

**METHOD OF SELECTING BEST-SUITED CONDUCTOR/STRUCTURE  
COMBINATION FOR SUB-TRANSMISSION LINES BASED ON SPECIFIC  
NETWORK AND ENVIRONMENTAL CONDITIONS**

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One important consideration in the planning and design of growing Distribution Networks is the selection of the conductor/structure combination best suited for specific electrical and environmental conditions. Generally, the life cycle cost of a sub-transmission network may be reduced by a greater upfront investment on better-suited technologies. It is therefore necessary to determine if the projected decrease in the life cycle cost will justify the increased investment.

## 1. CONDUCTOR/STRUCTURE OPTIMISATION

In the past sub-transmission lines were designed and constructed on known standard conductor and structure combinations, without considering the life cycle cost effects of that selected combination on the line performance and environmental impacts. Although Investment Committees look at the return on investment (ROI) of projects, the ROI for network strengthening projects is low as there are no or very few newly connected customers generating income for the utility. Using the conductor/structure optimisation method, these life cycle effects are defined and used for the decision-making processes for sub-transmission line projects, especially in cases where the return on investment is low.

## 2. CRITERIA USED FOR CONDUCTOR AND STRUCTURE SELECTION

Conductor/structure optimisation utilises a mathematical process of selecting the best-suited range of conductor/structure combinations for sub-transmission lines given certain network and environmental performance parameters. There is an endless permutation of available conductor/structure combinations to select from but only a selected range would be suitable from an electrical and environmental point of view. The process is started with an initial selection of conductor and structure combinations based on the following four main criteria:

### 2.1 Load Transfer Capabilities

A certain amount of load needs to be transferred from the source to the load of the network. The minimum equivalent conductor area ( $A$ ) for the load transfer capability is determined from the current density ( $CD$ ) in the conductor, taking into consideration the load growth and probabilistic ampacity ratings ( $I_{AMP}$ ) of conductors using Eq-1 and Eq-2 below.

$$A \geq \frac{S_{MAX}}{\sqrt{3} \cdot V_L \cdot CD} \times 1000 \quad (\text{Eq-1})$$

$$I_{AMP} \geq \frac{S_{MAX}}{\sqrt{3} \cdot V_L} \times 1000 \quad (\text{Eq-2})$$

### 2.2 Corona Performance [1]

Corona performance of a certain conductor is determined by the conductor bundle configuration, conductor diameter, tower design, energised voltage and altitude of the network above mean sea level. The maximum electric field strength on the surface of the conductor bundle ( $E_{MAX}$ ) and Corona inception field strength ( $E_c$ ) is given by Eq-3 and Eq-4 respectively (See also Table 2)

$$E_{MAX} = \frac{q}{2 \cdot p \cdot e_0 \cdot N_b \cdot r} \cdot \left[ 1 + (N_b - 1) \cdot \frac{r}{S_b} \cdot \cos(f) \right] \quad (\text{Eq-3})$$

$$E_c = 30 \cdot m \cdot d \cdot \left( 1 + \frac{0.301}{\sqrt{d \cdot r_e}} \right) \quad (\text{Eq-4})$$

In order to prevent Corona from forming on a conductor, the Corona inception field strength should at least be 5% higher than the maximum electric field strength on the conductor. Substituting Eq-3 and Eq-4 into Eq-5, the minimum allowable conductor diameter is determined.

$$E_c > 1.05 \cdot E_{MAX} \quad (\text{Eq-5})$$

### 2.3 Impedance Matching to Surge Impedance

The line impedance (R, X & Y parameters of equivalent  $\pi$  circuit) of each conductor/structure combination is calculated and matched against the existing network's surge impedance (applying a

mean and standard deviation for a *Gaussian Distribution* function), in order to evaluate the impact of over voltages induced during switching operations or lightning strikes.

#### 2.4 Environmental Sensitive Structures

The last selection criterion is the environmental sensitivity of certain structures available to the designer. Some structures could cause unwanted animal interactions such as electrocutions or flashovers and should therefore not be considered as a possibility, especially where listed protected species are involved. This could be specific to a geographical region and needs to be evaluated on a per project basis.

Selecting only the conductor/structure combinations that satisfy all of the above criteria, the probable best-suited conductor/structure combinations are determined.

### 3. KEY PERFORMANCE INDICATORS

Once the conductor/structure combinations have been selected, the best-suited combination is determined using Key Performance Indicators (KPI's). The KPI's are an indication of how much capital is spent to obtain a certain network performance area. The following performance areas are evaluated in order to determine the best-suited combination.

#### 3.1 Life Cycle Costing (KPI<sub>1</sub>) [2]

Life cycle cost is defined as the total accumulated cost incurred over the life of the line. This cost is a combination of the initial Capital Investment Cost (*CIC*), total cost of losses (*TCL<sub>NPV</sub>*) and operating cost (*O&M<sub>NPV</sub>*) given by the following relationship:

$$KPI_1 = CIC + \int_0^{\infty} CL(t) + \int_0^{\infty} O \& M(t) \quad (\text{Eq-6})$$

$$KPI_1 = CIC + TCL_{NPV} + O \& M_{NPV} \quad (\text{Eq-7})$$

The total cost of energy losses over the life cycle of the line is calculated by using the Load Factor (and associated Loss Factor) of the load and the Long Run Marginal Energy Cost for generating the additional load on the sub-transmission network. A fixed operating activity cost (in present value of money terms) and an associated activity interval is used to calculate the total operating cost over the life cycle of the line.

The costs used in Eq-7 are all calculated as the total net present value of money, taking into consideration the projected Production Price Indexes (Inflation Rates) and Discounted Borrowing Rates, over the life of the line.

#### 3.2 Surge Impedance Loading (KPI<sub>2</sub>)

The surge impedance of a line is determined by its inductance (*L*) and capacitance (*C*). The surge impedance is used to determine the theoretical steady-state stability limit of a line [3] and is expressed in terms of the Surge Impedance Loading (*SIL*) given by:

$$SIL = \frac{V_L^2}{Z_c} = \frac{V_L^2}{\sqrt{L/C}} \quad (\text{Eq-8})$$

Under transient conditions the line is subjected to disturbances due to lightning strikes or switching operations. Voltage and current waves arise and travel along the line at a velocity near to the speed of light. Voltage and current reflections occur at line terminals and could cause damage to insulation of equipment or flashovers. The surge impedance of the line determines these line-end reflection coefficients of these voltage and current travelling waves.

The KPI value for surge impedance loading defines how much capital is invested per unit length of line to achieve 1 MW of surge impedance load rating and is calculated by:

$$KPI_2 = \frac{CI}{SIL} = \frac{CI \cdot Z_c}{V_L^2} = \frac{CIC}{l} \cdot \frac{Z_c}{V_L^2} \quad (\text{Eq-9})$$

### 3.3 Emergency Rating (KPI<sub>3</sub>)

The thermal power transfer capability of overhead lines is a function of the thermo dynamics properties of the conductor as well as the environment. There are two methods for determining the thermal current rating ( $I_{AMP}$ ) of a conductor: the deterministic method and the probabilistic method.

The deterministic approach [4] uses the heat gain/loss balance equation with certain bad cooling conditions (low wind speed, high ambient temperature, etc.) simultaneously applied to the conductor. The conductor current rating is then calculated as the current that would result in the conductor temperature equal to the line design (template) temperature.

The probabilistic approach [5], [6] uses actual weather data to simulate conductor ampacity. The conductor rating is determined based on the likelihood or probability of an unsafe condition.

The KPI value for emergency rating defines how much capital is invested per unit length of line to achieve 1 MVA of probabilistic thermal rating given by:

$$KPI_3 = \frac{CI}{\sqrt{3} \cdot V_L \cdot I_{AMP}} \quad (\text{Eq-10})$$

### 3.4 Voltage Regulation (KPI<sub>4</sub>) [7]

Voltage regulation could be defined as the change in voltage at the receiving end of the line when load varies from no-load ( $V_{RNL}$ ) to a full load ( $V_{RFL}$ ) at a specific power factor, while the sending end voltage is held constant, given by the following relationship:

$$\%VR = \frac{|V_{RNL}| - |V_{RFL}|}{|V_{RFL}|} \times 100 \quad (\text{Eq-11})$$

The KPI value for voltage regulation is an indication of how much capital is spent per unit length of line to achieve 1% of voltage regulation given by:

$$KPI_4 = \frac{CI}{\%VR} \quad (\text{Eq-12})$$

### 3.5 Route Selection (KPI<sub>5</sub>)

This KPI mainly assists with the evaluation of various line routes. When the line route has been fixed, it is not necessary to evaluate and compare this KPI as it would be the same for all combinations compared. Route Selection KPI is divided into an Engineering Rating and an Environment Risk Rating (the latter taking up to 80% importance ( $W_{ERR}$ ) in some cases).

With the Engineering Rating ( $ENG$ ), the difficulty of terrain, pollution effects, theft, lightning density and other environmental factors that have an impact on the line design, are evaluated.

Environmental Risk Rating ( $ERR$ ) identifies the potential positive or negative environmental, biophysical and social impacts associated with the line routes. The aspects that are considered [9] are Fauna, Flora, Visual Effects of the new line on the surrounding landscape, Natural Heritage, Land Use, Water and Infra Structure.

In order to evaluate the aspects and assign an order of priority, the following Characteristics ( $Char$ ) of each potential issue is identified. These are *Extent* of impact (local, limited to immediate

surroundings, sub-regional, regional or national impact), *Duration* (short, medium, or long-term implication), *Probability* (likelihood of the impact actually occurring indicated as unlikely, probable, highly probable or definite) and *Significance* to the environment should the specific impact actually occur as (low, medium or high).

A numeric number for each of the Characteristics is assigned (in ascending order) as listed above and then multiplied with one another to obtain the Risk Product ( $RP_i$ ) for each of the aspects as show by Eq-13:

$$RP_i = Char_1 \cdot Char_2 \cdot Char_3 \cdot L \cdot Char_n \quad (\text{Eq-13})$$

Some aspects may not be applicable to the Engineering portion or Environmental portion of the line and each *Risk Product* is therefore multiplied with an associated weight of applicability ( $W_{APP-i}$ ). The sum of the weighted *Risk Products* is then calculated to determine the overall Engineering and Environmental Risk Rating respectively. The KPI value is then given by the following:

$$ENG = \sum PR_i \cdot W_{APP-i} \quad (\text{Eq-14})$$

$$ERR = \sum PR_i \cdot W_{APP-i} \quad (\text{Eq-15})$$

$$KPI_5 = ENG \cdot (1 - W_{ERR}) + ERR \cdot W_{ERR} \quad (\text{Eq-16})$$

#### 4. KEY PERFORMANCE INDICATOR EVALUATION

After all the KPI values for each conductor/structure combination are calculated, each one is normalised (per conductor/structure combination) between 1 (best) and 0 (worst) to determine the per-unit Key Performance Indicator Rating ( $KPIR_i$ ) as indicated by Figure 1.

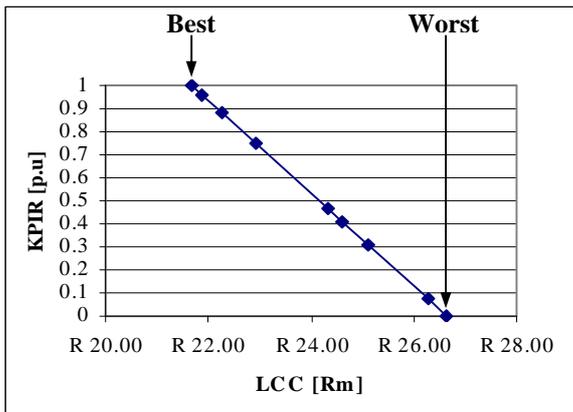


Figure 1: Example of KPI values normalisation

Each KPIR value is then multiplied with a Weight-of-Importance ( $W_i$ ) to determine the overall Performance Rating for that specific conductor/structure combination using the following equation:

$$PR = \sum_{i=1}^5 KPIR_i \cdot W_i \quad (\text{Eq-17})$$

A relative ranking list is then compiled using these Performance Ratings of each conductor/structure combination to obtain the best-suited conductor/structure combination for the specific electrical and environmental conditions.

#### 5. SENSITIVITY ANALYSIS

A sensitivity analysis (what-if scenarios) on the KPI's should be performed to determine if the identified best-suited conductor/structure combination holds true for changes to network performance and environmental conditions. Factors that could play a role are changes to the operational life of the line, accuracy of load prediction, changes in local economy, climatic effects on the line, criminal effects (probability of conductor theft), importance of on Environmental or Engineering aspect to another, etc.

#### 6. CASE STUDY

A new 70km, 132kV line should be built for the new Everest South Mine in Mpumalanga – South Africa. The forecasted load increases from 0MVA to 300MVA within eight years. The line will be

operated at 300MVA for the remainder of the line's life. Figure 2 shows the families of structures considered for the line.

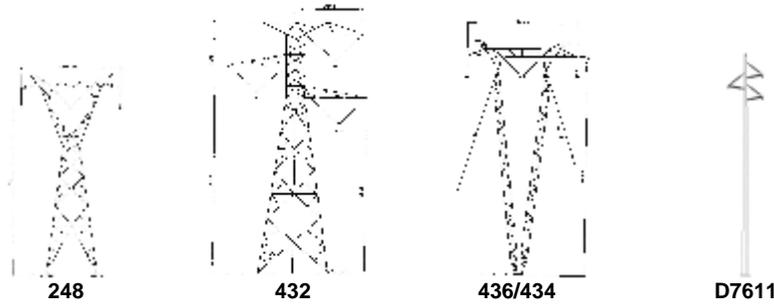


Figure 2: Family of structures considered

The load factor of the line is 0.75 in summer and increases to 0.8 in winter for 5 months of the year. Table 1 shows the most probable conductor/structure combinations based on criteria from Eq-1 to Eq-5 and equivalent conductor impedance to that of 2xTERN.

TABLE 1 – Conductor/Structure Combinations

Structure	Conductor	$I_{AMP}$	$r_e$	$Z_c$	CIC (R million)
248	2x Bear	1247.58	41.94	344.83	R 37,506,140
248	2x Kingbird	1377.89	42.32	343.49	R 37,325,330
248	2x Pelican	1154.44	39.40	349.14	R 340,354,700
248	2x Tern	1585.27	45.00	339.08	R 41,576,570
432	2x Bear	1247.58	41.94	371.59	R 52,126,130
432	2x Kingbird	1377.89	42.32	370.39	R 51,945,320
432	2x Pelican	1154.44	39.40	375.79	R 486,554,600
432	2x Tern	1585.27	45.00	366.13	R 56,196,560
436/343	2x Bear	1247.58	41.94	370.22	R 38,440,220
436/343	2x Kingbird	1377.89	42.32	369.98	R 38,259,410
436/343	2x Pelican	1154.44	39.40	374.46	R 349,695,500
436/343	2x Tern	1585.27	45.00	364.68	R 42,510,650
D7611	2x Bear	1247.58	41.94	325.80	R 34,489,070
D7611	2x Kingbird	1377.89	42.32	324.28	R 34,308,260
D7611	2x Pelican	1154.44	39.40	330.47	R 310,184,000
D7611	2x Tern	1585.27	45.00	319.48	R 38,559,500

Figure 3 shows the change of the KPIR values calculated for the Top-10 conductor/structure combinations from a Life Cycle Cost point of view. Note that an option that may be initially the best (cheapest), is not necessarily the best suited solution (i.e. RED line in Figure 3)

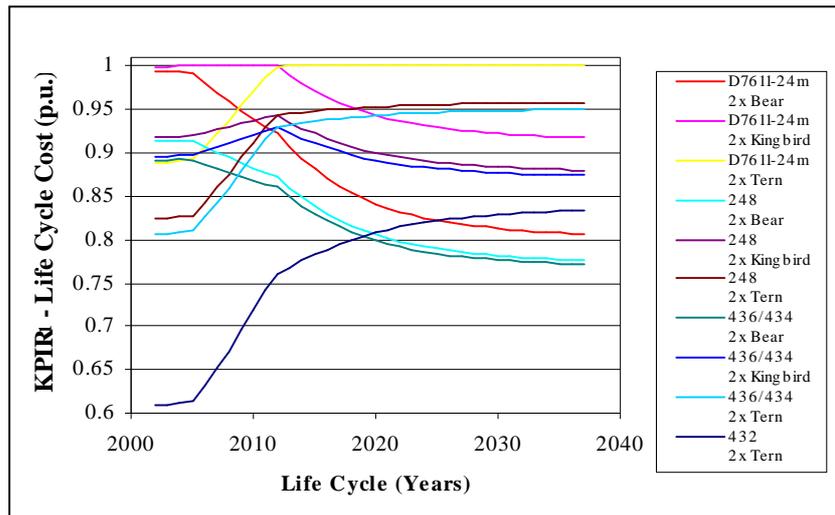


Figure 3: Normalised KPIR<sub>1</sub> values for Life Cycle Cost

Figure 4 shows the change of the weighted Performance Rating calculated for the Top-10 conductor/structure combinations over the life cycle of the line.

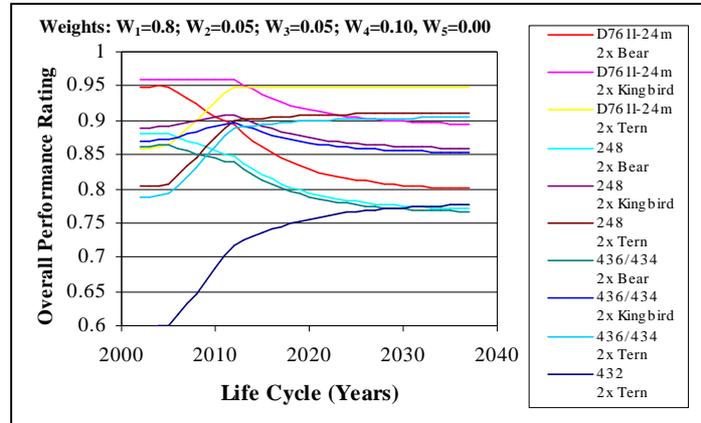


Figure 4: Top-10 conductor/structure combinations

## 7. CONCLUSION

From the case study it can be seen that by just looking at the lowest initial capital cost for sub-transmission line projects, it does not necessarily result in the best-suited conductor/structure combination. Looking only at initial cost (Figure 3) the best-suited conductor/structure combinations is either 2x Kingbird or 2x Bear on a D7611 structure. From a life cycle cost point of view, 2x Tern on a D7611 structure is the best-suited combination.

Taking the network performance parameters into account the differences in relative performances of these combinations becomes evident (2x Tern on a 432 structure vs. 2x Bear on a 248 structure in Figure 3 & Figure 4).

By evaluating the effects of network performance parameters as well as the environmental parameters (in some cases), the best-suited conductor/structure combination could analytically be determined. With the conductor optimisation method one could analyse the life cycle effect of the various network performance and environmental parameters on the relative Performance Rating of each conductor/structure combination.

TABLE 2 – List of other symbols use in equations

Var	Description	Unit
$CI$	Capital Investment (local currency = R)	R/km
$N_b$	Number of conductor in bundle	-
$q$	Total electrical charge on the bundle	C/m
$r$	Conductor radius	mm
$S_b$	Sub-conductor spacing within bundle	mm
$f$	Angle between centre of bundle to horizon	$^\circ$

## 8. REFERENCES

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