REPORT OF FEASIBILITY
OF HIGH PHASE ORDER TRANSMISSION
ERDA Contract E(49-18) 2066

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INTRODUCTION

The increasing need to improve utilization of electric utility rights-of-way has precipitated a number of alternative approaches to conventional power transmission methods. One unique approach, the feasibility of which is analyzed in this report, is extension of the number of phases beyond the conventional 3-phase configuration. This concept, designated as high phase order transmission (HPO), employs the inherent insulation characteristics of multiphase conductor arrays to increase spatial power transmission efficiency.

Table 1 illustrates representative spatial efficiencies of conventional 3-phase lines of 145 kV through 550 kV and high phase order arrays of 6 to 12 phases. The high phase orders have several-fold increases over conventional 3-phase lines. As discussed in the report, high phase order lines are more appropriately designated by a phase-to-ground voltage than phase-to-phase; therefore, the figure lists the phase-to-ground values. While the comparisons are based on typical circuit breaker ratings, similar comparative results would be obtained based on thermal ratings. A lesser increase in efficiency above six phases is realized for surge impedance loading criteria, as discussed in the report.

Table 1
Transmission Efficiency

(Power Density--kW/ft²)³

Voltage	Conventional Design		Compact Design	High Phase Order	
	Single Circuit ³	Double Circuit ³	Single Circuit	6-Phase	12-Phase
84 ¹ 145 ²	190	190	760	1520	3040
140 ¹ 242 ²	190	190	430 ⁴	860	1720
209 ¹ 362 ²	190	190	270 ⁴	540	1080
318 ¹ 550 ²	150	150	190 ⁴	380	760

1. Phase-to-ground
2. Phase-to-phase on a 3-phase equivalent
3. Based on approximately 75 percent of a continuous breaker rating of 3000 amperes per phase and power density = power (MW)/4HW, where H = height of conductors, W = distance between outside conductors.
4. Estimated

Figure 1 illustrates conventional 3-phase 230 kV and 550 kV structures and conceptual compact higher phase order structures based on Table 1 loading. Similarly, Figure 2 compares a 1200 kV phase-to-phase 3-phase line and a conceptual 462 kV phase-to-ground 6-phase line, both capable of approximately 6000 MW surge impedance loading. The reduced sizes of the high phase order lines are quite evident.

Figure 1. Examples of Conventional and Conceptual High Phase Order Structures

Figure 2. Alternate Configurations for Approximately 6000 MW SIL

Because of the foregoing potential benefits of this mode of electric power transmission, the basic technical considerations of the concept were analyzed and reported in the 1972 CIGRE paper entitled "High Phase Order Power Transmission" by L. O. Barthold and H. C. Barnes. The results of analyses in the paper encouraged this expanded study of feasibility. The objective of this study was to investigate the broader aspects of feasibility of high phase order transmission. The investigations were primarily directed to 6-phase systems and included electrical, mechanical, economic, and equipment areas. In several of these areas, however, systems up to 24 phases were also analyzed. This study was conducted to determine feasibility -- design and analytical analysis were conducted only to the extent necessary to ascertain such feasibility or the absence thereof.

From the study results it is concluded that high phase order transmission is feasible; however, much development and testing remain to bring the technology to the stage of design and subsequent prototype application on an operating system.

1.0 SUMMARY AND CONCLUSIONS

This feasibility study investigated a broad spectrum of technical areas potentially limiting to the concept of high phase order (HPO) transmission. The results confirm the general feasibility of high phase order transmission and suggest the next phase in a program to exploit the advantages of the technology.

SUMMARY

The following is a brief summary of the results of this investigation.

Definition of System Voltage

Several system voltage definitions for high phase order are possible. Investigators of this technology concurred that system nomenclature would be defined by phase-to-ground rms voltage.

Symmetrical Components

Symmetrical components and associated matrix methods are extended to higher phase orders. For each phase order, the number of sequence components is equal to the number of phases. As with 3-phase systems, sequence interconnections are possible for representation of system unbalances, both for numerical analysis and to gain physical understanding of the phenomena involved.

Circuit Impedances

Sequence impedances and transmission line surge impedances are computed for several 6-phase lines. The effects of a circular array of shield wires surrounding a symmetrical circular array of phase conductors and also symmetrical circuits enclosed in a pipe are analyzed. For practical configurations, thermally limited loading increases in proportion to the number of phases while surge impedance loading increases approximately proportional to the number of phases up to six phases, beyond which the loading increases less rapidly.

Unbalanced Operation

An ABCD matrix formulation is used to evaluate line current unbalances and negative sequence currents in a 3-phase generator feeding a high phase order line through a transformer. Symmetrical and unsymmetrical 6-phase lines with and without transpositions were modeled. Only rotation of the total conductor array is possible since proper phase relationship must be maintained (i.e., individual conductor positions relative to each other cannot be changed). Line current unbalance and negative sequence currents in generators are comparable to those experienced on 3-phase systems.

The effects of an open phase on lines both with and without shunt reactors applied are also evaluated (e.g., for single pole switching). Voltages on the open phase and secondary arc currents are either comparable or of lesser concern than on 3-phase systems.

For faults involving ground, the maximum phase-to-ground fundamental frequency voltage possible on a high phase order system is 2.0 per unit of normal phase-to-ground voltage. This occurs on ungrounded systems of six phases or more. (This compares with 1.732 per unit for a 3-phase system.) For practical high phase order system parameters, the actual fault voltages will be significantly lower than the 2.0 per unit value, although somewhat higher than typical fault voltages on 3-phase systems.

The voltage between adjacent conductors on a 6-phase system during a phase-to-ground fault is approximately 15 percent above normal. For higher phase orders, this voltage becomes excessive and can result in cascading phase-to-phase flashovers for most configurations with minimum spacings. Therefore the entire circuit must be switched to clear faults on systems with more than six phases.

Electrical Environmental Parameters

With increasing phase order, the electric field at the conductor surface decreases and the electric field at ground level increases. Therefore, with increasing phase order, corona related effects, including audible and radio noise, improve and ground level field effects are more severe. To assess these effects, ground level fields are calculated for various voltage levels, configurations, and phase orders. For certain high phase order line designs, ground level electric field strength may be an important design parameter. Calculated data remain to be checked in an experimental program.

Switching Surges

For conventional 3-phase lines, phase-to-ground switching surges rather than phase-to-phase surges are of most importance and may dominate line design at EHV levels. For a 6-phase system, phase-to-ground levels are comparable to surges on 3-phase systems, but phase-to-phase surges assume primary importance. For systems of more than six phases, phase-to-phase switching surges are even more dominant in line design. This is illustrated by a simple calculation showing the fundamental principles and by a more complex probabilistic traveling wave analysis.

Rate of Rise of Recovery Voltage (RRRV) on Circuit Breakers

A 6-phase system may exhibit slightly greater RRRV than a 3-phase system, depending on the specific assumptions chosen for the analysis. However, the difference is not significant in the majority of practical breaker applications.

Protective Relaying

The complexity of relaying is increased at higher phase order both because of the greater number of phases to protect and because the sequence network interconnection for phase-to-phase faults is different depending on the specific pair of phases being faulted. This is particularly true for backup relaying. However, while analysis is somewhat more complex, no new relaying concepts, hardware, or application techniques are required.

Hardware and Equipment

All hardware and equipment for high phase order transmission are available without new designs or development, although there is incentive for more optimized designs directly oriented to high phase order application. At system voltages above 200 kV phase-to-ground, where air clearances become significant, gas insulated substation technology can greatly reduce the buswork complexity of high phase order.

Terminal Insulation Requirements

Insulation levels are given in terms of system voltage and phase order. The required values do not exceed those presently applied on 3-phase systems of the same phase-to-ground voltages.

Economics

Transmission line installed costs (exclusive of right-of-way) are compared for a double circuit 3-phase and a 6-phase line of the same capacity. The 6-phase line costs are approximately 17 percent less per mile than a conventional double circuit 3-phase line, or 6 percent less than a compact double circuit 3-phase line. For this example comparison, the tower height for the 6-phase line was approximately 32 percent less than the conventional 3-phase line and 26 percent less than the 3-phase compact line, resulting in a greatly reduced tower aesthetic impact.

The 3-phase substation installed cost (exclusive of land cost) was approximately 11 percent less than the 6-phase alternative. Both were configured for equivalent reliability of power transfer.

For realistic line lengths, the differential in costs for this example tend to be offsetting, and therefore the total installed costs of the 3-phase and 6-phase alternatives appear generally comparable. More detailed economic analyses are necessary; however, experimental verification of parameters required for accurate comparative designs must be obtained before such costs can be rigorously defined.

Mechanical Considerations

Detailed investigation of mechanical requirements of high phase order lines (i.e., conductor motion due to wind, ice, fault currents, etc.), including experimental verification in several areas, is necessary. Preliminary results indicate that structure, insulator, and spacer design are presently possible using existing materials and methods, although significant optimization can be anticipated through testing and development directly oriented to high phase order systems.

CONCLUSIONS

The results of this study confirm the general feasibility of high phase order transmission and the attendant potential for significant increases in power density efficiencies of rights-of-way.

The next phase in the development of this technology is one of tests and experiments to verify and extend analytical results and define the mechanical characteristics of actual high phase order structures and conductor arrays. This includes experimental verification of electric field intensities, corona performance, radio interference, audible noise, television interference, and investigation of the electrical breakdown of closely spaced conductors during impulse. Of primary importance is investigation of mechanical characteristics of high phase order structures, insulators, and conductors during motions due to wind, ice conditions, and fault currents. The mechanical aspects are particularly important as high phase order arrays may have conductors suspended from, and insulated from, other conductors at different potentials.

These investigations will establish the data necessary for preliminary line designs and allow accurate economic studies of high phase order variations and comparison with 3-phase (or other) alternatives.

Although materials and components are presently available for construction of test lines, significant innovation in several areas, particularly insulator spacers, is possible. This study did not attempt to innovate in hardware or equipment design, but rather investigated feasibility of the concept using present technology.

An experimental program, including hardware designs specifically oriented to high phase order, is necessary to fully assess the potential application of the HPO concept.

2.0 DEFINITION OF SYSTEM VOLTAGE

The standard definition of system voltages for 3-phase power systems has historically been in terms of phase-to-phase voltage with a corresponding phase-to-ground voltage of $1/\sqrt{3}$ times the phase-to-phase value.

With a change in the phase order, the relationship between phase-to-phase and phase-to-ground voltages changes, suggesting a reassessment of system voltage nomenclature definition for high phase order systems. It is necessary to clearly specify the definition of voltage used in high phase order systems, since results and comparisons between phase orders must be based on a consistent definition.

Three definitions of voltage are possible.

1. Define system voltage in terms of phase-to-phase voltage as for the 3-phase case where the phase-to-phase voltage is the voltage between adjacent phase-to-ground phasors (see Figure 2.1(A)). For a constant system voltage and a circular array of conductors physically arranged with the same angular relationship as the phasors, the size of the conductor array increases as the phase order increases since the spacing between adjacent phases must be constant. While this approach offers certain practical advantages such as comparison of single circuit 6-phase lines against double circuit 3-phase lines of the same physical dimensions, the phase-to-phase voltage is quite small with respect to the phase-to-ground voltage at the higher phase orders and can be misleading in considering line capacities, working clearances, and insulation requirements.

For example, a 12-phase system designated as 138 kV would have a phase-to-ground voltage of 267 kV, and a 24-phase system so designated would have a phase-to-ground voltage of 529 kV.

2. Define system voltage in terms of phase-to-ground voltage (see Figure 2.1(B)). For the 6-phase case, phase-to-phase and phase-to-ground voltages are the same in magnitude. For higher than six phases, phase-to-ground voltage is higher than phase-to-phase voltage, and the phase-to-ground voltage nomenclature

more clearly reflects both the power handling capacity of the line and insulation level of the line and terminal equipment. However, comparison with conventional 3-phase is somewhat more obscure for this definition.

A. Example of Definition 1
(Constant $V_{\phi-\phi}$ with Phase Order)

B. Example of Definition 2
(Constant $V_{\phi-G}$ (Circle Radius) with Phase Order)

Figure 2.1. High Phase Order Voltages

3. Define system voltage in terms of equivalent 3-phase voltage; i.e., voltage phase-to-ground $\times \sqrt{3}$ (see Figure 2.1(C)). This approach has two advantages: it simplifies comparison with existing 3-phase technology and is in terms more familiar to utility industry engineers. The disadvantage is the loss of significance relative to spacings and insulation requirements, particularly beyond six phases.

Note: $V_{\phi-\phi}$ is a 3-phase system designation and therefore neither $V_{\phi-\phi}$ nor $V_{\phi-G}$ changes with phase order.

C. Example of Definition 3
(Equivalent 3-Phase Voltage)

Figure 2.1. High Phase Order Voltages
System Voltage Nomenclature

System voltage will be given in terms of phase-to-ground voltage (definition 2) in this report. This definition is most appropriate for comparison of parameters for different phase order systems occupying the same physical space, which is a good basis for comparison, while also specifying a voltage which reasonably defines system insulation requirements.

3.0 FUNDAMENTAL FREQUENCY SYSTEM PARAMETERS

The foundation for feasibility analysis of high phase order technology must be based on fundamental frequency (i.e., 60 Hz) operation. This section illustrates the practicality of extension of symmetrical component theory to higher phase orders, and the use of both symmetrical components and phase quantities to illustrate the effects of unbalanced system operation. The conditions of unbalance include: steady-state operation with unequal line impedance due to nontransposition; system faults; and open conductors. The latter can prove particularly appropriate to high phase order lines because of the high percentage of normal power which could be transmitted with one conductor out of service. This, in turn, suggests single phase switching as an attractive alternative to switching all phases simultaneously. Because of the single phase switching option, the question of secondary arc current is also examined.

Symmetrical Components

Three-phase symmetrical components transform a 3-phase network into three single phase networks which are defined in terms of balanced systems of voltages and currents. The three sequences are traditionally defined in terms of:

1. A positive sequence component of three phasors of equal magnitude spaced 120 degrees.
2. A negative sequence component which is the same as the positive sequence except for opposite sense of rotation.
3. A zero sequence component which is identical on all three phases.

An alternative definition of 3-phase symmetrical components is:

1. A positive sequence component of three phasors of equal magnitude spaced 120 degrees (same as the conventional definition).
2. A negative sequence component of three phasors of equal magnitude spaced 240 degrees and having the same sense of rotation as the positive sequence.
3. A zero sequence component of three phasors of equal magnitude spaced 360 degrees and having the same sense of rotation as the positive sequence.

The second definition describes the identical sequence voltages and currents as the more common definition. The negative sequence has the same identical three distinct phasors, and the zero sequence has the same identical single phasor in both cases. This redefinition, however, allows ease in transition of symmetrical components to higher phase orders.

Six phase symmetrical components have been described by Clarke and others.^(3-1,3-2) These are shown in Figure 3.1 and can be summarized as follows:

- ①. A positive sequence component of six phasors of equal magnitude spaced 60 degrees.
- ②. A second sequence component of six phasors of equal magnitude spaced 120 degrees. These reduce to three distinct phasors, each representing two phases; i.e., this can be visualized as traversing the circle of phasors twice. The second sequence is equivalent to defining two 3-phase circuits from the six conductors arranged a b c a b c as the circle is traversed.
- ③. A third sequence component of six phasors of equal magnitude spaced 180 degrees. These reduce to two distinct phasors, each representing three phases; i.e., this can be visualized as traversing the circle of phasors three times. The third sequence is equivalent to defining three single phase circuits from the six conductors.
- ④. A fourth sequence component of six phasors of equal magnitude spaced 240 degrees. This is identical to the second sequence with the opposite sense of rotation.
- ⑤. A fifth (or negative) sequence component of six phasors of equal magnitude spaced 300 degrees. This is identical to the first (positive) sequence with the opposite sense of rotation.
- ⑥. A sixth (or zero) sequence component of six phasors of equal magnitude spaced 360 degrees. This reduces to one distinct phasor and is identical in concept to zero sequence in conventional 3-phase components.

Figure 3.1. 6-Phase Symmetrical Components

The transition to increasingly higher phase orders follows the same pattern. For an N phase system a set of N phasors of equal magnitude spaced $360/N$ degrees is chosen for the first (positive) sequence. The second sequence is defined from phasors spaced $2 \times 360/N$ degrees. The m 'th sequence is defined from phasors spaced $m \times 360/N$ degrees. The process continues through N sequences, whereafter no additional sequences are created, already existing ones merely being rediscovered. As illustrated by the second, third, fourth, and sixth components of the 6-phase case, many of the sequences contain redundant phasors which are eliminated to give the final set of components.

Applying the foregoing to a 12-phase system results in the set of components as shown in Figure 3.2:

- ①. (Positive sequence) 12 phasors equally spaced 30 degrees.
- ②. Six phasors equally spaced 60 degrees (each representing two phases, equivalent to two 6-phase circuits).
- ③. Four phasors equally spaced 90 degrees (each representing three phases, equivalent to three 4-phase circuits).
- ④. Three phasors equally spaced 120 degrees (each representing four phases, equivalent to four 3-phase circuits).
- ⑤. With 12 phasors each equally spaced 150 degrees, the sequence retains 12 unique phasors but in the following order: 0, 210, 60, 270, 120, 330, 180, 30, 240, 90, 300, 150 degrees.
- ⑥. Two phasors equally spaced 180 degrees (each representing six phases, equivalent to six single phase circuits).
- ⑦. Fifth sequence in the opposite sense of rotation.
- ⑧. Fourth sequence in the opposite sense of rotation.
- ⑨. Third sequence in the opposite sense of rotation.
- ⑩. Second sequence in the opposite sense of rotation.
- ⑪. (Negative sequence) First sequence in the opposite sense of rotation.
- ⑫. (Zero sequence) Identical voltage on all phases.

Figure 3.2. 12-Phase Symmetrical Components

From the above definition, the phase-to-sequence and sequence-to-phase transform matrices can be derived by inspection and used to determine the sequence components of a transmission line. For example, the 12-phase transformation matrices are shown in Figure 3.3.

$$[V_P] = \begin{matrix} & \begin{matrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 \end{matrix} \\ \begin{matrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \end{matrix} & \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & c^{11} & c^{10} & c^9 & c^8 & c^7 & c^6 & c^5 & c^4 & c^3 & c^2 & c^1 \\ 1 & c^{10} & c^8 & c^6 & c^4 & c^2 & 1 & c^{10} & c^8 & c^6 & c^4 & c^2 \\ 1 & c^9 & c^6 & c^3 & 1 & c^9 & c^6 & c^3 & 1 & c^9 & c^6 & c^3 \\ 1 & c^8 & c^4 & 1 & c^8 & c^4 & 1 & c^8 & c^4 & 1 & c^8 & c^4 \\ 1 & c^7 & c^2 & c^9 & c^4 & c^{11} & c^6 & c^1 & c^8 & c^3 & c^{10} & c^5 \\ 1 & c^6 & 1 & c^6 & 1 & c^6 & 1 & c^6 & 1 & c^6 & 1 & c^6 \\ 1 & c^5 & c^{10} & c^3 & c^8 & c^1 & c^6 & c^{11} & c^4 & c^9 & c^2 & c^7 \\ 1 & c^4 & c^8 & 1 & c^4 & c^8 & 1 & c^4 & c^8 & 1 & c^4 & c^8 \\ 1 & c^3 & c^6 & c^9 & 1 & c^3 & c^6 & c^9 & 1 & c^3 & c^6 & c^9 \\ 1 & c^2 & c^4 & c^6 & c^8 & c^{10} & 1 & c^2 & c^4 & c^6 & c^8 & c^{10} \\ 1 & c^1 & c^2 & c^3 & c^4 & c^5 & c^6 & c^7 & c^8 & c^9 & c^{10} & c^{11} \end{bmatrix} \end{matrix} [V_S]$$

$$[V_S] = \frac{1}{12} \begin{matrix} & \begin{matrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{matrix} \\ \begin{matrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{matrix} & \begin{bmatrix} 1 & c^1 & c^2 & c^3 & c^4 & c^5 & c^6 & c^7 & c^8 & c^9 & c^{10} & c^{11} \\ 1 & c^2 & c^4 & c^6 & c^8 & c^{10} & 1 & c^2 & c^4 & c^6 & c^8 & c^{10} \\ 1 & c^3 & c^6 & c^9 & 1 & c^3 & c^6 & c^9 & 1 & c^3 & c^6 & c^9 \\ 1 & c^4 & c^8 & 1 & c^4 & c^8 & 1 & c^4 & c^8 & 1 & c^4 & c^8 \\ 1 & c^5 & c^{10} & c^3 & c^8 & c^1 & c^6 & c^{11} & c^4 & c^9 & c^2 & c^7 \\ 1 & c^6 & 1 & c^6 & 1 & c^6 & 1 & c^6 & 1 & c^6 & 1 & c^6 \\ 1 & c^7 & c^2 & c^9 & c^4 & c^{11} & c^6 & c^1 & c^8 & c^3 & c^{10} & c^5 \\ 1 & c^8 & c^4 & 1 & c^8 & c^4 & 1 & c^8 & c^4 & 1 & c^8 & c^4 \\ 1 & c^9 & c^6 & c^3 & 1 & c^9 & c^6 & c^3 & 1 & c^9 & c^6 & c^3 \\ 1 & c^{10} & c^8 & c^6 & c^4 & c^2 & 1 & c^{10} & c^8 & c^6 & c^4 & c^2 \\ 1 & c^{11} & c^{10} & c^9 & c^8 & c^7 & c^6 & c^5 & c^4 & c^3 & c^2 & c^1 \end{bmatrix} \end{matrix} [V_P]$$

$$c = 1 \angle 30^\circ$$

Figure 3.3. 12-Phase Transformation Matrix

Figure 3.4 illustrates the phase impedance matrix of a 12-conductor circular array. Applying a similarity transformation using the given matrices gives the 12-phase sequence impedance matrix of Figure 3.5.

	1 7	2 8	3 9	4 10	5 11	6 12	
1	.2215E+06						
2	.1171E+06	.2217E+06					
3	.9720E+05	.1165E+06	.2204E+06				
4	.8639E+05	.9648E+05	.1156E+06	.2192E+06			
5	.7980E+05	.8562E+05	.9548E+05	.1144E+06	.2180E+06		
6	.7612E+05	.7918E+05	.8476E+05	.9443E+05	.1133E+06	.2171E+06	
7	.7494E+05	.7580E+05	.7861E+05	.8403E+05	.9365E+05	.1127E+06	
8	.7412E+05	.7494E+05	.7556E+05	.7821E+05	.8358E+05	.9338E+05	
9	.7380E+05	.7442E+05	.7499E+05	.7544E+05	.7805E+05	.8358E+05	
10	.7365E+05	.7433E+05	.7480E+05	.7503E+05	.7544E+05	.7821E+05	
11	.7359E+05	.7425E+05	.7462E+05	.7503E+05	.7544E+05	.7821E+05	
12	.7350E+05	.7417E+05	.7448E+05	.7503E+05	.7544E+05	.7821E+05	
13	.7340E+05	.7408E+05	.7439E+05	.7503E+05	.7544E+05	.7821E+05	
14	.7330E+05	.7400E+05	.7430E+05	.7503E+05	.7544E+05	.7821E+05	
15	.7320E+05	.7391E+05	.7421E+05	.7503E+05	.7544E+05	.7821E+05	
16	.7310E+05	.7382E+05	.7412E+05	.7503E+05	.7544E+05	.7821E+05	
17	.7300E+05	.7373E+05	.7403E+05	.7503E+05	.7544E+05	.7821E+05	
18	.7290E+05	.7364E+05	.7394E+05	.7503E+05	.7544E+05	.7821E+05	
19	.7280E+05	.7355E+05	.7385E+05	.7503E+05	.7544E+05	.7821E+05	
20	.7270E+05	.7346E+05	.7376E+05	.7503E+05	.7544E+05	.7821E+05	
21	.7260E+05	.7337E+05	.7367E+05	.7503E+05	.7544E+05	.7821E+05	
22	.7250E+05	.7328E+05	.7358E+05	.7503E+05	.7544E+05	.7821E+05	
23	.7240E+05	.7319E+05	.7349E+05	.7503E+05	.7544E+05	.7821E+05	
24	.7230E+05	.7310E+05	.7340E+05	.7503E+05	.7544E+05	.7821E+05	
25	.7220E+05	.7301E+05	.7331E+05	.7503E+05	.7544E+05	.7821E+05	
26	.7210E+05	.7292E+05	.7322E+05	.7503E+05	.7544E+05	.7821E+05	
27	.7200E+05	.7283E+05	.7313E+05	.7503E+05	.7544E+05	.7821E+05	
28	.7190E+05	.7274E+05	.7304E+05	.7503E+05	.7544E+05	.7821E+05	
29	.7180E+05	.7265E+05	.7295E+05	.7503E+05	.7544E+05	.7821E+05	
30	.7170E+05	.7256E+05	.7286E+05	.7503E+05	.7544E+05	.7821E+05	
31	.7160E+05	.7247E+05	.7277E+05	.7503E+05	.7544E+05	.7821E+05	
32	.7150E+05	.7238E+05	.7268E+05	.7503E+05	.7544E+05	.7821E+05	
33	.7140E+05	.7229E+05	.7259E+05	.7503E+05	.7544E+05	.7821E+05	
34	.7130E+05	.7220E+05	.7250E+05	.7503E+05	.7544E+05	.7821E+05	
35	.7120E+05	.7211E+05	.7241E+05	.7503E+05	.7544E+05	.7821E+05	
36	.7110E+05	.7202E+05	.7232E+05	.7503E+05	.7544E+05	.7821E+05	
37	.7100E+05	.7193E+05	.7223E+05	.7503E+05	.7544E+05	.7821E+05	
38	.7090E+05	.7184E+05	.7214E+05	.7503E+05	.7544E+05	.7821E+05	
39	.7080E+05	.7175E+05	.7205E+05	.7503E+05	.7544E+05	.7821E+05	
40	.7070E+05	.7166E+05	.7196E+05	.7503E+05	.7544E+05	.7821E+05	
41	.7060E+05	.7157E+05	.7187E+05	.7503E+05	.7544E+05	.7821E+05	
42	.7050E+05	.7148E+05	.7178E+05	.7503E+05	.7544E+05	.7821E+05	
43	.7040E+05	.7139E+05	.7169E+05	.7503E+05	.7544E+05	.7821E+05	
44	.7030E+05	.7130E+05	.7160E+05	.7503E+05	.7544E+05	.7821E+05	
45	.7020E+05	.7121E+05	.7151E+05	.7503E+05	.7544E+05	.7821E+05	
46	.7010E+05	.7112E+05	.7142E+05	.7503E+05	.7544E+05	.7821E+05	
47	.7000E+05	.7103E+05	.7133E+05	.7503E+05	.7544E+05	.7821E+05	
48	.6990E+05	.7094E+05	.7124E+05	.7503E+05	.7544E+05	.7821E+05	
49	.6980E+05	.7085E+05	.7115E+05	.7503E+05	.7544E+05	.7821E+05	
50	.6970E+05	.7076E+05	.7106E+05	.7503E+05	.7544E+05	.7821E+05	
51	.6960E+05	.7067E+05	.7097E+05	.7503E+05	.7544E+05	.7821E+05	
52	.6950E+05	.7058E+05	.7088E+05	.7503E+05	.7544E+05	.7821E+05	
53	.6940E+05	.7049E+05	.7079E+05	.7503E+05	.7544E+05	.7821E+05	
54	.6930E+05	.7040E+05	.7070E+05	.7503E+05	.7544E+05	.7821E+05	
55	.6920E+05	.7031E+05	.7061E+05	.7503E+05	.7544E+05	.7821E+05	
56	.6910E+05	.7022E+05	.7052E+05	.7503E+05	.7544E+05	.7821E+05	
57	.6900E+05	.7013E+05	.7043E+05	.7503E+05	.7544E+05	.7821E+05	
58	.6890E+05	.7004E+05	.7034E+05	.7503E+05	.7544E+05	.7821E+05	
59	.6880E+05	.6995E+05	.7025E+05	.7503E+05	.7544E+05	.7821E+05	
60	.6870E+05	.6986E+05	.7016E+05	.7503E+05	.7544E+05	.7821E+05	
61	.6860E+05	.6977E+05	.7007E+05	.7503E+05	.7544E+05	.7821E+05	
62	.6850E+05	.6968E+05	.6998E+05	.7503E+05	.7544E+05	.7821E+05	
63	.6840E+05	.6959E+05	.6989E+05	.7503E+05	.7544E+05	.7821E+05	
64	.6830E+05	.6950E+05	.6980E+05	.7503E+05	.7544E+05	.7821E+05	
65	.6820E+05	.6941E+05	.6971E+05	.7503E+05	.7544E+05	.7821E+05	
66	.6810E+05	.6932E+05	.6962E+05	.7503E+05	.7544E+05	.7821E+05	
67	.6800E+05	.6923E+05	.6953E+05	.7503E+05	.7544E+05	.7821E+05	
68	.6790E+05	.6914E+05	.6944E+05	.7503E+05	.7544E+05	.7821E+05	
69	.6780E+05	.6905E+05	.6935E+05	.7503E+05	.7544E+05	.7821E+05	
70	.6770E+05	.6896E+05	.6926E+05	.7503E+05	.7544E+05	.7821E+05	
71	.6760E+05	.6887E+05	.6917E+05	.7503E+05	.7544E+05	.7821E+05	
72	.6750E+05	.6878E+05	.6908E+05	.7503E+05	.7544E+05	.7821E+05	
73	.6740E+05	.6869E+05	.6899E+05	.7503E+05	.7544E+05	.7821E+05	
74	.6730E+05	.6860E+05	.6890E+05	.7503E+05	.7544E+05	.7821E+05	
75	.6720E+05	.6851E+05	.6881E+05	.7503E+05	.7544E+05	.7821E+05	
76	.6710E+05	.6842E+05	.6872E+05	.7503E+05	.7544E+05	.7821E+05	
77	.6700E+05	.6833E+05	.6863E+05	.7503E+05	.7544E+05	.7821E+05	
78	.6690E+05	.6824E+05	.6854E+05	.7503E+05	.7544E+05	.7821E+05	
79	.6680E+05	.6815E+05	.6845E+05	.7503E+05	.7544E+05	.7821E+05	
80	.6670E+05	.6806E+05	.6836E+05	.7503E+05	.7544E+05	.7821E+05	
81	.6660E+05	.6797E+05	.6827E+05	.7503E+05	.7544E+05	.7821E+05	
82	.6650E+05	.6788E+05	.6818E+05	.7503E+05	.7544E+05	.7821E+05	
83	.6640E+05	.6779E+05	.6809E+05	.7503E+05	.7544E+05	.7821E+05	
84	.6630E+05	.6770E+05	.6800E+05	.7503E+05	.7544E+05	.7821E+05	
85	.6620E+05	.6761E+05	.6791E+05	.7503E+05	.7544E+05	.7821E+05	
86	.6610E+05	.6752E+05	.6782E+05	.7503E+05	.7544E+05	.7821E+05	
87	.6600E+05	.6743E+05	.6773E+05	.7503E+05	.7544E+05	.7821E+05	
88	.6590E+05	.6734E+05	.6764E+05	.7503E+05	.7544E+05	.7821E+05	
89	.6580E+05	.6725E+05	.6755E+05	.7503E+05	.7544E+05	.7821E+05	
90	.6570E+05	.6716E+05	.6746E+05	.7503E+05	.7544E+05	.7821E+05	
91	.6560E+05	.6707E+05	.6737E+05	.7503E+05	.7544E+05	.7821E+05	
92	.6550E+05	.6698E+05	.6728E+05	.7503E+05	.7544E+05	.7821E+05	
93	.6540E+05	.6689E+05	.6719E+05	.7503E+05	.7544E+05	.7821E+05	
94	.6530E+05	.6680E+05	.6710E+05	.7503E+05	.7544E+05	.7821E+05	
95	.6520E+05	.6671E+05	.6701E+05	.7503E+05	.7544E+05	.7821E+05	
96	.6510E+05	.6662E+05	.6692E+05	.7503E+05	.7544E+05	.7821E+05	
97	.6500E+05	.6653E+05	.6683E+05	.7503E+05	.7544E+05	.7821E+05	
98	.6490E+05	.6644E+05	.6674E+05	.7503E+05	.7544E+05	.7821E+05	
99	.6480E+05	.6635E+05	.6665E+05	.7503E+05	.7544E+05	.7821E+05	
100	.6470E+05	.6626E+05	.6656E+05	.7503E+05	.7544E+05	.7821E+05	
101	.6460E+05	.6617E+05	.6647E+05	.7503E+05	.7544E+05	.7821E+05	
102	.6450E+05	.6608E+05	.6638E+05	.7503E+05	.7544E+05	.7821E+05	
103	.6440E+05	.6599E+05	.6629E+05	.7503E+05	.7544E+05	.7821E+05	
104	.6430E+05	.6590E+05	.6620E+05	.7503E+05	.7544E+05	.7821E+05	
105	.6420E+05	.6581E+05	.6611E+05	.7503E+05	.7544E+05	.7821E+05	
106	.6410E+05	.6572E+05	.6602E+05	.7503E+05	.7544E+05	.7821E+05	
107	.6400E+05	.6563E+05	.6593E+05	.7503E+05	.7544E+05	.7821E+05	
108	.6390E+05	.6554E+05	.6584E+05	.7503E+05	.7544E+05	.7821E+05	
109	.6380E+05	.6545E+05	.6575E+05	.7503E+05	.7544E+05	.7821E+05	
110	.6370E+05	.6536E+05	.6566E+05	.7503E+05	.7544E+05	.7821E+05	
111	.6360E+05	.6527E+05	.6557E+05	.7503E+05	.7544E+05	.7821E+05	
112	.6350E+05	.6518E+05	.6548E+05	.7503E+05	.7544E+05	.7821E+05	
113	.6340E+05	.6509E+05	.6539E+05	.7503E+05	.7544E+05	.7821E+05	
114	.6330E+05	.6500E+05	.6530E+05	.7503E+05	.7544E+05	.7821E+05	
115	.6320E+05	.6491E+05	.6521E+05	.7503E+05	.7544E+05	.7821E+05	
116	.6310E+05	.6482E+05	.6512E+05	.7503E+05	.7544E+05	.7821E+05	
117	.6300E+05	.6473E+05	.6503E+05	.7503E+05	.7544E+05	.7821E+05	
118	.6290E+05	.6464E+05	.6494E+05	.7503E+05	.7544E+05	.7821E+05	
119	.6280E+05	.6455E+05	.6485E+05	.7503E+05	.7544E+05	.7821E+05	
120	.6270E+05	.6446E+05	.6476E+05	.7503E+05	.7544E+05	.7821E+05	
121	.6260E+05	.6437E+05	.6467E+05	.7503E+05	.7544E+05	.7821E+05	
122	.6250E+05	.6428E+05	.6458E+05	.7503E+05	.7544E+05	.7821E+05	
123	.6240E+05	.6419E+05	.6449E+05	.7503E+05	.7544E+05	.7821E+05	
124	.6230E+05	.6410E+05	.6440E+05	.7503E+05	.7544E+05	.7821E+05	
125	.6220E+05	.6401E+05	.6431E+05	.7503E+05	.7544E+05	.7821E+05	
126	.6210E+05	.6392E+05	.6422E+05	.7503E+05	.7544E+05	.7821E+05	
127	.6200E+05	.6383E+05	.6413E+05	.7503E+05	.7544E+05	.7821E+05	
128	.6190E+05	.6374E+05	.6404E+05	.7503E+05	.7544E+05	.7821E+05	
129	.6180E+05	.6365E+05	.6395E+05	.7503E+05	.7544E+05	.7821E+05	
130	.6170E+05	.6356E+05	.6386E+05	.7503E+05	.7544E+05	.7821E+05	
131	.6160E+05	.6347E+05	.6377E+05	.7503E+05			

The off-diagonal terms of the symmetrical component matrix of Figure 3.5 are low, as would be expected from a transformation which diagonalizes the matrix for a perfectly transposed transmission line. For a 3-phase line, the positive and negative sequence impedances are equal as there is nothing in the line to physically distinguish between the two different phase rotations. For a 12-phase line, the distinct sequence impedances are 0, 1, 2, 3, 4, 5, and 6. Eleven, 10, 9, 8, and 7 duplicate 1, 2, 3, 4, and 5 respectively, for the same reason as for the 3-phase line.

From the sequence impedance matrix, it can also be seen that:

$$Z_0 > Z_1 > Z_2 > Z_3 > Z_4 > Z_5 > Z_6$$

The generality of this relationship can be more easily illustrated for a 6-phase example. For illustration, (Figure 3.6), assume: 1) mutual impedances between adjacent conductors are 10 percent of the self impedance, 2) mutual impedances between all other conductors are zero, and 3) a balanced sequence current is applied to the line. For the first and fifth sequence currents, there is a 60 degree angle between adjacent phases. The total voltage drop due to the self and mutual impedances add to give a voltage drop larger than that due to the self term alone. For the second and fourth sequence currents, there is 120 degrees between adjacent phases, as there would be for two 3-phase circuits. Adding the voltage drop gives a drop smaller than that due to the self term alone and thus smaller than the drop in the positive sequence network. For the third sequence current, there is 180 degrees between adjacent phases, as there would be for three single phase circuits. Adding the out-of-phase component gives a drop smaller than the second sequence. Likewise for the in-phase zero sequence currents the voltage drops add to give the largest impedance of all the sequences.

Figure 3.6. 6-Phase Sequence Impedances

While simplified, this analysis illustrates:

1. Six-phase positive sequence line impedance is greater than the per circuit impedance of two 3-phase circuits.
2. For a 6-phase line, $Z_1 > Z_2 > Z_3$.
3. Z_2 approximates the 3-phase positive sequence impedance per circuit.

Caution must be exercised when selecting the proper impedances for comparing characteristics of various phase orders. For some purposes, the correct impedance when comparing 6-phase against two 3-phase circuits is the impedance per circuit; at other times the parallel combination is proper. For example, assuming voltages V_S and V_R are phase-to-ground voltages at the sending end and receiving ends of the line respectively, the power transfers are:

$$\text{One, 3-phase circuit: } P_{1-2} = \frac{3|V_S||V_R| \sin \delta}{X_1}$$

where X_1 is the positive sequence line reactance of the circuit

$$\text{Two, 3-phase circuits: } P_{1-2} = \frac{6|V_S||V_R| \sin \delta}{X_1}$$

where X_1 is the positive sequence line reactance of one 3-phase circuit

$$\text{One, 6-phase circuit: } P_{1-2} = \frac{6|V_S||V_R| \sin \delta}{X_1}$$

where X_1 is the positive sequence line reactance of the 6-phase circuit.

Therefore, for comparisons of load transfer (or stability) of the various alternatives, per circuit positive sequence impedances are applicable. In the section on Unbalanced Operation, those impedances applicable for other areas of comparative analysis are discussed.

Certain characteristics of sequence impedances can be visualized by multiplying the phase impedance matrix by a unity current of the desired sequence and observing the resultant voltages. For the zero sequence, where the current is unity at an angle of zero for all the phases, the resultant voltage is the sum

of the phase impedances for an entire row of the phase impedance matrix. By using this simple approach, it can be seen that the zero sequence impedance increases with phase order. The effect of this increase will also be discussed in the section on Unbalanced Operation.

For the high phase orders, as with 3-phase systems, sequence networks can be interconnected to represent unsymmetrical faults. As shown in Figure 3.7, the interconnection of the networks for a single phase-to-ground fault on a 6-phase system is a series circuit of all six sequence networks. This is analogous to the 3-phase case. Other interconnections are derived and discussed in the section on Protective Relaying.

Figure 3.7. Single Phase-to-Ground Fault on 6-Phase System

Transmission Line Impedances

A basic index of power transfer capability of a transmission line is the positive sequence surge impedance. This parameter was investigated for a 6-phase line for several variations in number and location of shield wires as well as location of conductors. For selected configurations, the series impedance was also examined since, particularly at lower voltages, voltage regulation can dictate loading limits. The series impedance matrix also indicates the degree of unbalance for various line configurations.

Nine specific configurations for a 6-phase, 80 kV phase-to-ground transmission line with a minimum conductor height of 35 feet above ground were selected for this analysis.

Configurations I through IV, shown on Figure 3.8, consist of a compact circular array of conductors with a spacing of $\sqrt{3}$ feet between adjacent phase conductors. This was based on a minimum phase-to-phase spacing of 3 feet for compact 138 kV 3-phase lines as determined from a recently completed EPRI project (RP 260-1). The phase-to-phase voltage between adjacent phases for a 3-phase line is $\sqrt{3}$ times the voltage between adjacent phases for a 6-phase line. Therefore, if 3-foot phase spacing is minimum for a 3-phase line, a possible minimum of $3'/\sqrt{3} = \sqrt{3}'$ is suggested for a 6-phase line. Although this is likely less than practical minimum spacing because of conductor motions due to wind, fault currents, or ice loading, it does represent a lower limit for comparison of impedances. Configuration I considers the 6-phase circular array with no ground wires; for Configuration II six shield wires are added radially outboard at $\sqrt{3}$ feet from the phase conductors; Configurations III and IV also have six shield wires, the shield wires located radially midway between the phase conductors with distances of 1.94 and $\sqrt{3}$ feet respectively between the shield wire and two nearest phase conductors.

Figure 3.8. 6-Phase Lines
 ($\sqrt{3}$ ft Phase Spacing)

For Configurations V through VII, shown on Figure 3.9, the conductor circle is increased to 3 feet between adjacent phase conductors, a more likely minimum from mechanical constraints. Configuration V has no shield wires; Configuration VI has six shield wires, 3 feet radially outboard from the phase conductors; Configuration VII retains only the two lowest shield wires of Configuration VI. Addition of shield wires outboard from the phase conductors has several effects, including reduction of electric fields at ground level and possible reduction of series reactance and surge impedance. As the number of shield wires is increased, the configuration approximates a 6-phase circuit in a conducting pipe, a possible alternative to better utilize the space within a gas-insulated enclosure.

Figure 3.9. 6-Phase Lines
(3-ft Phase Spacing)

Configurations VIII and IX, shown in Figure 3.10, are rectangular arrays of six conductors to illustrate the effects of unsymmetrical conductor configurations. Configuration VIII is a horizontal array of three conductors above three identical conductors. Configuration IX has three conductors vertically beside three others and is physically similar to present double circuit 3-phase lines. No shield wires are considered for these arrays.

Figure 3.10. 6-Phase Lines
Rectangular Arrays

The positive sequence surge impedances and SIL's for Configurations I-IX are given in Table 3.1. The impedances vary over a range of 284 ohms to 331 ohms, or approximately 15 percent. For comparison, a compact 138 kV double circuit line would have dimensions approaching Configuration V and a per circuit surge impedance of 268 ohms. SIL for a double circuit is 143 MW.

Table 3.1

6-Phase Lines

System Voltage: 80 kV Phase-to-Ground

<u>Conductor Arrangement</u>	<u>Configuration</u>	<u>Surge Impedance (ohms)</u>	<u>SIL (MW)</u>
Circular Array $\sqrt{3}$ ' phase-phase	I	298	128
	II	287	133
	III	284	134
	IV	286	133
Circular Array 3' phase-phase	V	331	115
	VI	321	119
	VII	329	116
Rectangular Array 3' phase-phase	VIII	316	121
	IX	316	121

Figures 3.11 and 3.12 summarize the effect on surge impedance of increasing the number of ground wires beyond six for 3-foot phase spacing and shield wires spaced radially from the conductors. An infinite number of shield wires (line enclosed in a pipe) results in an 8.4 percent reduction in surge impedance when compared to no shield wires. While the surge impedance reduction is not major, the reduction in ground level electric field can be significant (see Section 5).

Figure 3.11. Positive Sequence Surge Impedance as a Function of Number of Shield Wires

Figure 3.12. Positive Sequence Surge Impedance as a Function of Number of Shield Wires

The foregoing results indicate that variation in conductor and ground wire array dimensions for a 6-phase line do not significantly alter the positive sequence surge impedance characteristics.

A summary of the individual sequence impedance elements for Configurations V, VI, and VII is shown in Table 3.2. The corresponding sequence surge impedances can be calculated from this table if desired. This table also confirms the observation that the zero sequence series reactance is largest, followed by the first, second, and third, in descending order. The addition of shield wires (Configurations VI and VII) reduces the zero sequence reactance but increases the zero sequence resistances. Very small effect is noted on the other five sequence impedances.

Table 3.2
6-Phase Lines
Sequence Impedances

<u>Configuration</u>	<u>Sequence</u>	<u>R Ω/mi</u>	<u>X_L Ω/mi</u>	<u>X_C mΩ-mi</u>
V	0	.670	5.31	.643
	1	.114	.683	.160
	2	.114	.515	.119
	3	.114	.483	.112
	4	.114	.515	.119
	5	.114	.683	.160
VI	0	1.74	3.65	.290
	1	.118	.682	.151
	2	.114	.515	.119
	3	.114	.483	.111
	4	.114	.515	.119
	5	.118	.682	.151
VII	0	1.24	4.73	.443
	1	.115	.683	.158
	2	.114	.515	.119
	3	.114	.483	.112
	4	.114	.515	.119
	5	.115	.683	.158

Table 3.3 illustrates the complete 6 x 6 series sequence impedance matrix for the line of Configuration V. Due to the symmetry of the circular array, the off-diagonal terms are small. This matrix also indicates that the mutual coupling between the closely spaced phase conductors dominates over the effects of ground. From the data in this table, for a circular compact array, unbalances due to ground are expected to be small.

Table 3.3
Sequence Impedance Matrix--Configuration V
(R + jX)

	0		1		2		3		4		5	
0	.66966	5.30747	-.00054	.00029	-.00011	.00007	.00000	.00000	.00012	.00006	-.00002	.00061
1	-.00002	.00061	.11406	.68347	-.00010	.00014	-.00012	.00007	.00000	-.00000	.00011	-.00038
2	.00012	.00006	.00008	.00016	.11408	.51515	-.00010	.00014	-.00029	-.00027	.00000	-.00000
3	.00000	.00000	.00012	.00007	.00008	.00016	.11399	.48307	-.00010	.00014	-.00012	.00007
4	-.00011	.00007	.00000	-.00000	.00012	-.00026	.00008	.00016	.11408	.51515	-.00010	.00014
5	-.00054	.00029	-.00029	-.00040	.00000	-.00000	.00012	.00007	.00008	.00016	.11406	.68347

Figure 3.13 shows the effect of increasing phase order on circuit loading. As the phase order increases, the effect of the mutual coupling between phases results in progressively smaller increments in surge impedance loading.

Figure 3.13. Power Density as a Function of Phase Order

Thermal loading does increase linearly with phase order; and therefore, lines of phase order higher than six would likely be justified by thermal rather than surge impedance loading criteria.

To further explore the effect of high phase order systems enclosed in a pipe, such as an SF_6 or air insulated system, the number of phases within the pipe was varied. The results for a 3-foot circular array are shown in Figure 3.14 for a $\sqrt{3}$ -foot clearance between conductors and pipe, and Figure 3.15 for approximately 0.5 inches between conductors and pipe. The latter is primarily to illustrate the effect of very high conductor gradient on surge impedance, although it is conceivable that SF_6 systems approaching this dimension might be possible.

The results of Figures 3.14 and 3.15 were analyzed by Attwood's calculation for a pair of eccentric cylinders (3-3). From Attwood's work, potential coefficients can be determined, and surge impedance and SIL can then be calculated.

Figure 3.14. High Phase Order Pipe System

Figure 3.15. High Phase Order Pipe System

For a pipe $\sqrt{3}$ -feet from the phase conductors, a pronounced saturation in surge impedance with phase order is observed. The saturation occurs at a slightly higher phase order than for the same conductor array in air. For conductors very close to a pipe, the saturation occurs at much higher phase orders, beginning in the vicinity of 40 phases with only moderate saturation as high as 120 phases.

This indicates that, for SIL increases with phase order similar to thermal increases, a high phase order line in a pipe must be more sophisticated than simple air insulation, with some form of high dielectric required such as SF_6 .

Unbalanced Operation

Line Unbalance and Negative Sequence Currents: For computation of line unbalance, a complete phase impedance description of the line is necessary to properly represent the mutual coupling effects since this coupling has a marked influence on closely spaced lines. The PTI computer program entitled "Couple" uses a sequence of ABCD matrices to build a system for unbalanced conditions.

For investigation of steady state line unbalances, a generator is represented as a voltage behind a synchronous impedance, feeding a generator step-up transformer, a 3- to 6-phase transformer, a line section, and a system equivalent (voltage behind impedance) as illustrated in Figure 3.16.

Figure 3.16. Example System for Unbalance Analysis

Although the generator step-up transformer could also transform to 6-phase, the more general case would include a double transformation as in Figure 3.16 since there would normally be a 3-phase bus at the high side of the generator step-up. For the system represented, however, the only difference between the two variations is the addition of a balanced impedance in all sequences due to the 3- to 6-phase transformer.

For each configuration, the array was initially analyzed as a double circuit 3-phase line for comparison with the 6-phase results. Table 3.4 summarizes the results including a single 3-phase line.

Table 3.4
Negative Sequence Currents in Generator
Line Current Unbalance

80 kV phase-ground
80-mile line
2 x SIL
All phases energized

Description	Configu- ration	Phase Order	% Negative Sequence Generator Current		% Line Current Unbalance	
			No Transpo- sition	Full Transpo- sition	No Transpo- sition	Full Transpo- sition
Circular Array No SW	V	2, 3 ϕ	.0150		7.890	
Circular Array 6 SW	VI	2, 3 ϕ	.0030		7.870	
Circular Array 2 SW	VII	2, 3 ϕ	.0110		7.920	
Circular Array No SW	V	6 ϕ	.0140	.0018	0.080	.018
Circular Array 6 SW	VI	6 ϕ	.0047	.0019	0.027	.016
Circular Array 2 SW	VII	6 ϕ	.0560	.0074	0.695	.107
::: No SW	VIII	2, 3 ϕ	6.19/.301*		16.8/9.30*	
::: No SW	IX	2, 3 ϕ	6.20/.285*		16.9/7.18*	
::: No SW	VIII	6 ϕ	3.9400	.0420	7.260	.109
::: No SW	IX	6 ϕ	3.9400	.0550	7.310	.189
1, 3-phase circuit	--	3 ϕ	1.9400	.0600	12.100	.590

* ABC / ABC
ABC / CBA

Negative sequence currents in generators must be limited to a few percent of rating (typically 6-8 percent or less), and therefore, the negative sequence currents due to the line unbalances were initially calculated. The results are in terms of percent of line current; and therefore generator currents must be interpreted on this basis. Since twice surge impedance loading is in the order of 250 MW for this representative case, and the generator is rated 500 MVA, the percentages in Table 3.4 can be divided by 2 to obtain approximate currents on the generator base. The circular array, being symmetric, results in negligible generator negative sequence current, whether 3- or 6-phase. However, the line current unbalance is nearly 8 percent when energized 3-phase, and is reduced to under 1 percent for 6-phase. For the 6-phase configuration, six shield wires spaced symmetrically around the array results in the most balanced currents -- under 0.3 percent unbalance. Without shield wires, the unbalance is still less than 0.1 percent. Two shield wires result in the most unbalance, almost 0.7 percent. The only transposition possible, if the spacing advantages of high phase order is retained, is rotation of the entire array since adjacent phase conductors have voltage phase differences of 60 degrees, which defines unique individual phase positions within the array. For a complete transposition (six 60-degree rotations for the circular array), the unbalance is reduced to 0.1 percent for two ground wires and under 0.02 percent for the other two cases.

The unsymmetric 2 x 3 conductor rectangular arrays for two 3-phase circuits, depending on the relative phasing, produce negative sequence currents in the generator of 0.3 and 6.0 percent. The line current unbalances are approximately 17 percent for either configuration with one phasing relationship, or 7 and 9 percent for the different two configurations with the alternate phasing relationships. The 6-phase configuration results in 4 percent negative sequence current in the generator and 7 percent line current unbalance. One complete rotational transposition of the 6-phase array reduces these unbalances to the 0.05 percent range for generator negative sequence currents and 0.1 to 0.2 percent range for line current unbalance.

Comparison of results for two 3-phase circuits and one 6-phase circuit illustrate that 6-phase circuits are inherently better balanced than two 3-phase circuits with the same conductor configuration. Also, 6-phase results in less unbalance than a single 3-phase line. The improvement due to a circular (symmetrical) conductor configuration is also apparent, and transposition appears unnecessary. Where the rectangular array may be preferred for constructional reasons, transposition is possible for better balance.

The foregoing considered all six conductors energized from both terminals. Because of the high percentage of power transfer possible with one open phase, operation in this mode for extended periods can be considered. De-energization of one of the conductors results in negative sequence currents in the generator in the range of 13.2 to 14.2 percent of the positive sequence current for the 6-phase lines or two 3-phase circuits. These results assume a single 6-phase circuit carrying the entire generator output, and therefore define the worst case. Multiple circuits would reduce the negative sequence current in the generator.

Voltage Unbalance Due to System Faults

A primary cause of fundamental frequency overvoltages on transmission systems is the neutral shift due to faults between one or more phases and ground. Surge arrester ratings are a function of the magnitude of these voltages. The insulation levels of the equipment are dependent on the arrester protective levels and are, therefore, also a function of the fault overvoltages.

Most existing transmission systems in the US are effectively grounded (i.e., have an R_0/X_1 ratio of 1 or less and an X_0/X_1 ratio of 3 or less), which results in overvoltages due to faults involving ground to be limited to approximately 1.35 times normal phase-to-ground voltage or less. Although double circuit 3-phase lines can have X_0/X_1 ratios slightly higher than 3, the combination of the line impedance and system impedance will normally reduce this overall ratio to 3 or less. This same trend in reduction of system X_0/X_1 ratio below that of the line will exist for high phase order systems (i.e., system X_0/X_1 ratios will be less than the line X_0/X_1 ratios).

For conceptual analysis of neutral shift due to faults, a simple 3-phase circuit is shown in Figure 3.17A. The corresponding phase diagrams for both prefault (balanced) conditions and a fault from Phase A to ground (N) are shown in Figure 3.17B. During the fault the Point A and N coincide as a result of the neutral shift $V_{nN} = I_f X_n$. Due to this neutral shift, V_{CN} and V_{BN} rise, reaching a maximum value of $\sqrt{3}$ times the prefault voltage (i.e., $\sqrt{3}$ p.u.) when Points a and N coincide due to very large values of X_n . For a 6-phase system the phasor diagrams for both prefault and for a fault between Phase A and N are shown in Figure 3.17C. For this system, the maximum possible phase voltage to ground during the fault is 2.0 p.u. and occurs between Phase D and N. The voltages V_{C-N} and V_{E-N} are $\sqrt{3}$ p.u. while the voltages V_{B-N} and V_{F-N} are 1.0 p.u. (i.e., equal in magnitude to either normal balanced phase-to-ground voltage or phase-to-phase voltages).

A. 3-Phase System

B. Neutral Shift on 3-Phase System

C. Neutral Shift on 6-Phase System

Figure 3.17. Neutral Shift Due to Phase-to-Ground Faults

Detailed calculations of overvoltages on a representative system during fault conditions were conducted using a phase analysis method. This technique allows complete representation of all unbalances including coupling due to nontransposed (i.e., non-perfect balance) transmission lines and interphase coupling in equipment (e.g., transformers). The system of Figure 3.16 was energized from the generator end and the 6-phase line opened at the remote end. A single phase-to-ground fault was applied on Phase A at the open end. The voltages at the open end (i.e., at the point of fault) were:

Phase-to-Ground Voltage at Open End
(in p.u. of prefault voltage)

A-G	0.00 p.u.
B-G	0.90 p.u.
C-G	1.32 p.u.
D-G	1.35 p.u.
E-G	1.39 p.u.
F-G	0.83 p.u.

Several other variations which could affect fault voltage magnitudes were also analyzed including the line configurations of Figures 3.9 and 3.10, both with and without shield wires; faults at a number of system locations; and faults involving more than one phase-to-ground. The maximum voltage from phase-to-ground for any of these conditions was approximately 1.48 p.u., which is slightly higher than the maximum for a single phase-to-ground fault as listed previously (i.e., 1.39 p.u.).

To further explore this, the more simplified analysis of Figure 3.17 can be expressed in terms of the X_0/X_1 ratio of a system at the point of fault using the relationship:

$$Z_n = \frac{1}{3} (Z_0 - Z_1)$$

A typical derivation for a 3-phase system is shown in Reference 3-4. This approach can be extended to high phase order systems. For example, for a 6-phase system, letting

$$K = X_0/X_1:$$

$$\frac{|V_{DN}|}{|V_{DN}|_{\text{prefault}}} = 1 + \frac{K-1}{5+K}$$

$$\frac{|V_{EN}|}{|V_{EN}|_{\text{prefault}}} = \sqrt{\left(\frac{1}{2} + \frac{K-1}{5+K}\right)^2 + \frac{3}{4}}$$

The results of this calculation technique for 3, 6, 12, and 24 phases as a unique function of the X_0/X_1 ratio are given in Table 3.5 and are plotted in Figure 3.18. Increasing the number of phases from 3 to 6 increases the maximum voltage rise (i.e., for $X_0/X_1 = \infty$) from $\sqrt{3}$ p.u. to 2.0 p.u. due to the addition of phases which are diametrically opposed. With this exception, the general trend is for less voltage rise with increasing phase order for the same X_0/X_1 . In general, X_0/X_1 increases with increasing phase order, as shown in Figure 3.19, which results in an increase in voltage with phase order. Therefore, the two trends tend to be somewhat offsetting. To illustrate the effect of these trends, typical line X_0/X_1 ratios were obtained from Figure 3.19 and the attendant overvoltages calculated. The results are shown in Table 3.6.

Table 3.5
Neutral Shift Due to Phase-to-Ground Fault
Voltage Rise on Unfaulted Phases

X_0/X_1	Corresponding Phases				Maximum Phases			
	3 ϕ	6 ϕ	12 ϕ	24 ϕ	3 ϕ	6 ϕ	12 ϕ	24 ϕ
	V_{BN}	V_{EN}	V_{IN}	V_{RN}	V_{BN}	V_{DN}	V_{GN}	V_{MN}
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	1.146	1.079	1.041	1.021	1.146	1.143	1.077	1.040
3	1.249	1.146	1.079	1.041	1.249	1.250	1.143	1.077
4	1.323	1.202	1.114	1.060	1.323	1.333	1.200	1.111
10	1.521	1.400	1.270	1.161	1.521	1.600	1.429	1.273
20	1.615	1.529	1.410	1.279	1.615	1.760	1.613	1.442
∞	1.732	1.732	1.732	1.732	1.732	2.000	2.000	2.000

Figure 3.18. Voltage Rise on Unfaulted Phases

Figure 3.19. X_0/X_1 Ratio as a Function of Phase Order

Table 3.6

Fault Overvoltages for Typical Line X_0/X_1 Ratios

No. of Phases	Line X_0/X_1 Ratio	Fault Overvoltage
3	5.00	1.35 p.u.
6	7.77	1.53 p.u.
12	10.60	1.45 p.u.

This table indicates that, for typical X_0/X_1 trends, the fault overvoltages increase as the phase order increases from 3 to 6 and decrease somewhat for 12 phases. Therefore, maximum overvoltages calculated for typical 6-phase systems would be conservative maximums for typical high phase order systems. Further, recognizing that the foregoing example is conservative, since the characterization of other system impedance would tend to reduce the X_0/X_1 ratios, typical maximum fault overvoltages on representative transmission systems with up to 12 phases appear to be in the order of 1.50 to 1.60 p.u.

For a further benchmark on the relative degree of conservatism when using this simplified approach, the fault overvoltages for a single line-to-ground fault on the open end of the 6-phase line (Configuration V) of Figure 3.9 was analyzed by both detailed phase calculation and the X_0/X_1 method. Table 3.7 illustrates the results for the voltages on the two highest phases.

Table 3.7
Comparison of Fault Voltage Calculation Methods

<u>Phase Voltage</u>	<u>Phase Calculation</u>	<u>Simplified Calculation</u>
V_{D-G}	1.35 p.u.	1.47 p.u.
V_{E-G}	1.39 p.u.	1.30 p.u.

The voltage V_{D-G} is higher than the exact phase calculation while the voltage V_{E-G} is lower. However, the variations are within 10 percent indicating the simplified method yields conservative approximate results and can be used to determine generic values for various phase order systems.

If phase-to-phase voltage magnitudes increase sufficiently under fault conditions, flashover between phases may also occur with a possible cascading effect. This is a consideration in the potential use of single-phase switching on high phase order systems. The phasor diagram of Figure 3.17C indicates that voltages between adjacent phases do not increase due to a phase-to-ground fault. This diagram is for a simplified situation, and analysis of phase-to-ground faults on the system of Figure 3.16 indicates that voltages between adjacent phases do not exceed approximately 1.15 times

normal phase-to-phase voltage. For a 12-phase system, however, the voltage between adjacent phases can reach 1.93 times normal phase-to-phase voltage, and the relative value increases at higher phase orders. Therefore, cascading of faults does not appear to be limiting to single-phase switching for six phases but may be at higher phase orders.

The phase-to-ground overvoltages due to faults tend to be higher on systems with more than the conventional three phases. The impact of these voltages on system insulation levels is discussed in Section 6. Further, the increase in phase-to-phase voltages during faults does not appear to limit single-phase switching on 6-phase systems, although this could be limiting at higher phase orders.

Interphase Coupling and Secondary Arc Current

Conductors in close proximity are coupled by both electric and magnetic fields. A simplified sketch of the basic electrical circuit of two conductors is shown in Figure 3.20A. The electric field coupling (i.e., capacitive) couples voltages between the conductors, which in turn can cause currents to flow in the coupled circuit. Similarly, current flow causes coupling through the magnetic circuit which, in turn, can cause voltages in the coupled circuit. Therefore, both current flow in a circuit and the voltage on the circuit conductors must be considered when determining the effects of coupling between conductors. If one or more of the conductors are opened (de-energized) at both ends but are in proximity to an energized conductor, currents may still flow in the "de-energized" conductor, and voltages exist on the conductor. This is illustrated in Figure 3.20B, where the current flows and the voltages of the "de-energized" conductor are a function of the voltage and current of the energized circuit and the values of impedance elements.

This is a problem commonly addressed in the design of single-phase switching schemes, since the coupled currents ("secondary arc currents") and voltages affect the extinction characteristics of a fault arc subsequent to breaker pole opening at the line terminals. A further possible complication is the application of shunt reactors to transmission lines for capacitive var compensation. This essentially adds an inductive impedance (L) in parallel with the line capacitance, as shown in Figure 3.20C, resulting in the possibility of additional resonant modes with consequential

A. Simplified Electrical Circuit of Two Energized Conductors

B. Voltages and Currents on "De-energized" Conductor

C. Shunt Reactor Compensation Added

Figure 3.20. Resonant Coupling

high voltages or currents. Typical coupled voltages on the "de-energized" circuit of a double circuit 3-phase 765 kV transmission line are illustrated in Figures 3.21 and 3.22.

As previously discussed, operation of a 6-phase (or higher order) line for an extended period with one phase open may be an attractive option.

Figure 3.21. Resonant Coupling on Double Circuit Line (Untransposed)

Figure 3.22. Resonant Coupling on Double Circuit Line (Transposed)

Therefore, while successful application of 6-phase lines is not dependent upon the application of single pole switching, the use of single pole switching could have beneficial system aspects regarding reliability and power capacity. As an example of coupling effects on a 6-phase system, the circuit of Figure 3.16 (and line Configuration VII) was loaded to approximately 2.25 times surge impedance loading. This results in a line current of 560 amperes. A fault on Phase A of the line at the generator end gives a 4105 ampere fault current.

Using an ABCD matrix analysis and opening Phase A at both ends gives a voltage at each end of the open conductor of 6054 and 5805 volts. Faulting one end of the open phase results in a 3.6 ampere fault current. The voltage on the open end of the faulted phase is 1918 volts. The 3.6 ampere secondary arc current is sufficiently low that arc interruption would occur for single pole switching. Typically, self-clearing can be expected with up to 20 amperes secondary arc current. For a corresponding double circuit 3-phase configuration, the current is 6.6 amperes.

Repeating the calculation for conductor Configuration V results in 3975 and 3630 volts at the two ends of Phase A.

The following analysis illustrates the partitioning of the matrix of potential coefficients and indicates that for one phase open only one resonance is possible.

The potential coefficient matrix is:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \\ e_d \\ e_e \\ e_f \end{bmatrix} = \frac{1}{j\omega} \begin{bmatrix} P_{aa} & P_{ab} & P_{ac} & P_{ad} & P_{ae} & P_{af} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ P_{fa} & . & . & . & . & P_{ff} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_d \\ i_e \\ i_f \end{bmatrix}$$

Inversion of this matrix results in the capacitance matrix:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \\ i_d \\ i_e \\ i_f \end{bmatrix} = j\omega \begin{bmatrix} C_{aa} & C_{ab} & C_{ac} & C_{ad} & C_{ae} & C_{af} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ C_{fa} & . & . & . & . & C_{ff} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \\ e_d \\ e_e \\ e_f \end{bmatrix}$$

If Phase f is open (shunt reactor compensation is similarly considered):

$$\begin{bmatrix} i_a \\ i_b \\ i_c \\ i_d \\ i_e \\ i_f \end{bmatrix} = j\omega \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & . & . & . & . & . \\ 0 & . & . & . & . & . \\ 0 & . & . & . & . & . \\ 0 & . & . & . & . & . \\ 0 & 0 & 0 & 0 & 0 & Y \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \\ e_d \\ e_e \\ e_f \end{bmatrix}$$

Partition the matrices as above.

$$\begin{bmatrix} i_I \\ i_f \end{bmatrix} = j\omega \begin{bmatrix} C_{II} & C_{If} \\ C_{fI} & C_{ff} \end{bmatrix} \begin{bmatrix} e_I \\ e_f \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ i_L \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & Y_L \end{bmatrix} \begin{bmatrix} e_I \\ e_f \end{bmatrix}$$

The total current with the one phase open at both ends is:

$$\begin{bmatrix} i_I \\ 0 \end{bmatrix} = j\omega \begin{bmatrix} C_{II} & C_{If} \\ C_{fI} & (C_f + \frac{1}{j\omega} Y_L) \end{bmatrix} \begin{bmatrix} e_I \\ e_f \end{bmatrix}$$

The line-to-ground voltage on the open phase is:

$$[0] = j\omega [C_{fI}] [e_I] + j\omega [(C_f + \frac{1}{j\omega} Y_L)] [e_f]$$

$$\underbrace{[e_f]}_{1 \times 1 \text{ matrix}} = - \underbrace{[(C_f + \frac{1}{j\omega} Y_L)]}_{1 \times 1 \text{ matrix}} \underbrace{[C_{fI}] [e_I]}_{1 \times 1 \text{ matrix}}$$

From this, only one resonance is possible and occurs when:

$$C_f + \frac{1}{j\omega} Y_L = 0$$

or

$$j\omega C = -Y_L$$

Therefore, if one phase is open, the resonance will occur at 100 percent shunt reactor compensation of the phase self-capacitance. In terms of positive sequence capacitance, only one resonance is possible and occurs near 100% compensation.

To confirm this conclusion and illustrate the resonant characteristic of a 6-phase line, a range of single-phase shunt reactors was applied on line Configuration V for the system of Figure 3.16 with one phase open. The total reactor rating was equally divided between each end of the line. The steady-state voltages at the terminals of the energized phases were 80 kV phase-to-ground. Table 3.8 summarizes the results for a reactor range of 8000 ohms at each end (50 percent compensation) to 3600 ohms at each end (111 percent compensation). A solid fault was also placed on the line (i.e., reactor ohms = 0). These results clearly illustrate the single resonant point and the relatively sharply-tuned characteristic. While the voltage is essentially infinite for 105 percent compensation, the voltage is only 32 percent of normal for 85 percent compensation.

Although this is not a problem specific to high phase order lines, a compensated high phase order line must be carefully analyzed if single (or three-) phase switching is contemplated.

Table 3.8

6-Phase Line Resonant Coupling Results

Line Configuration V (Figure 3.9) Phase A Open

<u>Reactor Ω Each End</u>	<u>Percent Compensation</u>	<u>Voltage at Open Ends</u>		<u>Percent Maximum Voltage</u>
0		3,975	3,630	5
3600	111.1	96,000	96,000	121
3800	105.3	1,519,000	1,519,000	1900
4000	100	93,600	93,500	117
4211	95	49,500	49,400	62
4444	90	33,800	33,600	42
4706	85	25,600	25,500	32
5333	75	16,800	16,600	21
8000	50	10,100	10,000	13

Protective Relaying

The protection of a transmission line must consider relaying sensitivity, selectivity, and speed while simultaneously avoiding tripping unfaulted lines. For analysis of feasibility of protective relaying, conventional distance relaying was investigated assuming all phases of a faulted circuit would be opened. Actual application studies would also require other approaches.

There are normally several zones of protection in distance relaying to provide selective backup protection in the event of failure of a circuit breaker to clear a fault. The primary zone of protection consists of a set of six relays, three connected between pairs of phases for phase-to-phase faults; the other three are phase-to-ground relays for ground faults. Each relay is typically set for an impedance circle with a reach of about 95 percent of the length of the protected line. These relays are set using the positive sequence impedance of the line.

For six phases, there are 15 pairs of phases to monitor for phase-to-phase faults as well as six phases to ground. In addition, it is not evident that all 15 phase-to-phase relays should have the same setting. The settings must consider a multitude of factors. For example, due to the strong coupling between zero sequence networks of parallel lines, care must be exercised to ascertain that a fault on one circuit does not trip another. Similarly, a fault on one pair of phases beyond the line must not cause a false trip between a different pair of phases.

The elements of phase-to-phase fault analysis can be illustrated by a symmetrical component approach. For a 6-phase line, a fault may occur between Phase A and any of five other phases. Symmetry suggests that faults to Phases B and F would be identical; faults to Phases C and E would be identical (but different than to Phases A and B); and a fault to Phase D would be different than either.

For a fault between Phases A and B, the terminal equations at the fault point are:

$$V_0 + Z_0 I_0 = 0$$

$$V_A = V_B$$

$$V_1 + Z_1 I_1 = E_1$$

$$I_A = I_B$$

$$V_2 + Z_2 I_2 = 0$$

$$I_C = I_D = I_E = I_F = 0$$

$$V_3 + Z_3 I_3 = 0$$

$$V_4 + Z_4 I_4 = 0$$

$$V_5 + Z_5 I_5 = 0$$

These can be solved for the symmetrical components by the following matrix equation:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ I_0 \\ I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & Z_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & Z_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Z_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Z_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Z_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & Z_5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & B^4 & B^2 & 1 & B^4 & B^2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & B^3 & 1 & B^3 & 1 & B^3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & B^2 & B^4 & 1 & B^2 & B^4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & B & B^2 & B^3 & B^4 & B^5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 2 & (1+B^5) & (1+B^4) & (1+B^3) & (1+B^2) & (1+B^1) \\ 0 & (1-B^5) & (1-B^4) & (1-B^3) & (1-B^2) & (1-B^1) & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ E_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{matrix} -1 \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \end{matrix}$$

$$B = 1/60^\circ$$

Similar equations are obtained for the other possible phase-to-phase faults.

Since $I_A = I_0 + I_1 + I_2 + I_3 + I_4 + I_5$, if the source voltage were $E_1 = 1$ and the inverted matrix elements are m_{ij} , the fault current is $m_{72} + m_{82} + m_{92} + m_{102} + m_{112} + m_{122}$. Using constants representative of one mile of typical line gives the following results:

Faulted Phases	$ I_A $	$ V_{oc} $	$ Z_{th} $
A B	0.95	1	0.95
A C	1.46	$\sqrt{3}$	0.84
A D	1.63	2	0.81
A E	1.46	$\sqrt{3}$	0.84
A F	0.95	1	0.95

where I_A is the fault current; V_{oc} is the open circuit voltage between the affected pair of phases previous to the fault; and Z_{th} is the Thevenin equivalent impedance (i.e., the open circuit voltage divided by the fault current). The sequence impedances for the calculation are:

$$Z_0 = 5.3 \text{ ohms/mile}$$

$$Z_1 = Z_5 = 0.68 \text{ ohms/mile}$$

$$Z_2 = Z_4 = 0.51 \text{ ohms/mile}$$

$$Z_3 = 0.48 \text{ ohms/mile.}$$

These faults can be represented as an interconnection of sequence networks as well as by the matrix approach. Since ground is not involved, the zero sequence network is eliminated. Interconnections between the remaining five networks for the three phase-to-phase faults are shown in Figure 3.23.

The equations for the sequence interconnections are complicated but solvable. The networks of Figure 3.23 illustrate that the impedance as seen by the relay is dependent on which pair of phases is faulted. Therefore, three different settings are necessary for the phase distance relays.

While the relaying of high phase order lines is more complicated than for conventional 3-phase lines, both analysis and application techniques are available, as well as relay hardware. Therefore, protective relaying is not limiting to high phase order systems. The added complexity of high phase order relaying, however, requires additional engineering development before practical application is achieved.

A: a-d fault

B: a-c or a-e faults

Note: The polarity (+) of the phase shift depends on whether the fault is a-c or a-e

C: a-b or a-f faults

Note: The polarity (+) of the phase shift depends on whether the fault is a-b or a-f

Figure 3.23. Symmetrical Component Sequence Network Connections--6-Phase Circuits

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4.0 TRANSIENT OVERVOLTAGE PERFORMANCE

Switching Surges

Conventional 3-phase transmission systems must consider both phase-to-ground and phase-to-phase switching surges in determining insulation requirements; however, phase-to-ground requirements are normally more limiting. This can be conceptually illustrated by the phasor diagram of Figure 4.1A. If a surge of 2.0 p.u. (i.e., 2.0 times normal phase-to-ground) occurs on Phase A, from the phasor diagram the phase-to-phase voltages A-C or A-B will be 2.65 p.u. or 1.53 times the normal phase-to-phase voltage. Therefore, for phase-to-ground or phase-to-phase insulation or clearances that are proportional to the steady-state voltages, the phase-to-ground surge would be more limiting. In general, transmission towers and station buses have grounded structural members between phases; and therefore, the ratio of phase-to-phase clearances to phase-to-ground clearances is even greater than the $\sqrt{3}$ ratio between the respective 60 Hz normal voltages. As phase order increases, however, the phase-to-phase surges become an increasingly important parameter.

From Figure 4.1, if a 2.0 p.u. surge occurs on Phase A of a 6-phase system (all other phases being at normal voltage), the maximum phase-to-phase surge is 1.73 times normal phase-to-phase voltage for a 6-phase system and 2.39 times normal for a 12-phase system. This oversimplified analysis illustrates that phase-to-phase surges become increasingly important relative to phase-to-ground values. This is further emphasized by the basic high phase order objective of reduced clearance between adjacent conductors.

A:

$$\text{3-phase: } V_{\phi-\phi} = \sqrt{3} V_{\phi-G}$$

$$\text{For } V_{a'-n} = 2 V_{a-n}: V_{a'-c} = 2.65 V_{a-n} \\ = 1.53 V_{a-c}$$

B:

$$\text{6-phase: } V_{\phi-\phi} = 1.0 V_{\phi-G}$$

$$\text{For } V_{a'-n} = 2 V_{a-n}: V_{a'-f} = 1.73 V_{a-n} \\ = 1.73 V_{a-f}$$

C:

$$\text{12-phase: } V_{\phi-\phi} = 0.52 V_{\phi-G}$$

$$\text{For } V_{a'-n} = 2 V_{a-n}: V_{a'-1} = 1.24 V_{a-n} \\ = 2.39 V_{a-1}$$

Figure 4.1. Effect of Phase Order on Phase-to-Phase Switching Surges

To investigate switching surge characteristics of a representative 6-phase system, an 80 kV phase-to-ground 6-phase line was energized from an equivalent source as shown in Figure 4.2, both with and without surge suppressing resistors in the operating circuit breaker.

Circuit Breaker Characteristics:

- All phases close within 8.33 ms
- Resistor in closing circuit is 400 ohms inserted for 6.95 ms (where applicable)

Figure 4.2. One-Line Diagram of Representative System

The operation was repeated with a 3-phase line for comparison of surge characteristics. For representational and comparison simplicity, both the 3-phase and the 6-phase lines were assumed to be fully transposed. The switching surge analyses were conducted on a PTI digital switching surge program.

For each switching configuration the circuit breaker was closed 50 times with random closing angles for each phase but within the closing constraints listed in Figure 4.2. The maximum magnitudes for this study of both phase-to-ground and phase-to-phase surges are listed in Table 4.1.

Table 4.1
Maximum Magnitudes of Energization Surges

Phases	Insertion Resistance	ϕ -G p.u. of Normal ϕ -G Voltage	ϕ - ϕ p.u. of normal ϕ - ϕ Voltage
3	No	2.864	2.093
3	Yes	1.454	1.316
6	No	2.764	3.200
6	Yes	1.462	1.547

To simplify the comparison, the maximums are in per unit of the respective normal voltages (i.e., either phase-to-ground or phase-to-phase). The phase-to-ground switching surges for the 3-phase and the 6-phase lines are approximately the same for the same conditions, with less than 4 percent difference. The per unit phase-to-phase surges are significantly higher for 6-phase, particularly when no resistors are used in the circuit breaker. In this case the 6-phase case is approximately 50 percent higher than the 3-phase case. This confirms the conceptual analysis shown in Figure 4.1.

These results also confirm that phase-to-phase switching surges, rather than phase-to-ground surges, will dominate switching surge insulation design, including line clearances. The surge reductions obtained with circuit breaker resistors, however, indicate that phase-to-phase surges can be adequately controlled to allow very closely-spaced conductors on 6-phase lines. Phase-to-phase surges in addition to limiting clearances may also set a practical upper limit to phase order achievable.

Rate of Rise of Recovery Voltage (RRRV) On Circuit Breakers

The ability of a circuit breaker to interrupt faults near its terminals is greatly influenced by the rate of rise of the voltage (recovery voltage) across the breaker terminals during the opening. The insulation of the breaker gap must increase more rapidly than the rate of rise of the recovery voltage (RRRV) to assure successful interruption without restrikes and re-establishment of the arc.

The recovery voltage can be calculated by the current injection technique. A current equal and opposite to the fault current is injected at the breaker contacts, resulting in zero current flow in the breaker, thereby simulating breaker current interruption. The voltage across the breaker can then be calculated by multiplying the equivalent impedance as seen across the terminals by the injected current. Since only the initial interval of interruption is of interest for calculation of RRRV, the injected current can be represented as a ramp function.^{4-1,4-2} Figure 4.3 illustrates the equivalent circuit for the first phase to open on an ungrounded 3-phase fault on a 3-phase system.

Figure 4.3. Equivalent Circuit: 3-Phase Ungrounded Fault (First Phase to Open)

The Equivalent Impedance = $\frac{3}{2} Z_1$

and

$$RRRV = \sqrt{2} I_{\omega} 10^{-6} \left(\frac{3}{2} Z_1 \right) \text{ kV}/\mu\text{sec}$$

For a 3-phase grounded fault, the recovery voltage is most severe for the last phase to open. The equivalent circuit for this condition is shown in Figure 4.4.

Figure 4.4. Equivalent Circuit: 3-Phase Grounded Fault (Last Phase to Open)

For this case, the Equivalent Impedance = $Z_1 + \frac{Z_0 - Z_1}{3}$

and the RRRV is:

$$RRRV = \sqrt{2} I_{\omega} 10^{-6} \left(\frac{2}{3} Z_1 + \frac{1}{3} Z_0 \right) \text{ kV}/\mu\text{sec}$$

The same analysis can be extended to a 6-phase system. For an ungrounded 6-phase fault, the equivalent circuit is shown in Figure 4.5.

Figure 4.5. Equivalent Circuit: 3-Phase Fault (First Phase to Open)

The Equivalent Impedance = $\frac{6}{5} Z_1$

and the RRRV is:

$$RRRV = \sqrt{2} I_{\omega} 10^{-6} \left(\frac{6}{5} Z_1 \right) \text{ kV}/\mu\text{sec}.$$

For the same fault MVA on both 3-phase and 6-phase systems, and recognizing the difference in phase currents due to the difference in number of phases, a comparison of the first phase to open on an ungrounded fault can be compared as follows:

$$I_{f \ 6\phi} = \frac{1}{2} I_{f \ 3\phi}$$

and

$$RRRV_{3\phi} = \sqrt{2} I_{f \ 3\phi} \omega 10^{-6} \left(\frac{3}{2} Z_1 \ 3\phi \right)$$

$$RRRV_{6\phi} = \sqrt{2} I_{f \ 6\phi} \omega 10^{-6} \left(\frac{6}{5} Z_1 \ 6\phi \right)$$

$$= \sqrt{2} \frac{I_{f \ 3\phi}}{2} \omega 10^{-6} \left(\frac{6}{5} Z_{1 \ 6\phi} \right)$$

or

$$RRRV_{6\phi} = \frac{2}{5} \frac{Z_{1 \ 6\phi}}{Z_{1 \ 3\phi}} \times RRRV_{3\phi}$$

Six-phase line positive sequence line impedance is typically in the order of 20 percent higher than a three-single circuit line; therefore,

$$Z_{1 \ 6\phi} < \frac{5}{2} Z_{1 \ 3\phi}$$

and the RRRV is less for a 6-phase system than for a 3-phase system.

However, analysis of severity of RRRV as a function of the phase opened shows the fourth phase to open results in the maximum RRRV on a 6-phase system. For this case:

$$RRRV_{6\phi} = \sqrt{2} I_{f \ 6\phi} \omega 10^{-6} \left(\frac{3}{2} Z_{1 \ 6\phi} \right)$$

For the same fault MVA and the first phase to open on a 3-phase ungrounded fault:

$$RRRV_{6\phi} = \frac{1}{2} \frac{Z_{1 \ 6\phi}}{Z_{1 \ 3\phi}} \times RRRV_{3\phi}$$

The RRRV for the 6-phase case is still much less severe than the 3-phase case. For the same fault current in each phase (i.e., the 6-phase fault MVA is twice the 3-phase fault MVA), the RRRV for the first phase to open is:

$$\begin{aligned} RRRV_{6\phi} &= \sqrt{2} I_{f \ 3\phi} \omega 10^{-6} \left(\frac{6}{5} Z_{1 \ 6\phi} \right) \\ &= \frac{4}{5} \frac{Z_{1 \ 6\phi}}{Z_{1 \ 3\phi}} \times RRRV_{3\phi} \end{aligned}$$

and the RRRV for each system is comparable.

For the same fault currents for both 6-phase and 3-phase cases, and the fourth pole to clear on the 6-phase line:

$$RRRV_{6\phi} = \sqrt{2} I_{f \ 3\phi} \omega 10^{-6} \left(\frac{3}{2} Z_{1 \ 6\phi} \right)$$

$$= \text{RRRV} \frac{Z_1 \ 6\phi}{Z_1 \ 3\phi} \times \text{RRRV}_{3\phi}$$

For the typical values of Z_1 , the 6-phase RRRV will be approximately 20 percent higher than the 3-phase. From the foregoing, for ungrounded 3-phase faults:

$$\frac{2}{5} \frac{Z_1 \ 6\phi}{Z_1 \ 3\phi} < \frac{\text{RRRV}_{6\phi}}{\text{RRRV}_{3\phi}} < \frac{Z_1 \ 6\phi}{Z_1 \ 3\phi}$$

Figure 4.6 illustrates the equivalent circuit of a 6-phase grounded fault.

Figure 4.6. Equivalent Circuit: 6-Phase-to-Ground Fault
(Last Phase to Open)

For the last phase to clear:

$$\text{RRRV}_{6\phi} = \sqrt{2} I_{f \ 6\phi} \omega \cdot 10^{-6} \left(Z_1 + \frac{Z_0 - Z_1}{6} \right)$$

$$= \sqrt{2} I_{f \ 6\phi} \omega \cdot 10^{-6} \left(\frac{5}{6} Z_1 + \frac{1}{6} Z_0 \right)$$

For the assumption of the same fault MVA:

$$I_{f \ 6\phi} = \frac{1}{2} I_{f \ 3\phi}$$

and

$$\begin{aligned}
 \text{RRRV}_{6\phi} &= \frac{\frac{5}{6} Z_{1\ 6\phi} + \frac{1}{6} Z_{0\ 6\phi}}{\frac{2}{3} Z_{1\ 3\phi} + \frac{1}{3} Z_{0\ 3\phi}} \times \text{RRRV}_{3\phi} \\
 &= \frac{1}{4} \frac{5Z_{1\ 6\phi} + Z_{0\ 6\phi}}{2Z_{1\ 3\phi} + Z_{0\ 3\phi}} \times \text{RRRV}_{3\phi}
 \end{aligned}$$

Therefore, if

$$\begin{cases} Z_{0\ 6\phi} = 4Z_{0\ 3\phi} \\ Z_{1\ 6\phi} = \frac{8}{5} Z_{1\ 3\phi} \end{cases}$$

each has the same RRRV.

Representative values for the impedances for a single circuit 3-phase line and a single circuit 6-phase line are:

$$Z_{1\ 6\phi} \approx 1.20 Z_{1\ 3\phi}$$

$$Z_{0\ 6\phi} \approx 1.80 Z_{0\ 3\phi}$$

and a representative value for X_0/X_1 of a 6-phase line (Configuration V, Figure 3.9) is:

$$\frac{X_0}{X_1} \approx 7.77$$

Therefore, for these representative values:

$$\text{RRRV}_{6\phi} \approx 0.5 \text{ RRRV}_{3\phi}$$

For a grounded 6-phase fault, the RRRV is less severe than for a 3-phase system, assuming equivalent fault MVA. If the phase fault currents are equal (i.e., the 6-phase fault MVA is twice the 3-phase fault MVA):

$$\text{RRRV}_6 = \frac{\frac{5}{2} Z_{1\ 6\phi} + \frac{1}{2} Z_{0\ 6\phi}}{\frac{2}{3} Z_{1\ 3\phi} + \frac{1}{3} Z_{0\ 3\phi}} \times \text{RRRV}_{3\phi}$$

Therefore, if

$$\begin{aligned} Z_{0 \ 6\phi} &= 2 Z_{0 \ 3\phi} \\ Z_{1 \ 6\phi} &= \frac{4}{5} Z_{1 \ 3\phi} \end{aligned}$$

each has the same RRRV. For the same representative impedance relationships as previously assumed:

$$RRRV_{6\phi} \approx 1.1 RRRV_{3\phi}.$$

In summary, for all cases analyzed, the circuit breaker RRRV for a 6-phase system is less than for a 3-phase system for equivalent fault MVA. For equal fault currents in each phase, the 6-phase RRRV may be somewhat higher than for a 6-phase system. For representative system impedances, this could be in the order of 20 percent.

Lightning*

The lightning performance of a transmission line is normally defined as the number of lightning-caused tripouts per year. A lightning stroke can initiate an arc between phases or more usually from one or more phases to a grounded portion of the structure. This arc is sometimes self-extinguishing, depending on the instantaneous value of the phase voltage and certain characteristics of the lightning stroke. If the line voltage is sufficient to sustain the arc, the fault must be cleared by fuse or circuit breaker operation.

Lightning flashovers may be caused by induced voltages from a nearby stroke or by direct strokes to the line. For performance analysis of transmission lines, all lightning arcs are assumed due to direct strokes, as indirect strokes do not induce sufficient voltage to flash over transmission insulation levels.

Direct stroke flashovers are classified as shielding failures or back-flashovers. Shielding failures are due to strokes to a phase conductor bypassing a shield wire, causing a rise in potential of the phase conductor and subsequent flashover to the tower. Back-flashovers are due to strokes to a tower or shield wire (if there is one) causing a rise in potential of the local ground and subsequent flashover from the tower to the phase conductors.

Derivation of the lightning performance of a high phase order transmission line is quite complex. To clarify the derivation in the discussion that follows, a typical 138 kV 6-phase line is compared with a double circuit 138 kV line. Figure 4.7 illustrates the representative structure geometries.

* Mr. I. S. Grant is the primary contributor for this subsection on lightning.

Figure 4.7. Comparison of Standard 80 kV Phase-to-Ground (138 kV) Double Circuit and 138 kV 6-Phase Compact Line Geometries

Stroke Characteristics

Electrically, a lightning stroke can be considered as a pulse of current. This pulse of current flows from the charged cloud through an ionized length of air (the jagged stroke seen in the sky) through the transmission line (or tree, or whatever it may strike) to ground. The impulse voltages that develop on the line due to the stroke are a complex function of the stroke itself, the current pulse magnitude and shape, the size and height of the various line components, the exposure of the line or the shielding by trees or terrain, the line insulation, and the line structure resistance to ground (footing resistance). The stroke rise time and magnitude have a reasonably well-known statistical distribution.

The number of strokes to a line is derived from the local isoceraunic level for the region. Isoceraunic level is the average number of thunderdays per year, based on regional observation; and the relationship between this and strokes to ground per square mile (ground flash density) is empirical and varies with world location.

For the continental U.S., this relationship is usually taken as:

$$N = I \times (0.0189 \times h + 0.0047 \times b)$$

where N = strokes/year/100 miles of line

I = isoceraunic level in thunderdays/year

h = average conductor height (shield wire)

b = structure width (shield wire or conductor spacing).

Thus the first comparison of performance considers the number of strokes to the two line types. Using the dimensions of Figure 4.7:

- Number of strokes to double circuit line = $I (0.0189 \times 100 + 0.0047 \times 26)$
 $= 2.01 I/100 \text{ miles/year}$
- For the 6-phase line, number of strokes = $I (0.0189 \times 80 + 0.0047 \times 6)$
 $= 1.54 I/100 \text{ miles/year}$

Considering only the conductor configurations. However, any supporting structure will typically be external to the conductors and will increase the effective line width.

Thus, a more representative value would be:

$$\begin{aligned} \text{Number of strokes to 6-phase line} &= I (0.0189 \times 80 + 0.0047 \times 14) \\ &= 1.58 I \end{aligned}$$

Therefore, due to the reduced dimensions of a 6-phase line, the number of strokes to the line will be less than for the double circuit line.

Backflashover Rates

As previously noted, backflashovers occur when a stroke to a tower has sufficient current to elevate the tower potential above remote ground. The potentials on the phase conductors, which are insulated, remain essentially the same as previous to the stroke, i.e., at remote ground potential plus an instantaneous value of 60 Hz voltage, and a flashover thus occurs between tower and remote ground across the line insulators.

The phase-to-ground system voltages for the lines of Figure 4.7 are the same, and therefore the same phase-to-ground insulation for each can be assumed. The expression for backflash voltage is:

$$V_{ins} = V_{tower} - k \times V_{shield} - V_{60}$$

where V_{ins} is the instantaneous voltage across an insulator string following a lightning stroke,

V_{tower} is the instantaneous tower potential above remote ground,

V_{shield} is the instantaneous shield wire potential above remote ground (usually virtually identical to V_{tower}), and

V_{60} is the instantaneous value of 60 Hz phase voltage.

For the purposes of comparison, there will be only minor differences in V_{ins} for the two structures of Figure 4.7. The tower impedance will be slightly less for the 6-phase tower, due to reduced surge impedance and travel time; impedance of the shield wires will be slightly more, however, due to the smaller spacing of the two shield wires; V_{60} will be similar in each case; and k will be approximately the same.

The backflash performance, therefore, will be very similar in terms of phase flashovers per 100 strokes per year.

Approximately 15 percent of all lightning-caused backflashovers do not require circuit breaker operation to clear the fault. Statistically, about this number of flashovers occur when the instantaneous 60 Hz voltage is sufficiently close to zero such that the arc is not maintained by 60 Hz voltage and extinguishes. However, where the instantaneous 60 Hz voltage is sufficient to maintain the arc, circuit breaker operation is necessary to clear the fault. Note that this represents a significant difference between the two types of line. If single-phase switching is not considered, the double circuit line retains one circuit in normal operation following a lightning-caused tripout, whereas all six phases of the 6-phase line must be opened.

In a significant number of cases, however, a double circuit line will lose both circuits. Since the double circuit outage results due to flashover of two conductors, and 6-phase outage occurs due to flashover of one conductor, the risk of complete loss of supply may be greater on the 6-phase line. As discussed previously, single-phase switching is a logical option for higher phase order and, if fitted to both types of line, eliminates this difference.

Midspan Flashovers

If a stroke hits the shield wire between structures rather than at the structure, a potential difference develops between shield wire and phase conductors. This results in a more severe voltage stress than for a structure in parallel with shield wires, due to the high surge impedance of the shield wire, and the relatively long time before reflected travelling waves return from adjacent structures and reduce this voltage. Midspan strokes might be expected to be a significant source of flashovers; however, the conductor-to-conductor stress is greatly reduced by pipe-to-pipe predischage currents (up to several thousand amperes) found to exist between the two conductors.⁴⁻³ While breakdowns are greatly reduced by this phenomenon, some may still occur but at times considerably later than a classical theoretical analysis would predict. Calibration with field experience suggests that midspan flashovers contribute only a minor number of tripouts, and midspan flashovers are usually not considered as a source of tripouts, assuming an adequate midspan shield wire-to-conductor spacing is maintained.

Shield Wire-to-Phase Conductor Spacing

Table 4.2 gives midspan clearances calculated as a function of span length for typical conductor sizes and heights. These clearances can be reduced at the tower top, as occurs when the sag of the phase conductor is greater than the sag of the ground wires.

Table 4.2

Midspan Clearance Between Shield Wires and
Phase Conductors for Avoidance of Midspan Flashovers

Span (ft)	600	1000	1400
Clearance at Midspan (ft)	15	32	45

There is no obvious reason that these clearances cannot be as easily obtained on 6-phase as on conventional double circuit lines.

Shielding Failures

As previously noted, a shielding failure occurs when a stroke leader contacts a phase wire rather than a shield wire or tower member. The probability of flashover following a shielding failure is much higher than for a backflashover following a stroke to the shield wire, since the surge impedance of the phase conductor is much higher than the surge impedance of a tower with shield wires, and therefore results in a higher potential per ampere of stroke current.

Results from field investigations of lightning include derivation of a model of shielding failure.^{4-5,4-6} This is illustrated in Figure 4.8.

Figure 4.8. Shielding Failure Geometry

Shielding protection angles are calculated from the model of Figure 4.8 using the following:

$$\beta = 1.0$$

$$\hat{S} = 29.53 I^{0.65} \text{ feet}$$

where I = stroke current in kA.

This includes a margin to ensure absence of shielding failure flashovers. Actual non-zero shielding failure rates can be calculated from the expression:

$$\bar{S} = 32.8 I^{0.65} \text{ feet.}$$

These are slightly different from the expressions found in Reference 4-5 through 4-7 and are based on recent and as yet unpublished work by Whitehead.

As shown from the model of Figure 4.8, the shielding protection of a 6-phase line can be designed to give the same (nominally zero) shield failure rate as for a conventional double circuit line.

One important difference does exist, however. If a shielding failure should occur, in about 50 percent of cases the tendency will be to flash over to an adjacent phase conductor, rather than to the structure. Thus the probability of phase-to-phase flashovers is much higher on a 6-phase line. In practice, for normally shielded lines this is of no significance since shielding failure rates of virtually zero are possible from good line design. In unshielded operation were a consideration, however, this would be of concern.

Penetration to the Center Phase

Improvement of shielding of the outer phases generally requires increasing the spacing of the shield wires. Thus, the possibility of a stroke between the shield wires to the center phase is increased.

Figure 4.9 illustrates an example of center phase protection with the leader stroke tip intercepted by the shield wires.

Figure 4.9. Illustration of Protection of Center Phase to Single Circuit Structure

For a double circuit configuration there is no "center phase" as shown in Figure 4.9; thus, the possibility of a penetration and shielding failure is zero.

Some arrangements of higher phase order lines may have an equivalent center phase. However, in actuality the stroke leader tip dimensions can be shown to be such that only very low current strokes, incapable of causing a flashover, can penetrate, and the problem is of significance only on very large structures associated with UHV.

Summary

1. This comparison has been for a standard double circuit 3-phase 138 kV line with an 80 kV phase-to-ground voltage versus a 6-phase compacted line with the same phase-to-ground voltage.
2. The smaller size of the 6-phase line will reduce the number of strokes terminating on the line.
3. Stroke for stroke, the backflashover rate of the two types of line will be very similar for any given level of phase-to-ground insulation. Loss of supply may be more likely with a single 6-phase line compared to a double circuit line if single phase switching is not used.
4. Design for zero midspan flashovers is equally obtainable for the two types of line.
5. Design for zero shielding failures is equally obtainable for the two types of line. However, if unshielded lines are used or if shielding failures do occur, the 6-phase line will have more multiphase flashovers than the double circuit line.

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5.0 ELECTRICAL ENVIRONMENTAL EFFECTS

Electric Fields

Electric field intensity at ground level can be an important design criterion for 3-phase transmission lines at the higher EHV (or UHV) levels. At 115-230 kV, electric fields have not been a significant factor. However, previous studies have indicated increases in field intensity at high phase orders.⁵⁻¹ To explore the electric field intensities for high phase order lines, the basic configurations of Figures 3.8 and 3.9 were analyzed. These configurations are illustrated below in Figures 5.1 and 5.2.

Figure 5.1. 6-Phase Lines ($\sqrt{3}$ -ft Phase Spacing)

Figure 5.2. 6-Phase Lines (3-ft Phase Spacing)

For twelve phases, the additional phases were symmetrically interposed between the conductors of the 6-phase array at the appropriate potential locations. The results of calculations of maximum conductor surface gradients and maximum ground level field gradients are summarized in Table 5.1 and Figure 5.3.

Table 5.1

Electric Field as Function of Phase Order
Symmetrical Conductor Array
(Configuration V, Figure 5.2 for 6-phase)

80 kV Phase-to-Ground Voltage

Phases	Max. Surface Field Gradient (kVp/cm)	Max. Ground Level Field Gradient (kV/m)
3	17.0	0.4
6	14.9	0.7
12	10.5	1.0

Figure 5.3. Ground Level Electric Fields

With increasing phase order, the electric field at the surface of the conductor decreases, while the field at ground level increases. This indicates that corona related phenomena which are related to the electric field on the conductor surface become a lesser concern with higher phase order, while ground level electric effects are increased with higher phase order.

Design of a high phase order line would accommodate a balance between fields at the conductor and those on the ground as is presently done for 3-phase circuit design. The electric fields for Configurations I through VII are shown in Table 5.2, and the ground level field profiles for Configurations V, VI, and VII are illustrated in Figure 5.4.

Table 5.2
Electric Fields for 6-Phase Configurations of
Configurations 5.1 and 5.2

<u>Line-to-Line</u> (ft)	<u>SW's</u>	<u>Configu- ration</u>	<u>Max. Surface Electric Field</u> (kVp/cm)	<u>Max. Ground Level Electric Field</u> (kV/m)
$\sqrt{3}$	0	I	16.5	0.47
$\sqrt{3}$	6	II	17.8	0.27
$\sqrt{3}$	6	III	17.9	0.28
$\sqrt{3}$	6	IV	18.2	0.28
3	0	V	14.9	0.70
3	6	VI	15.8	0.43
3	2	VII	15.9	0.36

The addition of shield wires increases the surface field on the conductors and reduces the ground level field, as expected. The conductor surface gradients are increased up to 10 percent, and the ground level fields decreased as much as 43 percent. The maximum conductor surface field is approximately the same for Configurations VI and VII; however, the difference in ground level field is very significant as shown in Figure 5.4. Either of the shield wire configurations reduces the peak ground level field compared with Configuration V without shield wires. While the profile of the configuration without shield wires and the profile for the six radial shield wires result in the same profile, the field is reduced at all distances for the latter. With

two underslung shield wires, the field directly under the center of the line is minimized, peaking at about 7 feet from the center line. This peak is lower than the peak with six shield wires. Beyond 5 feet from the center line, the double shield wire configuration gives a higher field than does the 6-wire configuration. Beyond approximately 13 feet from the center of the line, the double shield wire configuration results in a higher field than the line without any shield wires.

Figure 5.4. Ground Level Electric Fields

Electric fields under fault conditions are important to the feasibility of applying single pole switching. For Configuration V, one phase at a time is de-energized. In each case, the open conductor(s) are both grounded and ungrounded. The maximum conductor surface field varies from 14.9 kVp/cm with all phases in service to a maximum of 17.0 kVp/cm. Figure 5.5 shows the effect on ground level field. A ground on the open phase results in only a minor effect. De-energization of a lower phase shifts the location of the peak field but does not significantly change the magnitude. De-energization of one of the topmost phases results in the largest increase at the ground.

Figure 5.5. Ground Level Electric Fields

The 55 percent increase in maximum field on the ground may be an important factor in line design if single pole phase switching is applied. The small variation in electric field for one conductor open and unfaulted as compared with the same conductor grounded can be explained by examining the results of Section 3. In Section 3, it was shown that an open, unfaulted, conductor with no reactive compensation had a coupled voltage of about 4 kV compared to the 80 kV normal line-to-ground voltage. This coupled voltage is nearly ground potential relative to effect on the field profile.

Figures 5.6 through 5.13 compare ground level electric field profiles for 3-, 6-, and 12-phase lines of the same phase-to-ground voltage for a range of voltages from 80 kV phase-to-ground (138 kV 3-phase) through 442 kV phase-to-ground (765 kV 3-phase). Also shown are curves for two 3-phase double circuits with the same phase-to-phase system voltage as the single 3-phase circuit and phasings of ABCABC or ABCCBA. One phasing yields better line current balance, the other lower ground level fields. The conductor heights above ground were based on typical 3-phase circuits with the same phase-to-ground voltages. No shield wires were assumed. The 3-, 6-, and 12-phase lines have the conductors equally

spaced around the same radius circle. The double circuit 3-phase circuits are also a circular configuration, but the radius of the circle is larger to allow the same phase-to-phase spacing as the initial single 3-phase circuit.

In each of Figures 5.6 through 5.13, five curves are plotted showing:

- Single 3-phase line
- 6-phase line
- 12-phase line
- Two 3-phase lines, phasing ABC-ABC
- Two 3-phase lines, phasing ABC-CBA

for system voltage levels from 80 kV phase-to-ground through 442 kV phase-to-ground (138 kV through 765 kV 3-phase phase-to-phase). In each case, the conductor size was determined for a conductor surface field of 23.5 kVp/cm for the single circuit 3-phase arrangement. The single conductor per phase is an equivalent representation for bundled conductors at the higher voltages, and the calculated results are the same as would be obtained if bundled conductors were represented. As noted before, the conductor surface gradient decreases with an increase from six to twelve phases.

Each curve shows an increase in ground level field intensity as the number of phases increase from three to six to twelve. The 12-phase line and the two 3-phase circuits with phasing for low unbalance (ABC-ABC) have approximately the same peak magnitude. Note that the 12-phase curves show higher fields at greater distances from the center line.

For the 289 kV phase-to-ground (500 kV 3-phase phase-to-phase) case, two conductor spacings were analyzed. Increasing the radius of the circle of conductors reduces the field cancellation and results in a higher electric field at ground level. For this voltage level, curves are also given for 10- and 20-foot increases in conductor height above the initial elevation and illustrate the decrease in ground level field.

These results illustrate the general trend in increasing ground level electric fields with an increase in number of phases. The highest field levels (i.e., for 12 phases) are in the same order as two 3-phase circuits with phases arranged for minimum current unbalance.

Figure 5.6. Ground Level Electric Fields

Figure 5.7. Ground Level Electric Fields

Figure 5.8. Ground Level Electric Fields

Figure 5.9. Ground Level Electric Fields

Figure 5.10. Ground Level Electric Fields

Figure 5.11. Ground Level Electric Fields

Figure 5.12. Ground Level Electric Fields

Figure 5.13. Ground Level Electric Fields

Radio Noise

The radio noise performance of a 6-phase line was investigated and the results are shown in Figures 5.14 through 5.16. Line Configuration V (Figure 5.2) was analyzed as two 138 kV 3-phase circuits. The radio noise profile is illustrated in Figure 5.14. The same conductor configuration was then analyzed as a 6-phase line. As shown in Figure 5.15, changing the line to six phases without changing the physical structure of the line results in a decrease of about 8.6 dB in the peak radio noise. This is due to reduction in the peak conductor surface field from 19.86 to 14.87 kV/cm.

A more meaningful comparison with the 3-phase line is obtained by reducing the 6-phase conductor spacing to $\sqrt{3}$ feet, to reflect the reduced phase-to-phase voltage with the increased phase order. The radio noise profile for this 6-phase line is shown in Figure 5.16. Radio noise increases about 2.4 dB over the 6-phase case of Figure 5.15, but is still 6.2 dB less than the two separate 3-phase circuits. The peak conductor surface field gradient is 16.50 kV/cm.

This comparison illustrates an improvement in radio noise performance in higher phase order circuits compared with two 3-phase circuits having the same number of conductors.

Figure 5.14. Radio Noise Profile

Figure 5.15. Radio Noise Profile

Figure 5.16. Radio Noise Profile

Audible Noise

An investigation of audible noise from a 6-phase line was made for the same three cases as for radio noise. The same trends were observed as for radio noise, which is logical since both phenomena are functions of the conductor surface electric field. Audible noise profiles are shown for the three cases in Figure 5.17.

Under heavy rain conditions, a single 6-phase circuit has a noise level of 12.1 dB less than two 3-phase circuits. Reducing the phase spacing of the 6-phase circuit to 1.73 feet increases the noise 7.3 dB, but is still a 4.8 dB improvement over the two 3-phase circuits.

As for radio noise, high phase order results in a reduction of conductor surface electric field which results in an improvement in the line audible noise performance.

Audible noise calculations require a number of assumptions based on experimental work. Experimental work specifically oriented to high phase order lines is necessary to confirm the validity of present assumptions or determine the proper assumptions for audible noise analysis.

Figure 5.17. Audible Noise
(3-ft Phase-to-Phase Circular Array)

REFERENCES

- 5-1. H. C. Barnes, L. O. Barthold, High Phase Order Power Transmission," presented by CIGRE SC 31, ELECTRA, No. 24, 1973, pp. 139-153.

6.0 HARDWARE AND EQUIPMENT

SYSTEM COMPONENTS

The functional requirements of hardware and equipment are essentially the same as for conventional transmission systems with some minor variations. This section briefly examines the individual component status.

Transformers

Six-phase transformation requires a second set of 3-phase phasors shifted 60° . This can be obtained by a 3-winding transformer with wye windings or a combination of wye and delta windings. Similarly, if individual transformer banks for each set of phases are required, the banks can be either 2-winding wye connected (or one auto connection and one wye connected), or banks of wye and delta combinations. For 12- or higher phase order systems, delta windings are necessary. In general, insulation levels comparable to presently operating 3-phase systems of the same phase-to-ground voltages are applicable although the balance in insulation levels as a function of normal voltage between phase-to-ground and phase-to-phase may change. Delta windings are presently available through the 345 kV 3-phase voltage_level (i.e., for systems of 199 kV phase-to-ground). It is probable that higher voltage delta windings can be designed and produced if required.

Multiple secondary phases in a single unit (either single or 3-phase primary winding transformers) are presently manufactured for rectifier application. Therefore, there is experience in such designs, although higher voltages than those generally used in rectifier applications are required. Higher voltages, at least through the equivalent of 199 kV phase-to-ground, appear practical at present.

Circuit Breakers

Multiple phase breakers can be assembled by ganging single phase units or by ganging 3-phase units. With presently achievable limits of contact closing and opening between individual 3-phase breakers, it appears possible to apply conventional 3-phase breakers. Common trip signals would be required for certain faults. Specific applications of individual breakers with common trip signals must be further investigated, particularly relative to evolved faults.

However, the option of ganging available breakers of single-phase design (normally air or gas) is presently practical and has the added benefit of single phase switching. Therefore, circuit breakers present no problem to application of higher phase orders.

Surge Arresters

Conventional arresters can be applied to high phase order systems using conventional insulation coordination concepts. Comparable ratings to those applied to presently operating 3-phase systems of the same phase-to-ground voltages are applicable.

Current Transformers and Potential Transformers

Conventional CT's and PT's are applicable with characteristics and insulation levels comparable to presently operating devices on 3-phase systems of the same phase-to-ground voltages.

Station Buswork, Disconnect Switches, Hardware, etc.

The buswork can be more complex in a high phase order substation than a 3-phase substation primarily where bus crossovers are required. However, this is not a severe limitation, and the trend to gas-insulated substations, particularly at the higher voltages, will reduce the difference in complexity.

Disconnect switches and other substation hardware are conventional. Phase-to-phase insulator spacers may be required both in the line and bus. The new fiberglass/composite materials are particularly attractive for this application; and, while geometric shapes specific to high phase orders have not been fabricated, basic feasibility has been shown. This includes limited application experience through 230 kV, 3-phase. Therefore, while development and test work remain to be done for insulator spacers, the technology is available.

INSULATION REQUIREMENTS

Terminal Insulation Requirements

The insulation of terminal transformers, capacitor dividers, switches, etc. is determined by the protective characteristics of properly applied surge arresters. The surge arrester application is dependent upon the sustained voltages impressed on the arresters and the duty imposed on the arresters by system transient voltages.

Specific system applications may require analysis of special problems such as dynamic overvoltages due to switching line/transformer combinations or load rejection.

In a generalized analysis, particularly in comparing high phase order systems with conventional 3-phase systems, lightning and switching surges must be considered.

The lightning response of a high phase order system is not significantly different from 3-phase systems as discussed in Section 4. The higher surge impedances inherent in high phase order lines (i.e., Table 3.1 indicated increases of approximately 10, 15, and 30 percent in surge impedances for 6-, 12-, and 24-phase lines respectively) enhances the arrester protective margin for both lightning and switching surges as illustrated for the equivalent circuit of Figure 6.1.

- Z_s is line surge impedance
- R_{sa} is equivalent impedance of S.A.
- V_s is equivalent surge voltage
- V_{sa} is protective level during surge current flow

Figure 6.1. Equivalent Circuit for Analysis of Overvoltage Protection

From this circuit:

$$I_s = \frac{V_s}{Z_s + R_{sa}}$$

and

$$\begin{aligned} V_{sa} &= I_s R_{sa} \\ &= V_s \left(\frac{R_{sa}}{Z_s + R_{sa}} \right) \end{aligned}$$

From this equation, it is evident that an increase in Z_s will result in a decrease in V_{sa} (i.e., a better protective margin).

Phase-to-ground switching surge levels at high phase orders will not change significantly from the 3-phase system values. This is illustrated in Table 4.1 for a 6-phase system. However, in per unit of phase-to-phase system voltage, phase-to-phase surges become more important. These can be accommodated by slight increases in minimum phase spacings and/or phase-to-phase application of surge arresters.

From the foregoing, high phase order systems will impose lightning and switching surge duties on surge arresters which are similar to 3-phase system requirements. Therefore, surge arresters can be applied by conventional techniques.

Arrester ratings are selected based on sustained overvoltages during phase-to-ground faults. The sustained overvoltage must be equal to or less than the arrester rating.

Figure 3.18 shows the calculated voltage rise for this fault condition as a function of the system X_0/X_1 ratio. For a representative high phase order line configuration, Figure 3.7 illustrates the line X_0/X_1 ratio. From these figures, representative fault overvoltages can be obtained as a function of phase order. Using these values and a range of switching surge protective levels from the ANSI "Guide for Application of Valve-Type Lightning Arresters for Alternating Current Systems," Table 6.1 was calculated. This table assumes a minimum switching surge protective margin of 15 percent. From this table it can be seen that, although the minimum insulation levels for high phase order systems are in some cases higher than for the comparative 3-phase system, the difference is small, and they are typical of insula-

tion levels presently applied. Therefore, conventional insulation levels may be used and protected by arresters normally applied at these system voltages.

Table 6.1
Representative Basic Lightning Insulation Levels
as a Function of Phase Order

System Voltage (Phase-to-Ground) (kV, Max.)	System Phase Order	Basic Lightning Insulation Level kV (BIL) (See Note 4)	
		Minimum	Maximum
83.72	3	450	450
	6	450	550
	12	450	450
	24	450	450
139.72	3	650	750
	6	750	900
	12	750	900
	24	650	750
209.00	3	900	1050
	6	1050	1050
	12	1050	1050
	24	1050	1050
317.55	3	1425	1425
	6	1550	1675
	12	1425	1550
	24	1425	1425
461.89	3	1925	2050
	6	2050	2175
	12	1925	2175
	24	1925	2175

Notes:

1. Surge arrester ratings based on fault overvoltages.
2. Line parameters calculated assuming no shield wires.
3. Insulation based on switching surge coordination.
4. Minimum and maximum arrester protective levels based on "Guide for Application of Valve-Type Lightning Arresters for Alternating Current Systems (Including Revised Appendix A, 1972)," ANSI C62.2-1969.
5. For reference, the phase-to-ground voltages correspond to phase-to-phase voltages on a 3-phase system as follows:

Phase-to-Ground	Phase-to-Phase (3-Phase)
83.72	145 kV
139.72	242
209.00	362
317.55	550
461.89	800

7.0 TRANSMISSION LINE MECHANICAL CONSIDERATIONS

Mechanical design considerations are primary to application of high phase order technology. These affect such items as structure design, minimum conductor spacing attainable (and hence the improvement in space efficiency with high phase order), and right-of-way requirements. An important adjunct is the application of insulator spacers between conductors to increase the degree of compaction permissible.

Structures

The design of structures capable of carrying the load of a high phase order circuit is presently feasible. An illustration of a possible wood pole design is shown in Figure 7.1. A possible fiberglass/composite insulator design for use at 6-phase is shown in Figure 7.2 with all members in tension. This was designed in conjunction with Ohio Brass and is considered to be feasible although a number of other designs are also possible, some of which may be simpler. The outer periphery insulator consists of a single piece with clamps attached for the conductors. This design is suspended from the tower and is likely applicable at voltages through 230 kV. At higher voltages, insulator arrays mounted on the top of the supporting structure with some insulation members in compression may be more applicable.

Figure 7.1. Potential 138 kV High Phase Order Structure

Figure 7.2. Possible 6-Phase Insulator Design

Conductor Spacing

To obtain the benefits of increased utilization of transmission corridor space, the line conductor spacing is reduced with phase order as the phase-to-phase voltage decreases for constant phase-to-ground voltage. This process is limited by motions of the individual conductors due to ice, wind, and fault currents. The degree of limitation will require careful subsequent investigation.

Ice is of concern under both static and dynamic conditions. The application of unequal loads to the different conductors in a single span caused by different amounts of icing is commonly used by utility engineers in determining the vertical distance allowed between conductors. In addition to this static condition, which frequently is applied in conjunction with switching surge clearances, a dynamic condition of motion caused by the release of ice from a span is also important. Because of the relative probabilities involved, 60 Hz withstand distances should be used for analysis of dynamic motion. The static and dynamic criteria customarily give comparable minimum vertical conductor spacings. In a compact high phase order circular array, some conductors are directly above others, and ice motion analysis is necessary. In addition, ice buildup on high phase conductor arrays (similar to buildup on bundled conductors) must be considered.

There are several possible wind induced motions. The maximum conductor blowout under wind is of importance in determining right-of-way width required for a specific line. In addition, for compact designs, differential blowout due to wind gusting is important. Although differential blowout is usually small in comparison with the total blowout, for the closely spaced conductors of high phase order lines, clearances may be sufficiently reduced to result in flashover. Aeolian vibrations of conductors are the same as for conventional 3-phase lines. Because of the small spacings involved at high phase orders, wake-induced oscillations, currently observed only with bundled conductors, may be significant. Galloping of conductors under certain conditions could be a serious problem for the large number of conductors in close proximity. Insulator spacers may be required in such cases.

Conductor motion may also be caused by fault currents. This occurs as a result of current flow in a line due to a fault on a different line ("through fault"). The magnetic forces from the fault current can cause conductor oscillation, possibly reducing clearance sufficiently to cause flashover of the unfaulted circuit.

As an example of motion limitations, consider a 6-phase 138 kV phase-to-phase system as shown in Configuration V of Figure 5.2 with:

- DRAKE conductor at conventional stringing tension
- 10 kA fault current for 20 cycles (backup time)
- Galloping prevented by spacers
- Electrical clearances required are 16 inches for 60 Hz, and 36 inches for switching surge

Table 7.1 shows horizontal and vertical clearances required for the above conditions for several span lengths.⁷⁻¹ From the table, for a 400-foot span, assuming no galloping, all criteria are met except horizontal motion due to fault currents. If the fault current is reduced, all the criteria can be met. Longer spans are possible if insulator spacers are used. Mechanical requirements do not limit the high phase order concept; however, mechanical design analysis and tests are needed before construction of a prototype line.

Table 7.1
Mechanical Motions of 6-Phase Compact Circular Array
(Configuration V, Figure 5.2)

Criteria	Minimum Spacing (ft) Needed for				
	200-ft Span	400-ft Span	600-ft Span	800-ft Span	1000-ft Span
Ice Shedding Clearance-- Vertical	1.5	3.0	4.8	6.5	8.5
Static Ice Clearance-- Vertical	4.2	5.2	6.2	7.0	7.4
Vertical Galloping	6.0	10.5	17.2	7.0	7.9
Vertical Motion due to Fault Current	3.9	5.1	5.7	6.0	6.2
Horizontal Galloping	4.5	6.3	9.0	7.1	7.7
Horizontal Motion due to Fault Current	4.2	6.3	7.5	8.4	9.0

Design Clearances: for Configuration V: Vertical 5.2 feet
Horizontal 3.0 feet

Insulating Spacer Dimensions

The following discussions assume reasonably conservative values for spacer characteristics, taken from prototype units already evaluated. The length of insulating spacers will be primarily determined by contamination requirements. For heavily contaminated areas, a value of 1.5 inches/kV rms creepage is representative. From available data, a reasonable value of creep is 3 inches creepage per 1 inch of spacer length. End fittings 6 inches long are assumed, and include some form of damping mechanism such as neoprene inserts. The units are mounted at 45° angles as shown in Figure 7.3. For compression strength, the units may be mounted in pairs.

Figure 7.3. Angle Mounting of Spacer

Table 7.2 lists phase spacings for:

- a) Heavy contamination (1.5 inches/kV rms)
- b) Moderate contamination (1.0 inches/kV rms)

Table 7.2
Spacer Limited Phase Spacing

Phase-to-Phase Voltage (kV)	Creepage-inches		Spacer Length-feet		Phase Spacing-feet	
	(a)	(b)	(a)	(b)	(a)	(b)
115	173	115	5.8	4.2	6.6	3.3
138	207	138	6.8	4.8	5.1	3.7
230	365	230	10.6	7.4	7.8	5.5
345	518	345	15.4	10.6	11.2	7.8
500	750	500	21.8	14.9	15.7	10.8
765	1148	765	32.9	22.3	23.6	16.1
1050	1500	1050	42.7	30.2	30.5	21.6

These results are plotted in Figure 7.4. As can be seen from the figure, a phase-to-phase clearance of 3.7 feet is required for 138 kV phase-to-phase voltage and moderate contamination. For the 80 kV phase-to-phase 6-phase examples cited earlier, a moderate contamination clearance of about 2.75 feet is required, less than the 3 feet which was used.

Figure 7.4. Phase-to-Phase Spacing Determined by Spacers

REFERENCES

- 7-1. Transmission Line Reference Book, 115-138 kV Compact Design, EPRI, 1977.

8.0 ECONOMICS

Two basic considerations of economic feasibility are installed line costs and installed substation costs. Both must be considered on a comparative basis, however, since reliability is an inherent parameter in economic analysis. While these areas indicate feasibility, detailed studies of the reliability/economic interface are necessary for both specific applications or detailed considerations of applications of higher phase order lines. Such studies include present worth assessments in addition to installed costs.

Line Costs

An algorithm for comparison of 138 kV line costs is developed in Reference 8-1. This method considers all labor and material costs (1976 data) for construction but does not include right-of-way, materials overhead, or interest during construction as these latter costs can vary widely in both treatment and actual value. Using the referenced method, three variations in 138 kV line configurations as shown in Figure 8.1 were costed. The system performance (i.e., tripout rate, etc.) is comparable for each alternative. Following is a summary of parameters for the three structure variations.

General

- Transverse loading equivalent to 60 mph wind, no reduction due to wind effectiveness factor ($\alpha = 1.0$)
- Vertical loading equal to weight of conductor with 1/2 inch of ice
- Vertical (weight) span equal to 1.5 times horizontal (wind) span
- 18 percent of UTS at 60°F final for sag-tension
- Sag for ground clearance at 120°F
- DRAKE conductor:
 - 795 kcmil ACSR 26/7
 - 1.108-inch outside diameter
 - 1.094 pounds/linear foot bare
 - 2.0938 pounds/linear foot with 1/2 inch of ice
 - 0.831 pounds/linear foot pressure of 60 mph wind on bare conductor
- Shield wire is 7 No. 7 Alumoweld
 - 0.433-inch outside diameter
 - 0.330 pounds/linear foot bare
 - 0.910 pounds/linear foot with 1/2 inch of ice
 - 0.325 pounds/foot pressure to 60 mph wind on bare conductor

- Shield angle is 30° for shield wires
- Average span length is 90 percent of the lowest of the following:
 - a) maximum span allowed by pole strength
 - b) maximum span allowable without violating ground clearance (assumed as 28 feet)
 - c) maximum span that may be supported by the crossarm(s) if applicable
 - d) maximum span allowed by the strength of the insulator
- Pole setting depth is 10 percent of pole length plus 2 feet
- Conventional double circuit:
 - pole - 65 feet high
 - average span - 296 feet (limited by pole strength)
 - insulators - horizontal porcelain posts, length = 59 inches (with load limiters)
- Compact double circuit:
 - pole - 60 feet high
 - average span - 236 feet (limited by pole strength)
 - insulators - horizontal porcelain posts, length = 59 inches (with load limiters)
- 6-phase:
 - pole - 45 feet high
 - average span - 441 feet (limited by pole strength)
 - insulators - composite/fiberglass (similar to Ohio Brass Hi*Lite design)

The results of the installed cost analysis are shown on Figure 8.1 as \$116,000 per mile, \$105,000 per mile, and \$96,000 per mile for conventional double circuit, compact double circuit, and 6-phase respectively. This indicates that 6-phase transmission line construction costs can be very competitive with both conventional and compact 3-phase at 138 kV. Preliminary estimates indicate there should also be cost advantages through EHV.

Figure 8.1. Comparison of Installed Costs

Substation Costs

A simple substation configuration for a 3-phase 80 kV phase-to-ground system (138 kV phase-to-phase 3-phase) ring bus is shown in Figure 8.2. The rating is 400 MVA (200 MVA per transformer bank). An approximate equivalent (from load flow and reliability considerations) for a 6-phase system (80 kV phase-to-ground system voltage) is also shown in Figure 8.2. Both alternatives meet the following criteria:

- either source(s) must be capable of feeding either line with one breaker failure (open or closed)
- full power transfer (i.e., S_1, S_2 to L_1, L_2) is required with one breaker failure (open or closed)
- in case of breaker failure, disconnect switching (dead bus) to accomplish the foregoing is permissible.

All equipment is conventional. The circuit breakers for the 6-phase alternative could be either single pole devices (i.e., air or gas) ganged to switch as a 6-phase unit (with capability to decouple into 3-phase units in contingencies) or two conventional 3-phase breakers (i.e., air, oil, or gas). Single pole operation could also be an option on those breakers with such capability. Because of the added buswork, disconnect, and relaying complexity, a 35 percent premium is assigned to the 6-phase circuit breaker position multiplier. It is further assumed that autotransformers are applied where possible. At these voltage levels, 3-winding transformers are frequently applied, which would decrease any differential between the two costed alternatives. Approximate costs of each alternative are given in Table 8.1.

A. 3-Phase Substation

B. 6-Phase Substation

Figure 8.2. Substation Configurations for Economic Comparisons

Table 8.1
Costing Alternatives

3-PHASE SUBSTATION

Quantity	Item	Unit Cost (\$k)	Installation Multiplier	Transportation to Site (\$k)	Total (\$k)
9	40 kV phase-ground Breaker Positions	23	2.5	--	517.5
2	80 kV phase-ground/40 kV phase-ground autotransformers	340	2.0	40	1,400.0
4	80 kV phase-ground Breaker Positions	51	2.5	--	510.0
	TOTAL				2,427.5

6-PHASE SUBSTATION

Quantity	Item	Unit Cost (\$k)	Installation Multiplier	Transportation to Site (\$k)	Total (\$k)
9	40 kV phase-ground Breaker Positions	23	2.500	--	517.5
1	80 kV phase-ground/40 kV phase-ground transformer	470	2.000	20	960.0
1	80 kV phase-ground/40 kV phase-ground autotransformer	340	2.000	20	700.0
3	80 kV phase-ground Breaker Positions	51	3.375	--	516.375
	TOTAL				2,693.875

The comparison illustrates an installed cost differential of approximately 11 percent, essentially in transformation costs. This difference, which can vary significantly based on substation configuration, size, and operational assumptions, is not of the order to be a limit to high phase order transmission, particularly if right-of-way power density and esthetic considerations are paramount.

REFERENCES

- 8-1. Transmission Line Reference Book, 115-138 kV Compact Design, EPRI, 1977.