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Transmission Line Compaction Using High Phase Order Transmission

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A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering

Degree awarded with distinction on 8 December 1998

Johannesburg, 1998

Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the university of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Jacob Bortnik

2nd day of APRIL 1998

Abstract

This report discusses high phase order (HPO) technology, i.e. the use of more than the conventional 3 phases for transmission of electric power, its use in the compaction of lines, and power density maximization over existing servitudes. It is structured in four parts. The first part introduces the concepts, establishes the need, and lists the advantages of HPO. The second part deals with the technology itself and shows that it is possible to analyze HPO systems using symmetrical component analysis, lists common transformer configurations, covers protection, and so on. The third part analyses 5 case studies, the first 3 being analytical, and the last 2 being the first experimental test line, and the world's first utility application of HPO lines.

The final section is a South African case study and compares an HPO line to an existing 400 kV 3-phase line and shows that the former is 87.5% more expensive to implement than the latter. Comparing the 3-phase and 6-phase lines on a more even basis, yielded a breakeven distance of 225.86 km, above which the 6-phase option becomes more economical. These results are then explained and discussed in the conclusions section.

Acknowledgments

I would like to thank first and foremost my supervisor, Prof. J. P. Reynders for his unfailing support and encouragement. He has been not only a supervisor, but a mentor, teacher, and colleague. Despite his busy schedule, I have never yet had the experience of being turned away from his door! For that, I wish to express my deepest and sincerest gratitude.

Secondly, I wish to thank Jim Stewart of PTI incorporated in the US. He has not only done by far the majority of the research in HPO (as can be seen from the references section), but has helped me by sending whatever documents I asked for, suggesting reading, and offering continuous liaison and support.

I would then like to thank Frans Ritky for his costing my transmission towers, Lawrence Ryan for helping me with substation costs, and Keith Plowden for being sharp as an arrow with any type of transformer information under the sun.

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1. Introduction

High phase order transmission (HPO) is defined as the use of more than the conventional 3-phases for the transmission of electric power, and was initially proposed in 1973 by Barnes and Barthold[1] as a means of compacting transmission lines, maximizing the power density in a given right-of-way (ROW), and generally employing existing transmission corridors as efficiently as possible. Subsequently, a great deal of work in this field has been performed by researchers such as Stewart and Guyker (see numerous references at the back of this report) who have taken the concept of HPO from a concept, to the implementation stage and the first utility demonstration project in Binghamton NY.

More recently, ESKOM (South Africa's sole electric energy provider) has commissioned an extensive literature survey into the current status of HPO technology worldwide, any recent developments in the field, and the applicability of HPO transmission in the South African context. This report is summary of the literature survey, and extends the current knowledge of this technology in South Africa by investigating a complete case study of a HPO line built in South Africa, at the present economic climate, compared to the most advanced.(and cheapest) 3-phase technology currently available.

The report is structured in four parts: principles behind HPO technology, the technology itself, a survey of case studies, and the first South African case study. The first part asks whether there is indeed a need for a new technology, and what are the criteria for such a technology. The basic principles are then introduced and it is shown how switching to 6-phases leads to line compaction. HPO technology offers a number of other advantages such as minimal current unbalances, ability to perform single pole switching, field mitigation, minimization of corona related effects, aesthetic appeal, complete compatibility with existing 3-phase systems, and in some cases a distinct economic benefit. These are listed and briefly discussed.

The second section deals with the technology of HPO transmission itself, and answers questions such as: How does one analyze faults on HPO systems? How does one interface this system to a 3-phase lines? Are transformers available and how can they be connected to achieve 6-phases (if at all)? Is protection expected to be a problem? and so on. Other aspects of the technology are also covered, such as switching and lightning surge performance, load flow studies, insulator and spacer designs, available software and analysis using existing software, and definitions regarding HPO technology such as a convention for system voltage, and potential coefficients.

The third section analyses 5 case studies which have been performed worldwide to date. The first 3 are analytical case studies and demonstrate where the economic strength offered by this system lies, whereas the last 2 case studies discuss the first test line constructed in Malta, NY, and finally the first utility demonstration which is a joint project between PTI, ESEERCO, and NYSEG.

The last section discusses the author's work in studying an existing South African line, and the economics of converting this line to 6-phase transmission. In addition, a general case is considered where a 3-phase line and 6-phase line are compared and a breakeven distance is obtained beyond which 6-phase transmission becomes the more economic option. This analysis is rather involved and a full discussion follows of the results obtained, as well as additional factors which have not been taken into account and the reasons for this decision.

The report ends with a comprehensive conclusion which places the document into perspective, discusses the most relevant conclusions, and provided reasons and explanations for the various results obtained. A general comment from the author is included which gives suggestions about the implementation and status of HPO transmission in South Africa at present, and its potential role in the future.

2. Principles of High Phase Order Transmission

2.1 The need for a new technology

It is common knowledge that electrical loads throughout the world are rapidly increasing and placing an ever-growing strain on existing transmission systems. In the US for example, the current transmission system was primarily constructed during the years of rapid expansion following World War II, and is approaching what is typically considered the end of its normal service life of 40 years.

It is clear then, that for many reasons (none the less of which are the increasing remoteness of generation from load centres, and the need for interchange capability to obtain maximum benefit from diversity and reserves[13]) the electrical infrastructure is heading for a period of extensive change, and in 1991[15] the addition of 13 000 circuit miles was planned[5]. However, during this post war period, several factors have come into prominence which significantly complicate the erection of new lines: firstly, the greatly increased, and sometimes prohibitive cost of land needed for the transmission corridors, and secondly is an opposition from the public itself, focusing on electrical environmental effects such as electric and magnetic field levels, and their alleged carcinogenic and pathogenic effects, as well as land use and aesthetic concerns.

The overall result was to delay or even prevent the addition of new transmission capacity. This is particularly true in the North-Eastern United States, where it can take between 3 and 7 years from the start of licensing of a new transmission facility until it is finally placed in service[13].

With the huge time lags involved, the ever growing demand for electric power and severe constraints on land availability and electrical environmental effects, it becomes essential to make a close examination of the efficiency with which right-of way (ROW) is being used, and any steps that can be taken to increase it while holding adverse effects in check..

In their classic 1973 paper[1], H. C. Barnes and L. O. Barthold were faced with the same questions and as a possible solution proposed a complete return to fundamentals: a reconfiguration of the basic philosophy with which power was being transmitted.

Their argument went as follows:
The flow of electromagnetic power at any point in space can be universally described by the Poynting vector as:

$$\mathbf{S} = \mathbf{E} \times \mathbf{H} \qquad \text{...(2.1-1)}$$

Where
$\mathbf{S}$[1] = Power density [Watts/m^2]
$\mathbf{E}$ = Electric field intensity [V/m]
$\mathbf{H}$ = Magnetic field intensity [A/m]

and the total power flowing through some plane (say for instance, the plane perpendicular to the transmission line) is:

$$P = \int_X \int_Y \mathbf{S}\, dx\, dy \qquad \text{...(2.1-2)}$$

with X and Y extending to infinity in both negative and positive directions.

[1] Please note that by convention, all vectors will be written in bold, capital letters.

Now, **E** and **H** are related by the impedance of free space Z_0 (377Ω), and the electric field intensity **E** has a natural limit at the electric breakdown strength of air, approximately 3MV/m. This implies that **H** is also limited, and thus there is only a limited amount of power that can be sustained by the air medium, under standard conditions.

This is:

$$|S| = |E \times H| = E.E/Z = (3\times10^6)^2 / 377 = 9\times10^{12} / 377$$

$$= 24 \text{ GW/m}^2 \quad \text{peak}$$
$$= 12 \text{ GW/m}^2 \quad \text{RMS}$$

Theoretically, the entire width of the ROW should have a power density at, or very near this limit to make optimal use of the available transmission corridor. In practice, however, densities of this magnitude are only approached very close to the conductor's surface.

Barnes and Barthold[1] go on to give a qualitative estimate of the efficiency of space utilization, by saying:

> *"Densities of this magnitude are approached only very close to the surface of conductors in traditional transmission line construction. It is estimated that on typical 3 phase lines, over 95% of the energy stored in the field surrounding a conductor is contained within a radius equal to 5% of the phase-phase spacing."*

This being the case, it seems that to increase the power transferred in a given servitude, it would be logical to fill that space with as many conductors - placed as closely together - as possible. This is precisely what the above authors proposed and until this day forms the logical basis for HPO transmission.

2.2 Concept of HPO Transmission

2.2.1 Three Phase Transmission

Traditionally, electricity has been transmitted in 3-phase, AC mode. This means that both the voltage's and current's instantaneous magnitude varied with time in the shape of a sinusoidal wave - commonly referred to as one phase. To complete the circuit, 2 other phases are added whose voltages and currents are displaced from each other by 120 electrical degrees. This is known as a 3 phase circuit, and the waveforms along with the associated phasor diagram are shown in fig. 2.2.1.a.

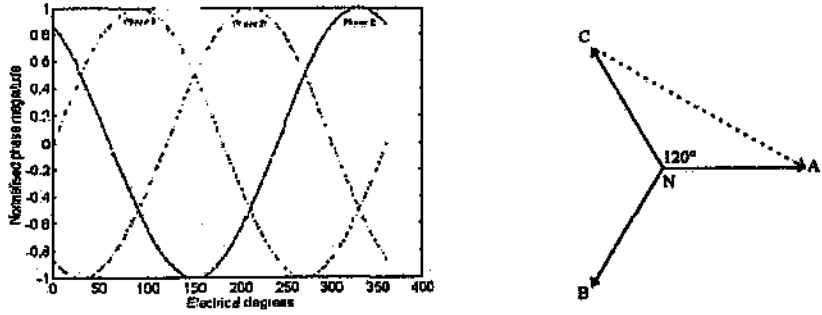


Figure 2.2.1.a: 3-Phase Waveform and Associated Phasor Diagram

This scheme had several advantages over other existing systems. Firstly, AC transmission is superior to DC because of simpler and cheaper generation, transformation, and ease of switching. Single phase transmission has the disadvantage of pulsating power which has undesirable effects on electrical generator prime movers, requiring them to likewise deliver energy at a non-uniform rate. Two phase transmission moves away from this problem, and actually achieves a steady power flow, however, it is a naturally unbalanced system and requires the neutral conductor to carry $\sqrt{2}$ times the phase current. A 3-phase system delivers constant power to the load and is completely balanced, meaning that the neutral conductor can be of lighter construction than a phase conductor, as it carries no current under normal (balanced) operating conditions. A 3-phase system also has superior material utilization compared to the lower phase order systems, and is the lowest and simplest of the N-phase, N+1 wire systems (where N>3) to achieve the above advantages[27] . It has thus been the scheme of choice for transmission line designers worldwide.

2.2.2 High Phase Order Transmission

High phase order transmission (HPO) requires the number of phases to be extended from the original 3, to 6, 12 or above (these being multiples of 3 to accommodate integration into an existing 3 phase network). The waveforms for a 6-phase system along with the associated phasor diagram are shown below.

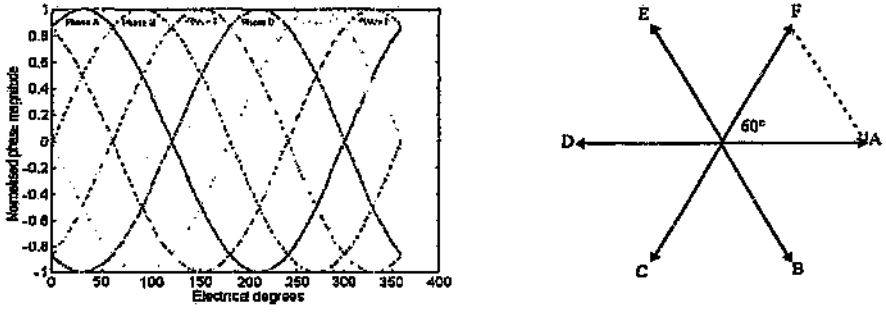


Figure 2.2.2.a Six-Phase Waveform and Associated Phasor Diagram

Gross[27] shows that material utilization remains constant for an N-phase system (N>3), so where do the benefits lie? The key to this question lies in the phase-phase voltage of the two systems. It can be geometrically shown that the phase-phase voltage in the 3-phase system is $\sqrt{3}$ times the phase-ground voltage. In a 6-phase system, the phase-phase voltage reduces to (equalling) the phase-ground voltage, and in a 12-phase system, this voltage is reduced to 2.Sin(15°) times the phase-ground voltage (approximately a half).

The benefits of an increasing phase order are thus readily apparent. The higher the number of phases, the smaller is the phase-phase voltage (assuming constant phase-ground voltage), and thus, the smaller is the phase-phase spacing. That means that it is possible to squeeze an ever increasing number of conductors into a servitude comparable to that of an existing 3-phase system, with a resultant dramatic increase in power density.

This is precisely what Barnes and Barthold[1] had in mind when they first suggested the use of HPO technology in line compaction. In addition, by arranging the conductors in a circular array, they achieved the most natural and compact HPO configuration that would utilize corridor space optimally.

Figure 2.2.2.b., reproduced from Reference [2] shows a size comparison of a 3 and 6 phase tower.

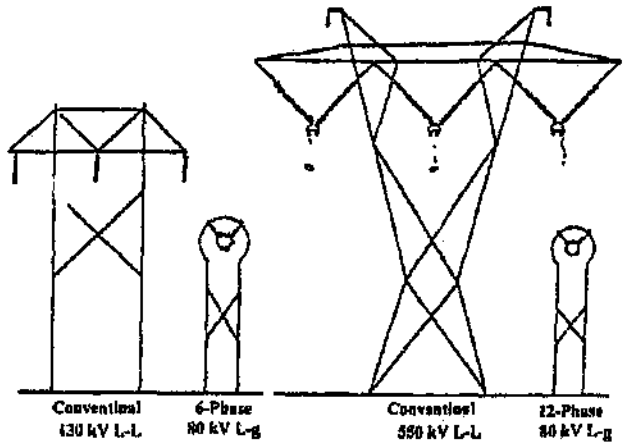


Figure 2.2.2.b Comparison of Conventional 3-Phase and Conceptual HPO Structures (Ref[2])

2.3 Generic Advantages of HPO Transmission

Clearly, the first and foremost advantage of HPO transmission is, as stated above, the maximization of power density and line compaction. This has formed the basis of many studies[1,8,10,11,12,13], and has been shown to be the most efficient method of electric power transmission in the air dielectric at low frequencies (50-60 Hz)[21]. Besides compaction, HPO transmission offers several other benefits, which are gaining importance due to tightening environmental controls, and public outcry. Some of these are listed below.

2.3.1 Current Unbalance

A simple system consisting of generator, transformers, 80 mile transmission line, and a load was studied to gain insight into the degree of current unbalance on the line, as well as negative sequence currents occurring in the generator for both 3 and 6 phase systems[2]. It was found that for both 3 and 6 phase systems, negligible generator negative sequence currents were produced. The line current unbalance, however, was nearly 4% when energized as 3 phase, but fell to below 0.5% for 6 phase. With 6 shield wires, the HPO array had a 0.02% unbalance. Without shield wires, the unbalance was still below 0.05%, but with 2 shield wires (representing the most unbalanced situation), the figure rose to 0.35%. With a full "roll transposition", the unbalance reduced to 0.1% for the 2 shield wire case, and under 0.01% for the other 2 cases.

2.3.2 Single Pole Switching

The 6 phase array can be switched as either a 6-phase circuit, two 3-phase circuits, or one phase at a time[7]. The latter has a tremendous benefit in that only 1 phase can be taken out during a fault, while keeping all the others energized. The remaining 5 phases are able to carry 83% of the load for a period of hours[2,7], due to low unbalances (discussed in section 2.3.1). This provides a high degree of reliability through resistance to transient faults[5]. In addition, electric field profiles of the line were obtained, when a single phase was de-energized in various positions, and with the de-energized conductor either floating or grounded[2]. This showed that electric fields on the ground were highest when the topmost conductor was de-energized and lowest when the bottom conductor was de-energized, whether the conductor was grounded or left floating made little difference on the profile.

Voltage levels developed on the open phase due to interphase coupling with shunt reactance[3] were also investigated, and showed a resonance at 105% compensation of positive sequence capacitive reactance. However, it is maintained that reactor configurations could be designed to alleviate this potential problem, and that single phase switching is both achievable and very beneficial.

2.3.3 Field Mitigation

The circular geometry of HPO lines promotes a large degree of field cancellation. This has been studied in numerous papers where 3 phase and HPO were designed to the same SIL capacity and electric field profiles were plotted using standard analytic software (such as EMTP), to reveal significantly improved profiles from the HPO lines[2,5,11,12,16].

Magnetic field profiles are also significantly reduced and are dealt with in a separate paper on the topic[14]. This can be explained by the fact that as one increases the number of phases, the array begins to look more and more like a cylinder, with net zero current flow, and hence zero magnetic field.

2.3.4 Corona Related effects

Perhaps the most dramatic effect of switching to a circular HPO array, is the sharp decrease in surface electric field gradient, and related effects. An 80kV (phase-ground) circular array was studied first for a 3, and then 6 phase energization without changing the physical structure. In changing from 3 to 6 phases, radio noise decreased by 8.6 dB, audible noise decreased by 12.1 dB, and peak surface electric field gradient changed from 14.04 to 10.51 kV_{RMS}/cm. A more meaningful comparison for HPO was to shrink the phase-phase spacing by a factor of $\sqrt{3}$, and this again yielded improvements of 6.2 dB for radio noise, 4.8 dB for audible noise, and 11.7 kV/cm electric field gradient[2]. Another practical study[3] shows that a change in energization for a 6 conductor array from a double circuit 3 phase, to a single circuit 6 phase, reduced total corona loss on that line from 2046W to 338W per conductor.

2.3.5 Aesthetics

The smaller more compact bundle is reported to be far more attractive in appearance, and poses far less of a visual intrusion than conventional lines[5,10,13].

2.3.6 Compatibility

High phase order lines are perfectly compatible with the existing 3 phase network. This has been not only theoretically predicted, but shown in practice at the test lines in Malta and Binghamton, NY[5,6,8,16,17,18,19,20].

2.3.7 Economic Benefit

Due to the smaller, lighter structures of high phase order lines, the line cost itself is below that of a conventional 3-phase line, however, the added phases require additional transformers and circuit breakers. Previous economic studies[5,6,9,10,11] have attempted to balance these 2 effects in a given economic climate, and derive a break-even distance for which 3 and 6 phase lines cost equal amounts. While the break-even distances are generally very favourable (6-35 miles depending on the operating voltage and loading levels) it is surprising to note that ROW costs (which are the prime motivators for HPO, or any compaction technology) have been excluded from the economic analysis due to their highly variable values.

2.3.8 Other Benefits

There are several other benefits which have not been included above, but nevertheless are noteworthy. The whole system is more stable, and gives a more damped response to transient events on the network[16], as well as a greater angular margin to instability[33]. Then, HPO lines operate at a lower voltage than their 3 phase counterparts, and give better matched ampacities to existing equipment. This is extremely beneficial in countries that do not have the technology to design and manufacture their own EHV equipment.

Having established a basis for HPO transmission, it becomes necessary to ask some practical questions regarding actual equipment, transformers, protection, analytic techniques, etc. applicable to HPO lines; whether these exist or can be developed. This forms the topic of the next section.

3. High Phase Order Technology

The development of any new technology brings with it many practical questions, and high phase order is no exception. It is necessary to establish definitions and nomenclature, then develop analytical tools and methodologies for line design. Finally, it is necessary to examine how a HPO line is practically implemented within a 3-phase network, including elements of protection and sub-station layout.

This section aims to do precisely that. It develops the technology gradually, starting from a "pen and paper" - type approach and proceeds right through to the "nuts and bolts". Where applicable, appropriate theory and design procedures will be given, however, since it is not the explicit aim of this project to develop a design guide, this will be briefly covered and not elaborated upon further, with references given for the interested reader.

3.1 Definitions and Analytical Tools

3.1.1 System Voltage Definition

To begin with, it is necessary to establish a system voltage for HPO lines (in order to obtain an intuitive feeling for capacities, insulation levels, and so on.) but this is not as trivial a matter as with 3-phase lines. Classically, the 3-phase system voltage is given as the phase-phase voltage of the line, but if this is applied to HPO lines, several problems arise. Firstly, the phase-phase voltage between any 2 phases in a 3-phase system is constant ($\sqrt{3}$ times the phase-ground voltage) whereas in a 6-phase systems for example, this can be 1, $\sqrt{3}$, or 2 times the phase-ground voltage. The number of possible combinations obviously increases with increasing phase order. If the phase-phase voltage is restricted to adjacent phases only, then the problem arises that the phase-phase voltage decreases relative to the phase-ground voltage with increasing phase order, and does not properly reflect the necessary insulation levels - especially at the higher phase orders.

Another alternative is to define the system voltage as the voltage of the constituent 3 phase sets. While this is a more familiar nomenclature to transmission line engineers, it again lacks significance with respect to spacing and insulation requirements, particularly beyond six phases.

A third option is to use the phase-ground voltage as the system voltage. This strikes a comfortable balance between insulation requirements and power capacity. It has thus been the chosen nomenclature for high phase order researchers, and is the definition used throughout this document.

3.1.2 Potential Coefficients and Line Constants

Potential Coefficients in a transmission system give a very important measure of the geometry of the system, and directly influence capacitance, inductance, and surge impedance of the line.

If a circular array of conductors is considered, each conductor being of radius r, and spaced equally around a circle of radius R, with the reference conductor at the bottom (as shown in figure 3.1.2.a), then the voltage on conductor A (V_a) due to the charge on conductor n (Q_n) is:

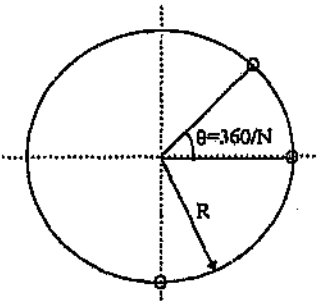


Figure 3.1.2.a Circular Array of N-Conductors

$$V_a(Q_n) = \frac{Q_n}{2\pi\varepsilon}\ln\left(\frac{R}{D_{an}}\right) \qquad ...(3.1.2\text{-}1)$$

Where:

D_{an} = Distance from conductor a to conductor n [m]

ε = Permittivity of the medium, in this case air $\approx 8.85 pF.m^{-1}$

Further,

$$D_{an} = 2RSin\left(\frac{\theta_{an}}{2}\right) \qquad ...(3.1.2\text{-}2)$$

where

θ_{an} = Angle between phase a and phase n

$$Q_n = Q_a Cos\theta_{an} \qquad ...(3.1.2\text{-}3)$$

Substituting (3.1.2-2) and (3.1.2-3) into (3.1.2-1) gives:

$$V_a = Q_a \times \frac{1}{2\pi\varepsilon}\left\{\ln\left(\frac{R}{r}\right) + \sum_{n=1}^{N-1} Cos\left(\frac{2\pi n}{N}\right)\ln\left(\frac{1}{2}Co\sec\left(\frac{\pi n}{N}\right)\right)\right\} \qquad ...(3.1.2\text{-}4)$$

or,

$$V_a = \frac{Q_a}{2\pi\varepsilon}[P_a] \qquad ...(3.1.2\text{-}5)$$

Where

$$P_a = \ln\left(\frac{R}{r}\right) + \sum_{n=1}^{N-1} Cos\left(\frac{2\pi n}{N}\right)\ln\left(\frac{1}{2}Co\sec\left(\frac{\pi n}{N}\right)\right) \qquad ...(3.1.2\text{-}6)$$

Equation (3.1.2-6) represents the positive sequence potential coefficient of the N-phase array. It consists of a "self term" and a "mutual term", the former depending only on its own geometry, and the latter depending only on the number of phases. Thus, at higher phase orders (>9) P_a increases almost linearly with increasing phase number as the mutual term becomes dominant (the opposite being true for lower phase orders).

The calculation of capacitance and inductance follows directly,

$$C = \frac{2\pi\varepsilon}{P_a} \qquad ...(3.1.2\text{-}7)$$

$$L = \frac{\mu P_a}{2\pi} \qquad ...(3.1.2\text{-}8)$$

and the surge impedance (i.e. the effective impedance experienced by an infinitely high frequency or step with infinitely fast rise-time) is:

$$Z_s = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \cong \sqrt{\frac{L}{C}} \qquad \text{for large values of } \omega$$

$$Z_s = \sqrt{\frac{\frac{\mu P_a}{2\pi}}{\frac{2\pi\varepsilon}{P_a}}} = \sqrt{\frac{\mu}{\varepsilon}}.P_a \qquad ...(3.1.2\text{-}9)$$

Thus, surge impedance is directly proportional to the potential coefficient, and consequently the number of phases for a HPO system (n>9)

In the same manner, the electric field at the surface of the conductor can be calculated from standard electrostatic theory as:

$$E_n = \frac{Q_n}{2\pi\varepsilon r} \qquad ...(3.1.2\text{-}10)$$

but

$$Q_n = C_n.V_n = \frac{2\pi\varepsilon V_n}{P_n} \qquad ...(3.1.2\text{-}11)$$

therefore

$$E_n = \frac{1}{P_n.r} \qquad ...(3.1.2\text{-}12)$$

Where:

E_n = Electric field gradient at the surface of conductor n [V/m]
Q_n = Electric charge on conductor n [C]
P_n = Potential coefficient of conductor n [m/F]
ε = Permittivitty of the medium - free space in this case = 8.85pF/m

Thus, for the same conductor radius, surface gradient diminishes for increasing phase order. The actual characteristic (of surface gradient plotted against phase number) is hyperbolic and is due to the fact that P_n is proportional to phase number (for n>9), and consequently E_n is inversely proportional to n. The lowered surface gradient leads directly to lower corona levels, and hence lowered corona related effects (such as radio interference, audible noise, and corona loss) discussed in section 2.3.4.

Finally, the surge inpedance loading of the line is given as:

$$P_s = \frac{NV^2}{Z_s} = \frac{NV^2}{\sqrt{\mu/\varepsilon}.P_n} \qquad ...(3.1.2\text{-}13)$$

Where:

V = Phase -ground voltage [V]
N = Number of phases
μ,ε = Permeability and Permittivity of the medium [H/m],[F/m]

This shows that the SIL power is directly proportional to the number of phases. However, since P_n also becomes proportional to the number of phases at high phase orders (N>9), the SIL tends to gradually flatten off as N increases. This shows a practical concern, and indicates that the most beneficial HPO systems are in the lower range, i.e. either 6 or 12.

3.1.3 Fault Analysis of HPO Systems

The subject of fault analysis on HPC networks is very large, and forms the topic of numerous papers and reports[2,3,7,15,16,19,22,23,24,25,26,30,31,32,33,35,36,39,40]. It has the potential to quite comfortably fill several MSc theses, and it is for this reason that this topic will be presented only briefly, with references to the various subjects given for the interested reader.

3.1.3.1 Fault Types

To begin with, the number of fault combinations rises very quickly with the number of phases. Table 3.1.3-a compares the number of fault combinations for a 6-phase system as opposed to a conventional 3-phase system[19,36,39].

Six-Phase Fault Combinations

Fault Type	Total Number of Combinations	Significant Number of Combinations	Faulted Phases for Significant Combinations
Six phase	1	1	a-b-c-d-e-f
Six phase to neutral	1	1	a-b-c-d-e-f-n
Five phase	6	1	a-b-c-d-e
Five phase to neutral	6	1	a-b-c-d-e-n
Four phase	15	3	a-b-c-d, b-c-e-f, a-b-e-f
Four phase to neutral	15	3	a-b-c-d-n, b-c-e-f-n, a-b-d-f-n
Three phase	20	3	b-d-f, a-b-d, a-b-f
Three phase to neutral	20	3	b-d-f-n, a-b-d-n, a-b-f-n
Two phase	15	3	a-b, a-c, a-d
Two phase to neutral	15	3	a-b-n, a-c-n, a-d-n
Single phase to neutral	6	1	a-n
Total	120	23	

Three-Phase Fault Combinations

Fault Type	Total Number of Combinations	Significant Number of Combinations	Faulted Phases for Significant Combinations
Three phase	1	1	a-b-c
Three phase to neutral	1	1	a-b-c-n
Two phase	3	1	b-c
Two phase to neutral	3	1	b-c-n
Single phase to neutral	3	1	a-n
Total	11	5	

Table 3.1.3-a: Fault Combinations on 3 and 6 Phase Networks

As can be seen, the table is differentiated into a "total number of combinations", and "significant number of combinations". This distinction comes about due to the fact that faults fall neatly into several "types" based on the phase angle between faulted phases. For example, consider a two-phase fault that does not involve the neutral; there are 15 possible fault combinations, but these are grouped into: a short between adjacent phases, a short between alternate phases, and one between opposing phases - corresponding to angular separations of 60°, 120°, and 180° between faulted phases. Whether the actual faulted phases are a-b, b-c, c-d, etc. is irrelevant since the analysis and protection all proceed in exactly the same way[19,39].

Another level of complexity is added, though, when several faults occur simultaneously on the network. This can take the form of several phase-phase faults, in any combination with several phase-phase-ground faults. This requires a far greater amount of analysis, and is a topic which typically does not present itself as a serious problem in 3 phase networks. Although moving slightly beyond the scope of this work, it should just be said in passing that this problem has been extensively analyzed by Bhat and Sharma[31], who have devised a very elegant "method of attack" involving only two matrices labelled the "phase fault coefficient matrix", α, and the "ground fault coefficient matrix", D_1. These two matrices are used in a single equation developed by the authors to analyze any type of fault. Further, the sequence currents, when written in the format suggested in the above work, indicate the method of connecting sequence networks for the simulation of the given fault.

3.1.3.2 Component Transformations and Eigenvalue Analysis

Having obtained the information pertinent to HPO system faults, one must ask the question - how does one analyze the complete profile of current flow, and voltage levels in all phases of the system, simultaneously, for a given fault condition?[2]

This is a question which plagued power engineers since the advent of transmission lines, and has only been satisfactorily answered in 1918, when C.L. Fortescue[43] published his classic paper on the subject. The key to this problem was to be found in the mathematical world, rather than the physical one, and in making the transition, one was able to once again analyze a set of balanced 3 phase systems. The approach has been generalized and is briefly presented below in a mathematical context, after which we will come back to Fortescue's work, it's physical significance, and application to fault analysis.

The most important technique in the analysis of polyphase systems is to utilize a transformation which will decouple the phases. What exactly does that mean?

Let us examine a typical problem:

The voltages and currents at the ports of an n-phase, lossless transmission line satisfy the first order system of partial differential equations:

$$-\frac{\partial E_p}{\partial x} = L\frac{\partial I_p}{\partial t} \qquad \text{...(3.1.3.2-1)}$$

and

$$-\frac{\partial I_p}{\partial x} = C\frac{\partial E_p}{\partial t} \qquad \text{...(3.1.3.2-2)}$$

Where E_p and I_p represent an n-dimensional column vector, and C and L represent an n×n dimensional, capacitance and inductance matrix respectively. Differentiating (3.1.3.2-1) and (3.1.3.2-2) with respect to x and t respectively, and making the appropriate cross substitutions, the system of second order partial differential equations below is obtained:

$$\frac{\partial^2 E_p}{\partial x^2} = LC\frac{\partial^2 E_p}{\partial t^2} \qquad \text{...(3.1.3.2-3)}$$

$$\frac{\partial^2 I_p}{\partial x^2} = CL\frac{\partial^2 I_p}{\partial t^2} \qquad \text{...(3.1.3.2-4)}$$

Now, to solve this problem a technique called "the method of characteristics" is applied, but requires that the matrix on the right hand side of the above equations be diagonal. We thus seek some transformation matrix Q, for voltage and current, so that $E_p = QE'$ and $I_p = QI'$. Substituting into equation (3.1.3.2-3) gives:

$$\frac{\partial^2 E'}{\partial x^2} = Q^{-1}LCQ\frac{\partial^2 I'}{\partial t^2} \qquad \text{...(3.1.3.2-5)}$$

[2] It should just be noted that this analysis applies strictly to system frequency faults. Lightning and switching surges will be dealt with in a subsequent section

For a balanced, transposed, three phase line (say), the inductance matrix L, the capacitance matrix C, as well as their product LC, have a special form which is written symbolically as:

$$E_p = \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \begin{bmatrix} a & b & b \\ b & a & b \\ b & b & a \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \alpha . I_p \qquad \text{...(3.1.3.2-6)}$$

Using the transformation to diagonalise α, we write:

$$E' = Q^{-1}E_p = Q^{-1}\alpha I_p = Q^{-1}\alpha . QI' = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} I' \qquad \text{...(3.1.3.2-7)}$$

The mathematical treatment proceeds from this point on and is beyond the scope of this text. Suffice it to say though, that the problem has been reduced to a standard eigenvalue problem, with the matrix α composed of the eigenvectors, corresponding to the diagonal matrix of eigenvalues λ as shown below:

$$\alpha I_p = \lambda I_p \qquad \text{...(3.1.3.2-8)}$$

Setting the determinant of α-λ equal to zero (i.e. $|\alpha-\lambda| = 0$) gives a set of 3 meaningful (non-trivial) solutions. This treatment however, imposes several constraints on the structure and nature of the transformation matrix Q[30].

Nevertheless, these restrictions do not uniquely define Q, which leads to the application of several transformations, namely Clarke's transformation, Park's transformation, and the symmetrical component approach. In 1943, Edith Clarke proposed the additional constraint of setting element (3,2) = -1×(3,3), which leads to a symmetric Q, unitary transformation and hence, $Q=Q^{-1}$ and $Q=Q^{T}$. A closely allied transformation was developed by R. H. Park, which relied on the rotation of stator quantities to align them with rotor co-ordinates, d and q, allowing the third current to be interpreted as a "stationary" current, which is proportional to - and conceptually not unlike the zero sequence current of Fortescue's approach. Finally, there is the symmetrical component method. This is the oldest, and most well known of the transformation, and lends itself comfortably to an n-phase network extension. This is the topic of the next section.

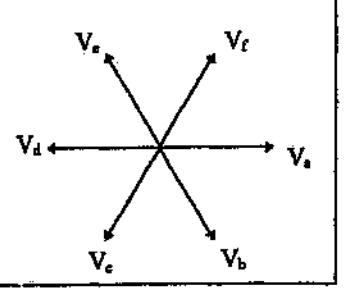
3.1.3.3 Symmetrical Component Analysis of HPO Systems

In 1918, C.L. Fortescue[43] proposed a theorem which stated that an n-phase, unbalanced system of voltage or current phasors could be completely represented by a set of n balanced systems of phasors, where each i^{th} sequence component (i= 0,...,n-1) would consist of a set of n phasors displaced from each other by i×60° in phase.

To apply this theorem to a six-phase system, let the six phases of the original system be a, b, c, d, e, and f, and with a phase rotation of abcdef. The six voltage phasors associated with this system are V_a , V_b , V_c , V_d , V_e , V_f , as shown in figure 3.1.3.a (which are arbitrarily unbalanced).

Figure 3.1.3.b shows the phasor system resolved into its sets of symmetrical components, where the zero sequence set is equivalent to 6 single phase systems, second and fourth sequences equivalent to 2 three phase systems, and so on.

Figure 3.1.3.a: System of Six Voltage Phasors



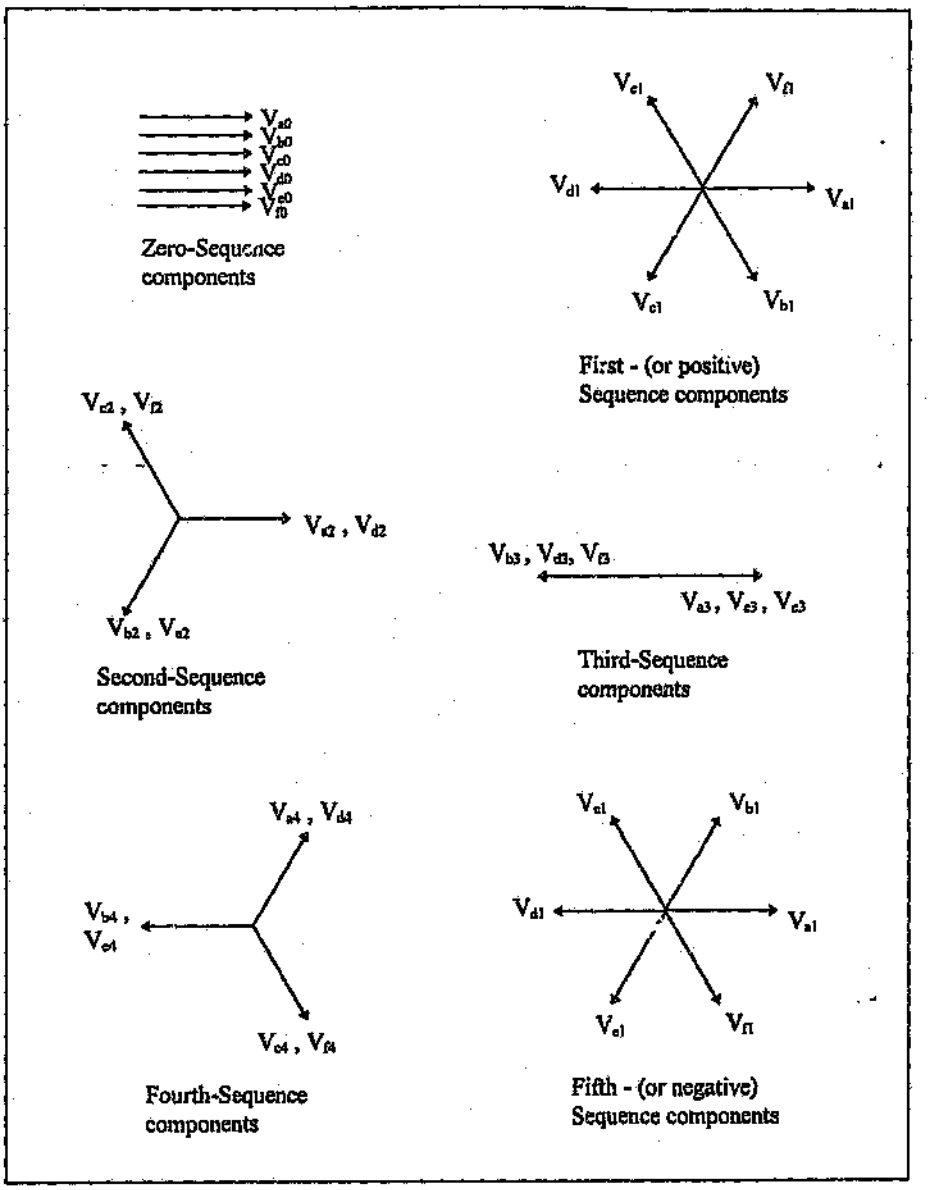


Figure 3.1.3.b: Six balanced sets of Symmetrical Components

The original unbalanced phasors can be represented in terms of their symmetrical components as:

$$
\begin{aligned}
V_a &= V_{a1} + V_{a2} + V_{a3} + V_{a4} + V_{a5} + V_{a6} \\
V_b &= V_{b1} + V_{b2} + V_{b3} + V_{b4} + V_{b5} + V_{b6} \\
V_c &= V_{c1} + V_{c2} + V_{c3} + V_{c4} + V_{c5} + V_{c6} \\
V_d &= V_{d1} + V_{d2} + V_{d3} + V_{d4} + V_{d5} + V_{d6} \\
V_e &= V_{e1} + V_{e2} + V_{e3} + V_{e4} + V_{e5} + V_{e6} \\
V_f &= V_{f1} + V_{f2} + V_{f3} + V_{f4} + V_{f5} + V_{f6}
\end{aligned}
\qquad \text{...(3.1.3.3-1)}
$$

In order to express the above set of sums as a transformation, we note that the phasors of each symmetrical set of components are not independent of each other, but are evenly spaced. We thus define the operator b, as:

$$b = e^{j\alpha 3} = 0.5 + j0.866 \qquad \text{...(3.1.3.3-2)}$$

and note that the various phasors making up each sequence component, can all be related to each other using multiples of the operator b, and hence the set of sums of eq. (3.1.3.3-1) can be written in matrix form as a transformation:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \\ V_f \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & b^5 & b^4 & b^3 & b^2 & b \\ 1 & b^4 & b^2 & 1 & b^4 & b^2 \\ 1 & b^3 & 1 & b^3 & 1 & b^3 \\ 1 & b^2 & b^4 & 1 & b^2 & b^4 \\ 1 & b & b^2 & b^3 & b^4 & b^5 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \\ V_{a3} \\ V_{a4} \\ V_{a5} \end{bmatrix} \qquad \text{...(3.1.3.3-3)}$$

or

$$\overline{V}_p = [T_6]\overline{V}_s \qquad \text{...(3.1.3.3-4)}$$

From section 3.1.3.2, it is readily apparent that $[T_6] = Q$, and we have found the transformation matrix. An added benefit however, is that each of the symmetrical components is a balanced system, and can be analyzed as such, regardless of the original set of phasors which can be arbitrarily unbalanced. To do this, however, there is still one piece of the puzzle which must be put into place - the source impedance of each symmetrical component.

A typical 6-phase line will have some impedance along each conductor, as well as some impedance between conductors which will allow currents and voltages to couple between phases, as shown by the typical impedance matrix below:

$$[Z_p] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} & Z_{ad} & Z_{ae} & Z_{af} \\ Z_{ba} & Z_{bb} & Z_{bc} & Z_{bd} & Z_{be} & Z_{bf} \\ Z_{ca} & Z_{cb} & Z_{cc} & Z_{cd} & Z_{ce} & Z_{cf} \\ Z_{da} & Z_{db} & Z_{dc} & Z_{dd} & Z_{de} & Z_{df} \\ Z_{ea} & Z_{eb} & Z_{ec} & Z_{ed} & Z_{ee} & Z_{ef} \\ Z_{fa} & Z_{fb} & Z_{fc} & Z_{fd} & Z_{fe} & Z_{ff} \end{bmatrix} \qquad \text{...(3.1.3.3-5)}$$

and

$$[V_p] = [Z_p][I_p] \qquad \text{...(3.1.3.3-6)}$$

In general it can be said that impedance is non-directional, and thus $Z_{ij} = Z_{ji}$ for i,j = 1,...,6. Further, if the line is completely transposed[3], then there are only two impedances in the whole matrix - the series impedance of the line which forms all the diagonal elements and remains the same because all phase conductors are assumed to be identical, and the mutual impedance which forms all the off-diagonal elements of the matrix, and will be the same between any two conductors in the whole array due to the full transposition. These two elements are denoted as Z_s and Z_m respectively. It is interesting, and instructive at this point to return to equation (3.1.3.2-6) and observe that $[Z_p] = \alpha$, and the structure is symmetrical as originally assumed.

[3] We will return to this assumption in due time, and establish why full transposition is impractical in HPO lines and what can be done to circumvent this difficulty.

Further, we are now in a position to find the eigenvalues of the system using equation (3.1.3.2-7), which will relate E^s and I^s (i.e. the sequence components E_s and I_s). This equation is rewritten in the present context for clarity:

$$\bar{E}_s = [T_6]^{-1}.\bar{E}_p = [T_6]^{-1}.[Z_p].\bar{I}_p = [T_6]^{-1}.[Z_p].[T_6].\bar{I}_s = [\lambda_6].\bar{I}_s$$

or

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix} = \begin{bmatrix} \lambda_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_5 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} \quad \text{...(3.1.3.3-7)}$$

Thus we have achieved what we set out to do - we have diagonalised the impedance matrix $[Z_p]$ into its eigenvalues by the sheer merit of our transformation; mathematically, all is sound. But let's examine the powerful implications of this operation. Each of the sequence voltages, V_0 ... V_5 , is only dependent on its own, respective sequence current and the impedance which relates them. V_0 for instance, will not be influenced at all by any of the sequence current values (aside from I_0 of course), regardless of their magnitude, phase, and so on. V_0 and I_0 form a complete and independent network, as do V_1 and I_1 , and so on. The phase quantities of the original, arbitrarily unbalanced system, have thus been "decoupled" into 6 balanced, independent systems.

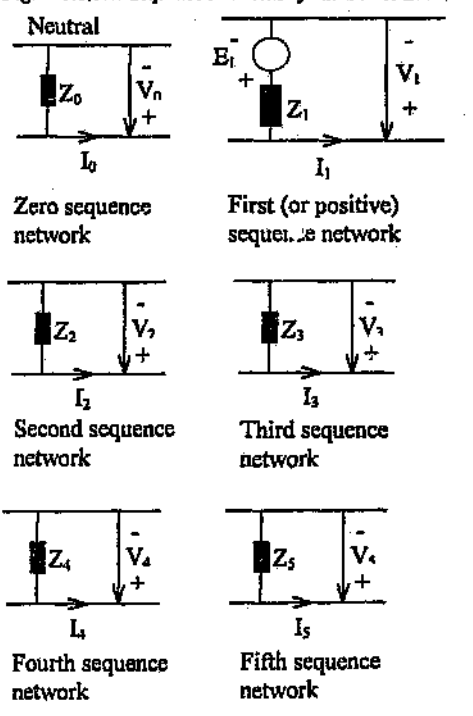
The six sequence networks are shown schematically in figure 3.1.3.c. As was already mentioned, the first or positive sequence network represents the phase voltages under normal, balanced operating conditions. It was thus assumed that the electric generator is completely balanced and contains only positive sequence currents, and is shown on the positive sequence network only as E_1.

Returning to the eigenvalue problem above, it can be shown by standard matrix methods that for an N-phase network there are only 2 distinct diagonal values, namely $Z_0 = Z_s + (N-1).Z_m$ and $Z_1 = Z_2 = Z_3 = \ldots = Z_N = Z_s - Z_m$

The values for a six phase system are thus:

$Z_0 = Z_s + 5Z_m$
$Z_1 = Z_s - Z_m$
$Z_2 = Z_s - Z_m$
$Z_3 = Z_s - Z_m$
$Z_4 = Z_s - Z_m$
$Z_5 = Z_s - Z_m$

Figure 3.1.3.c: Sequence Networks of Six -Phase Lines



Fault analysis proceeds directly from the above treatment. It is assumed that the six-phase line is balanced and unloaded during the pre-fault stage. Then, as soon as the type of fault occurring on the system is established, certain boundary conditions prevail which force various voltages and currents to take on certain values (for example, a bolted short to earth will force voltage on that phase to zero). Using these boundary conditions, the matrix equation can be solved directly (which is often tedious and unnecessary), or the various interconnections of the sequence networks for the specific type of fault can be deduced, and the problem solved using standard network analysis tools. This exercise has been carried out in full, and the equations for all 23 significant fault types are given in references [36] and [39].

While the analysis given above is valid and true for simple faults, a complexity arises due to an assumption made earlier on. In three phase systems, the conductors can be transposed in any sequence while retaining constant magnitudes of line-line voltage between adjacent conductors. In high phase order lines, however, full transposition cannot be made since voltage levels between various conductors vary, and adjacent conductors need to maintain their spatial relationship with each other. The closest we can come to a full transposition is a "barrel" or "roll" transposition, where the entire array of conductors undergoes six, 60° rotations, as opposed to the original 15 step transposition originally proposed by Bhatt et al[35] which would destroy the favourably low line-line voltages.

This type of transposition also results in four unique sequence impedances, and 3 different mutual impedances between phases (corresponding to the 3 different types of displacement between conductors, 60°, 120°, and 180°). It quickly becomes apparent that for line to line faults not involving ground, there are three distinct possibilities (i.e. a can fault to b,c, or d while e and f are repetitions of the previous 2), each having its own interconnection of sequence networks ranging from simple to quite complex. This however, is beyond the scope of this document, and well into the realm of system protection theory.

3.1.3.4 Clarke Transformation

While the theory and derivation of the Clarke transformation will not be entered into, it nevertheless is another analytical tool and is included for completeness. Of course, all diagonalization procedures on the impedance matrix yield the same sequence impedances since the eigenvalues for any square matrix are unique. However, the final condition of Edith Clarke's transformation matrix is different to Fortescue's, resulting in a different set of defining column vectors. For a six-phase line this transformation is given as:

$$[T_{c6}]=\begin{bmatrix} \frac{1}{\sqrt{6}} & \frac{5}{\sqrt{30}} & 0 & 0 & 0 & 0 \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{30}} & \frac{4}{\sqrt{20}} & 0 & 0 & 0 \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{30}} & \frac{-1}{\sqrt{20}} & \frac{3}{\sqrt{12}} & 0 & 0 \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{30}} & \frac{-1}{\sqrt{20}} & \frac{-1}{\sqrt{12}} & \frac{2}{\sqrt{6}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{30}} & \frac{-1}{\sqrt{20}} & \frac{-1}{\sqrt{12}} & \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{30}} & \frac{-1}{\sqrt{20}} & \frac{-1}{\sqrt{12}} & \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{2}} \end{bmatrix} \quad \text{...(3.1.3.4-1)}$$

While this transformation lacks the apparent physical significance of the symmetrical component approach, it nevertheless is a real transformation as opposed to Fortescue's complex transformation where sinusoidal steady state is implicit. This leads to a potential application of the Clarke transformation to transient event analysis on HPO networks.

3.1.4 Load Flow Studies on HPO Lines

To facilitate HPO transmission line planning, or conversion thereto, it is necessary to observe the behaviour of the whole system once the modification has been put into effect. An added challenge is that HPO lines will need to be integrated (at least initially) into an existing 3 phase network, and analyzed as such.

To investigate this topic and develop techniques for load flow analysis, Venkata et al.[38] examined a part of Alleghany Power System (APS) which was still in the planning stages and consisted of 110 busses and 162 three-phase lines and transformers. In this system, there were 8 lines which were identified as potential candidates for HPO upgrading, that were currently configured as 138 kV three-phase double-circuit lines (80 kV phase-ground), and would be modified to operate as 138 kV (phase-ground, or phase-phase), single circuit, six-phase lines, consequently allowing the passage of 73.2% additional power through the existing transmission corridor.

One such candidate line (Charleroi - Lake Lynn) was isolated, and consisted of a point to point link, with one tee-off from each of the two 3-phase circuits comprising the line. This was modelled using two methods. The first, modelled the ' s a complete, single, six-phase line using the nominal π-representation, which resulted in 2 busses alor 'he line (representing the tee-off's), 3 line segments (each having its own π-representation), and two additional busses to accommodate the two-terminal three-phase/six-phase interface transformers, with attendant phase shifting networks. This represented the biggest disadvantage of this type of modelling, since the modelling of the phase shifting network will itself introduce additional busses into the system. In addition, the modifications of the existing line data are relatively complex, and imply major changes and much preparation in the line and bus data before conducting load-flow studies.

To circumvent this problem, the 138 kV six phase line was modelled as two, interleaved 230 kV three phase lines, one operating as the "a-c-e" conductors and the other as the "b-d-f" conductors. If need be, one should keep in mind the 60° phase shift between circuits and build that into the model. The lines were modelled using the nominal π-representation, as though they were independent 3 phase lines. The advantage of this technique over the previous one, is that it is:

1. simpler, straight-forward, and requires only minimal changes in the line data, and
2. allows the use of existing load-flow software, since all the busses are still treated as 3-phase busses.

The second model is thus the preferred method for modelling HPO lines for load-flow studies, in integrated 3-phase systems. In order to preserve the mutual impedance between the conductors in the array, Venkata et al.[Ibid], assumed that each component 3-phase circuit will have an impedance of $2Z_L$ on a per mile, per phase basis, thus avoiding the need for any mutual impedance, although in reality such impedance could be significant since full transposition is impractical in HPO lines.

3.1.5 Computational Aids

Perhaps the most powerful and flexible of all the analytical tools discussed so far is the use of computer simu' on. Between the years 1976-79, Alleghany Power Systems (APS) conducted a joint study with West-Virginia University, which produced as one of its outputs, a program entitled "Electrical Parameters and Performance Characteristics" (EPPC). This program has subsequently been used in many studies, by many researchers, and thus warrants a closer examination.

The EPPC program has been developed in the FORTRAN language, and consists of approximately 2300 lines of code, which make up one main program and nineteen subprograms which are called from the main program and sometimes from another sub-program. The program expects the following data on starting: Number of: phases, circuits, subconductors per phase, and ground wires, then earth resistivity, system frequency, base power (MVA), base voltage and system voltage. In addition, conductor data is required such as horizontal distance, tower height, mid-span height, conductor outside diameter, geometric mean radius, conductor AC resistance, as well as conductor identification.

Once the information has been entered, the program runs through its subprograms in a particular sequence which is summarized in the table below:

Subprogram	*Function*
1. UNTRNP	Calculates line parameters in all forms for the untransposed case, then calls subroutines 2, 3, and 4.
2. SYMUTR	Obtains the sequence components of the line constants
3. TRANSPS	Obtains the parameters for the transposed case
4. CHARAC	Calculates simple, steady-state performance measures
5. UBF	Calculates all sequence unbalance factors for an untransposed three phase, or six-phase line.
6. GRADNT	This subprogram evaluates electric and magnetic field gradients around each phase conductor's surface, and at any point in the transmission corridor including the points along the edge of the tower. It is also called from 1. In turn, it calls 7, 8, 9, 10, and 11.
7. CORONA	Evaluates corona loss along the line
8. ANL	Obtains audible noise profiles
9. YZLINE	Obtains line parameters at a stipulated radio frequency (for HF analysis)
10. ATTENU	Obtains attenuation constants at the above frequency and calls 12
11. RADIO	Computes radio noise profiles
12. MODAL	This sub-program finds the modal propagation constants using a built-in real transformation matrix.
13. FAULT	This is one of the most important subroutines in EPPC, and calculates fault currents and voltages for all 23 significant fault types. It also requires the source impedance behind the two end busses.
14. CMAT	Calculates all forms of the capacitance matrix from the corresponding potential coefficient matrix found in 1
15. RP	Performs rectangular to polar conversions and vice versa
16. EQUI	Reduces the size of a given matrix
17. INVERS	Inverts real matrices
18. INVERC	Inverts complex matrices
19. WRITE	Gives the user an output in the desired form, providing either all the information contained above, or part thereof, thus expediating the analysis

Table 3.1.5-a: EPPC Sub-program Description and Sequence of Execution

In broad terms, the program consists of 2 parts: given the information listed above, the program computes the electrostatic and electromagnetic line parameters of the line using generalised Carson's formulae with the ground wires and earth return effect included. These parameters can be obtained in both actual, and per-unit values, under transposed and untransposed conditions. The second part of the program develops several performance measures such as surge impedance loading (SIL), thermal limit, voltage regulation, corona and copper losses, efficiency and stability limit. In addition, it computes more complex phenomena such as electromagnetic unbalance factors under a given load, conductor surface gradients and gradients at any point in the transmission corridor (including points along the tower edge), audible noise and radio noise profiles, as well as fault currents and voltages for all 23 significant fault types.

The algorithms used in the above sub-routines are in general relatively simple, but do tend to become rather lengthy, and thus will not be listed. The interested reader is advised to consult references [28], as well as [45] and [46] which are the EPPC manual, and HPO design manual respectively.

3.2 *Line Spacing*

The question of how to space the phases of a transmission line is inevitably a complex one which involves many factors, however, there are only 2 basic elements which play an almost exclusive role in determining line spacing, and simplify the analysis greatly while giving an intuitive "feel" to the line designer of the space required and width of ROW needed.

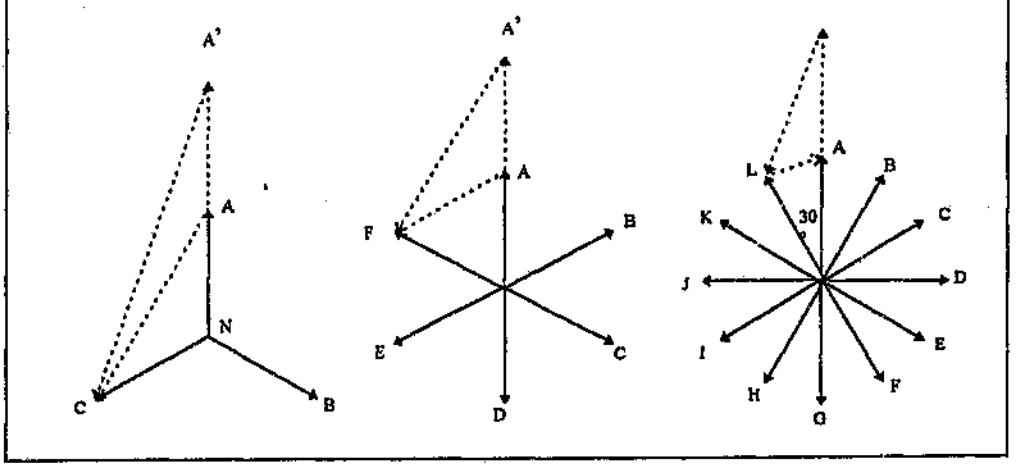
The first element is the steady state voltage of the system. Having this knowledge, and taking into account the pollution levels of the environment one is able to determine the necessary creepage distance, choose the type of insulator to be used, and hence determine the number of units required per string (if ceramic insulators are chosen). The second element is the type, frequency, and severity of transient events on the system. This section begins by examining techniques that have evolved in dealing with such transient events, and their effect on HPO systems, before proceeding to an actual line design example which demonstrates how the two elements combine in producing a line design.

3.2.1 Switching Surges

A switching surge is a transient event in which a high voltage impinges on a circuit for a period of 100's to 1000's of microseconds. This occurs due to a sudden release of previously stored energy by a switching action and can arise from within the circuit or be injected or coupled into the circuit from an outside source. Further, these may be repeatable such as commutation voltage spikes, inductive load switching, transformer energization or de-energization, switch arcing, etc. or random. Whatever the case, these must be considered and their harmfulness on HPO lines assessed.

Consider the example below; if a 2.0 p.u. (of phase to ground voltage) surge occurs on phase A of a 3-phase transmission line, as shown in the diagram below

Figure 3.2.1.a: Effect of Surge With increasing Phase Order



then the phase-phase voltage A'B will be 2.65 p.u. of the phase-ground voltage but only 1.53 times the normal phase-phase voltage. Thus, the highest stress is imposed on the phase-ground insulation (which is proportional to the steady state voltage) in a 3-phase system, which is traditionally the case.

If however, a 2.0 p.u. surge occurred on phase A of a 6-phase or a 12-phase system (as shown in figure 3.2.1.a), then the phase-phase voltage will be 1.73 times the normal phase-phase voltage for a 6-phase system, and similarly 2.39 times for a 12-phase system.

From this simple analysis it becomes clear that as the number of phases increases, the phase-phase surges become increasingly important relative to the phase-ground values. This is further complicated by the fact that it is a HPO objective to reduce clearances as much as possible between phases, and in addition to setting a limit on clearances, phase-phase surges may also set an upper limit to the phase order practically achievable[3].

An extensive switching surge study was conducted on a 6-phase system[4,7] to quantify the above effects and provide a pool of data for further switching surge applications. This required defining the parameters for such a test, as well as the variables.

In a 6-phase system, there are 6 phase-ground voltages, and 15 phase-phase voltages (this rises to 12 phase-ground voltages and 66 phase-phase voltages for a 12-phase system), however, it is possible to group the phase-phase voltages into 3 generic types.

Group I: Consists of all adjacent phases, i.e. AB, BC, CD, etc. with a base voltage = phase-ground voltage

Group II: Consists of all alternate phases, i.e. AC, BD, CE, etc. with a base voltage = $\sqrt{3}$ × phase-ground voltage

Group III: Consists of all opposing phases i.e. AD, BE, CF, etc. with a base voltage = 2 × phase-ground voltage

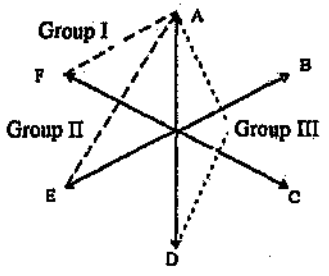


Figure 3.2.1.b: Phase Grouping in a 6-phase System

The following parameters were varied for the study:

- the number of phases (either 6 or 12)
- system voltage (83.7 kV or 462 kV phase-ground)
- line length 16-160 km (for 83.7 kV case) and 40-241 km (for 462 kV case)
- source impedance: 2000-10 000 MVA short circuit for 83.8 kV case, and 10 000 - 50 000 MVA short circuit for 462 kV case
- operation: energizing or reclosing, 6 and 3 pole switching
- circuit breaker pre-insertion resistors (0-1500Ω)

The results of this study revealed that on a per-unit basis of the respective groups' steady state voltage, the maximum surge magnitudes with 500Ω resistor pre-insertion were:

Group I = 2.24 p.u.
Group II = 1.71 p.u.
Group III = 1.72 p.u.

Thus, group I surge magnitudes seem to be the limiting factor in phase-phase spacing. In addition, group II surges were compared to switching surges on a standard 3-phase line[7] to show that with resistor pre-insertion (except for one very unlikely case), switching surges on a 6-phase and 3-phase lines were comparable. Thus, since alternate phases can be spaced in the same manner as the original 3-phase system, interleaving another 3-phase circuit into this system to give a 6-phase system would dramatically increase the capacity of the line, and result in significantly increased power density and line compaction.

3.2.2 Lightning Surges

A lightning surge is a transient event very similar to that of a switching surge, except that it is much shorter in duration (typically a few, to tens of microseconds), and has a very wide range of values, and wave-shapes. More importantly though, due to the fact that the surge is generated by lightning, it can be protected against, and the number of strikes to a particular line can be predicted (if only statistically).

Lightning tripout rates are dependent upon the number of strokes to the line, the ratio of strokes terminating on the tower or shield wire (causing a rise in potential and possible flashover to the line), to the strokes terminating on an actual phase conductor, the number of strokes which are self-extinguishing (i.e. don't sustain a follow-through current) and stroke characteristics.

The number of strokes to the line can be estimated by[47]

$$N = I \times (0.0189 \times h + 0.0047 \times b) \qquad ...(3.2.2\text{-}1)$$

where:

N = Strokes/year/100 miles of line
I = Isokoraunic level in thunderdays/year for the given location
h = Average height of shield wire (including sag)
b = Structure width

For a typical line, the reduced dimensions of the 6-phase line result in a 20% reduction in the number of strokes to the line, as opposed to a similarly rated double circuit 3-phase line.

The voltage across the phase-ground insulation is given by

$$V_{ins} = V_{tower} - (k \times V_{shield} + V_{50}) \qquad ...(3.2.2\text{-}2)$$

where

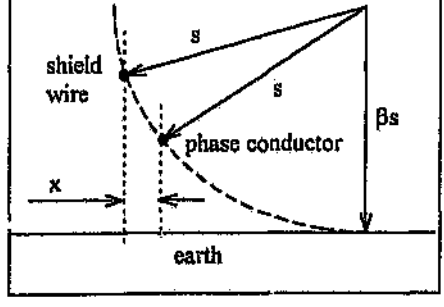
V_{ins} = Instantaneous voltage across the insulator
V_{tower} = instantaneous tower potential, given as the sum of the incident voltage on the shield wire, the reflected voltage back on that span, the transmitted voltage to the next span, the forward wave down the tower, and the reflected wave from the tower ground, i.e. the sum of all travelling waves
k = Coupling constant between shield wire and phase conductor
V_{shield} = Instantaneous shield-wire potential, given as the forward voltage wave coming in from the lightning hit (it is this voltage that couples onto the phase conductor via the coupling constant k).
V_{50} = Instantaneous value of 50Hz phase voltage

The tower surge impedance and travel time will be slightly less for the 6-phase tower, shield wire impedance will be slightly higher due to the closer spacing, V_{50} will remain approximately the same in both cases as will k. Thus, the backflash performance will be very similar.

If a shielding failure does occur, the higher surge impedance of the 6-phase line will cause a higher voltage for the same stroke current, and a resultant greater incidence of insulation flashover. Thus, shielding is crucial and it is recommended that the line be shielded for zero failures.

This can be done using the shielding failure model proposed in ref. [47], which is repeated for convenience in the diagram on the right:

Figure 3.2.2.a: Shielding Failure Model



where:

β = 1.0

s = critical distance = $29.53\ I^{0.65}$ in feet , and

I = return stroke's peak current in kA

This model includes a safety margin to ensure that shielding failure does not occur.

It should be noted that when shielding failure does occur, 50% of faults will be to an adjacent phase conductor rather than the structure, so the probability of phase-phase flashover is much higher on a 6-phase line.

The overall performance of a HPO line, assuming effective shielding, is thus comparable or better than an equivalent double circuit 3-phase line. For unshielded lines, more multiphase failures will occur resulting in a higher tripout rate, however, in some instances this is not considered a significant problem since the single phase tripping scheme will temporarily disconnect only the faulted phases, allowing the remainder of the 6-phases to carry the load.

A computer simulated lightning analysis was performed on the Goudey-Oakdale line[16] (which included a voltage uprating), which resulted in the total flashovers per year for the 2.4 km line decreasing from 0.155 for the 115 kV (phase-phase) 3-phase line, to 0.127 for the 93 kV (phase-ground) 6-phase line.

Using the above procedures, fault voltages as a function of phase order[Table 1, ref 3], as well as a range of protective levels from the ANSI "Guide for Application of Valve-Type Lightning Arrestors for Alternating Current Systems", Stewart and Wilson[3] were able to compile the table of basic lightning insulation levels which is listed below:

System Voltage (phase-ground)	System phase order	Basic Lightning Insulation Level	
kV - MAX		Minimum [kV - BIL]	Maximum [kV - BIL]
83.72	3	450	450
	6	450	450
	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

Table 3.2.2-a: Basic Lightning Insulation Levels as a Function of Phase Order

3.2.3 Line Spacing Example

When spacing a line from a switching surge point of view, surge magnitudes, distribution, and insulation strengths all need to be known. Then, spacing for an appropriate probability of withstand can be computed given the line length and pertinent meteorological conditions[7].

For a 6-phase, 462 kV line:

Energizing surge distribution

Case 50, line receiving end (i.e. location 3 in the table), Table 1 of ref [24] gives:
2% = 1.71 p.u., 50% = 1.45 p.u., max = 1.79 p.u.

Reclosing surge distribution

Case 55, line receiving end, Table I of ref [24] gives:
2% = 2.19 p.u., 50% = 1.62 p.u., max = 2.62 p.u.

These distributions are for a 100 mile line, 25 000 MVA source impedance, and 400Ω resistor pre-insertion. The assumed weather conditions were:

Relative air density = 1.018
Absolute humidity = 7.0 gm/m^3
Relative humidity = 60%

Spacing is then calculated using the algorithms given in reference [48] to yield the following[4]:

Number of phases	Voltage	Phase-phase Switching Surge: Air Gap					
		Energizing distribution		Reclosing distribution		Insulators	
		no damper	damper	no damper	damper	Energizing	Reclosing
6	462	8.4'	9.3'	11.7'	13.0'	8.8'	12.2'
12	462	7.2'	8.0'	14.6'	-	8.8'	16.4'

Table 3.2.3-a: Phase-Phase Spacing Requirements for Example HPO Line

Insulators have the effect of introducing a floating object into the air gap and thus reducing the gap's insulation strength. If the average span length was 500ft (giving a total of 1057 towers), with 6 phase-phase insulators per tower, there would be 6342 insulators in total between the phases. If the maximum switching surge occurred on one third of the line, there will only be 2114 gaps to consider. Choosing a probability of flashover (PFO) of 0.001, the calculation can proceed as in ref 22 (chapter 15, p157). Once again this procedure will not be entered into, but the values obtained were compared with NCI catalogue data and results listed in table 3.2.3-a above.

While it is beyond the scope of this section to go into further detail about line design, mention should just be made that there are many other factors that need to be evaluated before a final spacing can be agreed upon. Some of these are:

- Ice loading: Static displacement of conductors can take place due to unequal ice loading, and dynamic jumps occur when ice buildup is suddenly released from a span.
- Wind: This can cause various effects; differential blowout puts a strain on insulation, and total blowout may necessitate a wider ROW - this is especially prevalent during gusting winds. Aeolian vibrations are set up along the length of the span in a similar way to the 3-phase case. Wake induced oscillations (especially in bundled conductors) could be a problem due to the proximity of compact array structures, and finally galloping could prove a problem due to the large number of conductors in the array.

[4] Please note that the spacings given for air do not take into account phase-phase insulators

- Fault currents: These are notorious for producing differential motion in conductors, and happens as a result of magnetic interaction due to the large zero sequence currents, and "through faults" (a fault on a different line)
- Floating objects: As mentioned above, electrically floating objects that are introduced into the gap tend to decrease the insulating strength of that gap. Unfortunately, these objects are often vital from a mechanical point of view (such as motion dampers or insulators), or from an insulation perspective. This forms the subject of our next topic.

3.2.4 Insulator and Spacer Design

In order to compact the conductor array, it is necessary at times to limit differential conductor motion as much as possible. For this reason, various insulating midspan spacer designs were produced as shown below:

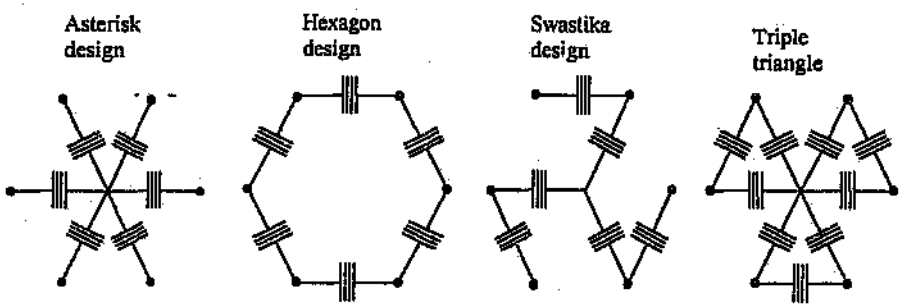


Figure 3.2.4.a: Insulating Mid-Span Spacer Designs

The asterisk is the simplest of the designs, and has the advantage of no phase-phase members. A disadvantage however, is that some insulators are loaded in bending, and adequate rigidity can only be achieved at a significant weight penalty. The next design is the hexagon which has the clear disadvantage of phase-phase components, however, all the insulators in this design are loaded in compression, the structure is more rigid and lighter. The swastika design attempts to blend the advantages of its 2 predecessors, but unfortunately tended do the opposite in practice. The final design was the triple triangle or "civil defense" shape, and while this gave a very rigid structure, it nevertheless contained 3 additional struts and was overly heavy for practical use.

Thus, it seems that the overall best design is the hexagon, which does lower the insulation strength of the air due to its phase-phase members, but is the most economical and lightest of all designs. It should also be noted that non-ceramic insulators have been used throughout the design process due to their light-weight, high strength, good resistance to damage, ease of erection, and pleasing appearance.

Using the above designs and NCI data, Stewart et al[3] were able to derive a table which gave spacer length and creepage distance for heavy and moderate contamination, based on the system voltage, which is an invaluable tool for HPO line designers. It should also be noted, as before, that this type of arrangement prohibits full transposition of the line, as phase relationships need to be maintained. What results is a type of transposition coined "roll" or "barrel" transposition where the entire array is revolved as a whole leading to 4 different elements in the impedance matrix (related to the 4 different phase separations, phase-ground, 60°, 120°, and 180°). This topic was discussed in greater detail in section 3.1.3.3.

3.3 The Protection of HPO Systems

Fault analysis on HPO lines has been extensively discussed in section 3.1.3 and methods presented for evaluating fault voltages and currents for all 23 significant fault types that could occur on the line. Furthermore, various combinations of simultaneous faults have been analyzed by Bhat and Sharma[31] to provide an elegant yet powerful method for dealing with such faults. This section aims to present the actual protection schemes used on HPO lines, and uses the analytical methods discussed previously in the setting of fault current and voltage levels.

We begin by examining the criteria for the protection of HPO systems, how many schemes to apply and the benefits of each option. Then, the question arises of which types of schemes to choose, and especially, which schemes will work best when combines to offer the widest coverage of faults. After deciding how the lines will actually be tripped, i.e. as single phases, two groups of 3 phases each, or one 6-phase circuit, the criteria for tripping are developed, and a full trip logic diagram is presented. The section concludes with a few of the limitations facing today's equipment and how this could be overcome in the future.

It should finally be noted that this section is based on the collaborative work of PTI, NYSEG, and Ebasco Services Inc. for the 2.4km, 6-phase demonstration line running from Goudey to Oakdale, in Binghamton, New York[19]. The trip logic diagram is copied with permission of Dr. J.R. Stewart of PTI, NY.

3.3.1 Protection Criteria

The role of protection in power systems is to detect any faults or abnormalities and initiate action as quickly as possible so that the faulted phase can be isolated and saved from damage. In choosing an arrangement, there is an inherent tradeoff between security and dependability. Dependability refers to the responsiveness of the protection to a fault - it must hence be depended upon to isolate the line if a fault occurs. Security refers to the protection system's ability to discern between a genuine fault which would require immediate and decisive action, and some non-critical event on the line (such as branches of a tree which have been blown too close to the line) which will clear itself in several cycles and requires no action.

Protection arrangements which were investigated for the Goudey-Oakdale line were:

- one out of two arrangement
- two out of two arrangement
- two out of three arrangement

A one out of two arrangement consists of two independent protection systems where the operation of either one will initiate the tripping of circuit breakers. This type of system is very dependable, but decreases the security slightly, in that any small, non-critical faults could initiate a trip. A two out of two arrangement is similar to the above, except that both protection systems must operate before a trip is initiated. While this effectively reduces erroneous trips, it somewhat desensitizes the system and decreases dependability. A two out of three arrangement achieves a very high reliability as both security and dependability are increased. The next task is to choose the 3 types of protection schemes to provide optimum coverage and reliability against faults.

3.3.2 Selection of Protection Systems

Based on the protection criteria laid out above, 3 protection systems were chosen. The primary and backup systems were relay-type, and used a fibre optic communication channel, whereas the third was a non-communication based system, and relied on the apparent impedance of the line to detect faults.

The primary protection scheme employed a pilot-based, current differential relay which has the advantage that it is commercially available, can be used as is, and is invariant to the vectorial displacement of adjacent phases. The scheme uses two current transformers (CT's) at the ends of the line, whose

secondaries are connected to the relaying scheme and a communication channel. Normal load flow, or through faults will present CT secondary voltages of opposite polarity and hence will not operate. Internal faults, on the other hand, will cause secondary voltages of similar polarity at the two terminal CT's and hence actuation of the tripping coils - this will isolate the line from both ends, and will work whether the fault is being fed from either end of the line, or both.

The pilot circuits selected are fiber optic based, and will be phase wrapped on one of the six conductors of the six-phase line. This is preferred to the 2-wire pilot scheme due to the latter's susceptibility to induced EMI.

Back-up (or secondary) protection was chosen to be a fibre optic based segregated phase comparison protection, as above, and utilizing the same physical optic fibre. This scheme compares the phase angle of each phase current, at the beginning and end of the line, and is very similar to the current differential protection scheme above except that it uses phase angle as its measurement parameter. This scheme is connected on the 6-phase side of the CT's at both ends of the line and encompasses its own back-up protection comprised of direct tripping relays in the form of high-set instantaneous overcurrent relays.

The third protection system chosen, was non-communication based and commonly known as a "distance protection". This senses the apparent impedance of the line, that is, the voltage/current ratio and in this way can detect a fault (if the impedance takes on some unstandard value). The art of distance relaying is very complicated and involves a large number of parameters, however, the availability of microprocessor based protection developed for double circuit, 3-phase lines, offers an excellent opportunity for their application to 6-phase lines. This requires the development of a series of algorithms for proper operation, while the actual signals will be supplied from the VT's and CT's located on the 6-phase side of the line.

Although slightly beyond the scope of this project, it should nevertheless be briefly mentioned that transformers will be protected using differential relays with inrush restraint, and distance relays at remote terminals of the line, while busses will be protected as before but with the addition of a back-up ground detection relay.

3.3.3 Fault Types

While the topic of fault combinations has been covered in section 3.1.3.1 and different generic fault types given in Table 3.1.3.a, it should be reiterated that the possible number of significant fault combinations rises from 5 to 23 for a 6-phase line. In addition, the 6 phase-ground voltages, and 15 phase-phase voltages of a 6-phase line will require a total of 21 relays at each end of the line. This is considered to be an excessive number of relay modules, and so it is almost inevitable that micro-processor based systems will be used.

3.3.4 Tripping Options for a 6-Phase Line

Due to the increased number of phases, the line can be tripped out in one of several ways:

- Switching all 6 phases simultaneously
- Switching as two sets of 3-phase lines
- Switching one phase at a time

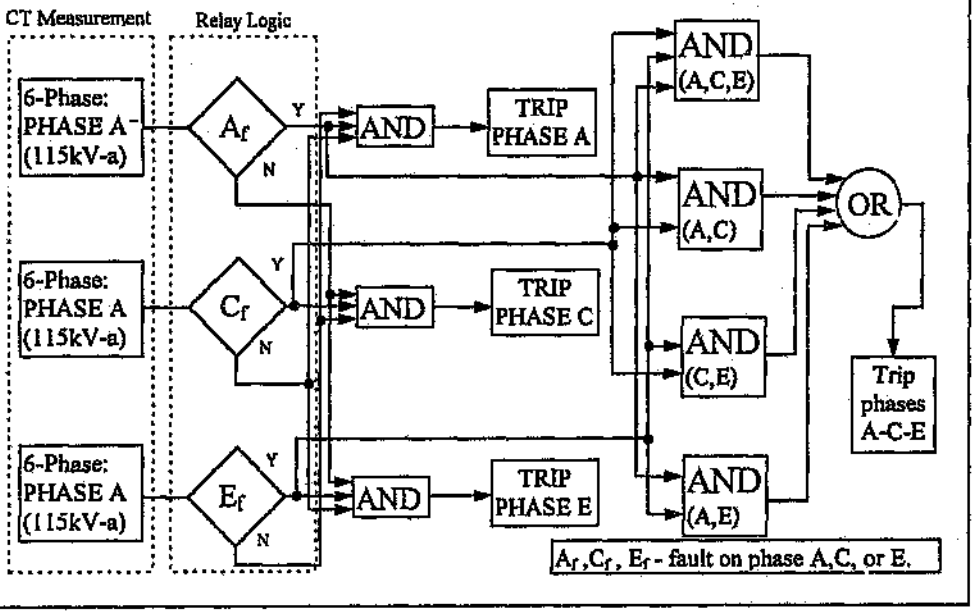
The first option is the simplest and easiest to achieve, but has the disadvantage of generating the largest magnitude surges, and is somewhat unfavourable since only one phase could be temporarily faulted and there would not be any need to isolate the healthy 5 phases. The second option is also easy and economical and has the advantage of retaining symmetrical sets of 3 phasors, however, it too imposes relatively large stresses on insulation and is only cautiously considered. Single phase tripping has the double disadvantage of necessitating processing and decision making for correct operation, as well as generating unbalance currents.

It is the favoured system though, because it allows the remaining 5 healthy phases to carry the load, and imposes far less stress on insulation than the previous 2 methods. It also adds a tremendous element of flexibility for protection engineers which simply cannot be achieved in 3 phase lines; the Goudey-Oakdale line has as one of its main objectives the demonstration of single phase tripping, and transient studies conclude that transient overvoltages thus generated are well with equipment design range.

3.3.5 Criteria for Single Phase Tripping

The trip logic for the 6-phase Goudey-Oakdale line proceeds in the same manner as two independent 3-phase circuits, phases A-C-E, and B-D-F. The diagram below presents the logical flow chart for one of the 3-phase circuits, and is identical for the other, if A,C, and E are replaced by B,D, and F.

Figure 3.3.5.a: Trip Logic Diagram for Current Differential and Segregated Phase Comparison



The logic proceeds as follows: for a single phase-ground fault, the appropriate line shall be tripped out (corresponding to the condition A AND (NOT C) AND (NOT E) = TRUE) and automatically reclosed after a suitable dead time. If the fault is cleared, all protection shall be reset. If the fault is still on the line when the breaker pole closes, then all three phases shall be tripped, and locked out.

For a phase-phase fault on any adjacent phases, the respective poles will be tripped out and reclosed automatically after a suitable dead time (as though they were two single phase-ground faults). If the fault has cleared, all protection shall be reset, and if the fault is still on the line then all 6 phases will be tripped out and no more reclosing will take place.

Single phase tripping will not be attempted on faulted phases that are 120° apart (as indicated on the flow chart), or 180° apart (something which has not been shown in the figure above). If the fault has been contained to the phases of only one of the 3-phase circuits, then only that circuit will be tripped out, leaving the other fully operational, otherwise, all 6 phases will be tripped and not reclosed.

The trip logic diagram for the distance protection has been omitted due to a need for brevity, but follows very much the same logic as the above diagram with only a few minor additions[19].

3.3.6 Limitations of Available Equipment for 6-Phase Protection

While the protection aspect of HPO transmission seems viable, it is nevertheless important to be aware of some crucial differences and take them into account when setting protection levels. Firstly, consideration should be given to the case where one phase is de-energized and the other 5 phases are carrying the load; often, the voltage on the isolated phase will have some non-zero value depending on the load flow in the other 5 phases, and this should not be mistaken for a persistent fault.

Next, the existing double circuit, 3 phase protection does not include many of the fault combinations associated with 6-phase lines, and this can be overcome by modelling the entire line on a phase basis (including neutral shift), to determine all possible fault levels.

Finally, a potential problem is that when a ground fault occurs on one of the 3-phase circuits, it induces zero sequence currents in the parallel healthy circuit which can cause zero sequence directional elements to make incorrect directional decisions. The above is a well documented problem, and a proposed solution is to use negative sequence quantities in making directional decisions, and zero sequence currents only to verify the presence of a ground fault before allowing tripping.

3.4 Transformer Configuration

3.4.1 Preliminaries

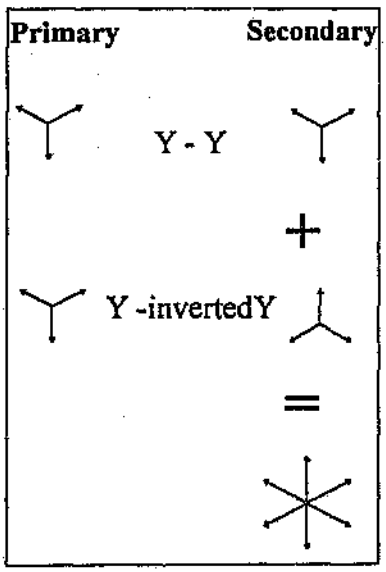


Figure 3.4.1.a: 3-Phase to 6-Phase Transformation

Arguably, one of the most common questions asked with regard to high phase order transmission is to do with transformer connections, i.e. how can transformers be wired to produce 6 phases from 3? As it happens, these connections are simple, implementable in a variety of different ways, and rely on only one principle which is described next.

It has already been mentioned earlier in this document, that a 6 phase set can be thought of as 2 separate 3 phase sets, and further, it can be implemented as such. If a 3 phase set is connected to a Y-Y transformer as shown in the figure on the left, then the resulting secondary voltages will be in phase with the original set. If a parallel transformer is connected to the original 3 phase set, but is wired as a Y-inverted Y, then the resulting secondary voltages will be inverted with respect to the original. All that remains is to combine the two secondary sets to achieve a resultant 6 phase set.

At a first pass, this can be practically achieved as follows: if a 3 phase transformer is wound with 1 primary, and 2 secondary coils on each of its legs, and the two secondaries are wound in opposite senses with respect to one another, then a single primary voltage (or current), will be transformed into 2 secondary voltages (or currents) which are phase displaced by 180° from one another. Again, by combining the secondary voltages, a complete and balanced 6 phase set can be achieved.

In essence, this principle lies at the heart of all 3 to 6 phase transformation, but having obtained the required number of phases, one is left with a variety of choices regarding their implementation and the possible applications of each connection. This forms the topic of the following sub-section.

3.4.2 Transformer Winding Interconnections

Four principle winding interconnection possibilities have been studies by Guyker et al[34,42] which are depicted in figure 3.4.2.a below:

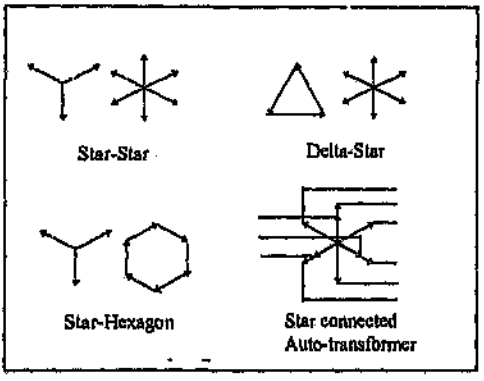


Figure 3.4.2.a: Transformer Interconnections

The star-star, and delta star connections are ideally suited for converting 3-phase generation voltages up to the 138kV (or South African 132kV) transmission voltages, but the latter has a distinct advantage over the former in that the delta breaks the zero sequence network, and provides a well defined shunt path in the zero sequence network without a tertiary winding (as opposed to flux linking through the transformer tank)[17].

The star-hexagon could be used for transforming the 6-phase transmission voltages to 3-phase primary distribution voltages. The star connected autotransformer is the preferred connection due to its low short-circuit impedance and greatly reduced cost[34,42].

Of course, these interconnections do not dictate any transformer arrangement (besides the auto-transformer) and can be physically achieved in a variety of ways.

3.4.3 Physical Implementation

Both Stewart[17] and Guyker[34,42] have broached the subject of practical transformer implementation with regards to cost, space requirements, and viability. Four different methods have been identified to implement the above interconnections:

- 6 single phase units
- two 3-phase units - three leg core form
- two 3-phase units - five leg core form
- a single, 6 phase unit.

Using 6 single phase units gives a great degree of flexibility and has been implemented at PTI's 6-phase test line in Malta[5]. It allows single pole switching from the primary side (for a star-star connection) since there is no magnetic interaction between phases in the transformer. From an analytical point of view, the positive, negative and zero sequence models are all a simple series leakage reactance of the same value in all 3 phases. Further, single phase units provide the clearest demonstration of single pole tripping using the transformer's impedance to simulate longer line, and primary and secondary currents are clearly related and in phase.

Unfortunately, single phase units cost more, and take up significantly more space than the other options. This is particularly a problem since 6-phase transmission lines will be an upgrade onto existing 3-phase lines, which means that substation space is very limited and often cannot house the additional units.

Using two 3-phase units reduces both the cost and space requirements relative to the first option. However, since one of the two transformers will be wound as a Y-inverted Y, there are definite insulation problems which arise between the primary and secondary windings and necessitate an increase in clearances. In addition, no winding arrangement of three leg core form transformers will allow single pole switching from the primary side. In each case, there is a voltage introduced onto the isolated phase through magnetic coupling in the transformer.

The five-leg core form transformer attempts to combine the advantages of the previous two options, by retaining the reduced cost and space requirements of the 3-phase units, and addressing the magnetic coupling problems. However, since the 2 outer legs of this transformer do not have infinite permeance, there is still a degree of magnetic coupling to the open phase, and both the cost and space necessary are increased over the 3 leg core form option.

In addition, there is a likelihood of ferroresonnance between the lowered magnetizing impedance of the transformer and the capacitance of the line. While studies have shown that the transformer source impedance is below that of the line capacitance, and decreases with saturation, it should be remembered that saturation is a non-linear phenomenon with significant harmonic generation, which leads to a possibility of ferroresonance in any of the higher harmonics.

While a single, 6-phase unit connected as an auto-transformer would seem like the ideal choice from a cost, and space requirements point of view, such a unit was designed by a transformer company[34] and found to be excessively large for any kind of transportation or shipping. This option was thus disregarded completely.

Taking all factors into consideration, the option which was finally selected as the winner was the 2 unit, 3-phase, three leg core form design, wound in a delta-star fashion. This gave the best cost, and was small enough to fit into most existing substation yards. It had no problems with transportation or shipping, and the delta-star connection provided additional benefits by breaking the zero-sequence network without the usual tertiary winding.

3.5 Sub-Station Modifications

Before closing the section on high phase order technology, mention should briefly be made about the modifications necessary at the sending and receiving end substations. Of course, many of these are quite involved, and specific to the sub-station under consideration, however, some modifications are generic and will be briefly listed below.

As noted earlier, to provide proper phase transformation, two three phase transformers will be necessary at each substations, while the existing transformer can be removed (unless it can be reused). In any case, there is a net addition of one transformer to the substation.

This introduces another challenge in that the conductors leaving the H2 bushing from each transformer must be transposed at the first transmission line tower exiting the substation. This is necessary to provide a symmetrical conductor configuration with 60° between adjacent phases. A similar transposition must obviously be made at the opposite end of the line.

The line will be switched with line side circuit breakers (i.e. on the 6-phase side of the transformers) in order to achieve single pole switching. Retrofitting an existing substation with this gear requires the use of compact design due to space limitations. For this purpose, SF_6 gas insulated dead tank circuit breakers are recommended (and have been used on the Goudey-Oakdale demonstration line[18,20]).

4. Survey of Case Studies

4.1 Background

Ever since their inception in 1973[1] HPO lines were continuously pitted against the more established 3-phase system of transmission. Typically, a 6 or 12 phase line would be compared to a 3-phase line of equivalent power carrying capacity in categories such as magnetic or electric field emissions, size, cost, aesthetics, corona related effects, upgradeability, compatibility, stability, and so on. This has been done for various lengths of line, for varying voltages and power carrying capacity, using standard software packages such as EMTP, as well as tailor written software such as EPPC (discussed in section 3.1.5 "Computational Aids").

As a result, there has been a generation of a plethora of information which is very beneficial on the one hand, but on the other is sometimes contradictory and inconclusive. Thus, there is a formidable challenge in compiling a survey of case studies, and careful thought must be given to the selection of cases and their applicability.

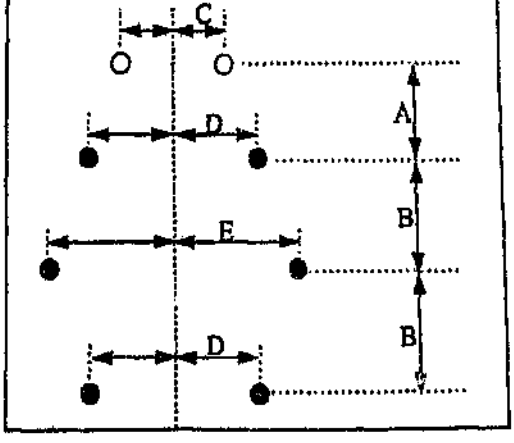
For this section, 5 case studies were chosen, each contributing to the overall feasibility of HPO lines. The first 3 case studies are purely "pen and paper", and even within this classification the various cases move from purely hypothetical, to an actual study of a particular line and then an all important cost comparison. The fourth case describes the initial attempts to construct a 6 and 12-phase test line in Malta, NY and the results obtained from that exercise, and finally, the fifth and final case describes the first utility demonstration of a 6-phase line, its operation, and discussion about the lessons learned.

4.2 Double Circuit 3-Phase Line Upgrading to 6-Phase Operation

It is most likely that 6-phase lines will (at least initially) be implemented only as upgrades of existing double circuit 3-phase lines, and in anticipation of this fact, Guyker and Stewart each wrote a paper on the subject in 1981. The investigations of both authors have been included because while they both address the same problem, they do so in very different ways which makes for a very interesting comparison of the methods and consequent results.

4.2.1 Case Study 1: "Uprating Without Reconductoring"

Figure 4.2.1.a: Generic Representation of Double circuit 3-Phase Line



In this case study, Stewart et. al.[6] considered the uprating of 5 hypothetical transmission lines - with details given in the table below - from 115kV (or 161kV as in case 5) to either 230kV double circuit 3-phase, or 138kV single circuit 6-phase. The reason for this comparison is that a 138kV 6-phase line is equivalent to two interleaved (and phase shifted) 230kV 3-phase systems, and so the comparison becomes very direct, with exact power transfer, loading, etc.

Configuration	1	2	3	4	5
Structure	wood pole	concrete pole	wood pole	steel lattice	double wood pole x-braced
Voltage	115 kV	115 kV	115 kV	115 kV	161 kV
Conductor	Osprey	Drake	Linnet	Drake	Grosbeak
Shield Wire	3/8 EHS	3/8 EHS	3/8 EHS	7/8 AW	3/8 EHS
and number	1	1	1	2	2
Insulators	7-5.75	7-5.75	7-5.75	8-5.75	10-5.75
A (in meters)	3.66	3.05	4.88	3.66	4.42
B	2.74	3.35	3.66	3.51	4.27
C	0	0	0	1.52	1.45
D	1.98	1.80	1.83	2.90	3.81
E	2.44	1.80	2.13	3.66	4.42
Min clearance	7.32	10.06	7.32	12.20	7.93
Ave clearance	9.15	12.20	8.54	14.33	8.84
Structures/km	11.4	6.2	8.7	4.7	5.0

Table 4.2.1-a: Sample Line Configurations

This study begins by examining the radio noise emitted by the two upgrade options since this is believed to be dominant as the limiting factor. This is then compared to the CSA standard which states that maximum fair weather radio noise at a lateral distance of 15m from the outermost phase of the power line, should be 50 dB above 1μV/m for lines of nominal phase-phase voltage of 200-300 kV. Of the 5 lines, only choice 2 is suitable for a double circuit 3-phase upgrade, whereas for the 6-phase upgrade, choices 2,4, and 5 meet the above criterion.

Next, the remaining 3 choices were examined for audible noise compliance. The regulations stated that wet conductor audible noise 15m laterally from the outermost conductor should not exceed 50 dBA, and it was found that all 3 lines passed this test for both upgrading options. This once again demonstrated that radio noise was the limiting factor in line selection.

The lines were then tested for their ground level electric fields, insulation requirements, mechanical motion considerations, and ground clearance to show that all choices passed comfortably, the only modification being the number of disks in the insulator string which was raised to 10 in both cases.

Finally, the economics of the lines were examined. This was done by outlining the economic conditions in 1981, inflation rates, transmission costs, etc., and defining the economic life for payback as 30 years. Now, the cost examination could take 2 routes: either uprating with no load growth in which case savings would be made simply on the cost of losses in running the line, or uprating with a corresponding increase in load to a maximum of the conductor thermal limit in which case the economic benefit would come from an increase in line capacity. It was decided to pursue the first option for the purposes of this study.

For each of the remaining lines, the savings/km were computed by calculating the saving made per kilometre each year for its lifespan of 30 years, bringing this saving to a "present worth" value, and summing all these values together. Terminal costs were assumed to be dominated by transformer costs, and to make the results more meaningful, Stewart gave breakeven distances where terminal costs would equal the savings made on the line. For options 2 and 4 the breakeven distances were 22km and for option 5 this distance was 42km since the voltage of this line was nominally 161kV as opposed to 115kV.

4.2.2 Case Study 2: "138 kV Uprating of a 138 kV Double Circuit Line"

In this case study, Guyker et. al.[34] selected a candidate line for upgrading to 6-phase and performed a complete feasibility study on this line from a utility perspective. The line spanned 15 miles, consisted of two 3-phase circuits suspended from APS 22 type towers as shown in figure 4.2.2.a below, and connected sub-stations at Charleroi and Yukon, with a connection off one of the 3-phase circuits to Westraver substation approximately 4 miles away from Yukon.

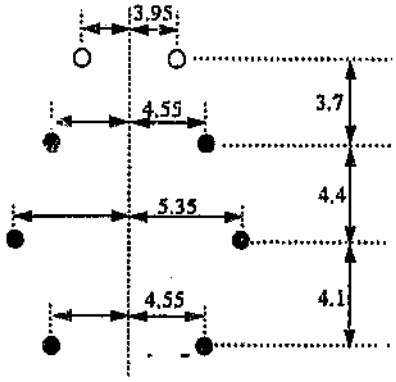


Figure 4.2.2.a: APS 22 138-kV Double Circuit Tower (Dimensions in m)

The existing line is nominally 138 kV (phase-phase) which is slightly larger than the lines examined in the previous case study (which were 115 kV) with subsequent increase in tower dimensions, however, the final voltage will be the same as above, i.e. two 3-phase circuits rated 230 kV phase-phase, or a single 6-phase circuit which consists of the interleaving of the above two circuits rated 138 kV (phase-ground). The line was assumed capable of being uprated to the thermal limit of the conductors which corresponds to 1074 MVA (winter) and 807 MVA (summer).

The paper begins by examining the existing line, and showing that from an insulation point of view (lightning, switching, and power frequency) the line can be uprated to either option with only a slight increase in outages due to lightning, but no structural modifications to towers, insulators, and so on.

The radio noise, audible noise, and ground gradient lateral profiles are obtained and it is concluded that even though both upgrade options result in increased field and noise levels, the 6-phase option will have lower levels than the double circuit 3-phase option. The former will however, have slightly higher electrostatically induced voltages on objects under the line, and this effect must be evaluated further on a site-specific manner for the entire length of the line. The above results are consistent with the observations made in the previous paper, and could be very useful in crowded or congested areas where audible noise, radio interference, and field levels are a major concern.

Guyker then continues by examining in detail the sub-station insulation co-ordination, and defines surge arrestor protective levels. These studies show that MOV's with maximum continuous operating voltages (MCOV's) of 180 kV will protect a transformer and its bushing with BIL of 550 kV for both upgrade options if applied at the transformer terminals. However, BIL of such low value are seldom used on 230 kV transmission systems, and final values decided upon were transformer BIL of 825 kV and bushing BIL of 900 kV.

Relay protection and circuit breakers were examined next and it was decided to use segregated phase comparison relay scheme, with tripping achieved as two sets of 3-phase circuits. For the 138 kV 6-phase and 230 kV 3-phase options, it was determined that standard 242 kV oil circuit breakers could be used for either option with standrard BIL of 900 kV.

Finally, the cost of both upgrade options is examined. This was done by designing 15 different transformers, 7 for use at Yukon, and 8 for use at Charleroi, of different types such as 3-phase (to be used as 2 units), autotransformers, single unit (two secondary windings), single phase - two phase, and so on, and submitted to an electrical manufacturer for preliminary design information. An evaluation of total costs showed that the 6-phase uprating option costs approximately $2.25 Million more than the double circuit 3-phase option, which is due mainly to the steep differential in transformer costs where lower cost autotrans formers with balanced phase impedances may be used for the 3-phase option, but 2-winding transformers must be used for the 6-phase option to obtain balanced phase impedances.

While the 3-phase option is cheaper for this particular line, Guyker concludes that this is only because on the APS system the 500 kV and 138 kV systems are in phase, and autotransformers may be used at Yukon. Other systems having a 30° phase shift between voltage levels would need to use 2-winding transformers for both options. This would result in a minimal cost differential, with 6-phase systems having an advantage in lower radio and audible noise emissions from conductors.

4.2.3 Discussion

As can be seen, the above 2 studies tackled essentially the same problem, examined virtually the same factors, and came to fundamentally the same conclusions. However, they did this with some subtle differences, which is very typical in studies addressing the same issue but performed by different organisations. These studies were both included with the aim of highlighting these differences in approach and methodology. Please note furthermore, that the discussion below is to a degree subjective, and represents solely the author's judgment.

To begin with, we examine the general approach of the paper. Stewart's approach is to take a broad sample of "limiting" cases, that is, cases which just barely pass or fail, in order to establish some kind of boundary conditions. He concentrates primarily on aspects such as field emissions, radio and audible noise, etc. and eventually calculates returns/km and finds theoretical breakeven distances. Guyker on the other hand, concentrates on transformers, BIL's, surge protection, insulation levels, circuit breakers, and only to a very small degree environmental effects. He chooses a line which is designed well away from any problem areas (unlike Stewart), and performs a complete cost study on that specific line. This is, in the author's opinion, directly relates to the purpose of the research, and the organizations backing it. Stewart is a researcher, working for PTI (Power Technologies Inc.) which is a research based company, and hence their approach is naturally more theoretical, and aims to derive general results which can serve as a quick guide to evaluate the feasibility of any line's conversion to HPO. Guyker on the other hand, is a design engineer, who works for a power utility (Alleghany Power Service), he has at his disposal any number of lines to choose from, and is interested in specific results, concerning a specific line. With this in mind, it may be that Stewart's work tends to slightly favour 6-phase lines, simply as a path of research, whereas Guyker could be more objective, and more ready to accept a negative conclusion if that is what the research indicated (as it did in this case).

Directly stemming from the above point is the way in which the economic analysis was carried out by the 2 authors. Stewart considered the present worth of the savings in transmission losses for the next 30 years, whereas Guyker concentrated on only the direct costs at the present time for the 2 upgrade options. Again, this may indicate a difference in philosophy, in essence, it is certainly better to consider all the returns for the life span of the line, but practically, it may be possible that utilities place far more emphasis on the present expenditure of money than is expressed by the "present worth of required revenue" mathematics.

In addition, the focus of the economic analysis was completely different. Stewart, in fact, did not perform an economic comparison between the 6-phase line and the double circuit 3-phase, but between the 6-phase line, and the existing (non-upgraded) 3 phase line. He has demonstrated that if we were to modify the existing line to 6-phase with nothing else changing, then over the next 30 years, this upgrade would actually be cheaper than keeping the line as it is, if the existing line were longer than a given length. He did not answer the question though, of whether it would be cheaper to upgrade the existing line to 230 kV double circuit 3-phase or single circuit 6-phase over the next 30 years, and so in that respect, the economic analysis (though definitely adding insight) did not give a satisfactory answer to this critical question.

Stewart also treated the question of transformer cost differentials quite glibly by simply stating that the difference between 3- and 6-phase transformers is that the 6-phase option utilises 2 transformers instead of one, each rated to half the required capacity for the necessary phase shift. There is nothing more in this regard, and it is shown that in fact, it was the transformers themselves which were the limiting factor in

Guyker's research. The significant saving that could be made by using an autotransformer as opposed to a 2 winding transformer is crucial, but as mentioned before, this was not the focus of Stewart's paper.

Guyker on the other hand, is very focused in his work. He has addressed the subject of cost viability very well, but did not even mention that savings could be made simply by minimization of losses, and for certain lengths of line, this alone could justify the upgrade.

Finally, let's examine the conclusions of both studies. Guyker's conclusion is essentially negative. The cheaper option turned out to be the 230 kV 3-phase upgrade due to the lower cost and feasibility of using autotransformers, so in this case, the HPO line would not be implemented even though Guyker mentions that where both voltage systems are not in phase (which would exclude the use of autotransformers for the 3-phase case) cost differentials would be minimal. Stewart's conclusion is essentially positive. He says that at the present moment, a large number of lines fitting his description could be running more economically and costing less to upgrade in the long run, than the total savings made.

In the author's view, both of these researchers have made significant steps to better understand the applicability of HPO lines. Certainly, they have both demonstrated that 6-phase lines are not the ultimate solution to power transmission, and certainly cannot be applied indiscriminately to any double circuit 3-phase line. However, when lines are sufficiently long, and transformer costs are comparable for both upgrade options, 6-phase lines can have a definite cost advantage, as well as go a long way in minimizing radio interference, audible noise, and ground level electric fields.

4.3 HPO as an Alternative to UHV Bulk Transmission

4.3.1 Background

As electrical loads continue to grow throughout the world, so the need for bulk transmission steadily increases, and to address this growing need research has been conducted into UHV transmission levels. The problems with this high voltage level is the increased public opposition, radio interference, audible noise, increases ground level electric fields, increased cost, and the significantly increased need for top notch expertise and innovative technology. It is precisely with these problems in mind that HPO transmission was proposed as an alternative solution to UHV bulk transmission.

The following case study deals purely with the economics of UHV 3-phase versus EHV 6- or 12-phase transmission[10], but before this can be presented, some background which is discussed in previous papers[9] must be covered. The base case for comparison is 1200 kV test line constructed at Lyons, Oregon, as part of the BPA UHV research program, and for comparison, 6 HPO lines have been designed to give the same power transfer capacity. These are:

Scheme	Phase No.	Phase-Ground Voltage (kV)	Conductor Bundles	Tower Description
1	12	462	2	Self supporting towers (tennis racquet design)
2	6	462	4	As above
3	12	317	1	As above
4	12	317	1	Guyed V-towers
5	12	317	1	Guyed portal towers
6	12	317	1	Guyed Y towers

Table 4.3.1-a: HPO Design Choices for Comparison with 1200 kV 3-Phase line

[5] Dimensioned drawings of the above towers can be found in reference [9]

These lines have all been designed to give the same maximum ground level electric field strengths, wet conductor audible noise, fair weather radio noise, and power transfer capability[6]. Mechanically, the towers have been planned for NESC heavy loading, high wind, and heavy ice accretion. The loading in various planes has been assessed, and finally base tower weights have been calculated. Furthermore, after this was done, it was found that scheme 4 was structurally indeterminate and was thus not considered further. Having this information, it is possible to proceed directly to the economic analysis.

4.3.2 Case Study 3: "Economics of EHV High Phase Order Transmission"[10]

The comparison begins by defining two different electrical loading levels:
1. 3000 MW: the initial load was assumed to be 1339 MW with a load growth of 6.5% per year, reaching 3000 MW at year 13.
2. 6000 MW: the initial load was assumed to be 2670 MW with a load growth of 6.5% per year, reaching 6000 MW at year 13.

The economic "climate", or terms upon which the comparison will be carried out are then defined and include factors such as generation charges, transmission charges, maximum demand and energy charges, economic payback-period, and so on. Furthermore, all material and labour costs are based on 1982 US dollars with inflation rate and generation reserves also taken from that period.

Having set the scene, it was necessary to make several selections. The first of these was the conductor type, and several factors play a role in this choice, such as diameter, conductor purchase price, strength to weight ratio (since a stronger conductor can be strung tighter and thus needs fewer support structures) and EMI criteria (which sometimes require a larger conductor than is economically feasible). Ten different ACSR conductor types were compared and optimum selections made.

Next, it was necessary to select ROW (right of way) requirements. These requirements are based on such varied factors as switching surges, maximum conductor blow-out, EMI, line voltage, etc. While there is a certain minimum ROW requirement for each line, there is no guarantee that utilities will necessarily use this minimum requirement, and furthermore, since land costs vary quite dramatically, it becomes difficult to assign some meaningful value to land. Thus, ROW requirements were ignored for the purposes of this study, but it should nevertheless be mentioned that HPO lines are significantly more compact and require less land area than the UHV line, and thus this decision favours the UHV option.

Performing an optimization procedure on the various candidate HPO lines with respect to conductor selection, span lengths, tower heights, base weights, etc. it was found that choices 5 and 2 were the most economic selections for the 3000 MW and 6000 MW loading cases respectively.

In order to determine how the various cost components affected the ranking of the most economic options, a sensitivity analysis was performed. This was done by selecting 8 of the most important cost components:
1. conductor cost
2. stringing and sagging cost
3. tower steel cost
4. tower erection cost
5. generation demand charge
6. generation demand escalation factor
7. generation energy charge
8. generation energy escalation factor

and applying a 50% adder to each of the chosen values. This showed that the rankings did not change, and schemes 5 and 2 were still the most economic for the loading of 3000 MW and 6000 MW respectively.

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[6] The basis of power transfer comparison is addressed in section 4.3.3

The next section of the comparison dealt with terminal costs. Naturally, the economic analysis of substations is far more complex than transmission lines due to the large number of combinations of bus arrangements, protection schemes, other lines that may terminate at the same substation, ground mats, utility specifications regarding switching and reliability, and EMC requirements. Thus a detailed study was not undertaken, but the terminal costs were estimated by considering transformer costs (which typically take 60-80% of the total sub-station cost), and circuit breaker costs. Other costs such as shipping, installation, protective relaying, etc. were included as a multiplier on the circuit breaker costs.

Naturally, terminal costs for HPO lines were greater than the UHV line as expected. This is because more transformer units are necessary for the phase and voltage transformation of the HPO line than for the voltage transformation of the 120 kV 3-phase line. That is, only one 3-phase transformer is necessary to terminate a 3000 MVA 3-phase line, whereas four 750 MVA 3-phase transformers are necessary for the 12 phase alternative. In time however, it is likely that dedicated 3 to 6 or 3 to 12 phase transformers will be built that will slightly reduce the value of this cost differential. Also, HPO lines need more circuit breakers (CB's) and associated hardware. As above, a single 3-phase CB is required for the 3-phase line, whereas 4 3-phase units are required for the 12-phase line. Each of the latter units will be rated lower than the former CB, and hence cost less, but the total cost will be higher.

Now, since line costs for HPO are less than UHV, and terminal costs are greater, we can use a method commonly used for comparison of HVDC with AC alternatives in which a breakeven distance is calculated where savings from the DC transmission line balance the additional cost of the DC terminals. The results of this study are tabulated below: (note the addition of scheme 3A, which is similar to choice 3 but uses a 2 conductor bundle which was shown to be slightly more economical than the the existing scheme 3)

Loading option	UHV	Scheme 1 12ϕ 462 kV	Scheme 2 6ϕ 462 kV	Scheme 3 12ϕ 317 kV	Scheme 3A as 3, 2 cond.	Scheme 5 12ϕ 317 kV
3000 MW	-	33 miles	6	8	7	6
6000 MW	-	35	0	never	5	never

Table 4.3.2-a: Breakeven distances (in miles) using UHV as base, for various loading options

As can be seen, the longest breakeven distance for the 3000 MW loading option is 33 miles. It is also reasonable to assume that a 1200 kV, 3000 MVA line will never be built for distances as short as 33 miles and so it can be concluded that all HPO options are cheaper than the UHV option for 3000 MW loading. It is interesting to note the trend that the various HPO options follow when the load is brought to 6000 MW. As can be seen, schemes 3 and 5 are always more expensive than the UHV option, but scheme 2 becomes cheaper for any distance. As before, the remaining options offer a definite economic incentive at this loading level.

4.3.3 Discussion

Of all the economic comparisons given in the literature, this is by far the most extensive. It covers a wide range of tower designs that have been meticulously planned, taken to civil engineering firms and tested for various mechanical environmental loads, producing base tower weights, and limiting conditions for vertical, longitudinal and transverse loads. The conductor selection, phasing, and arrangement has also been comprehensive, and while it is understood that reviewing each permutation of conductors is a near-impossible task, the authors must be congratulated for the large amount of work performed and the excellent quality of this work..

Before covering the general conclusions which can be derived from this paper, it is necessary to bring to the reader's mind several criticisms (and please bear in mind that these criticisms are solely the opinions of the author) which can be made about the paper and which contextualise the results somewhat.

The base case for this comparison is a 1200 kV 3-phase line, which means that the peak voltage between phases is $\sqrt{2} \times 1200 = 1.7$ MV! This voltage level is incredibly high, and presents tremendous problems in insulating everything in the system from transformers, to circuit breakers, to the line itself. It will require very specialized (and hence very expensive) terminal equipment and its associated topology, actual line design, and manufacture.

The obvious question then springs to mind: is this line a valid example to use as a base case? Perhaps, this line is several times more expansive than a more established technology, such as running two lines on the same ROW to transmit the same amount of power. If that is the case, then using a more expensive base case, would put HPO in a very favourable light, being cheaper than the UHV 1200 kV line (but saying absolutely nothing about the standing of HPO versus more conventional technology). The author of the paper (Stewart et al) makes no reference to the economic standing of the 1200 kV line versus the present, more conventional technology, and certainly from the author's point of view, this kind of information would have helped to contextualise the economic comparison.

Next, is the comparison of the lines themselves. Stewart et. al.[10] claims to compare the lines on the basis of capacity, but this is somewhat of a controversial issue. For short lines, where the line does not significantly affect the performance of the system, the capacity of the line is taken simply as the thermal MVA rating of the line. For the opposite case, where the line is very long, the rating of the line is taken as the SIL (surge impedance loading) of the line. Stewart has chosen a somewhat unconventional measure where the circuit breaker limits the line current to 6000 Amps, and this is then taken as the maximum power of the line. The table below shows the various loading comparisons:

Line description	SIL (MW)	Thermal (MW)	Breaker limited (MW)
3ϕ 1200 kV (ϕ-ϕ)	6300	23900	12500
6ϕ 462 kV (ϕ-g)	4800	17900	16600
12ϕ 462 kV (ϕ-g)	5600	17900	33300
12ϕ 317 kV (ϕ-g)	2800	13400	22800

Table 4.3.3-a: Comparison of HPO and UHV loading for various conventions

As can be clearly seen, the HPO lines seem to have been grossly underdesigned when SIL and thermal loading are considered. As mentioned before, line capacity comparisons are always a very controversial subject, but with such widely varying results, it is believed that a great deal of justification must be given to the selection of "breaker limitation" as the convention for capacity comparisons (for example, comparing the 12 phase, 317 kV line to the UHV case shows that the 12 phase line has only 44% of the SIL of the latter, but 82% more power when it is breaker limited). This selection seems to once again, favour the comparison towards HPO lines.

The final criticism is that, as in Stewart's previous paper (considered above), the subject of terminal equipment cost was not given sufficient attention. It is very probable that the 3-phase line could use a cheaper technology such as autotransformers and thus become significantly more feasible than the HPO option. Again, this is speculation, and requires a deeper examination.

Despite the above comments, the study is nevertheless extremely useful, and gives rise to a number of general conclusions:

- the terminal equipment costs for a HPO line are invariably higher than those for a 3-phase line. This is because 2 or 4 transformers are needed for HPO as opposed to 1 for 3-phase, and even though the former are rated to a half or quarter of the 3-phase transformer rating and are individually cheaper, their total cost is higher. The same analysis applies directly to circuit breakers.
- The cost of the transmission line itself is less than the cost of the 3-phase line. This is due to smaller, lighter conductor arrays which require smaller, lighter towers to support them.

- Due to a greater degree of field cancellation, HPO lines have lower line losses and other corona related effects, and are thus (in general) cheaper to run than their equivalent 3-phase counterparts.

Before concluding, one last comment must be made. The premise behind HPO lines is not so much economic superiority as line compaction. The object is to use the ROW as effectively as possible by squeezing into it as much power as possible while keeping the environmental criteria at the edge of ROW (such as E and H field, audible noise, etc.) the same. This comparison did not take into consideration the cost effect of the land savings - for reasons which have been discussed above - but in essence this is what this technology is primarily geared for. It is thus in the author's view that a more meaningful study would be to make some kind of breakeven point of the land costs, i.e. if HPO technology is slightly more expensive than 3-phase (which unfortunately it seems to be) but saves on land, how expensive does the land need to be in order to make compaction economically worthwhile?

4.4 The First Test Line

4.4.1 Background

In 1978 the United States Department of Energy sponsored a project for the construction and testing of a six, and twelve phase line in Malta, NY. While analytical information was abundant, nowhere in the world had anyone constructed such a line before, and as such, this represented a great leap forward in the evolution of this concept.

4.4.2 Line Description

The line itself was to be 366 m long, with a phase-ground voltage of 80 kV, representing two 138 kV 3-phase circuits appropriately phase shifted and interleaved. The conductors for both lines were chosen to be 336 kcmil[7] ACSR (18.3 mm diameter) which is considered small for this voltage level, but was done to give sufficient noise to be measurable, and quickly detect any problems if they were to occur. The conductors themselves were arranged into a circular array with a phase-phase spacing of 1 m, resulting in a tower window of 4 m for the 6-phase line, and 6 m for the 12-phase line.

4.4.3 Power Supply Sub-station

Electrically, the power was generated at 4800 V 3-phase and was stepped down to 208 V in a 150 kVA 3-phase pad mount transformer. This intermediate voltage was used in order to simplify switching and measurement, and a matrix of links allowed rapid shifting of the energization between 6-phase, double circuit 3-phase, and single circuit 3-phase with alternate conductors floating or earthed. This was especially important to radio and audible noise testing where rapid changes in energization allow comparative measurements to be taken without concern over shifts in weather. The line was then passed through a bank of 6, single phase, 50 kVA, 208/80500 V transformers connected in a delta-star configuration. At the high voltage side of the transformers, the line was fed through radio noise filters which served the dual purpose of isolating the line into a known length for short line radio noise measurements, and ensuring that the measured noise was actually generated by the line and not conducted from the power source. Incidentally, conductor hardware also needed minor treatment to eliminate hardware corona.

[7] kcmil is a US standard for specifying the cross sectional area of the aluminium in a an ACSR conductor. It is an abbreviation for kilo-circular mil, a circular mil having the area of a circle with diameter of one thousandth of an inch.

4.4.4 Support Structures

The towers and their associated insulator designs had several simultaneous requirements to fulfill: the structures needed to be flexible enough to allow a variety of electrical and mechanical experiments, there had to be an evaluation of the most promising tower and insulator design concepts, and practical construction techniques and hardware needed to be developed and demonstrated. To expediate the process, several different types of towers and insulators were placed on the line simultaneously, to generate as much data as quickly as possible.

Initially, the towers were envisioned as having circular tops with radial post insulators, thus offering simplicity, standard hardware, and no phase to phase insulators, but this design was abandoned since each post insulator needed an individual support point making the tower unnecessarily complicated. The three designs which were put into service on the line were:

1. a portal type, simple wood pole and crossarm structure for the twelve phase line
2. a portal type, laminated wood with laminated crossarm structure for the six-phase line
3. a steel lattice, tennis racquet design for the six-phase line, mounted on screw anchor foundations

All 3 towers were proven to be feasible, and in addition, Stewart[5] comments that:

> *"The savings in space and right of way together with the visual advantages of the smaller structures have been frequently remarked by visitors to the test site."*

4.4.5 Insulator Design

The design of insulators followed 2 different routes: using all suspension elements loaded in tension, which could be achieved with conventional suspension components, and using rigid insulators which permit cantilever loading.

The first option concentrated primarily on non-ceramic insulators due to their optimum appearance, light weight, high strength, resistance to damage and ease of erection. Two assemblies were made for 6-phase and an additional two for 12-phase, and this design proved to be universally very satisfactory.

The second option saw two designs being manufactured for 6-phase. The first suffered from installation difficulties as the support hardware design required simultaneous assembly of the insulators and the conductor clamp. The second design permitted preassembly in the normal way, but in general rigid insulators were found to be heavier and longer than the all tension assemblies. In conclusion then, it seems that tension assemblies give superior performance characteristics than their rigid counterparts and are most likely to be used in future implementations of HPO lines.

4.4.6 Insulating Midspan Spacers

To make optimum use of compaction technology, the differential motion of the conductors in the HPO array can be limited by using insulating midspan spacers. These include the "star", "hexagon", "Swastika" and triple triangle "civil defense" shapes which are discussed in greater detail in section 3.2.4. As mentioned previously, while the hexagon shape makes use of phase-phase members, it is lighter, more rigid, and is loaded completely in compression which makes it the design of choice for this type of application.

4.4.7 Lightning Performance

Although not strictly part of the practical testing, theoretical lightning predictions show that the HPO line can expect a marginally higher tripout rate than a similar 3-phase line, but that this variation is considerably less than typical annual performance variations caused by year to year differences in lightning activity or soil (grounding) conditions.

4.4.8 Electrical Testing

The success of HPO lines relies directly on its ability to mitigate various harmful electrical environmental effects, and as such, this is perhaps the most crucial aspect of the test program. As mentioned previously, the line was built with an excessively small conductor (1.83 cm diameter, 336 kcmil ACSR Linnet) so that conductor surface gradients will be at their maximum, and noise levels will be measurable. Four parameter were then examined: radio noise, audible noise, corona loss, and ground level electric fields, and each of these are discussed in turn below.

4.4.8.1 Fair Weather Radio Noise

The conductor array was energized in 6-phase mode, and double circuit 3-phase mode producing similar modal excitations but different in magnitude. The radio noise was then calculated using an empirical generation function, and modal propagation analysis to show that the lateral profiles for these two alternatives should be similar in shape but offset from each other in magnitude. The measured profile shapes were identical to the predicted shapes (within the accuracy of measurement), but the 6-phase profile was approximately 15 dB below the double circuit 3-phase mode. It can thus be said that both theoretical and empirical methods for radio noise prediction are valid for 6-phase lines.

4.4.8.2 Wet Conductor Audible Noise

A similar behaviour is observed for audible noise, where double circuit 3-phase, and 6-phase configurations result in similar curves but offset by a constant magnitude. Again, measured and theoretical results agree very well, but measured curves tend to attenuate quicker with increasing distance from the centre line than calculated profiles due to trees and other obstructions preventing a clear view of the entire line from greater lateral distances.

4.4.8.3 Corona Loss

The most direct measurement of excessive conductor surface gradients is arguably the amount of power lost to corona (while audible noise and radio noise are secondary corona related effects). This is a continuously varying quantity and requires a statistical analysis for a more accurate description.

By measuring the current and voltage put into the line and calculating the real power input, corona loss for the 366m line was calculated to be 2046 W per phase for the double circuit 3-phase case, and an astonishing 338 W per phase for the 6-phase case. This result is consistent with reduced conductor surface gradients, and lowered audible noise and radio noise levels.

4.4.8.4 Ground Level Electric and Magnetic Fields

Measured ground level electric fields directly below the conductor showed that 6-phase energization gave 0.52 kV/m, while double circuit 3-phase gave a significantly reduced 0.065 kV/m which is also in good agreement with calculated values. Although the present values are of no concern, ground level electric fields could assume greater significance at higher voltage levels. The magnetic field magnitudes at the centre of the array at ground level were 0.047 A/m for the 6-phase case, and 0.042 A/m when the line was energised as a 3-phase line with alternate phases left floating, which is in agreement with predicted values.

4.4.9 Mechanical Testing

The test line was also subjected to a series of mechanical tests, to determine the behaviour under wind and ice loading since this aspect can be critical in the spacing of a compact HPO array. Simulated ice loading was abruptly released using the blasting fuse technique and resulting conductor motions confirmed analytical predictions of jump magnitude and insulating spacer performance.

4.4.10 Switching Surges

An extensive Transient Network Analyzer (TNA) study was conducted on the line and while the details of this study are far too intricate, it is sufficient to note that surges behaved as expected, with phase-phase surges on phases separated by 60 electrical degrees were the most severe on a per unit basis of normal operating voltage, and thus ultimately determine the amount of compaction achievable.

4.4.11 Discussion

While there are no criticisms of this paper per se, it is necessary to appreciate that this work showed that HPO lines can physically be implemented, put into service and operated. The analytical techniques currently used are valid and can be used with confidence for future design of HPO lines.

The main lessons learned from this study are that towers are cheap and easy to make for 6- and 12-phase lines, standard insulator and hardware components can provide simple and attractive support systems, as well as optional midspan spacers for increased compaction. While corona related effects are dramatically reduced, the strength of ground levels electric fields is higher for HPO lines than for the same array energized as a double circuit 3-phase line. However, when compared to a similar thermal capacity standard 500 kV 3-phase line, the field strength of the HPO array are actually lower.

Having constructed and tested a physical HPO line, it seems at this stage that there is nothing preventing a utility from taking the initiative, and marching forward with the implementation of the first HPO transmission line to be put into service. In fact, this was precisely the case, and forms the topic of the next, and final case study.

4.5 First Utility Application: The Goudey-Oakdale Line

4.5.1 Background and Goals

The work described above had taken place over a period of almost 20 years and had reached a state where almost all technical issues had been addressed, accurate line models have been developed, and a short section of 6 and 12 phase line was physically constructed and tested. At this stage, the industry seemed poised for the next phase of the research, and in 1988 a project designed to demonstrate the commercial feasibility of HPO transmission was undertaken by the Empire State Electric Energy Research Corporation (ESEERCO), in collaboration with New York State Electric and Gas Corporation (NYSEG), and Power Technologies Incorporated (PTI)[13,15,16,17,18,19,20,26].

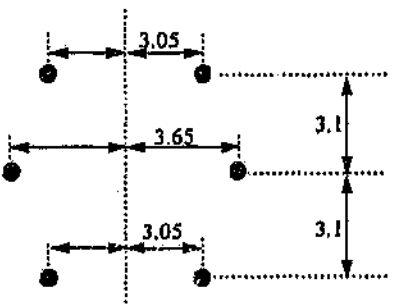


Figure 4.5.1.a: Goudey-Oakdale Line Dimensions

After an exhaustive search of all double circuit lines within the New York area, with due consideration to line length, outage potential, extent of modifications necessary, and accessibility to conduct tests, the 2.4 km line linking Goudey and Oakdale substations just outside Binghamton, NY was selected. This line was operated as a 115 kV double circuit 3-phase line, owned and operated by NYSEG, and was to be reconfigured to run as a single circuit 6-phase line with phase to ground voltage of 93 kV (which, incidently is equivalent to two, 161 kV 3-phase circuits appropriately interleaved and phase shifted). This represented an increase in power of 38% and involved not only a re-phasing, but also a voltage uprating, which would require a complete insulation co-ordination study.

From the very outset, it was necessary to define precisely what this project was aiming to demonstrate, and this was formalized into the following set of objectives[15]:

- to operate on a commercial basis, as a 6-phase system integrated into an existing 3-phase network
- to design and configure substation equipment at both ends of the existing line double circuit 3-phase line, to give 6-phase operation
- identify and resolve technical problems arising from the conversion
- develop guidelines and tools/techniques in building and converting existing lines to 6-phase
- identify environmental benefits arising from the conversion
- determine the economic break-even point of how 6-phase compares to other options
- utilize advanced equipment as much as possible
- demonstrate that existing double circuit 3-phase towers can be utilized or modified to accommodate 6-phase systems

These goals will serve both to guide the research, and focus attention on what needs to be done, philosophy of the design, and key questions that need to be answered. The entire program will be carried out in four phases:

Phase 1 : Analytical studies, development of design criteria, detailed cost estimates and schedules for phases 2 and 3 (May 1989 - May 1990)
Phase 2 : Design engineering, procurement and construction (May 1990 - April 1992)
Phase 3 : Testing, operation and maintenance (May 1992 - April 1994)
Phase 4 : Decommissioning (May 1994 - March 1995)

While these phases will be discussed in the following sections, the descriptions are deliberately kept very brief with the aim of the giving the reader a clear picture of the line, but not to involve him in the laborious details of design and planning. Instead, the focus has been placed on the outcomes of the project, and important lessons learnt.

4.5.2 Phase 1: Approach and Results

This phase of the project was completed in June 1990, and showed that it was possible to locate the 115kV/161kV transformers and their associated switchgear at both Goudey and Oakdale with modifications to the existing substations. A survey of the line confirmed that the line could be operated at the proposed 93 kV phase- ground (97.6 max) if the number of insulators per string is increased to 8. With these clearances insulation is sufficient for both power frequency, and switching surge stresses, with lightning performance essentially unchanged by the conversion. Candidate structures have also been identified for retrofitting with 6-phase, compact-structure tower tops.

Simulation has shown that radio, audible, and television noise will be within acceptable limits after the conversion, and a plot of ground level electric field strength indicates that the 6-phase line meets New York State edge-of-right-of-way limits. It is interesting to note however, that while all the above magnitudes remain comparable to the existing double circuit 3-phase line, the ground level magnetic field strength experiences a dramatic drop after the conversion for predicted loading levels.

Two Δ-Y 3-phase transformers will be installed at each substation, with the secondary of the one transformer reverse wound for the 180° phase shift. The increased impedances of these transformers cause a decrease in the loading of the line after conversion, as well as lowered fault MVA levels for 3-phase, and single line-to-ground faults near either end of the line. Transient stability remains essentially unchanged.

Protection will test the newly developed single phase tripping option, using live tank circuit breakers on the 6-phase side of the transformers. Single phase trip, reclose, and block logic will be implemented with the aid of a microprocessor controlled system, utilizing current differential relaying and segregated phase comparison relaying as the primary protection, and stand alone digital distance relaying as the back-up

protection. The primary protection will use multi-mode fibre optic cable, phase wrapped into one of the conductors. CT's and PT's will be linked to steady-state/ transient event recording instruments for analysis of the performance of the line. Other instruments necessary for field tests as well as measurements of the operating, reliability and maintenance of the line were identified.

4.5.3 Phase 2: Activities of the HPO project

This phase commenced in June 1990 and included detailed design activities of the project, including the development of substation design modifications, and procurement of equipment. This was done to support construction scheduled to begin in April 1991, and a target completion date of February 1992.

A complete list of equipment necessary for the upgrading of both substations was generated and included transformers, circuit breakers of the single pole, live tank design to demonstrate the substation compaction concept, switches, surge protection, and an extensive relaying and metering/monitoring system. Protection will be as discussed above, and the trip logic diagram is given in figure 3.3.5.a.

Exiting the transformers, the six phase conductors will connect to a horizontal lattice, and from there are rolled vertically to a structure where the phases will be transposed to achieve the required physical displacement between phases. From then on, the line continues through a series of towers composed of conventional double circuit 3-phase towers, and compact structures of the round-top "tennis racquet" design in order to demonstrate line compaction concepts associated with 6-phase technology.

4.5.4 Phase 3: Testing

Testing is scheduled for a two-year period over which measurements will be carried using the same basic procedure as the Malta test lines, with a view to extend the results of the previous experimental work. The testing is grouped into several categories:

- Power frequency parameters
- Switching measurements
- Corona loss
- Transient parameters
- Staged fault tests
- Electrical environmental parameters

The magnitude and angle of both voltage and current will be measured to determine line operation, the degree of unbalance, and provide data for other tests. The capacitance matrix of the line will be determined by measuring line charging current. By staging low voltage fault tests, the line sequence components and shield wire current will be measured.

To determine the effectiveness of single pole switching, measurements will need to be taken of open circuit voltage, and short circuit current induced onto the switched phase , as well as the degree of unbalance on energized phases in order to determine the feasibility of extended operation with only 5 working phases. A tremendous benefit of selecting this line is that it can be taken out of service for testing, which allows a variety of measurements to be made to verify predictive methods. Two examples of this are corona loss, and switching surge measurements.

4.5.5 Conclusions and Discussion

Unfortunately, there have not been any recent publications describing the outcomes of the Goudey-Oakdale line, or in fact anything in the literature past phase 3 of the project. For this reason, the head of the research team at PTI, Dr. James Stewart, was contacted personally by the author and asked to report on the results of the project.

Initially, Dr. Stewart was asked whether the line performed better or worse than he had anticipated. He answered that perhaps the most important single result of the project was that the line worked as expected. Line loading, electric and magnetic fields, radio and audible noise, single pole switching, coupling to switched phases and relaying all worked as anticipated, and correlated well with predicted values. Single pole switching was also tested to assess the line's performance with one or two phases out of service and the line operated for a period of time in the above state with no problems.

Another major result was that the relaying worked well. A series of staged fault tests, and two naturally occurring faults showed that the relaying operated as predicted from tests on a relay simulator based on EMTP calculations. The conclusion was that it was possible to protect 6-phase lines using commercially available relays.

The next question posed to Dr. Stewart was whether this technology was still feasible and economically justifiable, and if so under what conditions. He replied that the project definitely showed that the technology is not only feasibly but ready for application. It is economically justifiable for uprating of double circuit 3-phase lines, and for new construction in locations where right of way is constrained. If space is no object, then there is no reason to go to 6-phases, but if it is an issue, 6-phase may not only be technically advantageous but economically superior too.

Asked whether there were any problems on the line, Dr. Stewart replied that when the line was originally energized, fibre optic cable was placed on the lower two phases for relaying communication, and went into corona in the section where compact towers were used causing excessive radio noise. The optical fibre cable jacket had deteriorated after only a few months of operation. The phase wrap optical fibre was changed to an all dielectric self supporting fibre (ADSS) in the compact section which solved the problem. This, however, was not a function of 6-phase per se, but the actual compaction process, and could happen on any compact 3-phase line.

When the line was first energized, the line currents were not as balanced as expected. This was later found to be a problem with negative sequence current flow from the generator and not the 6-phase line. For magnetic field testing, some switching was done at Oakdale substation which balanced the line currents. Also, the first design of in-span insulating spacers in the compact section had mechanical and electrical problems, but the second design worked well.

Asked for any last comments, Dr. Stewart concluded by saying that simulated (power off) live line maintenance replacing of insulators and spacers had been performed in compact section to show that live line maintenance is possible. The transformers worked, but it was believed that a less expensive option should be possible for phase conversion.

In addition, William Guyker (another leading researcher in HPO working for Alleghany Power Systems) was also approached and asked for comments on the Goudey-Oakdale project. His view was that this project was very valuable in bringing attention to the prospect of HPO, this line was rather short (2.4km) and so could not act as an important system element, also the transformer was simplified and could not show value over simple voltage uprating.

4.6 General Conclusion Regarding Case Studies

Having examined a small sample of the available case studies in the literature, several conclusions can be made about 6-phase lines, and it is felt that these should be summarized below.

Throughout the literature, it is generally agreed that the cost of the actual high phase order line per unit distance is less than the power equivalent 3-phase line. This is due to the fact that HPO lines are more

compact and can generally run at a lower phase-ground voltage than their 3-phase counterpart, resulting in smaller, shorter, and subsequently lighter towers. It has been suggested that HPO lines require more conductors than 3-phase lines due to the increased phase number, but this is also generally not true, since 3-phase lines employ multi-conductor bundles whereas HPO typically uses one or two conductors per bundle, with conductors generally being smaller and lighter.

On the other hand, terminal equipment is more costly for HPO lines. This is inevitable due to the fact that more transformers are necessary to achieve the required phase shift, and more circuit breakers are necessary simply due to the increased number of phases. An added issue that arose on the first case study comparison (section 4.2) was that a 3-phase network could use an autotransformer to achieve its transformation, whereas the HPO network could not do this due to its inherent phase shift. This, in itself, is an issue which could reasonably exclude HPO from economic viability (unless there was an added factor such as land cost).

The third case study examined HPO technology used for bulk transmission and compared a 1200 kV experimental system with a similar capacity HPO system. While breakeven distances were generally low, the study has shown that it is important to carefully consider the choice of base case, in order to have a non-biased, valid comparison.

The fourth and fifth case studies were basically reports on practical lines that have been constructed and tested, and the feedback from these experimental test lines has been invariably positive indicating that the technology is viable, feasible and ready for application.

In general then, from the literature surveyed it is the conclusion of the author that while HPO lines offer many unique advantages, they invariably suffer from a cost disadvantage. Some work on economic comparisons of HPO and 3-phase lines has shown HPO to be economically superior, but it is believed that some v issues have been side-stepped, and practical comparisons in a given location for a given line will once demonstrate that HPO lines do suffer from slightly higher s.

This point was raised during an email consultation with William Guyker of Alleghany Power Systems, and the question was asked why work into HPO had stopped in the mid 80's. His reply was simple and straightforward:

> *"As to Alleghany Power; everything we do is based on engineering economics and need. HPO did not pass these tests. Today with the start of ISO's and open markets, a most severe market value assessment will replace engineering analysis i.e. will it pay back for itself in say 5 years as a vital, reliable, market asset."*

However, HPO technology is unarguably a very powerful method to maximize power transfer through a given right of way, and in the foreseeable future it is probable that land costs, and demand for electric power, will rise to such a degree that current technology will simply become economically inferior to more efficient methods of power transmission, such as HPO. In essence, the added cost of obtaining that efficiency will be offset by the added cost of the land, and from that perspective it is vitally important to be aware of this technology as a possible key player in future transmission (it should also be borne in mind that the massive transmission system which is currently operating will eventually reach the end of its normal service life, and will need replacing at approximately the time when land costs will become sufficiently high, again placing HPO in a very favourable light.)

Having examined the current position of HPO worldwide, it is necessary to turn our attention to an actual South African case study, and assess the viability of this technology for a local line, at the present economic climate.

5. HPO in the South African Context: A Case Study

5.1 Introduction

High phase order lines have been extensively studied for the past 25 years, generating the knowledge and experience necessary to successfully design, implement, and run such a line. While several case studies have been produced to ascertain the economic viability of HPO lines, these were all performed in the early to mid 80's and geographically limited to the United States only (and only 2 regions within the US to add to that.). It was thus felt that to truly gauge the economic standing of this new technology, a unique South African study would need to be carried out, and it is this endeavour which forms the subject of the last chapter.

The study proceeds in 2 parts: the first part is a comparison of a HPO line to an existing 3-phase line which is currently operating in South Africa, and takes the specific economics of this line into account. The second part examines a theoretical point-to-point link, comparing 3-phase and 6-phase transmission costs to determine a breakeven distance beyond which a 6-phase line becomes the more economic option.

As mentioned in previous sections, there are certain types of 3-phase lines which lend themselves more directly to comparison with 6-phase, and these must be borne in mind when selecting a 3-phase line for comparison. Firstly, since terminal equipment costs more for 6-phase than for 3-phase, but transmission line costs less, it is favourable (for the HPO case) to have as much transmission as possible relative to the amount of terminal equipment, that is, make the line as long as possible and minimize the number of "T-offs" which would require additional substations.

Next, it has been shown that with increasing voltage levels, the breakeven distances tend to become smaller[10], so the candidate line must have a high enough voltage in order for the 6-phase line to be comparable.

Finally, the greatest advantage of HPO technology is its ability to maximize the power density within a given right-of-way, or conversely, to minimize the ROW necessary for a given power transfer. To take advantage of this attribute, it is necessary to choose a 3-phase line which runs through an area having a relatively high land value.

Other considerations were to build a 6-phase line where audio, television, and radio noise were a problem since HPO transmission can dramatically improve on these. This was eventually discarded, however, since such lines were considered an atypical case rather than a typical one, and corona related problems can be addressed more easily by the installation of larger diameter conductors, and corona-free design.

Having delineated the necessary attributes of the 3-phase base transmission line, a search was initiated in collaboration with ESKOM transmission line design section through all the existing and planned transmission lines fitting the above description. The search yielded 3 candidate lines, of which one was selected and is discussed subsequently.

5.2 The Camden-Duvha Line

5.2.1 Spacing

The line chosen to be the base case for comparison was a single circuit, 400 kV, 3-phase interconnector running between Camden and Duvha power stations, and spanning approximately 100 km. This line thus satisfies all of the requirements outlined above (i.e. length, voltage level, minimal tap offs) and has dimensions as shown in fig. 5.2.1..a. A further characteristic which has made this line an interesting base

case is that it was built using the very latest technology by ESKOM, which makes it by far the cheapest line in its category. It utilises a "cross rope suspension tower" which is a slightly hybridized "guyed V" tower, having only a cable running across its top, from which the three phases are suspended with "I" type insulator strings.

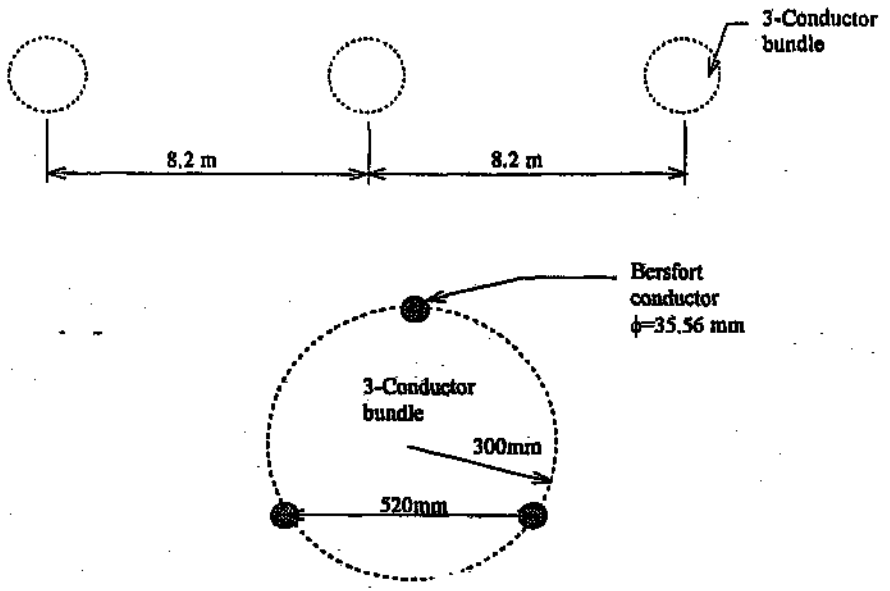


Figure 5.2.1.a: Dimensions and Layout of the 400 kV 3-Phase Camden-Duvha Line

Using only the dimensions of the line, and voltage level, it is possible to determine certain electrical characteristics which will form the criteria of the 6-phase line design.

5.2.2 Electrical Characteristics

The inductance and capacitance of a 3-phase transmission line of arbitrary symmetry is given by the following standard equations:

$$L = 2 \times 10^{-7} \ln\left(\frac{D_m}{D_s}\right) \qquad ...(5.2.2\text{-}1)$$

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{D_m}{D_s}\right)} \qquad ...(5.2.2\text{-}2)$$

Where:

L = inductance per metre [H/m]

C = Capacitance per metre [F/m]

ε = Permittivity of free space [8.85×10^{-12} F/m]

D_m = Geometric mean distance between phases = $\sqrt[3]{D_{12} \times D_{13} \times D_{23}}$ [m]

D_s = Geometric mean distance between the conductors of one phase = $\sqrt[nn]{(D_{11}D_{12}\ldots D_{1n}) \times (D_{21}D_{22}\ldots D_{2n}) \times \ldots \times (D_{n1}D_{n2}\ldots D_{nn})}$ [m]

Substituting the line spacing into the above equations, and remembering to correct the radius of individual conductors by a factor of $e^{-1/4}$ due to internal flux linkages, the following values of inductance and capacitance are obtained for the Camden-Duvha line:

L = 0.84 μH/m
C = 13.25 pF/m

Now, power transfer capacities of transmission lines can be compared in several different ways, and the means of comparison depends primarily on the characteristics of the line itself. For short lines that do not impact on the stability of the transmission system itself, the thermal limit applies; this is defined as the maximum current that can be carried, before thermal losses cause excessive sag on the line, or annealing of the actual material. Because of stability considerations, longer lines are limited to lower power transfer than shorter lines, and while short lines can be loaded to the thermal limit which can be several times the surge impedance loading (SIL), longer lines are limited to SIL[10,13].

SIL is defined as the power transferred by a transmission line, when that line is terminated by a star arrangement of resistors each having a value equal to the surge impedance of the line. When the line is loaded thus, the reactive power generated by the line capacitance approximately equals the reactive power used in the line inductance. For this case study, it was decided to design the 6-phase line to have comparable SIL to the existing line ' ·n its length.

The surge impedance of a lossless 3-phase line is given by the following formula:

$$Z_3 = \sqrt{\frac{L}{C}} \qquad \text{...(5.2.2-3)}$$

and substituting the above values yields:
$Z_0 = 251.75\ \Omega$

Surge impedance loading is calculated using the standard formula

$$SIL = \frac{3V_p^2}{Z_3} \qquad \text{...(5.2.2-4)}$$

giving $SIL = 635.6$ MVA

It is now possible to proceed with a design for the power-equivalent 6-phase line.

5.3 Power-Equivalent 6-Phase Line

5.3.1 Transmission Line Design

The formula for surge impedance loading power transfer for a 6-phase line is given by:

$$SIL_6 = \frac{NV_p^2}{Z_6} \qquad \text{...(5.3-1)}$$

where
N = number of phases in the system (6 in this case)
V = the phase to ground voltage [V]
Z_6 = surge impedance of the 6-phase line [Ω]

In order to achieve an equivalent power transfer from the 6-phase line, it was necessary to choose some standard voltage level (thus taking advantage of existing equipment), and then manipulate the geometry of the line until a suitable surge impedance was achieved.

The existing Camden-Duvha line had an operating voltage of 400 kV (phase-phase) and the nearest standard level below this was 275 kV. Thus, the first batch of designs was produced for this voltage level, but it was invariably found that 275 kV was just slightly too low to achieve the same SIL. Returning to 400 kV made the SIL far too large, and so an intermediate (and unfortunately non-standard) operating voltage of 300 kV was decided upon (note also that 300 kV is the phase-phase voltage of the 2 constituent 3-phase sets, which corresponds to 173.2 kV phase-ground).

Having set an operating voltage, and knowing the number of phases to be used, the only remaining factor was to determine the required surge impedance using equation (5.3-1). The spacing of the line follows directly from the surge impedance and is described by the equations below:

$$Z_6 = \frac{1}{2\pi} \times \sqrt{\frac{\mu}{\varepsilon}} \times P_a \qquad \text{...(5.3-2)}$$

where:

$$P_a = \ln\left(\frac{R}{r}\right) + \sum_{n=1}^{N-1} Cos\left(\frac{2\pi n}{N}\right) \ln\left(\frac{1}{2} Co\sec\left(\frac{\pi n}{N}\right)\right) \qquad \text{...(5.3-3)}$$

and:

R = Radius of the entire 6-phase array, when arranged in a circle [m]
r = Radius of one phase conductor, or effective radius of one conductor bundle [m]
N = Number of phases in the array

Again, an iterative process was used to dimension the line, sizing, calculating the surge impedance, resizing and so on. It was found that the surge impedance (SI) was very sensitive to the R/r ratio, which needed to be very low for the correct SI value, this meant that either the radius of the whole phase array was to be made extremely small, or the radius of the individual conductors was to be made extremely large. The solution finally adopted was to switch to a 2-conductor bundle for each of the phases, thus increasing the effective radius of each conductor dramatically, while saving on cost, and lowering the R/r ratio.

The conductor originally used for the 3-phase line was a 35.56 mm diameter Bersfort, but since there were originally 9 conductors in total (3 phases with 3 conductors per bundle), and the new number of conductors was increased to 12 (6 phases with 2 conductors per bundle), it was decided to use a smaller diameter conductor. A Tern conductor having a diameter of 27 mm was the next conductor in the range, and was the final choice for the 6-phase line.

There were several aspects which were not considered in the design of the HPO line, which were electric and magnetic fields, corona loss, radio, audible and television noise, as well as switching surge and lightning surge performance. This was done (or not done) for the following reason: it was felt by the author that the main focus of the project was an economic analysis of HPO lines, and for this reason a candidate line had to be designed so that an accurate costing could be done. Thus, the aspects described above do not need to be quantified per se, but only assured that they fall within acceptable limits. Referring to the literature, 3 cases of 6-phase lines were found[6] with a nominal voltage of 138 kV phase-ground, and R values of 1.8m, 2.44m, and 2.13m. These lines were completely analyzed with regard to the above parameters and performed satisfactorily under NY state regulations which is among the most severe in the US. Scaling the above distances to 173.2 kV phase to ground, the values of 2.26m, 3.06m and 2.67m are obtained respectively, and thus the chosen radius of 3m for the present line will perform satisfactorily with respect to E and H fields, corona loss and related effects, as well as switching and lightning surge performance.

The final dimensions of the line are shown on the diagram below:

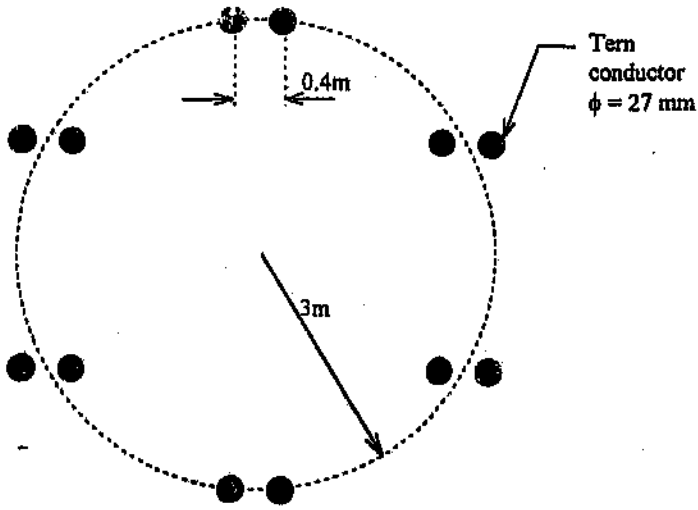


Figure 5.3.1.a: Geometry and Dimensions of the Candidate 6-Phase Circuit

5.3.2 Tower Design

The tower designed for the 6-phase line is based on the designs produced for the economic analysis of reference [8]. The final tower chosen was scheme 5, which was a guyed portal tower and was shown to be the cheapest of all the other designs. This tower is illustrated in figure 5.3.2.a.

As can be seen, this tower was originally designed for a 12-phase, 317 kV (phase-ground), single conductor per bundle system and needed minor modifications. Since the 6-phase design uses 2 conductors per bundle, the total number of conductors remains the same, and thus that component of the vertical loading remains unchanged. The voltage of the 6-phase system is much lower, and there are only 6-phases in total, so the win-dow of the portal tower can be made much smaller, and the clearance reduced.

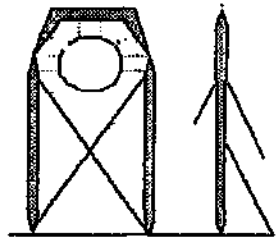


Figure 5.3.2.a: Schematic Representation of a 12-Phase, 317 kV Tower

It was decided to retain the span lengths originally used for the Camden Duvha line, implying that the total number of towers will remain the same. The ratio of strain towers to suspension towers was also kept constant for purposes of comparison, as well as the height of the towers.

It should be mentioned in closing, that the towers chosen for the 6-phase design require a much narrower ROW than do the existing cross rope suspension towers. This is because the latter towers have structural elements surrounding the outer conductors, and guys projecting from the top of the structural members outwards. While the 6-phase tower has a structural frame surrounding the 6-phase array, the guys project towards the centre of the tower, and not outwards, thus dramatically reducing the width necessary for the transmission corridor.

5.4 Costing Comparison

5.4.1 Overview

Admittedly, any costing comparison is a complicated and highly intricate exercise, and invariably must take into account the specific economics of the case at hand. However, if certain assumptions are made the costing comparison can be dramatically simplified with only a minor loss in accuracy. The latter route has been followed in this project because it would have been extremely costly (and to a large extent unnecessary) to hire out ESKOM's line design team for a comprehensive economic analysis of the line, towers and designated route, hire out substation designers for converting substations to HPO, and transformer manufacturers for the required 6-phase transformers. The assumptions made are simple, and can give a very good idea of the costs involved and breakeven distances necessary.

The first assumption was to ignore the cost of land. Now, since the 6-phase line requires a much narrower ROW than does the conventional 3-phase line, it would have saved a great deal of money on land costs, so effectively it's advantage is taken away by this assumption. This has been done because consultation with line designers revealed that transmission corridor width in South Africa is determined by the voltage level and configuration (eg. double circuit 3-phase) rather than edge-of-right-of-way field and noise levels. When told about the lowered voltage, it was again stressed by ESKOM that legislation for ROW of 6-phase lines was not in place, and as such would most likely be allocated the same ROW as the original Camden-Duvha line. Since this area was ill defined and land costs are extremely variable, it was decided to forego the advantages of a narrower ROW and disregard this part of the economic analysis.

The second assumption made was to consider that substation upgrading costs consist only of transformers, transformer bays, and line feeder bays. This assumption is very similar to the one made by Stewart where he considered[6,10] terminal costs to be dominated by transformers and circuits breakers, except that in this assumption, the substations for the 3-phase and 6-phase case are identical throughout, except for the very last stage where the 3-phase line is either fed into a single 3-phase transformer (which requires a single transformer bay) and out through a single line feeder bay, or is fed into 2 smaller 3-phase transformers (requiring 2 transformer bays) and then out via 2 line feeder bays. Thus, only the difference between the 2 substations is considered, and there is no attempt to obtain complete substation costs. Incidentally, the line feeder bays include a complete 3-phase circuit breaker, so having 2 line feeder bays for the 6-phase line automatically gives the correct number of circuit breakers.

Using the above 2 assumptions left only 3 components to be costed: the transmission line itself, line feeder bays and transformer bays, and the actual transformers. Each of these elements is discussed in turn below.

5.4.2 Transmission Line Costing

This element was by far the most difficult to assess, not only in terms of the actual costing itself, but finding the right utility, section, division, and so on. The final costing was done through a series of consultations with Frans Ritky[49] of ESKOM's line design section.

The costing proceeded as follows: first, the original scheme 5 design[9,10] was entirely cost assessed. The reason that this particular design was chosen was because it was the cheapest of the 6 designs considered in the paper, and most importantly, all vertical, longitudinal and transverse loading values as well as limiting conditions were given, in addition to computed base tower weights. Thus, all the necessary information was given and the costing could be done easily and precisely. The next step was to scale the tower to the specified size (because the original tower was designed for a 317 kV phase-ground, 12 phase system), and scale the various costs accordingly to obtain the final tower costs.

In scaling the towers (and costs), certain assumptions were made and are listed below:

1. Tower base weights are smaller because the mass of conductors is dramatically reduced which reduced the loading, towers are shorter due to a lower nominal voltage, and towers are narrower because there are only 6 phases as opposed to the original 12, operating at 173 kV as opposed to 317 kV. Taking all the above factors into consideration, the new tower costs are reduced to approximately 60% of the original tower costs.
2. Insulator costs are halved because there are only 6-phases as opposed to 12, requiring only 12 insulators as opposed to 24. In addition, the insulators are shorter and lighter due to the reduced system voltage, and are modelled as 6 "V" strings to be compatible with the costing program.
3. It is assumed that the line is a straight point to point link, and thus 280 of the 303 towers were made to be suspension towers, 15 were light strain towers, and 8 were heavy strain towers.
4. Conductor diameter was also reduced. The original scheme 5 tower used 12 conductors of 35 mm diameter, but this was considered to be too much, and so the next conductor in the range, a 27mm diameter conductor was used instead.

Appendix A contains printouts of 3 cases that were analyzed on the transmission line costing program. The first case is the original Camden-Duvha line which is the base case for comparison. The next is the 6-phase line designed with light, 27mm diameter conductors (Tern), and is the HPO representative case. The final case is a similar 6-phase design but using the original 35.5mm diameter conductors (Bersfort) to illustrate the effect of conductor diameter on cost.

The respective costs were:

1. Camden-Duvha 3-phase base case:	578 557,59	R/km
2. 6-Phase line, light conductor (Tern)	468 480,14	R/km
3. 6-Phase line, heavy conductor (Bersfort)	610 360,45	R/km

As can be seen, simply changing the conductor diameter - without modifying tower base weights, etc. - to the next value in the range has resulted in a sharp rise in costs, which is consistent with the observation that conductor costs are by far the dominant factor in line design (for this line, at least). Thus, to optimize the 6-phase line further, it is suggested that steps be taken to minimize conductor mass as much as possible, by either considering alternative configurations and bundling schemes, or raising the system voltage.

5.4.3 Bay Costing

Transformer and line feeder bays were priced with the help of Lawrence Ryan[50] of ESKOM's substation design section. As mentioned above, the only additional substation equipment necessary aside from the transformers themselves, are the bays in which they are housed, as well as line feeder bays which consist of the mechanical support structures and a complete 3-phase circuit breaker.

Another point which must be mentioned is that there is no bay equipment rated to a nominal 300 kV (which is the phase-phase voltage of the two, 3-phase circuits comprising the 6-phase line), and thus the approach taken was to price equipment for 400 kV systems price similar equipment for 275 kV systems, and linearly interpolate the prices to obtain a 300 kV system. The results are given in the table below:

Equipment Description	275 kV	400 kV	300 kV (interpolated)
Line feeder bay	R2.215 mil	R3.315 mil	R2.435 mil
Transformer bay	R1.635 mil	R2.40 mil	R1.788 mil

Table 5.4.3-a: Transformer and Line Feeder Bay Costs

5.4.4 Transformer Costs

Transformer costs were obtained with the help of Keith Plowden[51], chief executive of ABB PowerTech Power transformers. For this project, two types of transformers were necessary: a two winding transformer - two of which were to be used for the 6-phase transformation, and a standard autotransformer which was to be used for the conventional 3-phase line.

As was discussed earlier, the 300 kV nominal voltage level which was to be used for the double wound transformers was a non-standard one and so there were no "off the shelf" models which could be priced. However, ABB PowerTech stated that such a transformer could easily be built up, as could any other transformer in this voltage and power range, and priced according to the standard formula given below.

$$Price = \left(\frac{MVA}{800}\right)^{0.62} \times 15 \qquad ...(5.4.4\text{-}1)$$

This formula uses an 800 MVA transformer - costing 15 million rand - as a base. To obtain the price of the new transformer, its MVA rating is substituted into the formula, and the ratio of the new MVA rating over the 800 MVA base, raised to a constant power, gives a scale factor for the 15 million rand base and subsequently the new price.

A similar formula was obtained for the autotransformer price. Again, the formula used an 800 MVA transformer as the base for the calculation, but costing 11.2 million rand. The new formula is given below:

$$Price = \left(\frac{MVA}{800}\right)^{0.56} \times 11.2 \qquad ...(5.4.4\text{-}2)$$

Finally, the question remained of how to rate the transformers. Reference [13] shows a graph of transmission-line loading versus distance, using SIL as a base. This graph shows that the line is loaded to 1.0 SIL only at 300 miles, so rating the transformers to 600 MVA - the line's SIL would be too low. Also, the line's thermal MVA rating was approximately 2000 MVA, which is 3.3 SIL and this type of loading is only achieved with lines below 60 miles. The key was to establish a range of preliminary breakeven distances for the line in order to know the loading and hence transformer rating.

This exercise yielded distances of the order of magnitude of 200 - 250 km, and over this distance, loading was approximately 1.6 SIL. Thus, the total capacity of the line was set at 1000 MVA which is 1.67 SIL.

Another approach was to consider the original Camden-Duvha line and its rating. This line has a thermal limit of 2000 MVA, and a length of 100 km. If the length is doubled, the series impedance of the line is also doubled and stability-power limit is halved. If the thermal MVA is kept at a certain ratio to the stability-power-limit, then it is also halved and for a 200 km line the loading will be 1000 MVA (or less if the length is increased further.). Rating the transformers at 1000 MVA is thus considered accurate for this length of line. The table below shows transformer costs after equations (5.4.4-1) and (5.4.4-2) have been applied to the above data.

Line	Transformer rating	Number of transformers	Cost per transformer	Total cost of transformation
3-Phase	1000 MVA (Auto)	1	R 12.7 mil	R 12.7 mil
6-Phase	500 MVA (2 winding)	2	R 11.2 mil	R 22.4 mil

Table 5.4.4-a: Transformation Costs of 3- and 6-Phase Lines Loaded to 1000 MVA

5.4.5 The Camden-Duvha Comparison

The Camden-Duvha line has been discussed in detail in section 5.2, and after defining the specific elements to be evaluated, and their respective costs, an economic analysis can be carried out.

The line itself is an interconnector between the Camden and Duvha power stations, and directly links two 400 kV busses. Thus, to implement a 6-phase system, two sets of transformers, transformer bays, and line feeder bays will need to be installed on both ends of the line, as well as 100 km of actual line itself. The line will thus cost:

Equipment	Quantity	Cost per Unit (R)	Cost (R)
Transformers	4	11 200 000	44 800 000
Transformer bays	4	1 788 000	7 152 000
Line feeder bays	4	2 435 000	9 740 000
Line	100 km	468 480 /km	46 848 000
Total cost			***108 540 000***

Table 5.4.5-a: Total Costs of 6-Phase Camden-Duvha Line

The Camden-Duvha, being nominally rated to 400 kV does not need any terminal equipment at all, and its cost is comprised solely of the line cost itself. Its cost is then:
3 Phase Cost = R578 558/km × 100 km = ***R 57 855 800***

Comparing the prices of the two lines, it is immediately apparent that the HPO line costs very much more than the existing line. The difference in cost is approximately R50,7 million and represents an 87.5% increase in cost over the original line. Clearly, HPO is not the economic option in this case, and a detailed analysis will be given in section 5.5.

5.4.6 Breakeven Distance

To make the comparison more meaningful, a hypothetical situation is created where a point-to-point transmission line must be built, linking two 132 kV systems, and a breakeven distance is established where both options will cost the same amount - and above which, the 6-phase line will be the more economic option. Note too, that the two systems to be linked are of a different voltage level to the line, and thus terminal equipment will have to be taken into account for both 3- and 6-phase options.

As above, the 6-phase line requires two transformers, two transformer bays, and two line feeder bays at each end of the line, as well as the line itself, whereas the 3-phase line requires one transformer, one transformer bay, and one line feeder bay at each end of the line, as well as the 3-phase line itself. These two requirements can thus be written as two linear equations, with the independent variable x, being the line length.

Equipment	Quantity	Cost per Unit (R)	Cost (R)
Transformers	4	11 200 000	44 800 000
Transformer bays	4	1 788 000	7 152 000
Line feeder bays	4	2 435 000	9 740 000
Line	x km	468 480 /km	468 480x
Line equation			***Cost = 61 692 000 +468 480x***

Table 5.4.6-a: Line Cost Equation for 6-Phase Line

Equipment	Quantity	Cost per Unit (R)	Cost (R)
Transformers	2	12 700 000	25 400 000
Transformer bays	2	2 400 000	4 800 000
Line feeder bays	2	3 315 000	6 630 000
Line	x km	578 557 /km	578 557x
Line equation			Cost = 36 830 000 +578 557x

Table 5.4.6-b: Line Cost Equation for 3-Phase Line

To obtain the breakeven distance of the line, the line equation of the 3-phase line is set equal to the line equation for the 6-phase line, and the resulting equation is solved for x. This gives a breakeven distance of 225.86 km.

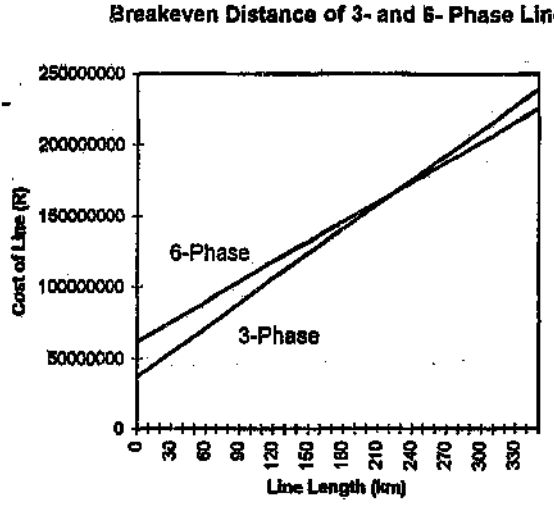


Figure 5.4.6.a: Breakeven distance

These equations are shown in graphical form in fig. 5.4.6.a and are seen to intersect at the breakeven distance. It is important at this stage to return to the assumption originally made about the breakeven distance being between 200 and 250 km, and to note that the actual value is 225.86 which falls exactly within the given limits, thus making the assumption true, and the analysis valid.

5.5 Discussion

The first case dealt with a specific economic comparison between an existing 400 kV 3-phase line connecting Camden and Duvha power stations, and an equivalent power 6-phase line. The study showed that for the same stretch of line, the 3-phase option would cost R57 855 800 and the 6-phase option would cost R108 540 000. This makes the latter line R50 684 200 or 87.6% more expensive than the former.

The reason for this dramatic difference in prices lies in the fact that the original 400 kV 3-phase line directly connects two 400 kV 3-phase systems, and thus does not need any voltage transformation or phase conversion, and consequently does not require any terminal equipment. The 6-phase line on the other hand, must have costly terminal equipment installed at both ends of the line for both voltage transformation, and phase shifting. Line feeder bays must be installed for the line side breakers.

Furthermore, the transformation capacity on both ends of the line was planned for a much longer line (200 -250 km) and thus is considered to be underrated for the 100 km Camden-Duvha stretch. To be more realistic, the transformation capacity should be brought closer to 2000 MVA, adding R24.1 million rand to the cost of transformation (this figure is the sum of all four transformers).

As can be clearly seen, this line is entirely unsuitable for upgrading to 6-phase transmission. The cost of terminal equipment far outweighs any cost advantage offered by the line, and unless the cost of the land saved - which has not been taken into account - can offset the additional terminal costs (which is practically impossible), it is the view of the author that the existing 400 kV 3-phase line is the better choice for this application.

The second case dealt with an economic breakeven point between a 275 kV, 6-phase line and a 400 kV, 3-phase line similar to the Camden-Duvha line but not restricted in length. To make the comparison more even, this line was assumed to connect two 132 kV 3-phase systems, which would necessitate transformation for both options, and associated terminal equipment.

Since the substations are essentially similar except for the transformers, transformer bays, and line feeder bays, the other costs were assumed equal and only the above elements were taken into account when considering terminal costs.

Performing the analysis showed a breakeven distance of 225.86 km and the question must now be asked: is this distance feasible? To answer this, there is a well known "rule of thumb" which states that the system voltage increases approximately 100 kV for every 100 km, and thus a 400 kV line should be approximately 400 km long. In light of this fact, a breakeven distance of 225.86 km is well within the line length of a typical 400 kV line, and would represent a saving of R19.17 million. If one considers further that the cross-rope suspension towers used for the Camden-Duvha line are the cheapest ones used by ESKOM, and represent the state of the art in tower design, the fact that the 6-phase line was able to save almost R20 million over a typical stretch becomes a significant achievement.

An anomaly to this rule is seen in the Camden-Duvha line which is rated to 400 kV but is only 100 km long. A discussion on this matter with ESKOM line design team revealed that this line is one of the most heavily loaded 400 kV lines in operation, and its voltage was deliberately made higher to account for this fact. This again, goes to explain the peculiarly high cost differential seen in the previous case.

An additional factor which goes to influence cost is the transformer type. So far this has not been mentioned, but the 3-phase line uses autotransformers exclusively for its transformation, which are by far cheaper than the 2-winding transformers used for the HPO line. This is permitted by the fact that both 132 kV systems were assumed to be in phase. If this were not the case, the 3-phase line would also need 2-winding transformers which would further reduce the breakeven distance.

A factor which was previously neglected was the effect of land savings. As mentioned previously, the HPO towers were designed specifically with reduction of ROW in mind, having outer phase distance of 6m, compared to 16.4m for the 3-phase line. The former also had an internal guy-rope system allowing for maximum compaction, whereas the latter had external guys. To assess the impact of land savings, Frans Ritky of ESKOM's transmission line planning division was consulted and asked for typical values. The Camden-Duvha line currently uses a servitude of 55m width, whereas if the 6-phase alternative line were to be built, it would most likely be assigned the same servitude as a 132 kV line, namely 35m. The existing line thus uses an additional 20m of land or 57% more then the 6-phase line. Looking further into the problem, the typical cost of land for the Camden-Duvha line is approximately R4000/hectare, which means that a saving of R8000 is achieved per kilometer of 6-phase line, or R800 000 for the 100 km stretch. Calculating a new breakeven distance with the inclusion of land costs, yields a slightly improved value of 214.2 km.

Although the above results do not show a dramatic difference, it is nevertheless believed by the author that land-value is the single most important factor in HPO line economics. The cost of land in this project forms approximately 2.2% of the total cost (for 100km, including substations) of the project, and is thus confounded by other cost factors. As soon as this factor takes on a more dominant role, the cost of HPO lines will become very competitive in relation to existing lines.

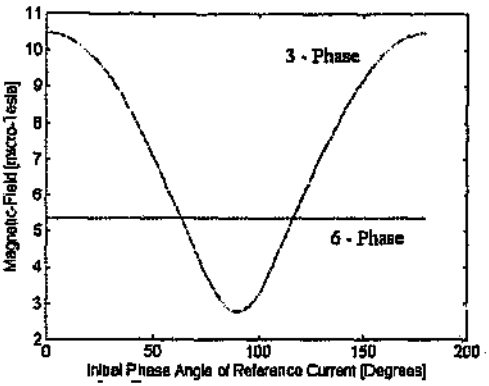


Figure 5.4.6.b: Magnetic Field at Ground Level at the Centre Line

An aspect which is steadily gaining attention is that of magnetic fields, and their mitigation. To study this, a short routine (which is listed in Appendix B) has been written, and computes the B-field magnitude at the centre line, ground level, for a half period of the power frequency. The variation of magnetic field at the given point with the angle of the current is plotted in figure 5.4.6.b.

As can be seen the maximum value of B-field for the 3-phase case is 10.48 μT whereas the value of the B-field for the 6-phase case is 5.33 μT, under maximum loading conditions, i.e. 1000 MVA. The value of the field itself is not only significantly reduced for the 6-phase case, but has a far smaller variation than its 3-phase counterpart showing a significant degree of natural field cancellation. This has a very important implication: the most damaging aspect of magnetic fields is considered to be their rate of change[53] since this induces an EMF (and hence current) into nearby objects. Comparing the rate of change of the 3-phase and 6-phase B-fields from fig. 5.4.6.b, it can be seen that the latter's derivative with respect to time is approximately zero, and its resultant damaging effect is negligible, whereas the former has a large derivative with the traditional damaging effects. Both options' field values were found to be well within stringent US limits[ibid].

Brief mention should just be made of thermal loading calculations. While the calculations themselves are long and laborious, a rough guide to check proper operation is the value of current density. At full load i.e. 1000 MVA, the current density of the 3-phase line is 0.70 A/mm^2, and 1.19 A/mm^2 for the 6-phase case. A consultation with Rob Stevens of ESKOM[52] revealed that while the current density for the HPO line is slightly on the high side, the conductor is smaller and permits more effective cooling. Although it is preferred to keep the current density slightly lower than 1.0 a/mm^2, this value is still acceptable and will work well. Mr. Stevens also commented that some lines are sometimes operated at 2.0 A/mm^2 for short periods, and the line under consideration will only be operating at full load for a small portion of the time.

It should be noted, in closing, that compacting the lines leads to a reduction in series impedance, and so it is believed that switching to HPO compaction technology could do away with expensive and clumsy series line compensation, which introduces another cost advantage. In addition, it has been mentioned previously that HPO lines are naturally very well balanced, and as such could eliminate the common - and costly - practice of line transposition.

6. Conclusions

This project has dealt with the novel means of compacting transmission lines, and maximizing the power density through transmission corridors using the technology of high phase order transmission. The report was divided and presented in four parts, namely: principles of HPO technology, HPO technology itself, a brief survey of case studies performed elsewhere in the world, and a unique South African case study performed by the author.

The first section sketched the brief principles underlying HPO technology. It was shown how Barnes and Barthold's[1] original analysis showed that 95% of the power carried by a transmission line could be found within a radius of 5% of the phase-phase distance, implying that transmission corridors were being utilized very inefficiently. The next subsection went on to introduce HPO using a 6-phase phasor diagram, and its associated sine waves, and finally the section established that besides the obvious compaction, HPO had many other advantages which could make it attractive as a design alternative, including minimal current unbalances, ability to perform single pole switching, electric and magnetic field mitigation, dramatic reduction in corona and corona related effects, aesthetic appeal (although this has not been scientifically established), total compatibility with existing 3-phase systems, and in some cases, a distinct economic benefit

The second section of the report discussed the actual technology of HPO systems. Initially, a means of defining system voltage was established, using the phase-ground voltage as the least ambiguous. Then, various technical aspects were discussed, potential coefficients were calculated, which allowed computation of inductance, capacitance and surge impedance. Then, the all important subject of fault analysis was developed and it was shown that symmetrical component transformations (using eigenvalue analysis as a base) could successfully be applied to fully transposed HPO lines. However, by their nature, HPO lines could not be fully transposed, but only "roll transposed", and this was taken into account in the impedance matrix by having 4 unique elements, as opposed to 2. Load flow analysis was then covered and it was shown that this could be easily performed using existing 3-phase packages, by simply treating the line as two interleaved 3-phase lines with appropriate compensation built into the line parameters.

In the same section it was shown that switching surge analysis could be divided into 3 groups of surges: those occurring between adjacent phases, those occurring between alternate phases, and those occurring between opposing phases (this is for a 6-phase system only). On a per-unit basis it was shown that surges occurring between adjacent phases were the most severe, and thus would limit the degree of compaction achievable, but compared to 3-phase switching surge data these results were comparable. Lightning surge performance remained approximately similar to 3-phase performance. The implementation of protection systems was then covered and appropriate criteria established. Finally, the vital element of transformer configuration was discussed. As it happens, transformer secondary interconnections which would achieve 6-phase operation were very simple, requiring only 2 sets of 3-phase phasors, the one shifted 180 electrical degrees with respect to the other, and then the two systems superimposed onto one another. Actual implementations of this using various types of transformers were numerous, but it was generally agreed that from a cost and space saving point of view, two 3-phase transformers connected as delta-star, and delta-inverted star, were the best option.

The third section of the report analyzed 5 case studies in HPO economics and technology. The first 2 cases both dealt with upgrading of double circuit 3-phase lines to 6-phase operation, but were written by different researchers (Stewart[6] and Guyker[34]), and approached the subject in different ways. Stewart considered 5 limiting cases and analyses them all for possible uprating to a higher voltage level, or 6-phase operation. He then calculated the operating savings per kilometer if the line was modified to 6-phase operation and established a breakeven distance where these saving would offset the added cost of terminal equipment. Guyker, on the other hand, considered uprating of an existing transmission line (the Charleroi-Yukon line) to either a higher voltage or 6-phase operation.

It was generally felt that Stewart did not compare 3- and 6-phase lines, but only 6-phase line performance and its savings. Guyker compared the 2 lines and found that the 6-phase option was the more costly, but only because the 3-phase lines used the much cheaper autotransformers, as opposed to 2 double-wound transformer sets. The next case study compared UHV transmission between a newly developed 1200 kV 3-phase system, and 5 different HPO designs having both 6- and 12-phase transmission and different voltage levels. While the HPO lines performed very well at this voltage and loading level several criticism were made about this comparison: firstly, is a 1200 kV line a valid base case for comparison, and how does it compare to existing methods of transmitting this amount of power? Is the capacity of the 3-phase line evenly matched with the capacities of the candidate HPO lines? (and there is some speculation about this question) And finally, was terminal equipment thoroughly considered in terms of the necessary ratings and availability?

The fourth case study described the first test line in Malta. This was a 366 m stretch of line, having both 6- and 12-phase lines running parallel each other, and along its way having many different types of towers, insulator configurations, mid-span spacers, and so on. The most important outcome of this test line was that it performed precisely as predicted by the computer simulations and thus these simulations could be trusted in the designs of further lines.

The fifth and final case study described the first utility application of a 6-phase line between Goudey and Oakdale substations, a 2.4 km stretch of line in Binghamton NY operated under the joint supervision of NYSEG, ESEERCO, and PTI. A discussion with the project supervisor revealed that the line's most important contribution to the field of HPO was in that it performed as expected, with fields, corona effects, and loading correlating well with predicted values. The line is also economically justifiable where ROW is constrained. Minor problems on the line included slight corona emanating from the optical fibre coat, and excessive unbalances which were later found to be a generator problems rather than a characteristic of the line itself. Finally, a series of simulated live maintenance operations were performed on the line and shown that this is technically viable, and safe.

The fourth and final section of the report discussed a South African case study. Here, the 400 kV, 3-phase, 100 km Camden-Duvha line was compared to an equivalent power 6-phase line and it was found that the latter line was at least R50.7 million, or 87.5% more expensive than the former. This can be attributed to the fact that the original line connected two 400 kV busses directly and did not use any additional terminal equipment, whereas the 6-phase line needed all the transformation and switching equipment added to its cost, on both ends of the line. This line was also unusual in that it was rather short for its voltage level, and very heavily loaded thus confounding the savings of the actual line itself.

To correct this discrepancy, a second comparison was carried out where a breakeven distance was established between 2 lines similar to the above, but connecting two 132 kV systems, which would require both options to have terminal equipment. The results of this study showed the breakeven distance to be 225.86 km, and taking into account the rule of thumb that line voltage is increased by approximately 100 kV for every 100 km, these line would typically be 400 km long, and thus this breakeven distance is considered a very positive result. In this comparison, several other factors need to be borne in mind, in order to contextualise the results:

- The type of line used as base case is a cross rope suspension tower which represents the cheapest, and most advanced technology used by ESKOM at the present time and the fact that for typical stretches a 6-phase line is cheaper than this technology, becomes a very significant discovery.
- The type of terminal equipment used is very important. For the 3-phase line, typical autotransformers were used as is standard practice at ESKOM for this voltage level. For the 6-phase line, two separate transformers were used, each a double wound transformer (which is far more expensive than an auto-transformer), rated to half the value of the original. This was done to make the comparison more realistic, but simultaneously imposed a severe cost penalty on the HPO line. If the two 132 kV systems were out of phase, the 3-phase line would also need to employ double wound transformers, which

would increase the cost of its terminal equipment, reduce the terminal equipment cost differential between the two options, and significantly shorten the breakeven distance. In addition, it is believed that if 6-phase lines became more common, dedicated transformers would be designed for this type of operation which would decrease their cost substantially.

- An important factor which has been excluded from the breakeven calculations was the cost of land. As has been previously mentioned, HPO technology works best when land is very expensive or constrained. In this case, the distance between outer conductors has been reduced from 16.4 m to 6 m and special towers with internal guy ropes were used as opposed to the external guys used for the cross rope suspension tower thus further reducing the ROW necessary. If the savings on land costs had been taken into account, the 6-phase option would present a far stronger case and breakeven distances would decrease. Land value has presently not been considered to make the comparison more realistic (following ESKOM's land allocation practices).
- Finally, the 6-phase option with its circular conductor configuration gives a far more balanced system than its 3-phase counterpart, and does not need transposition. In addition, bringing the respective phases closer together reduced the series inductance of the line, obliviating the need for series capacitor compensation. This represents another potential cost saving of HPO lines.

In conclusion, it has been demonstrated in this report that there is a vast body of knowledge that exists in the literature dealing with all aspects of HPO lines, from analytic techniques, to protection, to dedicated computer programs dealing specifically with HPO lines, to various studies showing the technical benefits of HPO lines. There is also a number of case studies which attempt to quantify the economic benefits of this technology using aspects such as reduced corona loss, lighter towers, and smaller conductor diameters for its costs saving mechanism. Finally, there is the first utility application of a 6-phase line, which has gone a long way in showing the feasibility of this technology and building confidence in its ability to performs as well as, if not better than, current lines.

Focusing specifically on South Africa, the following points can be made: land value, and current land allocation practices are not yet stringent enough to cause an overwhelming demand for any type of compaction technology. There is, however, evidence that the population is quickly increasing in numbers, as well as demand for electric power, so it is not too difficult to imagine that in the near future a situation will be created where land is expensive, very hard to attain, and there is a demand for large amounts of electric power - a scenario suited perfectly to high phase order technology.

Nevertheless, it was shown that even in the present times, 6-phase transmission can be cheaper than even the most advanced (and cheapest) technology, given that certain criteria are fulfilled. These are:

1. that the line be sufficiently long to allow savings on the actual transmission line to dominate over the added expense of HPO terminal costs
2. that there be as little terminal equipment as possible, that is, few tee-offs and only point to point applications.
3. that the voltage be sufficiently high to allow the reduction of field levels, land savings and corona related effects to become apparent. These can subsequently offer economic benefits.

In closing, it should just be said that this technology is available, and ready for application. While the present economic climate does not particularly favour its implementation, it is easy to envisage a time where such a technology will be widely used, and as such must not be forgotten as an invaluable future design alternative.

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Appendix A: Costing Printouts

This appendix contains printouts of the original EXCEL worksheets used to cost the transmission lines, and is broken down into very specific cost components.

The three worksheets are:

1. Costing of the original Camden-Duvha line
2. Costing of the final 6-phase
3. Costing of the 6-phase line using a heavier conductor (for comparison purposes)

Appendix B: MATLAB Code

B.1. Magnetic Field Plotting Program

```
function mag_fld2(h,current3,current6)
%
% this m-file will calculate the maximum magnetic field given by
% either a 3- or 6-phase line, as a function of the starting angle
% of the current, and plots a graph of it.
%
% enter the parameters as such:
% mag_fld(Height_above_ground, current_of_3phase, current of_6phase)
%

for j = 1:181

        angle(j) = (j-1);
        angle_rad = angle(j)/180*pi;

        fld_3(j) = field_3a(current3, h, angle_rad)*4*pi*0.1;

        fld_6(j) = field_6a(current6, h, angle_rad)*4*pi*0.1;

% I have multiplied H-field values by 4.Pi.e-7 but then multiplied back by
% e+6 to get values in microtesla. Hence the 0.1 factor

end;

plot(angle,fld_3,angle,fld_6)
xlabel('Initial Phase Angle of Reference Current [Degrees]');
ylabel('Magnetic-Field [micro-Tesla]')

end
```

B.2. 3-Phase Calculation Routine

```
function [total_H, angle] = field_3(current, height, phase)
%
% this function will calculate the value of magnetic field anywhere
% along the centre line of the Camden-Duvha line. It uses the geometric
% equivalent value of the 2 conductor bundle.
%
% inputs are given in the order:
% field_3(current_magnitude, height_above_ground, initial_phase_angle)
%
% outputs are total magnetic field magnitude, and angle above horizontal

% initialise all the beginning variables
%
```

```
total_x = 0.0;
total_y = 0.0;
total_H = 0.0;
angle = 0.0;


% initialise the currents in the conductors:
%
I(1) = current*sin(phase);
I(2) = current*sin(phase+2*pi/3);
I(3) = current*sin(phase+4*pi/3);


% initialise all the conductor angles to the centre line
%
theta(1) = 0.0;
theta(2) = atan( 8.2 / height );
theta(3) = -theta(2);


% initialise all the conductor distances to the point of interest
%
dist(1) = height;
dist(2) = sqrt(height^2 + 8.2^2);
dist(3) = dist(2);


% "for" loop to add elements of x and y fields together
%
for j = 1:3
field(j) = I(j) / (2*pi*dist(j));

total_x = total_x + field(j)*cos( theta(j) );
total_y = total_y + field(j)*sin( theta(j) );

end;


total_H = sqrt( total_x^2 + total_y^2 );
angle = atan( total_y / total_x );

end
```

B.3. 6-Phase Calculation Routine

```
function [total_H, angle] = field_6(current, height, phase)
%
% this function will calculate the value of magnetic field anywhere
% along the centre line of my 6 phase array. It uses the geometric
% equivalent value of the 2 conductor bundle.
%
% inputs are given in the order:
```

```
% field_6(current_magnitude, height_above_ground, initial_phase_angle)
%
% outputs are total magnetic field magnitude, and angle above horizontal


% initialise all the beginning variables
%
total_x = 0.0;
total_y = 0.0;
total_H = 0.0;
angle = 0.0;
y1 = 1.5*sqrt(3);


% initialise the currents in the conductors:
%
I(1) = current*sin(phase);
I(2) = current*sin(phase+pi/3);
I(3) = current*sin(phase+2*pi/3);
I(4) = current*sin(phase+pi);
I(5) = current*sin(phase+4*pi/3);
I(6) = current*sin(phase+5*pi/3);


% initialise all the conductor angles to the centre line
%
theta(1) = 0.0;
theta(2) = atan( y1 / (height-1.5) );
theta(3) = atan( y1 / (height+1.5) );
theta(4) = 0.0;
theta(5) = -theta(3);
theta(6) = -theta(2);

% initialise all the conductor distances to the point of interest
%
dist(1) = height-3;
dist(2) = (height-1.5)/cos(theta(2));
dist(3) = (height+1.5)/cos(theta(3));
dist(4) = height+3;
dist(5) = dist(3);
dist(6) = dist(2);

% "for" loop to add elements of x and y fields together
%
for j = 1:6
field(j) = I(j) / (2*pi*dist(j));
total_x = total_x + field(j)*cos( theta(j) );
total_y = total_y + field(j)*sin( theta(j) );
end;
total_H = sqrt( total_x^2 + total_y^2 );
angle = atan( total_y / total_x );
end
```

Abstract

This report discusses high phase order (HPO) technology, i.e. the use of more than the conventional 3 phases for transmission of electric power, its use in the compaction of lines, and power density maximization over existing servitudes. It is structured in four parts. The first part introduces the concepts, establishes the need, and lists the advantages of HPO. The second part deals with the technology itself and shows that it is possible to analyze HPO systems using symmetrical component analysis, lists common transformer configurations, covers protection, and so on. The third part analyses 5 case studies, the first 3 being analytical, and the last 2 being the first experimental test line, and the world's first utility application of HPO lines.

The final section is a South African case study and compares an HPO line to an existing 400 kV 3-phase line and shows that the former is 87.5% more expensive to implement than the latter. Comparing the 3-phase and 6-phase lines on a more even basis, yielded a breakeven distance of 225.86 km, above which the 6-phase option becomes more economical. These results are then explained and discussed in the conclusions section.

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