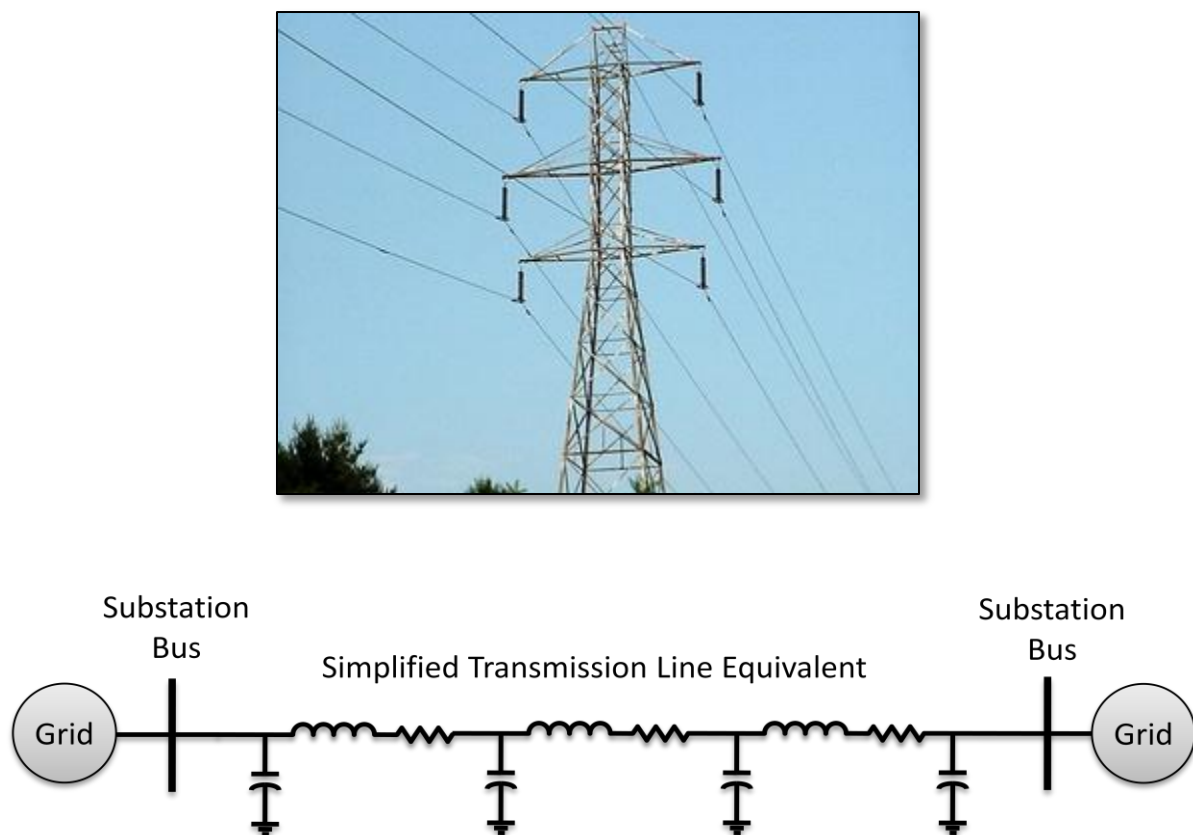

Figure 3 – Overhead Transmission Line Equivalent Circuit

Real Power Losses

Real power losses are caused by electrical current flowing through the series resistance ($\bigwedge\!\!\bigwedge$) in the transmission conductors (resistance losses) and by electricity discharging into the air (corona). Corona losses are very low except at EHV voltages and even there are less than 10% of total losses. Additionally corona losses are much higher during foul weather making them statistical in nature.

They are related to subconductor diameter and bundling but not conductor type, as they are a surface area, surface condition, voltage and weather related phenomenon. Corona losses should not normally be a factor in selecting the type of conductor and won't be discussed further.

Resistance losses vary directly with the resistance of the conductor. Resistance is primarily a function of:

- Cross sectional area of conducting material – Resistance is nearly proportional to the cross sectional area of conductor(s). A two subconductor bundle will have half the resistance of a single conductor and a three subconductor bundle one-third the resistance of a single conductor.
- Conductor material – Aluminum and its alloys used in electrical conductors can vary in resistivity by 20% or more, from about 64% International Annealed Copper Standard (IACS) to 52.5% IACS.
- Temperature of conductor – The resistivity of aluminum used in conductor will vary about 0.4% per °C. For example raising conductor temperature from 25 C to 100 C would increase resistance by about 30%.
- Frequency – AC current tends to flow toward the outside of the conductor. This is called skin effect and is higher at higher frequencies. For a homogenous conductor (no core) the difference in resistance between 50 Hz and 60 Hz could be negligible while for a large high strength ACSR conductor with a large core the resistance at 60 Hz could be on the order of 3% higher than at 50 Hz.

There are other factors aside from conductor characteristics that impact line losses. Obviously but importantly line resistance and losses vary directly with the length of the line. In addition 1) the presence of overhead ground wire(s) will also increase losses slightly due to circulating currents in the ground wire(s) and 2) unequal current distribution between phases can also cause a slight increase in losses. The losses for these two causes can rise to the level where mitigation in the form of insulated and segmented overhead ground wires and adding transposition structures can be cost effective. These issues are independent of conductor selection and will not be discussed further.

As described in the earlier calculations real power losses vary with the square of the current flowing through the line. For example if current were doubled real power losses would quadruple.

Line losses vary directly with the length of the line.

Reactive Power Loss

Reactive power losses are caused by electrical current flowing through the series inductance ($\overset{\frown}{\frown\frown\frown}$) in the transmission line.

As noted in the theory section inductance is an electrical property associated with the storage of energy in magnetic fields. Reactive power consumption in AC circuits varies directly with the inductive reactance of the circuit which is a function of:
- Frequency – Inductive reactance varies directly with frequency in Hz. See equation 8).
- Conductor diameter for single conductor designs – Larger diameter conductors reduce inductive reactance of the line. For example going from a small conductor (336.4 kcm or

170.5 mm^2 ACSR) to a large conductor (1590 kcm or 805.7 mm^2 ACSR) on a 138 kV H-frame line would result in a reduction in series inductive reactance and reactive power losses of approximately 11.4%.

- Subconductor diameter, number of subconductors and bundle spacing for bundled circuit designs – Larger diameter conductor, more subconductors, and larger bundle spacing reduce inductive reactance. For example going from a large single conductor (1590 kcm or 805.7 mm^2 ACSR) on a 230 kV H-Frame line to a two subconductor bundle of equivalent cross sectional area (2 x 795 kcm or 2 x 402.8 mm^2 ACSR) or to a three subconductor bundle of approximately equivalent cross sectional area (3 x 556.5 kcm or 3 x 282 mm^2 ACSR) would result in a reduction in series inductive reactance and reactive power losses of approximately 24.6% and 33.6% respectively.
- Phase to phase spacing - Reducing phase to phase spacing reduces inductive reactance. For example a 230 kV line with a two subconductor bundle of mid-sized conductors (795 kcm or 402.8 mm^2 ACSR) constructed on a compact monopole structure would have approximately 6.8% lower series inductive reactance and reactive power losses than an H-Frame design.

Line inductive reactance and losses vary directly with the length of the line.

As described in the earlier calculations reactive power losses vary with the square of the current flowing through the line. For example if current were doubled reactive power losses would quadruple.

Reactive Power Supply

Reactive power supply is caused by the electric transmission voltage applied across the shunt capacitance ( ) that exists between the phase conductors of the transmission line.

As discussed in the theory section capacitance is an electrical property associated with the storage of energy in electric fields. Reactive power supply in AC circuits varies directly with the shunt capacitive susceptance (susceptance) of the circuit. The susceptance and therefore the amount of reactive power supplied is a function of:

- Frequency – Reactive power supplied varies directly with frequency in Hz. See equation 11).
- Conductor diameter for single conductor designs – Larger diameter conductor increases susceptance and the amount of reactive power supplied. For example going from a small conductor (336.4 kcm or 170.5 mm^2 ACSR) to a large conductor (1590 kcm or 805.7 mm^2 ACSR) on a 138 kV H-frame line would result in an increase in susceptance and reactive power supplied of approximately 13.4%.
- Subconductor diameter, number of subconductors and bundle spacing for bundled circuit designs – Larger diameter conductor, more subconductors, and larger bundle spacing increase susceptance. For example going from a large single conductor (1590 kcm or 805.7 mm^2 ACSR) on a 230 kV H-Frame line to a two subconductor bundle of equivalent cross sectional area (2 x 795 kcm or 2 x 402.8 mm^2 ACSR) or to a three subconductor bundle of approximately equivalent cross sectional area (3 x 556.5 kcm or 3 x 282 mm^2 ACSR) would result in an increase in susceptance and reactive power supplied of approximately 31.8% and 49.5% respectively.

- Phase to phase spacing - Reducing phase to phase spacing increases susceptance. For example a 230 kV line with a two subconductor bundle of mid-sized conductors (795 kcm or 402.8 mm^2 ACSR) constructed on a compact monopole structure would have approximately 5.8% higher susceptance and reactive power supplied than an H-Frame design.

Ground clearance and sag have insignificant impact on the susceptance and the amount of reactive power supplied by a transmission line. A 20 m (65.6 ft) increase in line clearance for the 230 kV H-Frame two subconductor bundle line resulted in a less than 1% decrease on susceptance.

Susceptance varies directly with the length of the line.

Reactive power supplied varies with the square of the voltage on the line. For example if voltage were increased 10% reactive power supplied would increase 21%.

The current flowing through the shunt capacitances on the line (described as a susceptance for calculation purposes) results in current flowing on the conductors. The capacitive current flowing in the conductors is often referred to as line charging current.

On long unloaded or lightly loaded high voltage lines there can be significant and unacceptable increases in remote line end voltages a result of the charging current and reactive power flow.

TABLE 1 - REPRESENTATIVE TRANSMISSION LINE ELECTRICAL POSITIVE SEQUENCE REACTANCE AND SUSCEPTANCE														
STRUCTURE TYPE	EQUIVALENT PHASE SPACING		BUNDLE/ CONDUCTOR	CONDUCTOR DIAMETER		AL AREA PER CONDUCTOR		SERIES INDUCTIVE REACTANCE			SHUNT CAPACITIVE SUSCEPTANCE		
	ft	m		in	mm	kcm	mm^2	Ω/mi	Ω/km	Change	µS/mi	µS/km	Change
138 kV H Frame	19.5	5.95	1 x Linnet ACSR	0.720	18.3	336.4	170.5	0.8096	0.5031	Base	5.277	3.279	Base
138 kV H Frame	19.5	5.95	1 x Falcon ACSR	1.545	39.2	1590.0	805.7	0.7176	0.4459	-11.4%	5.986	3.720	13.4%
230 kV H Frame	24.6	7.50	1 x Falcon ACSR	1.545	39.2	1590.0	805.7	0.7457	0.4634	Base	5.775	3.588	Base
230 kV H Frame	24.6	7.50	2 x Drake ACSR	1.108	28.1	795.0	402.8	0.5621	0.3493	-24.6%	7.614	4.731	31.8%
230 kV H Frame	24.6	7.50	3 x Dove ACSR	0.927	23.5	556.5	282.0	0.4952	0.3077	-33.6%	8.636	5.366	49.5%
230 kV H Frame	24.6	7.50	2 x Drake ACSR	1.108	28.1	795.0	402.8	0.5621	0.3493	Base	7.614	4.731	Base
230 kV Monopole	16.5	5.03	2 x Drake ACSR	1.108	28.1	795.0	402.8	0.5237	0.3254	-6.8%	8.052	5.004	5.8%

Reactive Power and Line Loading

Figure 4 illustrates the interaction between the power transmitted through a transmission line and the supply and reactive power consumption in an electric transmission line.

The red curve represents the reactive power (Q) supplied by the shunt capacitance of the transmission line. Q supplied is proportional to the square of voltage which results in a curve that is nearly flat, with Q supplied decreasing a relatively small amount due to voltage drop as the line transmits more power (P).

The blue curve represents the Q consumption (losses) due to current flowing through the transmission line. As a first approximation the electrical current is proportional to P transmitted making Q losses approximately proportional to the square of the power transmitted. Q losses vary markedly with the power transmitted, starting at zero when P is equal to zero and growing very rapidly as P increases.

Surge Impedance Loading (SIL) is the point at which the Q supplied by the shunt capacitance of the line equals the Q lost in the series inductance of the line. For a unity power factor load at the SIL level the voltage would be constant for the entire length of the transmission line. Transmission lines are normally loaded in excess of the SIL; however the SIL is a useful figure of merit for the capacity of a transmission line.
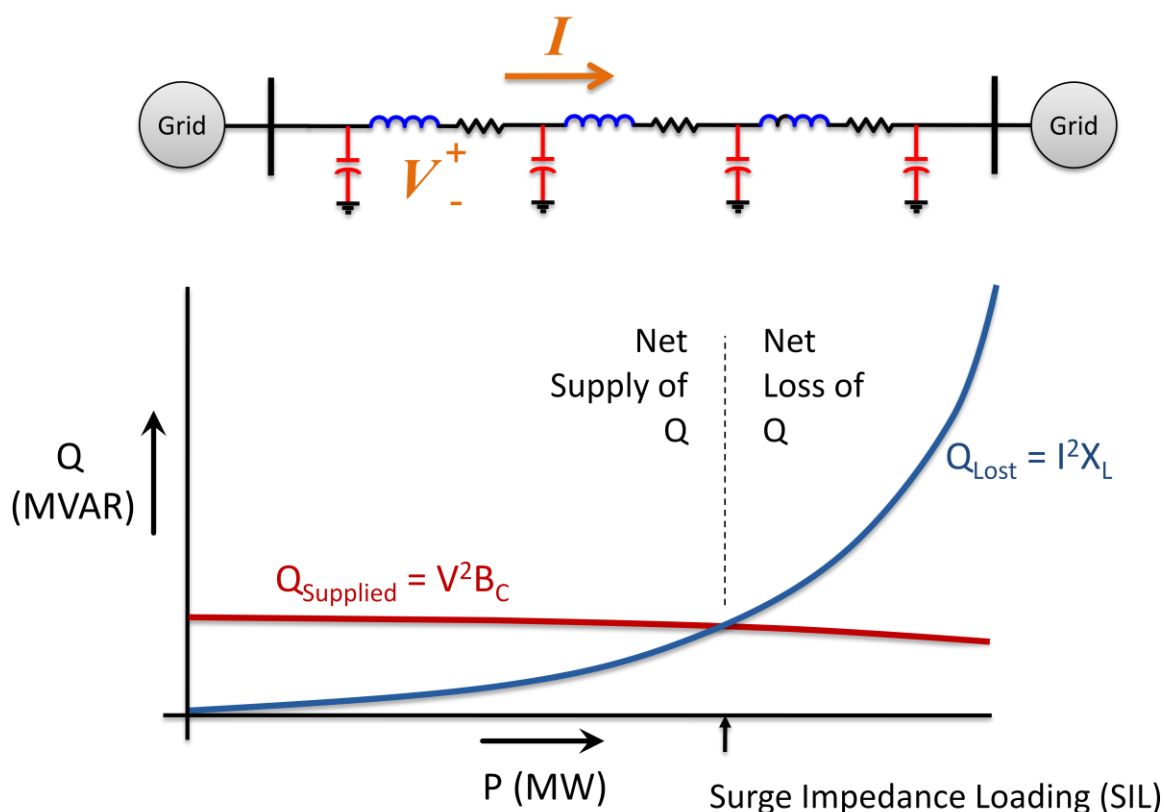
Figure 4 – Reactive Power vs. Transmission Line Loading

Changes in line design that increase shunt capacitive susceptance (B_C) and consequently increase the Q supplied (larger diameter conductor, more subconductors, larger bundle spacing, and closer phase spacing) move the red "Q Supplied" curve up. These same changes in line design also reduce series inductive reactance (X_L) and the Q losses moving the blue "Q Lost" curve to the right. The net effect is to increase capacity of the line, which is evidenced by the increase in the SIL, located at the intersection of these two curves.

Reactive Power Flow and Voltage

Figure 5 illustrates how transmission line voltages are affected by reactive power flow. Reactive power flows from higher voltage to lower voltage. Alternatively stated supplying reactive power will increase voltage. Devices that supply reactive power such as shunt capacitors are used to increase voltage when voltage levels fall below acceptable levels. Similarly devices that consume reactive power such as shunt inductors (commonly called reactors) are used to lower voltage when voltage levels are above acceptable levels.
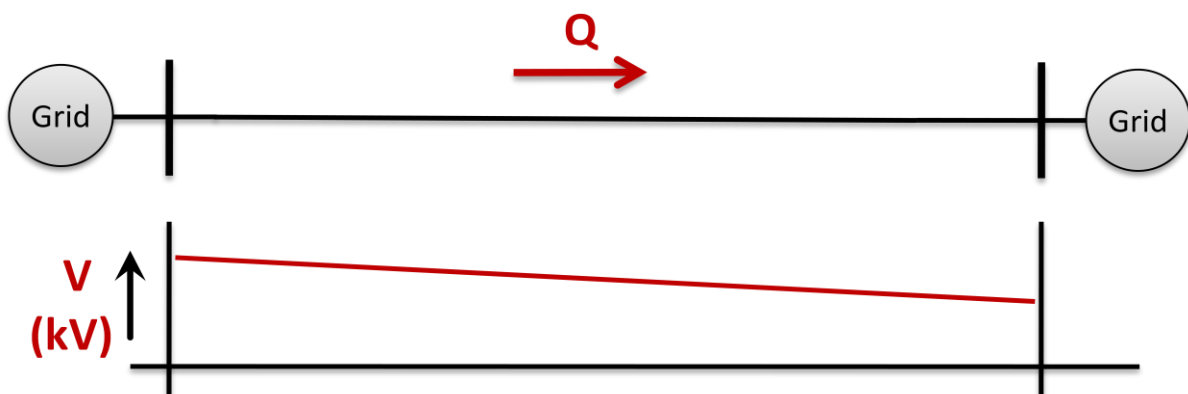
Figure 5 – Reactive Power Flow vs. Transmission Line Voltage

CONDUCTOR COMPARISON

The relative performances of a number of different conductors were compared for a representative 150 kV transmission line operating at 50 Hz. For this comparison transmission line parameters (inductance, resistance and susceptance) were calculated using the Alternate Transients Program (ATP). Single conductors and two subconductor bundles were considered. The results are summarized in a series of charts which follow.
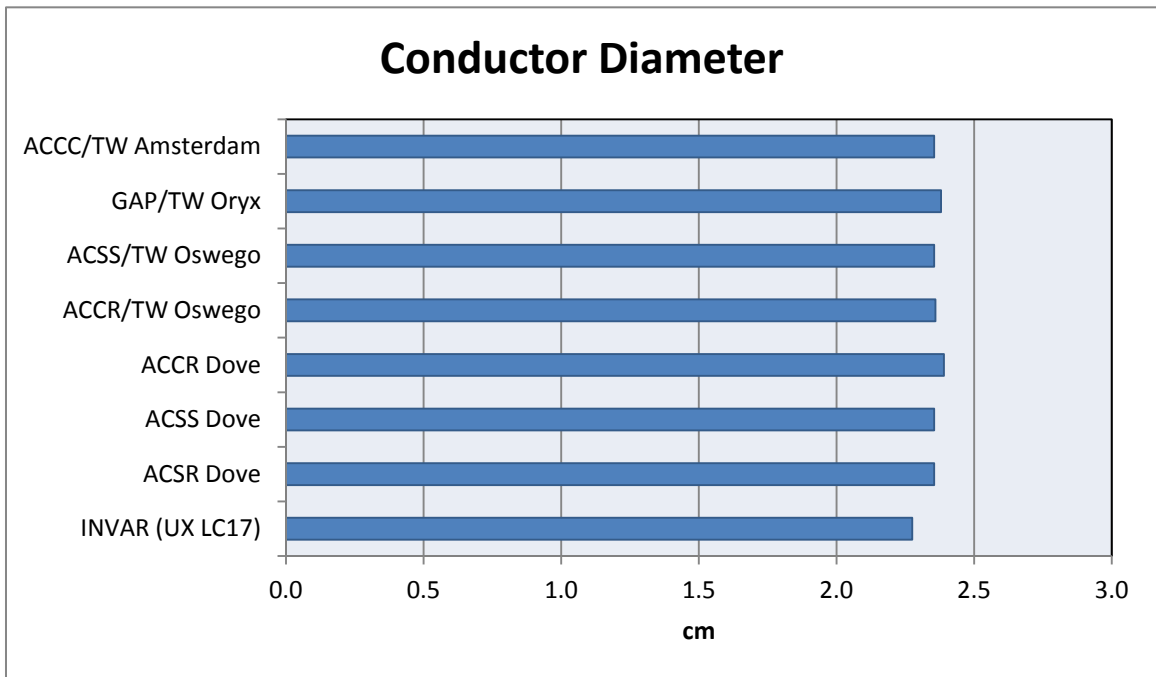
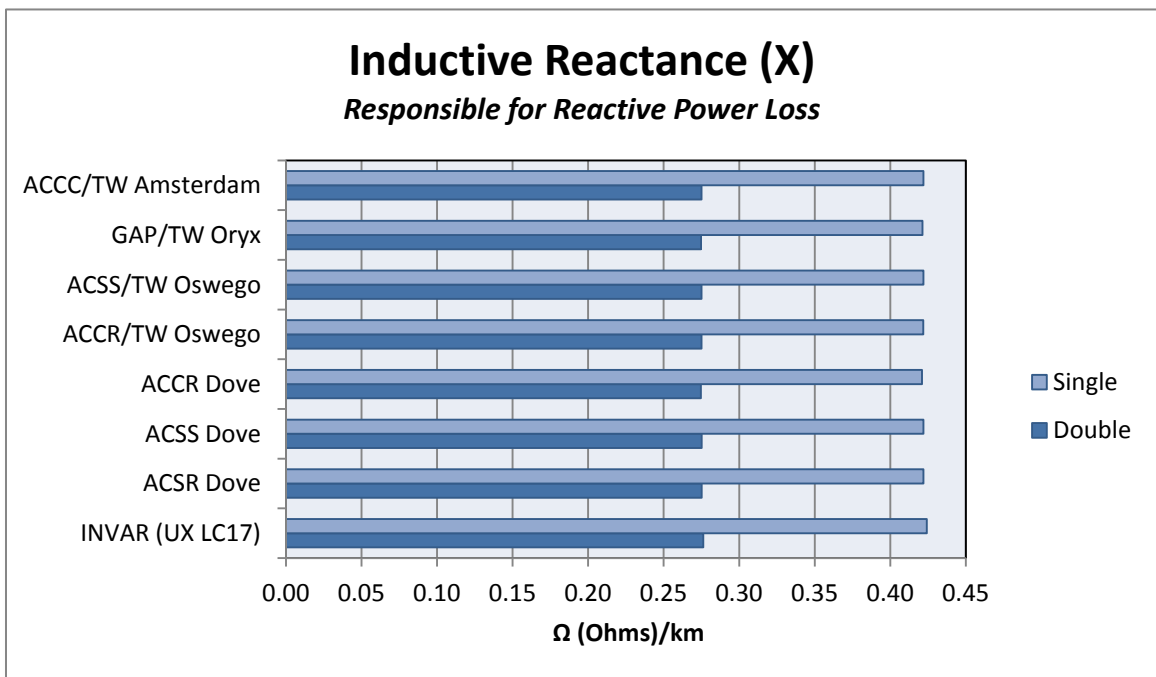**Figure 6 – Conductor Diameters of Conductors Compared**
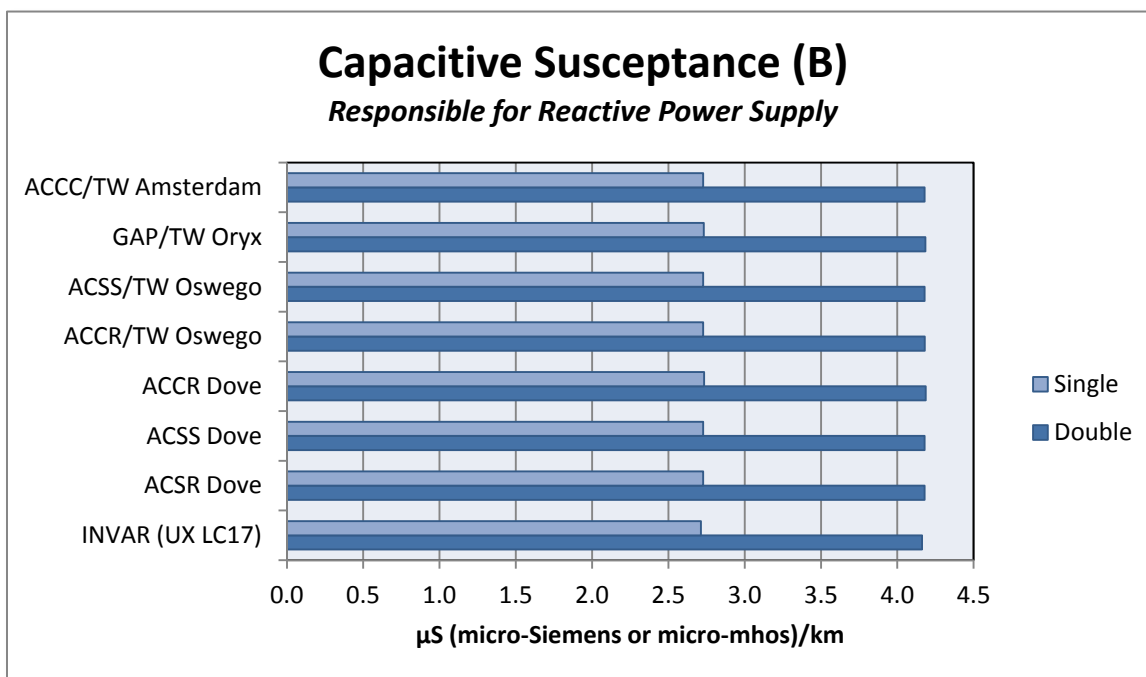

Figure 7 – Inductive Reactance of Conductors Compared

Capacitive Susceptance (B)
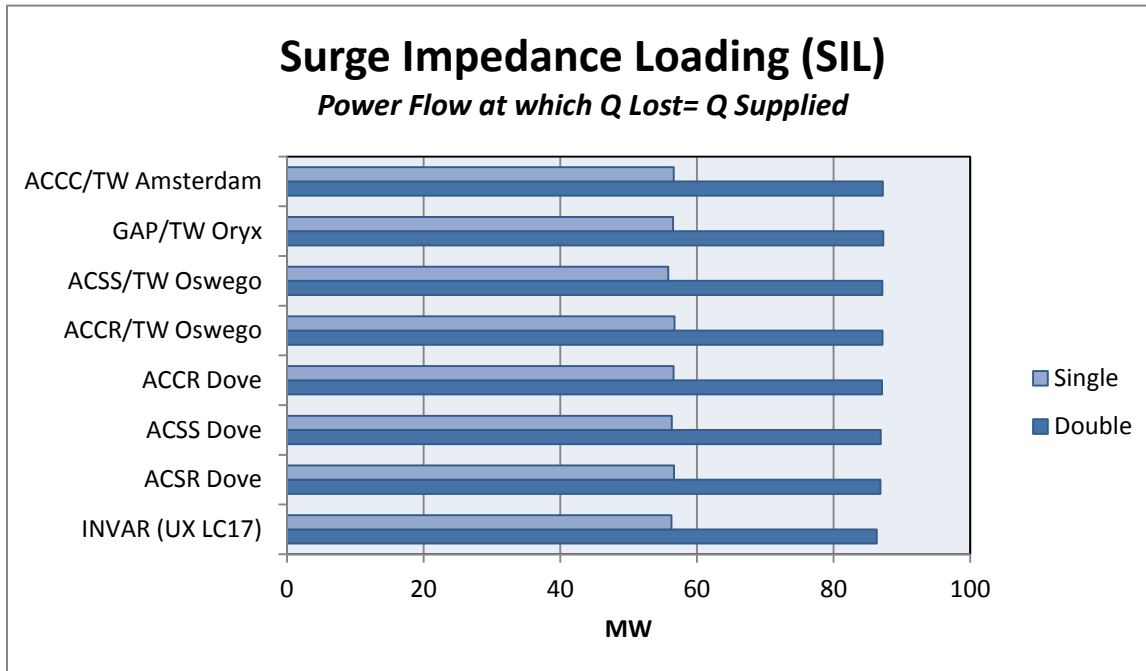### *Responsible for Reactive Power Supply*

Figure showing a horizontal bar chart titled "Capacitive Susceptance (B)" with categories ACCC/TW Amsterdam, GAP/TW Oryx, ACSS/TW Oswego, ACCR/TW Oswego, ACCR Dove, ACSS Dove, ACSR Dove, INVAR (UX LC17). X-axis labeled "µS (micro-Siemens or micro-mhos)/km" from 0.0 to 4.5. Legend: Single, Double.

Figure 8 – Capacitive Susceptance of Conductors Compared

Surge Impedance Loading (SIL)
Power Flow at which Q Lost= Q Supplied

Figure showing a horizontal bar chart titled "Surge Impedance Loading (SIL)" with categories ACCC/TW Amsterdam, GAP/TW Oryx, ACSS/TW Oswego, ACCR/TW Oswego, ACCR Dove, ACSS Dove, ACSR Dove, INVAR (UX LC17). X-axis labeled "MW" from 0 to 100. Legend: Single, Double.

Figure 9 – Surge Impedance Loading of Conductors Compared

Figures 6, 7, 8 and 9 illustrate that the inductive reactance (X), capacitive susceptance (B), and surge impedance loading (SIL) of the transmission lines are a function of conductor diameter, all other

characteristics of the transmission line being held constant. These results are consistent with discussion in the Theory section of this report.

The data also provides an example of the electrical performance improvement obtained when a two subconductor bundle is used in lieu of a single conductor.

All of the conductors compared had very nearly the same diameter and consequently very nearly the same X, B, and SIL values. Examining the values for INVAR (UX LC17) provides an example of how a slightly smaller conductor diameter exhibited a slightly larger X, slightly smaller B, and slightly lower SIL as expected.
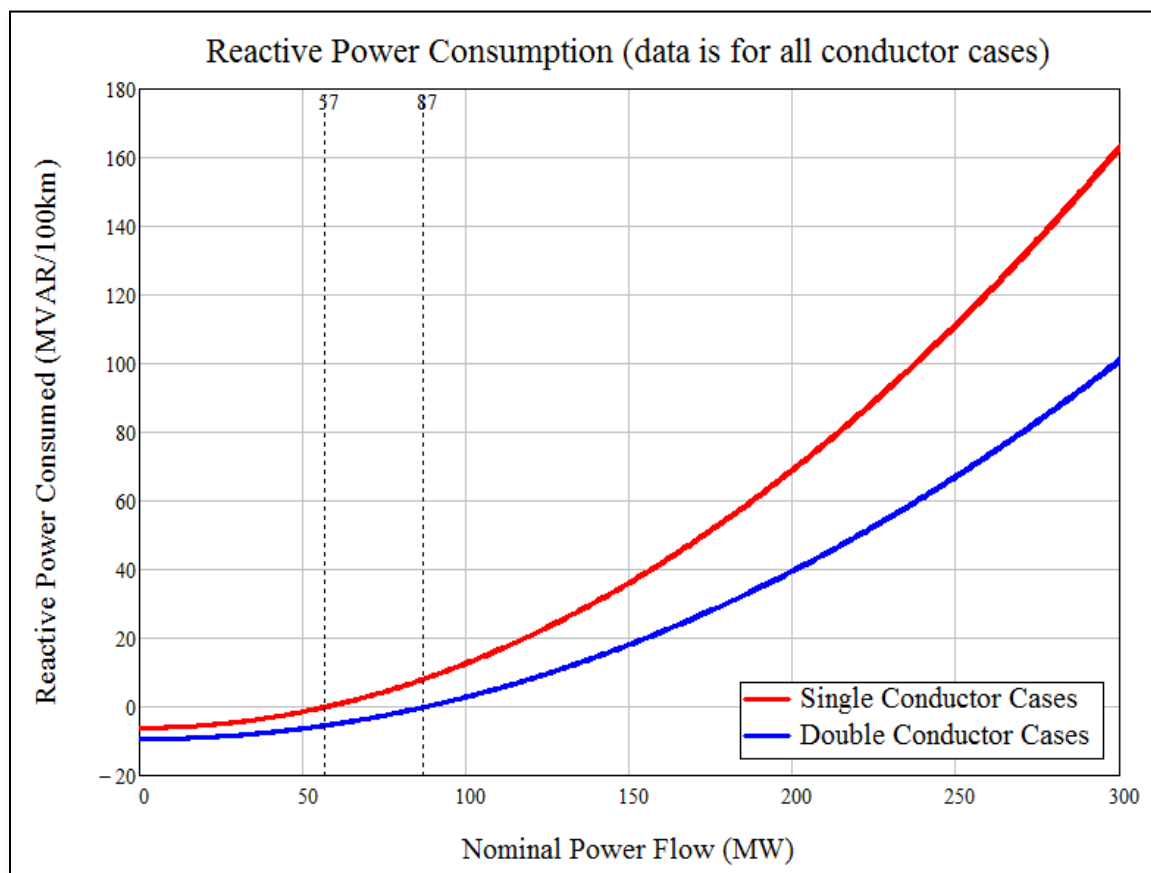
Figure 10 – Reactive Power Consumption of Conductors Compared
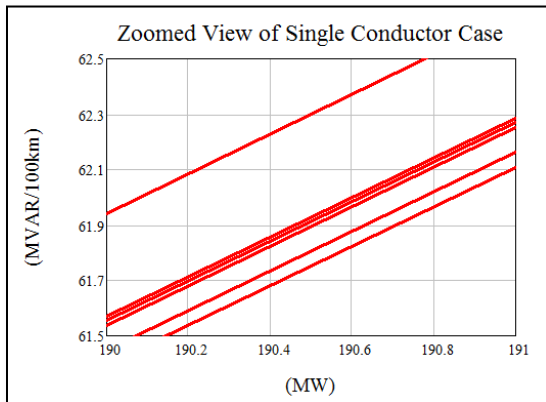
Figure 10a – Reactive Power Consumption of Conductors Compared, Zoomed in View

Figure 10 plots the net reactive power supply and losses for the representative 150 kV 100 km line. Figure 10a is a zoomed in view of part of the single conductor curve to show that data for all conductors is contained on the chart. The reactive power supplied and consumed is very nearly identical for all conductors so they appear as a single line in Figure 10. Because all conductors have nearly identical diameters the reactive power losses will for practical purposes be the same for all the conductors compared.

Compare Figure 10 with Figure 4. The curves in Figure 10 combine the "Q Supplied" and "Q Lost" curves from Figure 4 into a single trace. The reactive power losses are negative (reactive power is being supplied) for power flow levels below the surge impedance loading (SIL) levels of 57 Mega Watts (MW) for the single conductor case and 87 MW for the two subconductor bundle case. As loading increases above the SIL reactive power losses quickly increase and as loading increases larger amounts of reactive power compensation (typically shunt capacitors) will need to be applied to maintain system voltage.
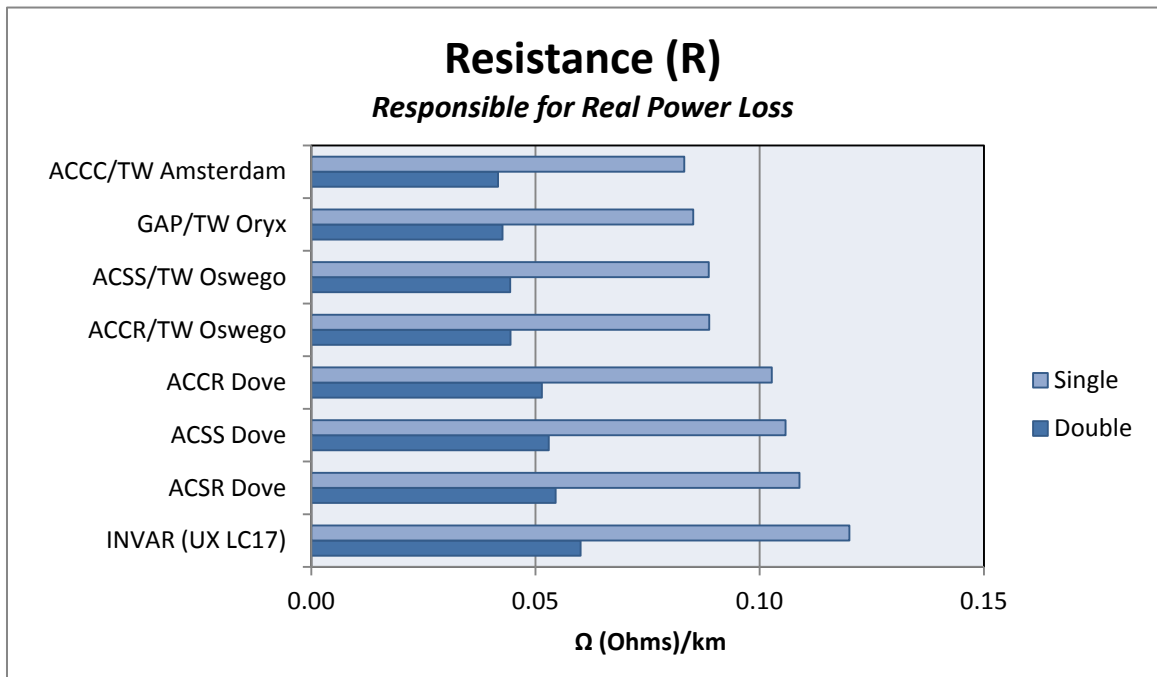
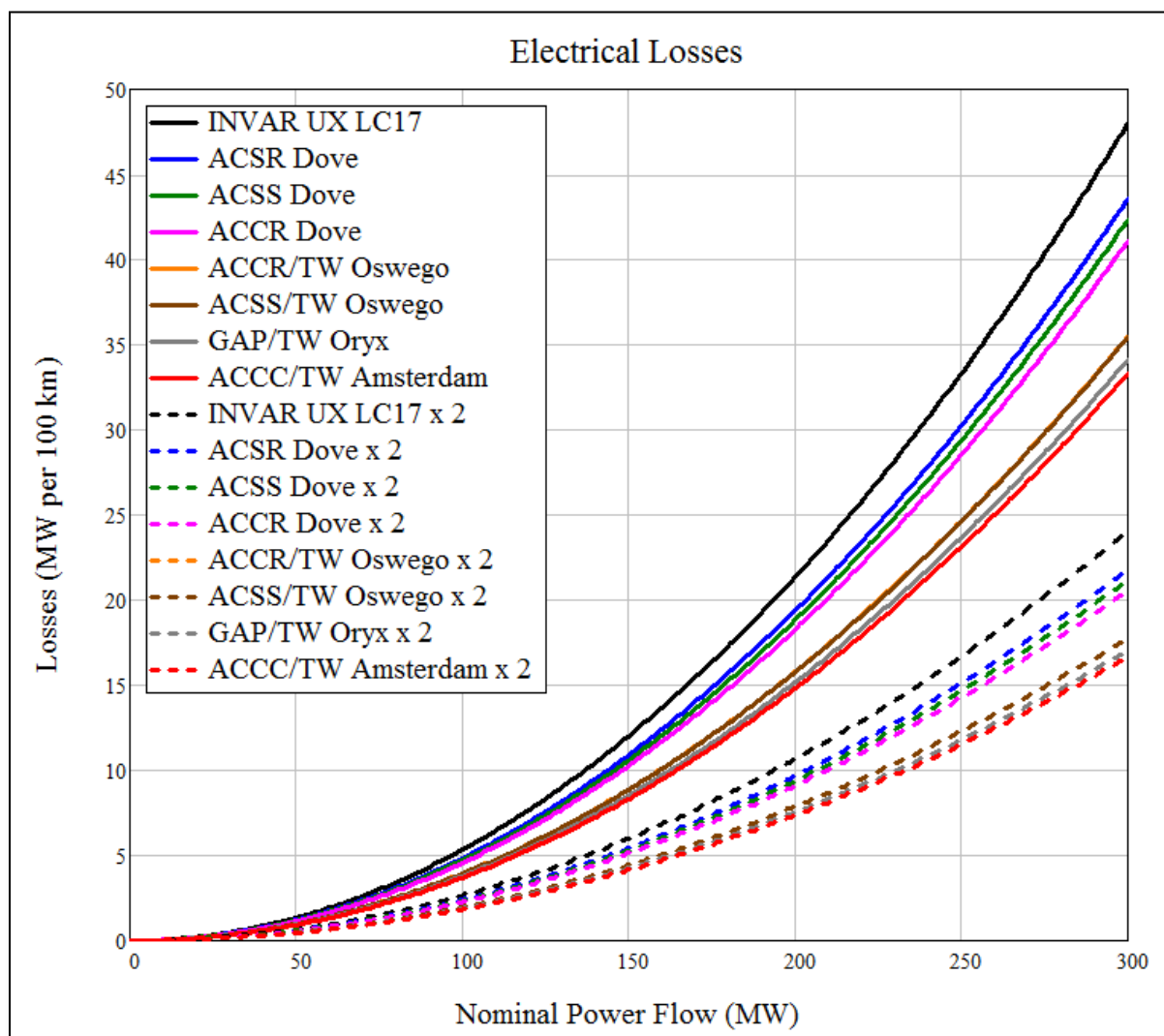**Figure 11 – Resistance of Conductors Compared**

Figure 12 – Real Power Losses of Conductors Compared

The data in Figures 6, 7, 8, 9 and 10 confirmed that the line characteristics affecting reactive power losses, reactive power supply and surge impedance loading were dependent upon conductor diameter rather than internal conductor construction.

Figures 10 and 11 illustrates that real power losses are dependent upon internal conductor construction, and that conductors with smaller cores and trapezoidal stranding, such the ACC/TW Amsterdam, can provide more aluminum cross sectional area in the same diameter significantly reducing resistance and real power losses. The resistances and losses of two subconductor bundles are one half that of a single conductor.

The exponential nature of real power losses is apparent in Figure 12. Doubling the power flow quadruples the losses.

REACTIVE POWER AND VOLTAGE MANAGEMENT

Overview

Reactive power and voltage are closely related and interdependent. Managing reactive power is an integral part of operating an electrical transmission system and must be done taking into account the entire transmission system which includes but is not limited to lines characteristics and length; load magnitude, power factor and location; generation plant size, location and ability to provide and absorb reactive power; reactive power management devices such as shunt reactors and shunt capacitors, including size location and switching capability; and ability to maintain voltage under contingency conditions such as loss of a line of generation station.

To introduce the topic reactive power and voltage management will be discussed for a radial (source on one end, load on the other) transmission line.
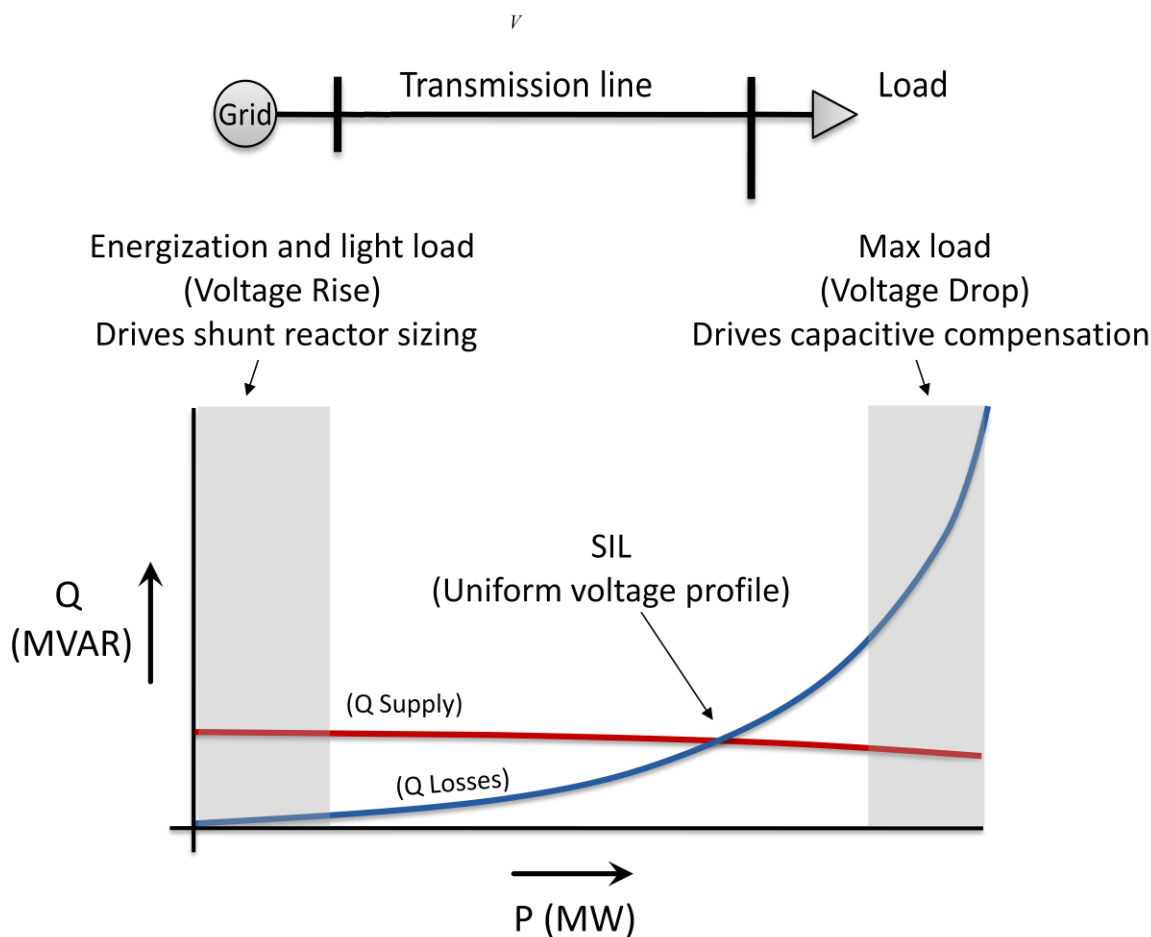

Figure 13 – Transmission Line Loading and Reactive Power Needs

For a no load or lightly loaded case surplus reactive power is generated and that reactive power flows from the end of the line back to the grid, raising the voltage on the end of the line. Refer to the explanation accompanying Figure 5. For longer and higher voltage lines the line end voltage can become high enough to damage equipment or risk insulation failure and shunt reactors (inductors) will be installed at the ends of the line to consume part of the reactive power supplied by the line and lower the voltage to an acceptable level. For a range of power transmitted, on either side of the surge impedance loading, the line end voltage will fall within acceptable ranges and no reactive power compensation will be required. As power transfers increase the line end voltage will fall below acceptable limits and reactive power compensation, most typically shunt capacitors, will be installed to supply additional reactive power and raise the line end voltage to keep it within acceptable limits. Equipment ratings, insulation capability, government regulations and industry standards determine acceptable voltage limits.
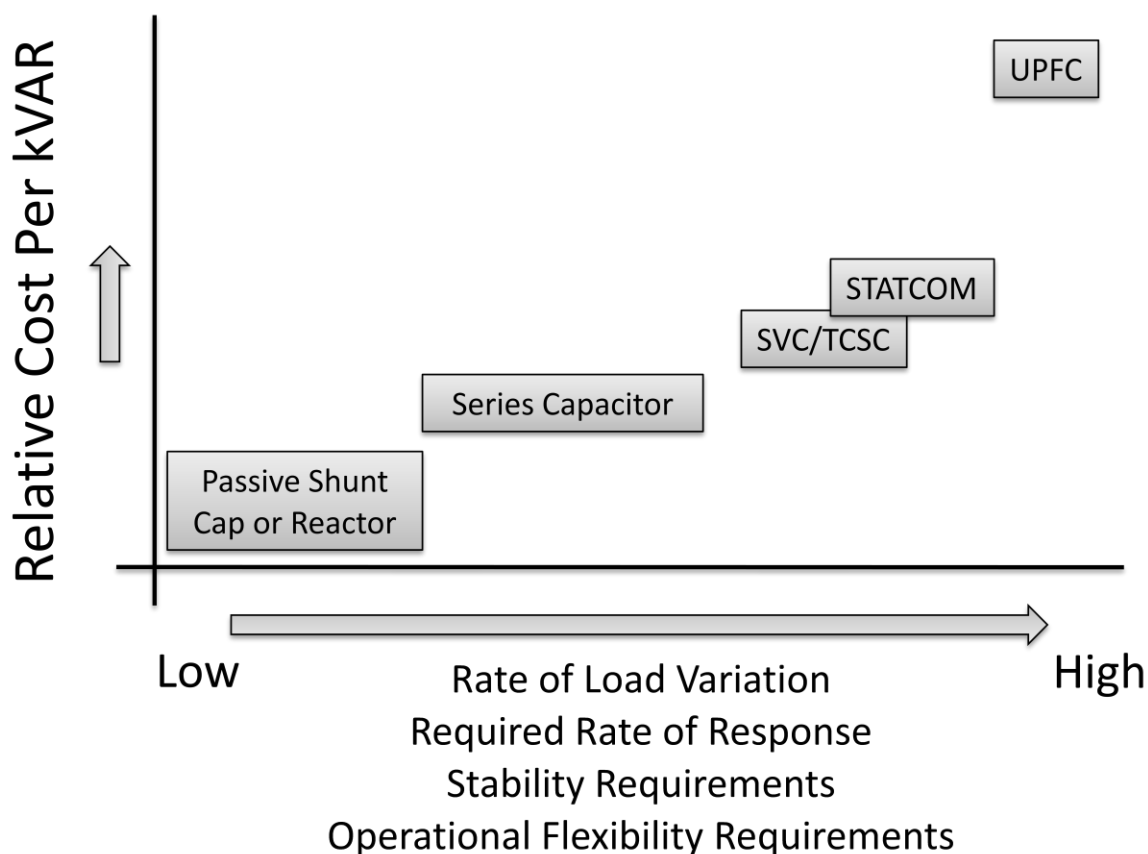
Figure 14 – Reactive Power Compensation Options

Options for managing reactive power control are shown in Figure 14.

- Shunt capacitors are most commonly used, due to both cost and simplicity. Shunt capacitors are connected to the power system through a circuit breaker and may be switched in steps to keep the change in voltage during switching to acceptable levels.
- Shunt reactors are often used on the ends of longer (greater than 100 km) transmission lines 345 kV and above to reduce line end voltages when the line is being energized. They are also commonly used in substations to manage reactive power during lightly loaded system conditions.
- Series capacitors are typically used on long (greater than 150 km) lines 345 kV and above. The capacitors are placed in series (in line) rather than connected between phases or to ground. The series capacitor has the effect of canceling out part of the line series inductance reducing reactive power losses and voltage drop on the line.
- Static VAr Compensators (SVCs) and Static Synchronous Compensators (STATCOMs) are power electronic systems that can automatically adjust reactive power output in small fractions of a second and are used when their automatic high speed operation is required to maintain system stability. They are typically applied at transmission voltages although in some special applications they are applied at lower voltages (e.g. managing reactive power at wind energy plants).
- Unified Power Flow Controllers (UPFCs) combine the features of a STATCOM with the ability to inject/absorb real power. UPFCs are not generally used.

Example

The results of a voltage drop study are shown on the following figures. The voltage drop study was based upon:
- 150 kV, 50 Hz AC source bus ("Grid" on diagram in Figures 15, 16 and 17).
- Single ACCC/TW Amsterdam conductor
- 50 km and 100 km radial lines
- A load varying from 0 to 300 MW at unity power factor at the end of the line. The load was modeled as a constant impedance, with the impedance adjusted for each loading level.
- Reactive power compensation using shunt capacitors

The voltage performance of the other conductors reviewed earlier in this paper would be for practical purposes identical. The diameters of all these conductors are nearly the same resulting in nearly identical line capacitance and inductance and therefore practically identical voltage performance.

The voltage performance of a line in a networked system, which is the more typical case, is also dependent upon the reactive power supplied by or absorbed into the grid at the ends of the line and requires a power flow study modeling the entire transmission system to analyze. The results of this simple radial system voltage drop study will, however, provide an example of the concepts discussed in this paper as well as be representative of many transmission lines that are in service.
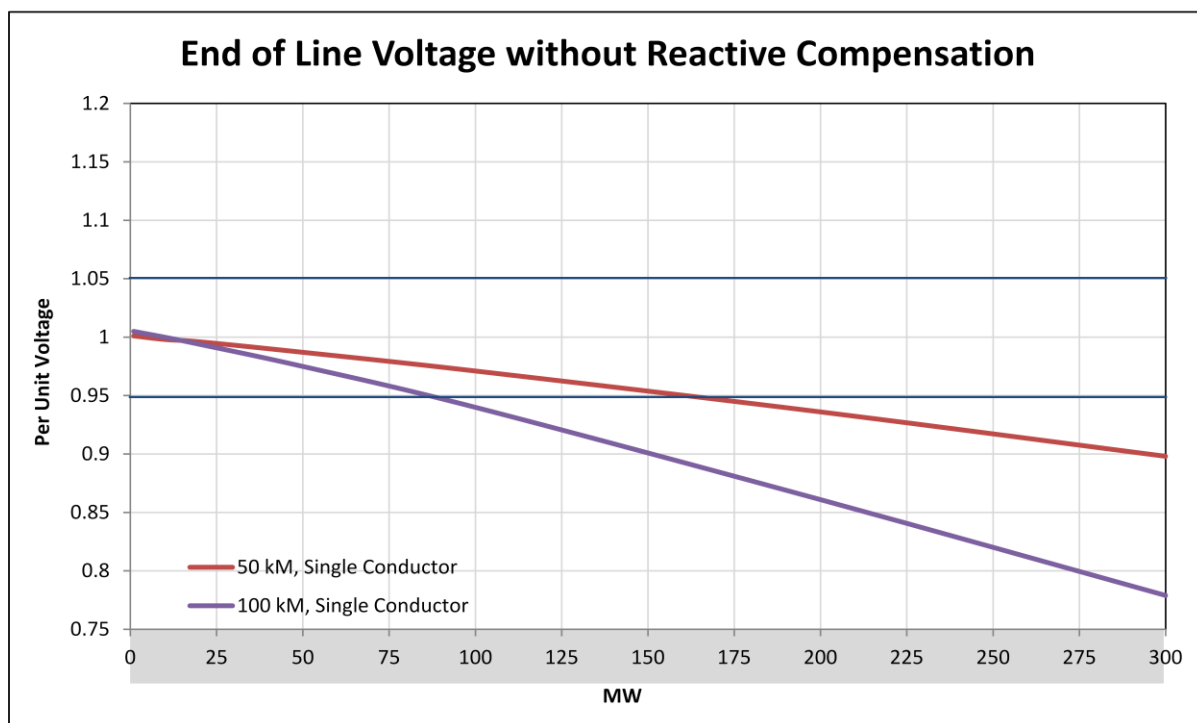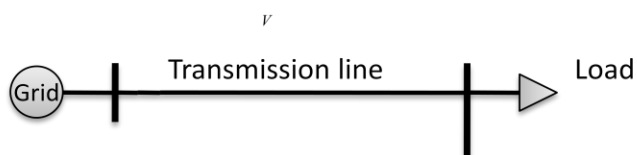
Figure 15 – End of Line Voltage without Reactive Compensation

Without reactive compensation the end of line voltage at zero or very light load is slightly higher than the grid source, which is held to 1.0 per unit. The voltage rise occurs because of reactive power supplied by the line is flowing back to the grid source, increasing the line end voltage. At maximum load the voltage drop on the 100 km line is more than double the voltage drop on the 50 km line. This effect becomes more apparent as line lengths are increased.
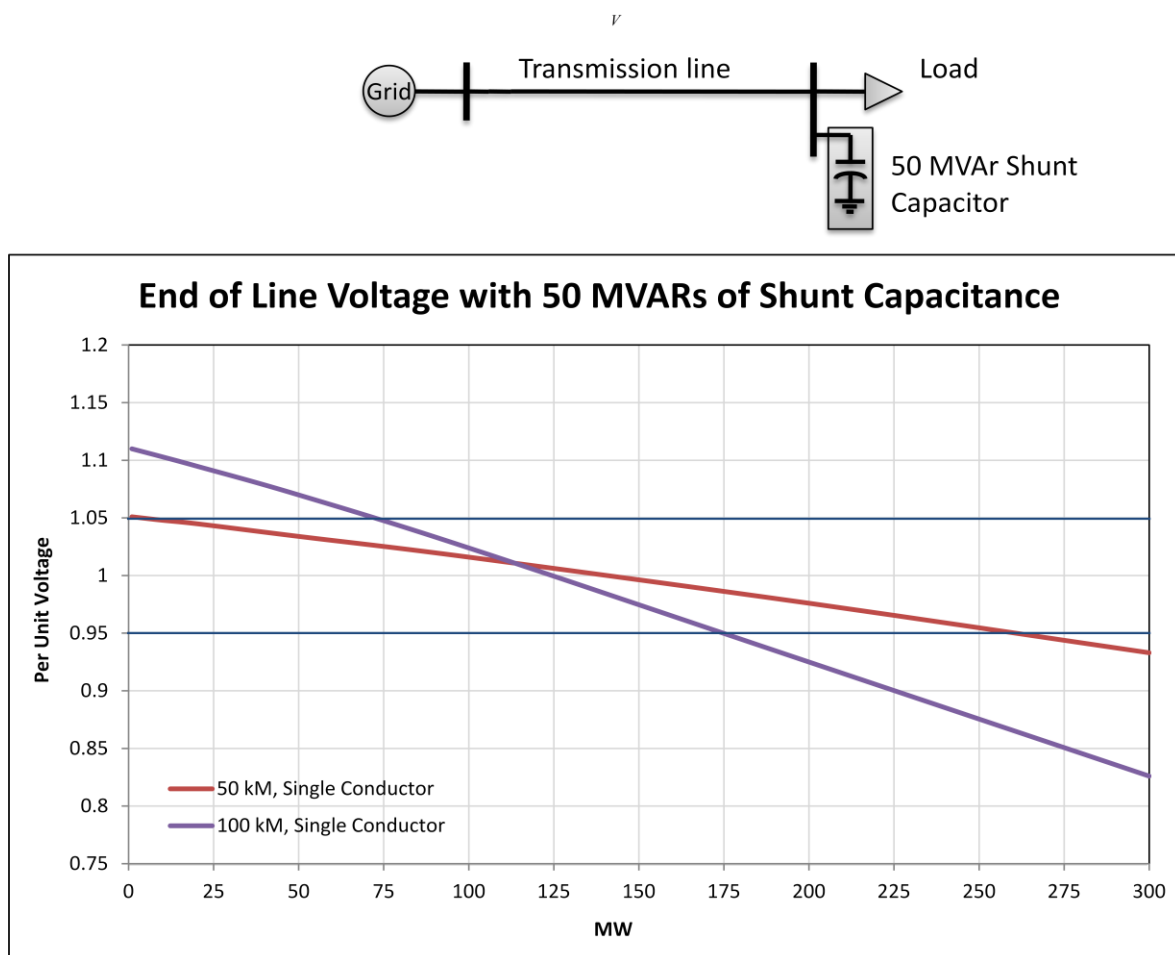
Figure 16 – End of Line Voltage with a 50 MVAr Shunt Capacitor

With a 50 mega Volt Ampere reactive (MVAr) shunt capacitor at the line end the line end voltage at no load exceeds the maximum allowable level indicating the capacitor would have to be switched off during lightly loaded conditions. Adding the 50 MVAr shunt capacitors significantly increased the amount of load that could be served without dropping below the 0.95 per unit minimum acceptable voltage. For the 50 km line the load increased from approximately 165 MW to approximately 260 MW, a nearly 100 MW increase. For the 100 km line the load roughly doubled from approximately 85 MW to 175 MW. This case illustrates the marked improvement in transmission line performance that can be obtained by the application of shunt capacitors.
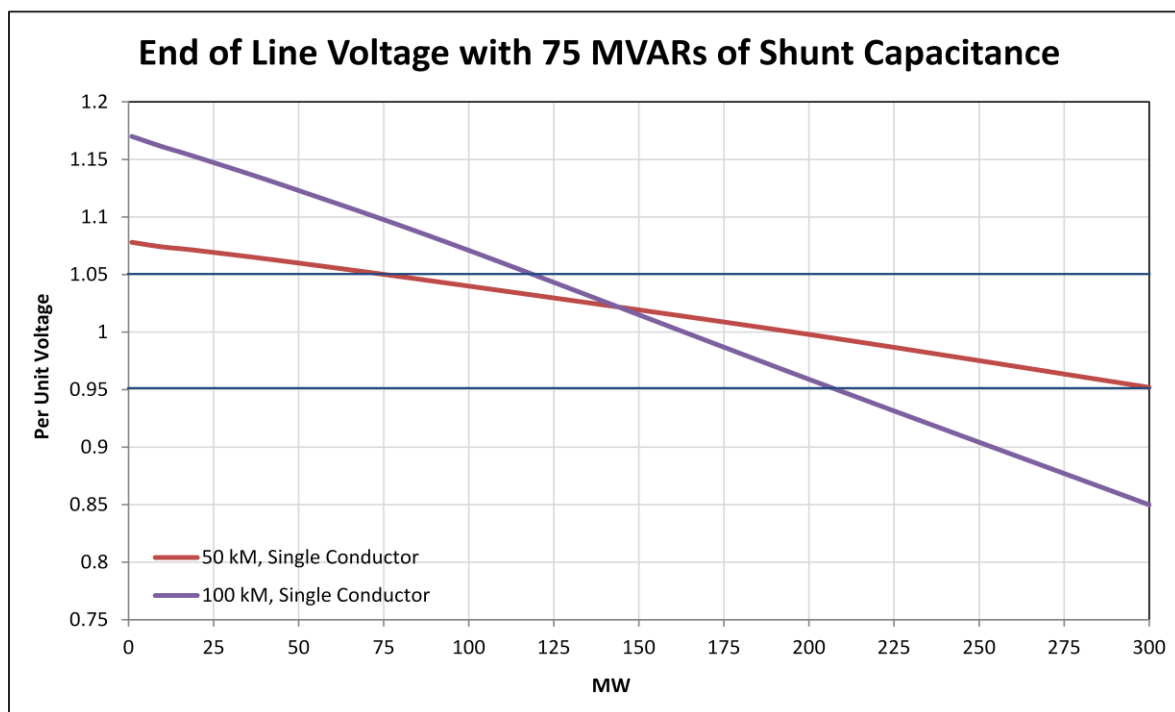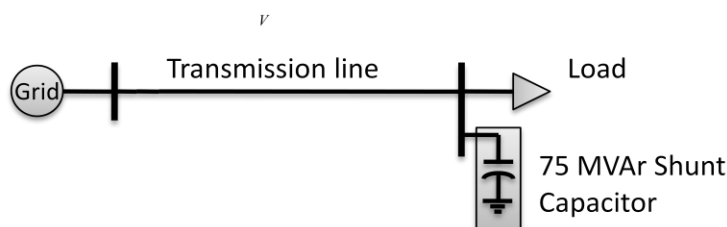
Figure 17 – End of Line Voltage with a 75 MVAr Shunt Capacitor

With 25 MVAr more of shunt capacitors added to the end of the line, for a total of 75 MVAr, the effects observed with the 50 MVAr shunt capacitor are increased. The line end voltage at no load exceeds the maximum allowable level by a greater amount and the capacitor would have to be switched off for light and moderate loading conditions to avoid violating allowable voltage limits. Additional load could be served but the increase from the 50 MVAr load levels is less than proportional to the 50% increase in capacitance. For the 50 km line the load increased from approximately 260 MW to 300 MW, only 40 more MW or 15.4%. For the 100 km line the load increased approximately 175 MW to 210 MW, 35 more MW or 20%. The diminishing return for added capacitance occurs because the reactive power losses that must be compensated for increase as the square of the power transmitted through the transmission line. As a consequence there are theoretical and practical limits to the amount of reactive power compensation that can be effectively applied to increase power transfer through a transmission line. The selection of reactive compensation type and size and the related decisions relating to conductor size, bundling, structure type and so on are best made with guidance from a comprehensive analytical and economic analysis.

CONCLUSIONS

Real power is a concept used to explain the conversion energy from one form to another. For example mechanical energy is converted to electrical energy in an electrical generator and electrical energy is converted to thermal energy in a space heater. The resistance in electrical conductors results in real power being converted to thermal energy as current flows through the line giving rise to real power losses.

Reactive power is a concept used to explain the effect of energy storage in and the transfer of energy between the electric and magnetic fields that surround transmission line conductors. Reactive power is both supplied and consumed in electric transmission lines. Reactive power is supplied by the shunt (phase to phase and phase to ground) capacitance of the transmission line. Reactive power is consumed when current flows through the series inductance of the transmission line.

Voltage drop and reactive power flow are related and interdependent. Reactive power flows from high voltage to low voltage. Adding shunt capacitors to increase the supply of reactive power will increase voltage.

Replacing conventional conductors such as aluminum conductor steel reinforced (ACSR) with one of the high temperature conductors such as aluminum conductor composite core (ACCC) or aluminum conductor steel supported (ACSS) of the same diameter can be a cost effective way to increase the transfer capacity of transmission lines. Maintaining the same conductor diameter makes it likely that existing structures can be used and with proper conductor selection and application ground clearances can normally be maintained.

Increasing power transfer will impact reactive power consumption, and therefore voltage, as well as real power losses.

The internal construction of conductors does not have a significant impact on the amount of reactive power supplied or lost or the voltage performance. So long as voltage remains constant the reactive power supply and consumption in an electric transmission line are primarily determined by the number of subconductors per phase, their diameter, and their spacing; along with the phase to phase spacing. Reactive power consumption will be the same regardless of conductor type selected so long as the conductor diameters are the same.

Adding shunt capacitors or other reactive power sources can increase the ability to transfer power over transmission lines significantly, however reactive power consumption varies with the square of current (or power transmitted) and this imposes practical upper limits on the ability to increase power transfer through the addition of shunt capacitors.

Real power losses vary directly with the resistance of the conductor, which is heavily influenced by the internal construction of the conductor as well as by the material used in the conductor. Conductors with relatively small cores using trapezoidal strands will have a larger cross sectional area of aluminum compared to other designs and will have significantly lower resistances and lower electrical losses as a result.