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College of Engineering

Wind Energy Initiative (WEI)

Frequency Dynamic Impact by a Transmission Overlay in a Renewable Sourced Power System

Elena C. Hoff
Wind Energy Science Engineering and Policy REU
Iowa State University
Ames, Iowa
Mentors: Dr. Dionysios Aliprantis and Hugo Villegas-Pico

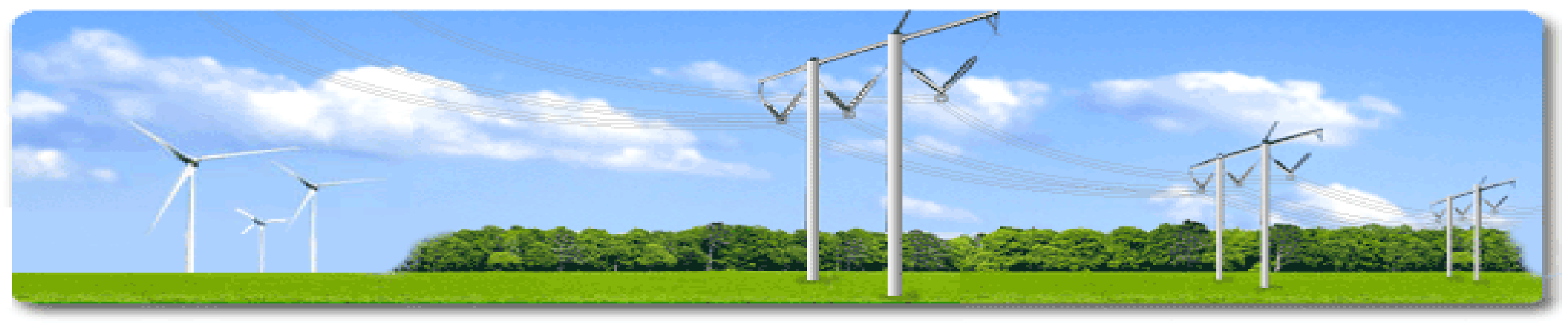
Introduction:

The nation's transmission grid system is currently divided into three main self-sufficient regions: the Eastern Interconnection, Texas, and the West [1]. The few existing transmission lines between these regions have very low capacity because there is little need for transferring energy between regions. However, this need is constantly growing due to further development of renewable energy sources specific to regions of the United States. In order to reach the progressive standard set by the 2008 Department of Energy report maintaining that 20% of the U.S. Energy portfolio can come from Wind Energy by 2030 [2], a complete renovation of the transmission system will be required.

The theorized system is one that would equally link all sections of the United States in a national transmission grid. This grid would require a new transmission overlay – a high-capacity network spanning the nation and integrated into the existing structure. Forming such a robust system could anticipate future energy needs of our country [3] by facilitating long-term flexibility for accessing diverse generation resources, such as renewables [4], and solving energy disruptions or crisis at a national level.

The analysis of frequency dynamic interplay between the sources and the loads is of the utmost importance. In an interconnected power system, one can simplify the model by assuming that frequency is the same inside each control area consisting of generators and loads due to the synchronous nature of the localized system, which can be visualized as one large rotating mass. Frequency analysis can be isolated to the tie-lines, the transmission lines between control areas. The real power balance of a system is what dictates the frequency, which ideally should remain constant [5]. However, areas with large amounts of renewable sources may experience some abnormal frequency fluctuations. We examine how a transmission overlay can help to improve, through damping, those fluctuations in frequency.

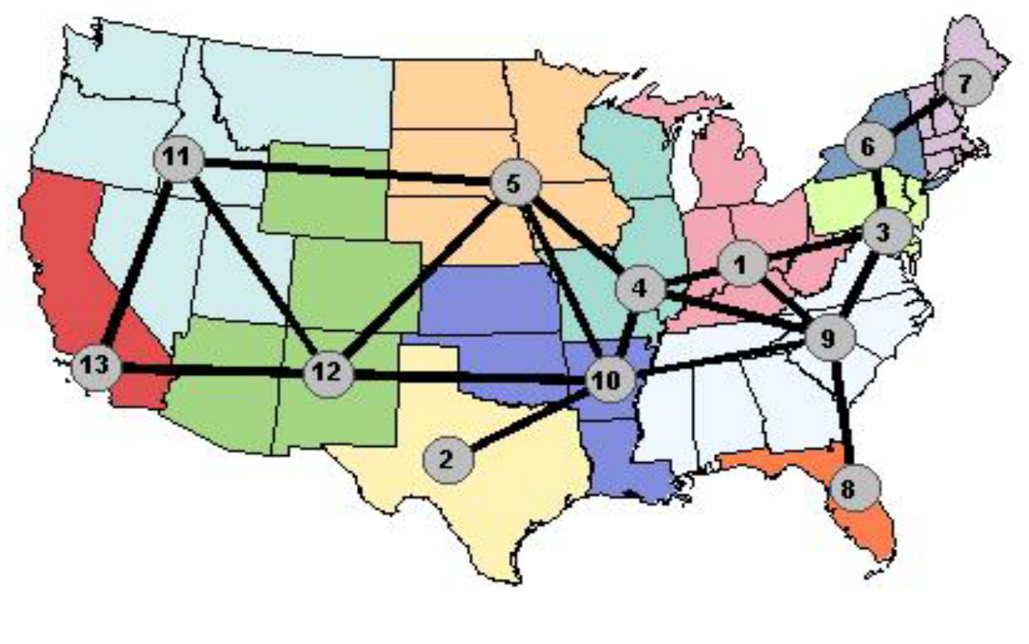
In order to lay out a comprehensive procedure for the analysis of frequency dynamics of a multi-line High Voltage AC national transmission system, it is necessary to break down the process into various steps. Once the procedure is established, further refinements of parameters – as well as a more extensive cost/benefit analysis – will better approximate the system and provide useful direction for further planning of a transmission overlay.



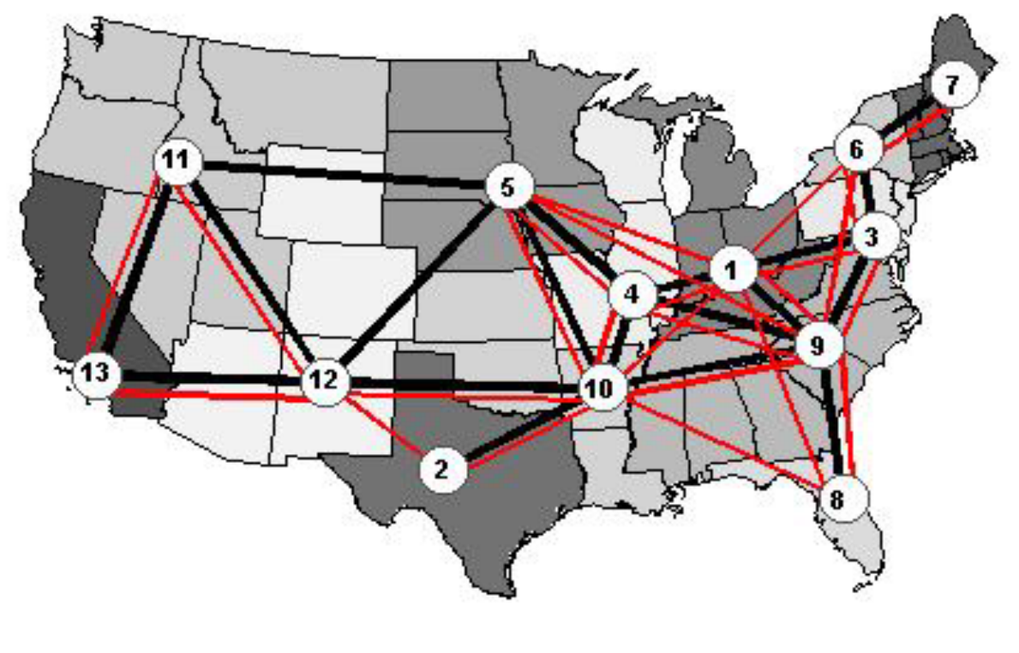
Experimental Methods:

Maps

In order to simplify our analysis, we combined our control areas into 13 separate regions across the United States and mapped out the existing interconnections. Presented with a proposed future overlay design[6] of over 250 additional transmission lines throughout the next 40 years, we sifted out the interregional connections – according to our defined areas – to use for our analysis. We added another layer to our transmission map in order to view the entire extent of the proposed system.



(Existing HVAC Transmission System)

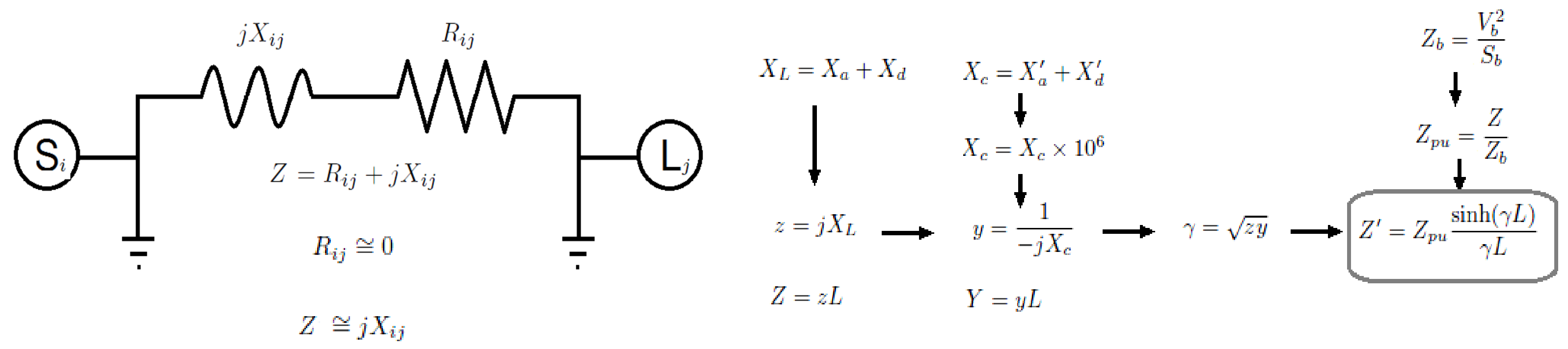


(Existing HVAC Transmission System with proposed overlay)

Calculating Impedance for HVAC – 765kV

We seek to model each interconnection as a single tie-line through estimation. It is necessary to first calculate the effective impedance, Z', of the tie-lines between the areas.

By approximating our resistance, *R*, to be negligible, we arrive at impedance, *Z*, to be relatively equal to the imaginary part of the reactance, *X*.



$$Z = R_{ij} + jX_{ij}$$

$$R_{ij} \cong 0$$

$$Z \cong jX_{ij}$$

$$X_L = X_a + X_d \quad\quad X_c = X'_a + X'_d$$

$$X_c = X_c \times 10^6$$

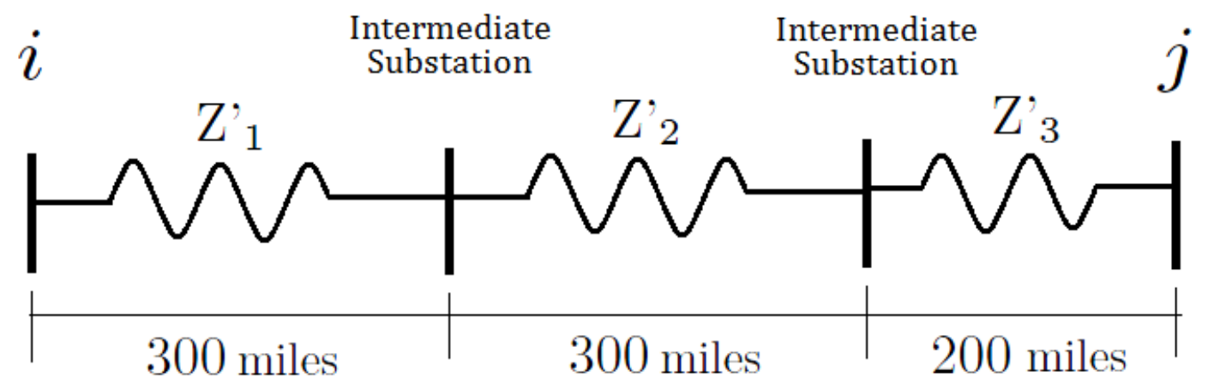
$$z = jX_L \longrightarrow y = \frac{1}{-jX_c} \longrightarrow \gamma = \sqrt{zy} \longrightarrow \boxed{Z' = Z_{pu}\frac{\sinh(\gamma L)}{\gamma L}}$$

$$Z = zL \quad\quad Y = yL$$

$$Z_b = \frac{V_b^2}{S_b} \downarrow Z_{pu} = \frac{Z}{Z_b}$$

We multiplied the inductive reactance by the theoretical length of the tie-line (in miles), converted to per unit (using a base power of 100MW), and supplied the correction factor that allows us to use our consolidated assumptions for lines longer than 100 miles [7]. This provided us with a *Z'* value for our supplementary calculations.

We expanded our data to divide the lengths of each transmission line into segments of 300 miles or fewer in order to transmit at 100% loadability [8].



$$Z'_{eq} = Z'_1 + Z'_2 + Z'_3$$

(The *Z'eq*, or equivalent impedance of the line, was calculated as the sum of impedances of each segment .)

Calculating P_{SIL}

The Surge Impedance Loading, P_{SIL}, is the power loading at which the reactive power is not produced or absorbed. The P_{SIL} of each line geometry is necessary to determine the number of required circuits needed for each line. It can be calculated by using the per-unit length impedance and admittance along with the Line-to-Line voltage, V_{LL}, of 765 kV and a power base, S_b, of 100 MW.

This is the maximum power capacity of each circuit per-unit, p.u, as determined by the line geometry. With this information, we can calculate the number of circuits necessary to reach the desired power capacity P_{Lij} delivered to the load.

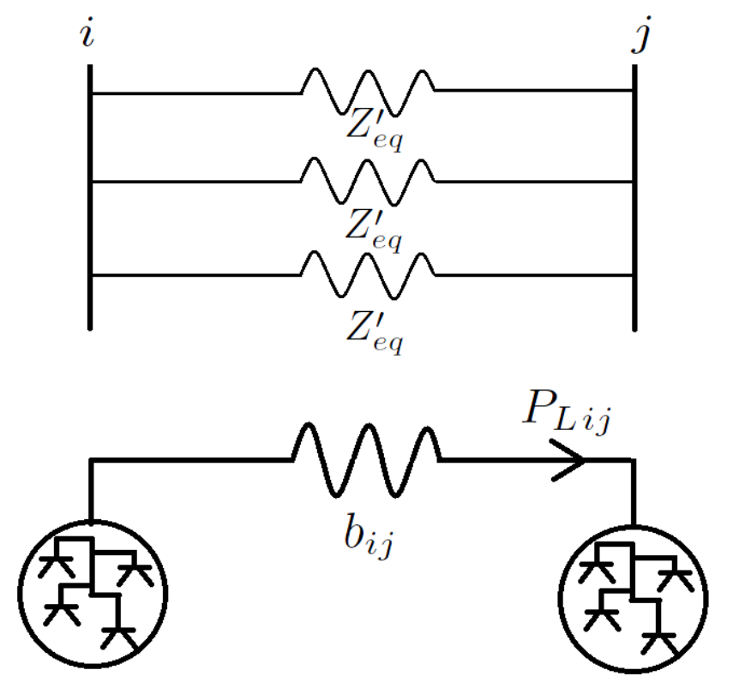
$$Z_c = \sqrt{\frac{z}{y}}$$

$$P_{SIL} = \frac{{V_{LL}}^2}{Z_C}$$

$$P_{SILpu} = \frac{P_{SIL}}{S_b}$$

Calculating b_{ij} and ΔΘ

For dynamic analysis, we are looking for the b_{ij} – a function of the impedance of each tie-line. To calculate this value, we again approximate and assume that the change in voltage across the tie-line is negligible and, since we are working in per-unit, V_i and V_j are both approximated to be 1 p.u. The final step is to calculate the ΔΘ, the phase shift within each circuit. This quantity is later used to determine whether or not an adequate transmission line was designed. A ΔΘ must be calculated for each tie-line for the first period and the second period of time.



$$P_{Lij} = \frac{V_i V_j}{Z'_{eq}} \sin(\theta_i - \theta_j)$$

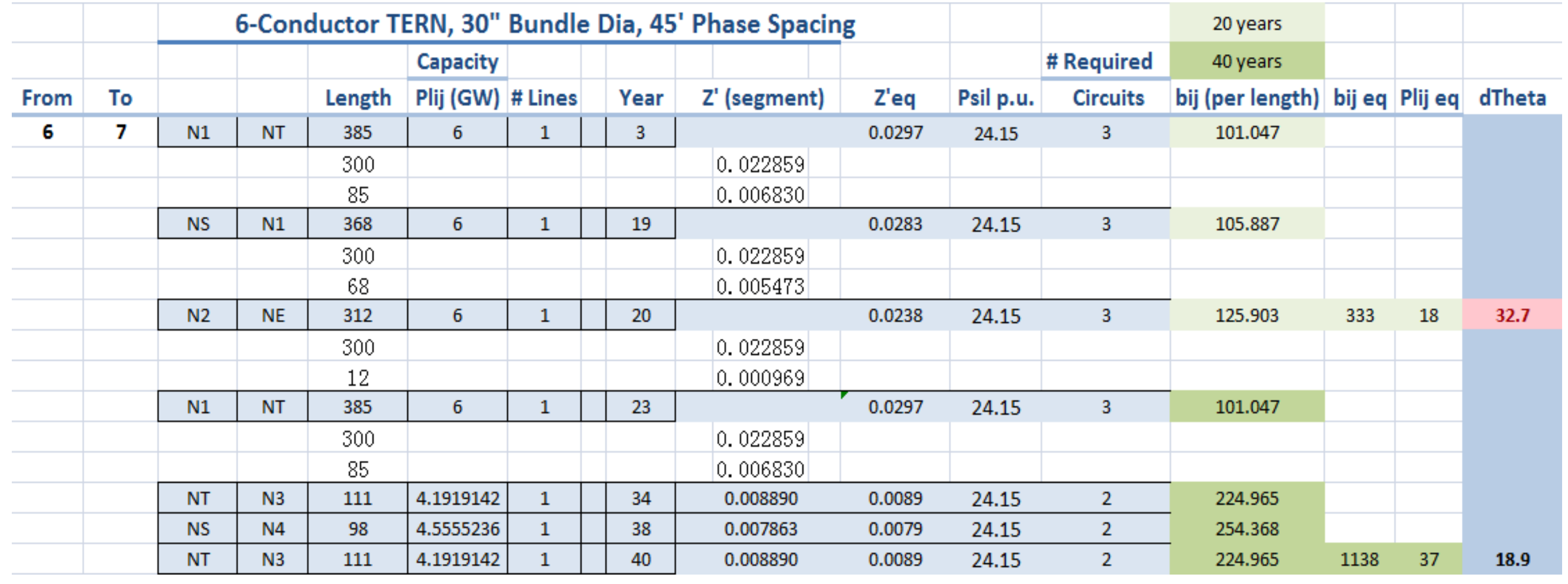
$$P_{Lij} = \frac{1}{Z'_{eq}} \sin(\theta_i - \theta_j)$$

$$b_{ij} = \frac{1}{Z'_{eq}} \times \#\ of\ circuits$$

$$P_{Lij} = b_{ij} \sin(\theta_i - \theta_j)$$

$$\Delta\theta = \theta_i - \theta_j = \arcsin\left(\frac{P_{Lijeq}}{b_{ijeq}}\right)$$

The following table contains the interregional connections that were sifted out from the original data, grouped from one specific region to another. The table contains the length of each line segment (miles), required transmission capacity (GW), number of proposed transmission lines at that capacity, the proposed year, along with the b_{ij} value and ΔΘ for the first and second analysis period.



				6-Conductor TERN, 30" Bundle Dia, 45' Phase Spacing								20 years			
					Capacity						# Required	40 years			
From	To			Length	Plij (GW)	# Lines	Year	Z' (segment)	Z'eq	Psil p.u.	Circuits	bij (per length)	bij eq	Plij eq	dTheta
6	7	N1	NT	385	6	1	3		0.0297	24.15	3	101.047			
				300				0. 022859							
				85				0. 006830							
		NS	N1	368	6	1	19		0.0283	24.15	3	105.887			
				300				0. 022859							
				68				0. 005473							
		N2	NE	312	6	1	20		0.0238	24.15	3	125.903	333	18	32.7
				300				0. 022859							
				12				0. 000969							
		N1	NT	385	6	1	23		0.0297	24.15	3	101.047			
				300				0. 022859							
				85				0. 006830							
		NT	N3	111	4.1919142	1	34	0.008890	0.0089	24.15	2	224.965			
		NS	N4	98	4.5555236	1	38	0.007863	0.0079	24.15	2	254.368			
		NT	N3	111	4.1919142	1	40	0.008890	0.0089	24.15	2	224.965	1138	37	18.9

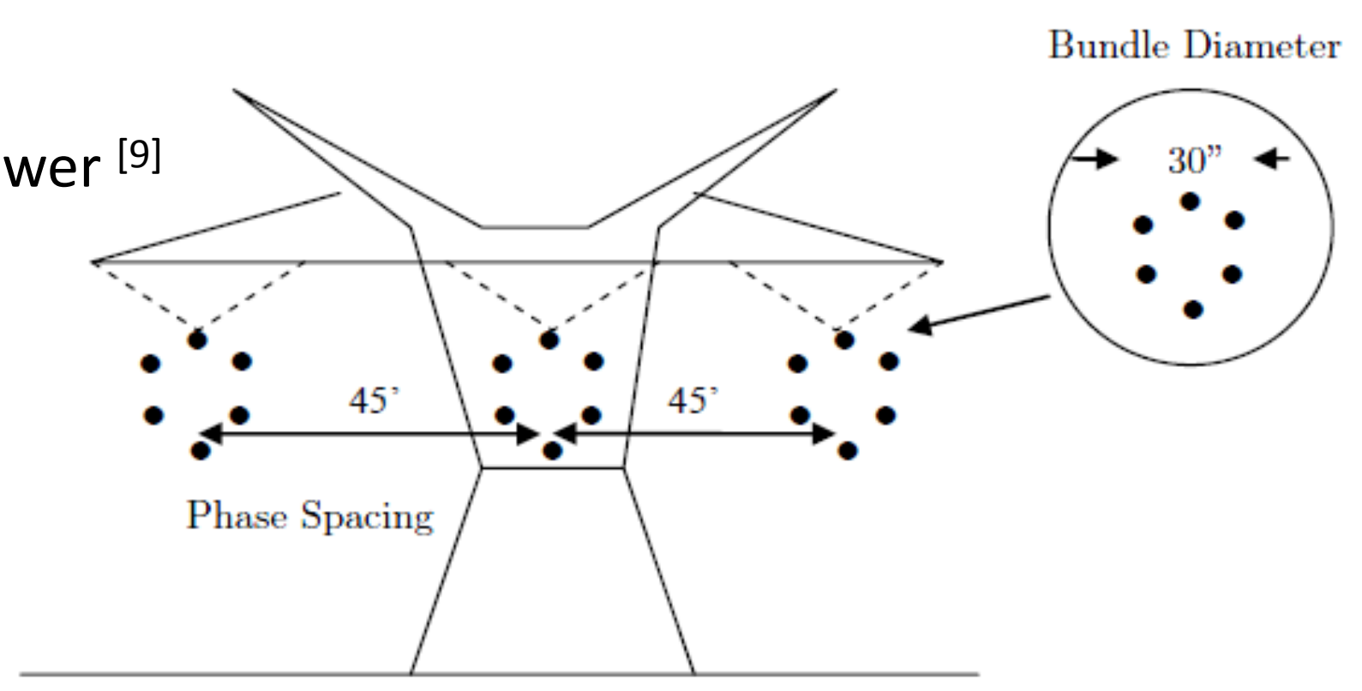
NOTE: This table selection represents one tie-line.

Determining Line Geometries

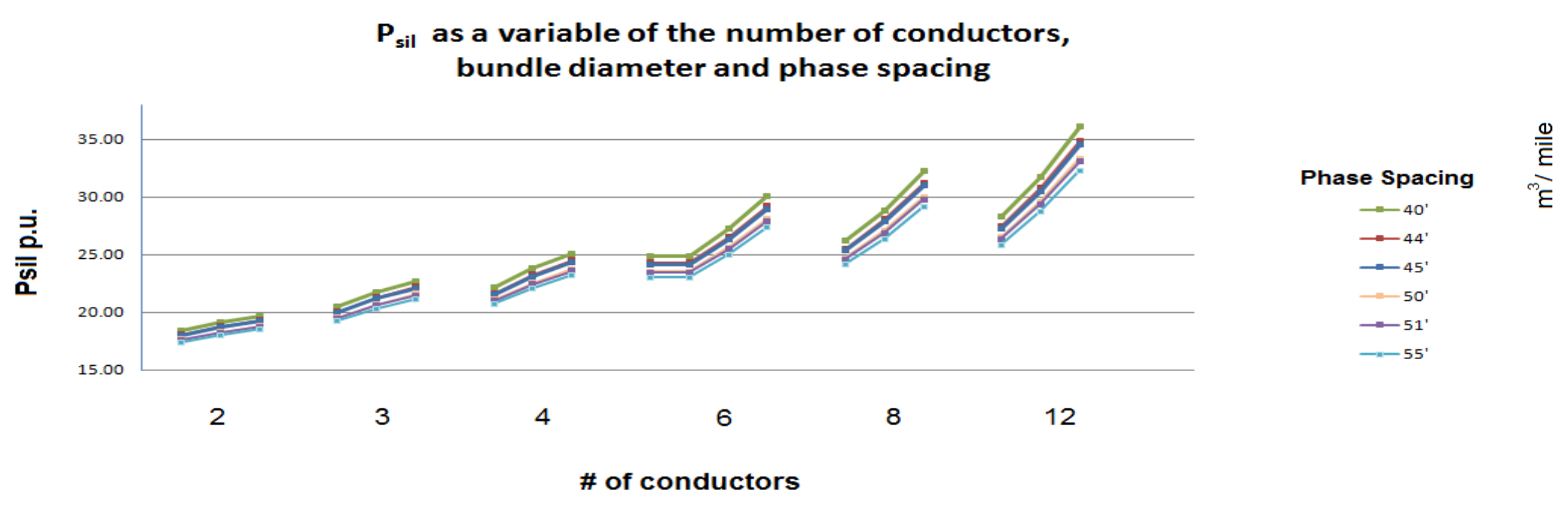
The characterizations of line geometry consist of the number of conductors used in each bundle and the bundle diameter and the phase spacing in each circuit, which involves three phases. There is no need to choose one specific line geometry to use throughout the entire transmission overlay. The requirements of each segment should be carefully studied to choose the best suited geometry for that individual segment.

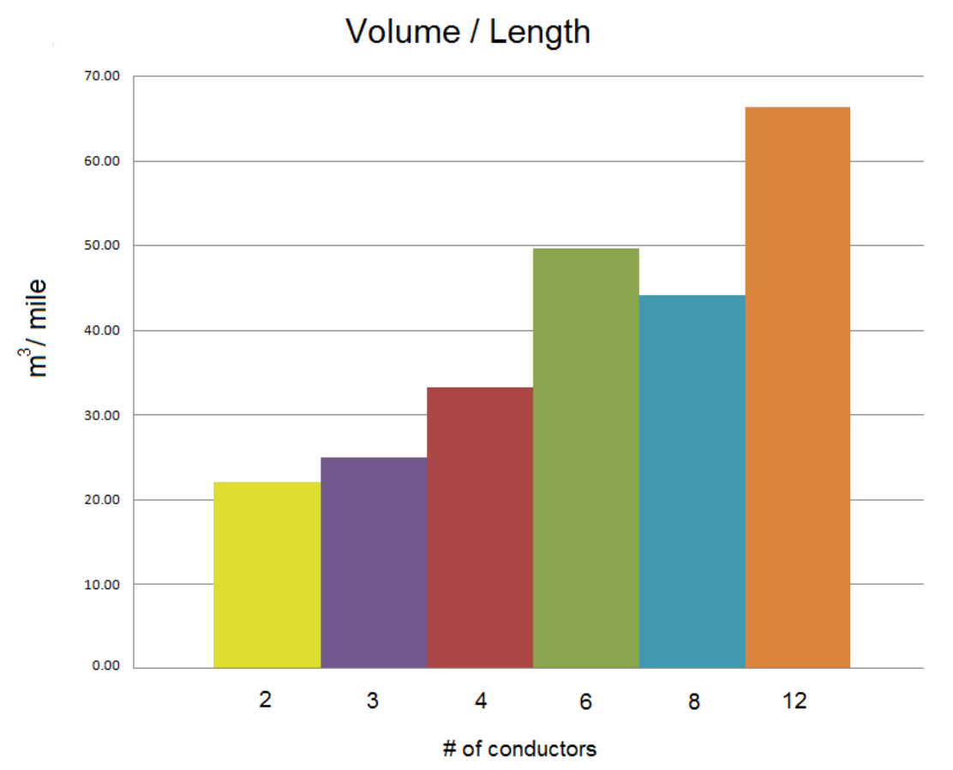
Minimize:
- —Economic Costs
  - ▪ # of circuits required
  - ▪ # of towers to suspend transmission lines (one tower for two circuits)
  - ▪ Volume of conductors used per mile
- —Environmental Costs
  - ▪ 200m Right-of-Way with each 765kV tower [9]

Maximize:
- —Transmitted Power

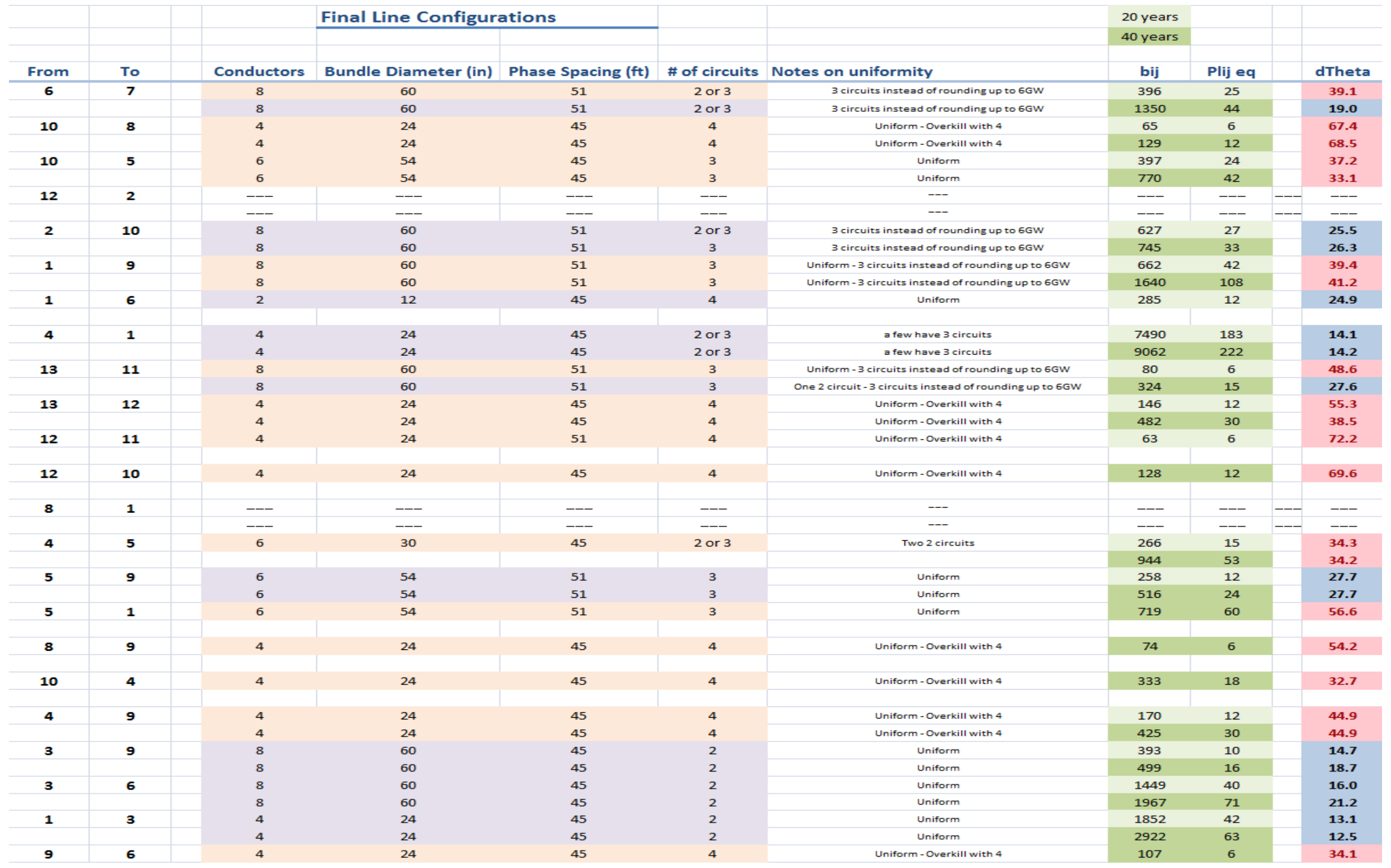


The benefit of each geometry can be portrayed through the P_{SIL}. A higher P_{SIL} is achieved by increasing the bundle diameter or decreasing the phase spacing. For the purposes of our calculations, we are generally focusing on 45 ft phase spacing presented by AEP 765kV specifications. In practice, a higher P_{SIL} generally creates a lower ΔΘ, phase change, indicating a better line geometry, ideally in the range of 10° – 30°.





The volume required for each geometry is weighed against the ΔΘ produced in each segment along with the number of circuits required to choose the best line geometry for that segment. By carefully scrutinizing this decision, we were able to determine the optimum b_{ij} associated with each proposed transmission tie-line. Analysis allows consideration of how the proposed overlay will interact with the existing system as if installed in 20-year increments.

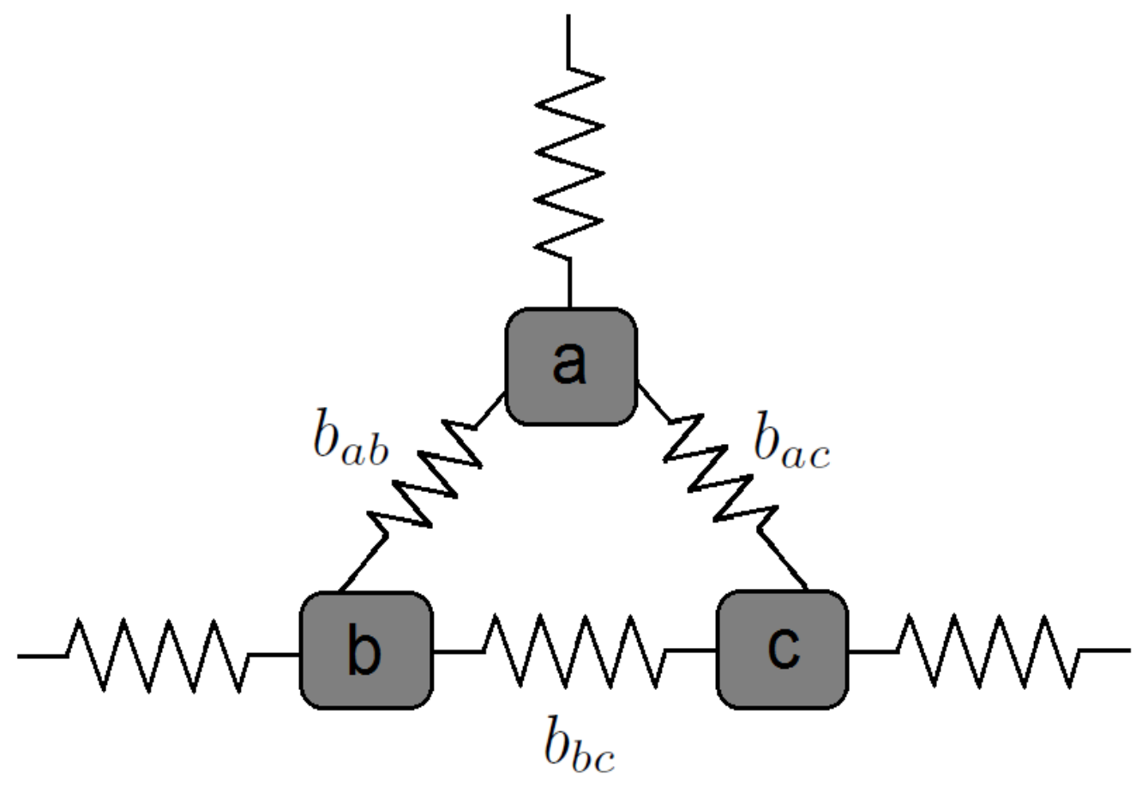


		Final Line Configurations					20 years			
							40 years			
From	To	Conductors	Bundle Diameter (in)	Phase Spacing (ft)	# of circuits	Notes on uniformity	bij	Plij eq		dTheta
6	7	8	60	51	2 or 3	3 circuits instead of rounding up to 6GW	396	25		39.1
		8	60	51	2 or 3	3 circuits instead of rounding up to 6GW	1350	44		19.0
10	8	4	24	45	4	Uniform - Overkill with 4	65	6		67.4
		4	24	45	4	Uniform - Overkill with 4	129	12		68.5
10	5	6	54	45	3	Uniform	397	24		37.2
		6	54	45	3	Uniform	770	42		33.1
12	2	---	---	---	---	---	---	---	---	---
		---	---	---	---	---	---	---	---	---
2	10	8	60	51	2 or 3	3 circuits instead of rounding up to 6GW	627	27		25.5
		8	60	51	3	3 circuits instead of rounding up to 6GW	745	33		26.3
1	9	8	60	51	3	Uniform - 3 circuits instead of rounding up to 6GW	662	42		39.4
		8	60	51	3	Uniform - 3 circuits instead of rounding up to 6GW	1640	108		41.2
1	6	2	12	45	4	Uniform	285	12		24.9
4	1	4	24	45	2 or 3	a few have 3 circuits	7490	183		14.1
		4	24	45	2 or 3	a few have 3 circuits	9062	222		14.2
13	11	8	60	51	3	Uniform - 3 circuits instead of rounding up to 6GW	80	6		48.6
		8	60	51	3	One 2 circuit - 3 circuits instead of rounding up to 6GW	324	15		27.6
13	12	4	24	45	4	Uniform - Overkill with 4	146	12		55.3
		4	24	45	4	Uniform - Overkill with 4	482	30		38.5
12	11	4	24	51	4	Uniform - Overkill with 4	63	6		72.2
12	10	4	24	45	4	Uniform - Overkill with 4	128	12		69.6
8	1	---	---	---	---	---	---	---	---	---
		---	---	---	---	---	---	---	---	---
4	5	6	30	45	2 or 3	Two 2 circuits	266	15		34.3
							944	53		34.2
5	9	6	54	51	3	Uniform	258	12		27.7
		6	54	51	3	Uniform	516	24		27.7
5	1	6	54	51	3	Uniform	719	60		56.6
8	9	4	24	45	4	Uniform - Overkill with 4	74	6		54.2
10	4	4	24	45	4	Uniform - Overkill with 4	333	18		32.7
4	9	4	24	45	4	Uniform - Overkill with 4	170	12		44.9
		4	24	45	4	Uniform - Overkill with 4	425	30		44.9
3	9	8	60	45	2	Uniform	393	10		14.7
		8	60	45	2	Uniform	499	16		18.7
3	6	8	60	45	2	Uniform	1449	40		16.0
		8	60	45	2	Uniform	1967	71		21.2
1	3	4	24	45	2	Uniform	1852	42		13.1
		4	24	45	2	Uniform	2922	63		12.5
9	6	4	24	45	4	Uniform - Overkill with 4	107	6		34.1

More than half of our calculated ΔΘ values are much higher than desired. This suggests that the implementation of a complementary technology for high-capacity transmission is necessary. One such option is High Voltage DC. HVDC transmission is the energy efficient choice for bulk transmission over large distances (over 400 miles) due to its controllability and insusceptibility to the impedance and reactive power behavior seen in AC lines. However, over shorter distances, Extra High-Voltage AC transmission is the preferred method considering cost efficiency [4]. Further studies are necessary on how best to integrate HVDC transmission into a primarily EHV AC transmission overlay in attempts to optimize results.

Dynamic Simulation:

In dynamic simulation, we will use the metaphor of a web of blocks – each representing the individual control areas – connected by springs. Our theoretical "spring constants" will be our b_{ij} values for each tie-line. The concept is to analyze what happens to the system when one spring is jostled. Ideally, the "springs" are stiff enough to account for a slight disruption and will hold the rest of the system intact by dampening any oscillations. If this is not the case, further improvements to the national transmission overlay will be proposed.



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