

Effects of Transmission Line Construction on Resonance in Shunt Compensated EHV Lines

Marta Val Escudero, Miles Redfern

Abstract—Series resonance can occur in shunt compensated transmission lines during unbalanced switching operations resulting in open phase overvoltages that can damage line connected equipment (instrument transformers, surge arresters, shunt reactors and open circuit breakers) and can therefore compromise system security and availability. This paper analyses the effect of different single-circuit line design parameters on the location of resonant points when shunt reactors are used for reactive power compensation.

A practical example of a system expansion is also illustrated and the implications of incomplete line transposition and presence of neutral reactors are discussed.

Key Words: Insulation Co-Ordination, Resonance, Shunt Reactors, Transmission Lines, ATP/EMTP.

I. INTRODUCTION

A. Planning and Design of Transmission Lines

The need for new Transmission Lines is normally determined by extensive planning analysis in the form of Power Flow, Power Transfer Capabilities and Stability studies. The outcome of the planning studies defines the connecting points, voltage level, minimum transmission capacity and the need for compensation. Often one of the first decisions to be made during a new OHL (Overhead Line) project is (a) to build the line to the largest capacity within practical limitations and thus delay new reinforcements as long as possible or (b) to build the line just to meet the required capacity. Option (a) has socio-environmental implications and a higher initial cost than option (b) but may result in a more economic solution in the long term in areas with a high load growth or high land price. Other than transmission capability, the OHL project engineers must evaluate and decide on a large number of practical design and implementation options which may have severe implications on both the system performance and the overall project cost. In order to maximize the performance/cost ratio, all design options have to be evaluated simultaneously. Some of these options are listed below and will be discussed in this paper from the point of view of line performance under unbalanced operating conditions:

⇒ Tower design. (Tower and Right of Way costs).

- ⇒ Single or Double Circuit construction. (Economics vs. reliability)
- ⇒ Phase conductors shielding and phase clearances. (Economics vs. performance)
- ⇒ Single or bundle conductors. (Economics vs. corona/interference performance)
- ⇒ Line Transposition and shunt compensation. (Economics vs. performance)
- ⇒ Need for Neutral Reactors. (Economics vs. performance)

B. The Application of Shunt Reactors

It is well known that OHL and cables generate reactive power due to their shunt capacitance. Although necessary to support voltage and to transmit power, excess reactive power at light loads can have the following undesirable effects:

1. Voltage rise at the receiving end due to capacitive current flowing through the line inductance.
2. Voltage rise at sending end due to capacitive current flowing through the source impedance.
3. Self-excitation of synchronous machines in the event of load dropping.

Voltage rises of 20% are not unusual for systems with long lines and low short-circuit power. If not controlled, line overvoltages will reduce the life-time of insulation materials and will eventually result in system faults, compromising both system security and availability. For that reason, and in order to keep voltages within acceptable limits, the excess of reactive power generated by long EHV OHL or cables needs to be drawn out. The desired voltage variation under normal conditions usually ranges between +5% and +10%, generally higher during heavy loading than under light loading.

Shunt reactors are by and large used in transmission lines longer than 200km (or even shorter if supplied by a very weak system) for reactive power compensation, voltage control and, sometimes, for synchronous stability improvement. The degree of shunt compensation (k) provided by a reactor bank is quantified as a percentage of the positive sequence susceptance of the line to which it is applied:

$$k = \frac{B_L}{B_C} = \frac{1/(\omega \cdot L)}{(\omega \cdot C_+)} = \frac{1}{\omega^2 \cdot L \cdot (C_{ph-gr} + 3 \cdot C_{ph-ph})} \quad (1)$$

where L is the shunt reactor inductance per phase, C_+ is the positive sequence line capacitance, C_{ph-gr} is the line capacitance to ground, C_{ph-ph} is the inter-phase line capacitance and ω is the system angular frequency. Typical compensation degrees range between 60% and 80%.

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Shunt reactors are generally Y-connected, either fixed or switched, at one of the following locations:

- ⇒ Transmission Line end.
- ⇒ Substation Bus Bars.
- ⇒ Transformer Tertiary Windings.

Permanently connected line shunt reactors allow a reduction in the line insulation level. This possibility is of great interest at the early stages of development of Transmission Systems for the following reasons: (a) the available short-circuit power is relatively low, so the overvoltage limitation achieved by the reactors is very important and (b) the line loading is normally well below the SIL, for which a continuous connection of a shunt reactor is tolerated. High degrees of shunt compensation can limit the stability limits. When the line loading is increased the net reactive power (generated – losses) is reduced and, in some cases, shunt reactors need to be disconnected to avoid excessive voltage drop. To overcome this problem it's not unusual to use a combination of fixed and switched reactors.

C. Resonant Conditions in Shunt Compensated Transmission Lines

Although shunt reactors are very effective in reducing overvoltages during light loading or following load rejections, their presence can actually increase the voltage induced on de-energized conductors under certain conditions:

- (a) in single-circuit lines when using single-pole switching: a series resonant circuit can be formed.
- (b) in double-circuit lines when only one circuit is energised: a parallel resonant circuit can be formed.

This paper deals only with the conditions that give rise to resonance in single-circuit shunt compensated lines. A detailed description on the parallel resonant phenomena on a double-circuit shunt compensated transmission line can be found in [4]- [7].

Unbalanced open phase conditions in single-circuit lines can occur when SPAR (Single Phase Auto-Reclosing) is used to clear and restore SLG faults or when 1 or 2 circuit breaker poles get stuck during a switching operation. In those conditions, the parallel combination of the disconnected phase(s) shunt reactor(s) and line capacitance in series with the inter-phase capacitance can form a series resonant circuit as illustrated in Fig. 1. Although published information dealing with this phenomenon is very limited, the risk of resonance for high shunt compensation degrees has been acknowledged since the 1970's [9]. An example of resonant overvoltages in a single-circuit line is reported in [2] where measurements performed in a 750kV line between Hungary and URSS are shown. A physical explanation of the phenomena and simplified expressions to locate resonant peaks were derived in [1] and are included below (2), (3). It should be noted that these formulas are based on the following assumptions:

- 1. All system components are linear and losses have been ignored.
- 2. System source and line series inductances are neglected.
- 3. Shunt reactors have no inter-phase coupling.

- 4. All system components are symmetrical (i.e. the transmission line is fully transposed).
- 5. Shunt reactors neutral is solidly grounded.

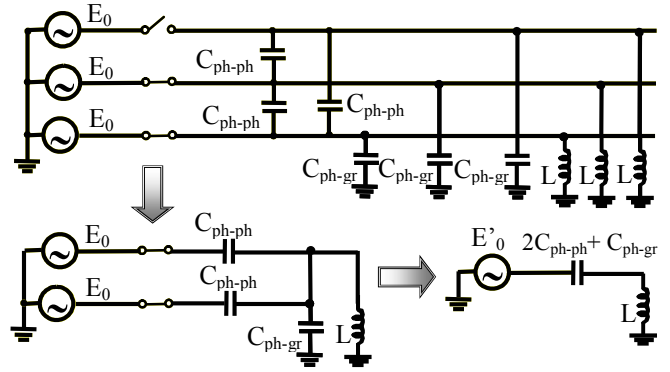


Fig. 1 Simplified circuit for analysis of series resonance in shunt compensated transmission lines with uneven pole operation.

⇒ Location of resonant peak at power frequency for one open phase condition:

$$k = \frac{1 + 2 \cdot m}{1 + 3 \cdot m} \quad (2)$$

⇒ Location of resonant peak at power frequency for two open phases condition:

$$k = \frac{1 + m}{1 + 3 \cdot m} \quad (3)$$

where k is the degree of shunt compensation, as defined in (1) and $m = C_{ph-ph} / C_{ph-gr}$.

It can be seen from (2) and (3) that the key factor defining the location of resonant points at power frequency is the ratio between phase-phase and phase-ground line capacitances. It is reasonable to assume therefore that line geometry plays an important part in the risk of resonance at power frequency. A more detailed analysis is performed in the next section.

It terms of resonant overvoltages, the most onerous scenario occurs when 1 or 2 breaker poles get stuck during a switching operation (line energization or de-energization). Single phase tripping after a SLG fault generally results in lower induced voltages. The resonant overvoltages will last as long as the unbalanced conditions remain in the system, stressing line insulation, surge arresters, shunt reactors, instrument transformers and open circuit breakers. Quick detection and clearance of the unbalanced condition is therefore critical to maintain system security and availability. Pole discrepancy protection schemes are commonly used and are set to trip the three circuit breaker poles in about 1 to 1.5sec, coordinated with SPAR dead time. Additionally, CB failure protection schemes stand as back-up to trip the entire busbar should the stuck pole condition remain.

It should be noted that this phenomenon can only happen with line connected shunt reactors. In well developed power systems where voltage rise due to load dropping do not represent a hazard to line equipment insulation, the shunt reactors can be located at the substation side of the circuit breaker, avoiding thus the occurrence of a series resonant circuit.

II. ANALYSIS OF SERIES RESONANCE IN SINGLE-CIRCUIT SHUNT COMPENSATED TRANSMISSION LINES

A. Effect of Tower Design

Four OHL constructions (Fig. 2) have been compared in terms of performance under uneven open-phase conditions: flat, vertical, delta and inverted delta.

While flat tower constructions may result attractive for their simplicity, reduced cost and lower visual impact, the Right of Ways tend to be wider than with the other tower constructions and land cost or space limitations may require consideration for other designs. Delta constructions involve higher tower costs but not as high as vertical constructions. Additionally, if full line transposition is not applied, delta configuration results in the lowest degree of unbalance and, consequently, lower interference levels with nearby telecom circuits or metallic pipelines. Vertical configurations in single circuit lines are very rare and only attractive when space limitation is a critical issue. Then again, obtaining Right of Ways and planning permission for building new OHL is becoming increasingly difficult. Optimum use of available land by means of double circuit construction is becoming the preferred option, operating just one circuit and keeping the possibility of adding a second circuit at any time with relatively low cost.

In order to facilitate comparison between the different structures shown in Fig. 2, inter-phase distances have been set to 10m in all cases and a minimum ground clearance of 15m has been selected. One conductor per bundle (600SCA) and full line transposition have been assumed. Reactors neutral point is solidly earthed.

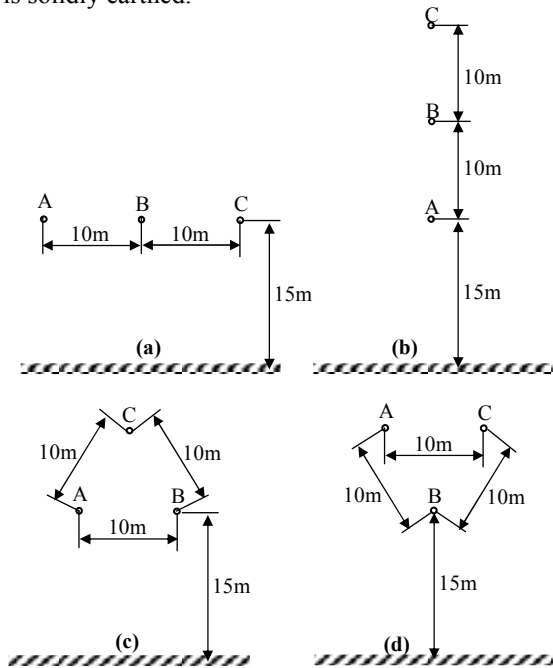


Fig. 2 (a) Flat Tower configuration, (b) Vertical Tower Configuration, (c) Delta Tower Configuration, (d) Inverted Delta Tower Configuration.

The calculated line capacitances for each line design are included in Table I. Shunt compensation degrees that cause resonance at power frequency are included in Table II and steady state open-phase voltages as a function of

compensation degree are depicted in Fig. 3. It can be seen that the flat configuration results in resonance at the highest compensation degrees. Delta and vertical configurations perform very similar.

TABLE I
LINE CAPACITANCES CALCULATED FOR TOWER DESIGNS IN FIG. 2 WITH ONE CONDUCTOR PER PHASE (600SCA)

Construction	C_+ [nF/km]	C_0 [nF/km]	C_{ph-ph} [nF/km]	C_{ph-gr} [nF/km]	m
Flat	8.477	5.867	8.869	5.867	0.14
Vertical	8.428	5.195	1.077	5.195	0.20
Delta	8.682	5.404	1.092	5.404	0.20
Inverted Delta	8.652	5.191	1.153	5.191	0.22

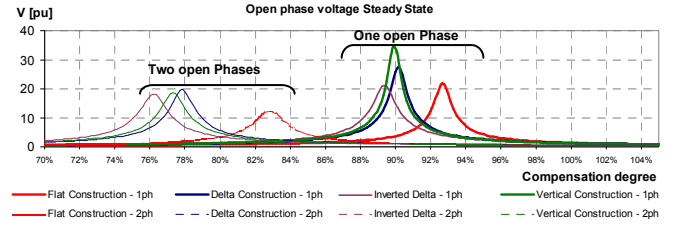


Fig. 3 Open Phase Voltages in Single Circuit Transmission Lines (one conductor per phase) as a function of Shunt Compensation degree for different Tower Constructions. Shunt reactors neutral is solidly grounded.

The following conclusions can be drawn from the Tower Design comparison:

- ⇒ Flat construction results in resonance at the highest compensation degrees.
- ⇒ Delta and vertical configurations present similar resonant peaks.
- ⇒ One open phase results in resonance at higher compensation degrees than two open phases.
- ⇒ Open-phase voltages are higher when only one phase is open than when two phases are open.
- ⇒ Voltages above 1pu are present for a wide range of shunt compensation degrees.

B. Effect of Bundle Conductors and Conductors Size

Increasing the conductor size in a transmission line results in reduced losses and increased thermal current capability. However, the final decision on conductor size is normally based on corona performance rather than power transfer capability and bundle-conductors are generally necessary to achieve the desired performance (radio interference, audible noise and corona losses). Increasing the number of conductors in a bundle reduces the corona related effects but may increase the total weight and require stronger towers. An additional benefit of the bundle conductor configuration is that it reduces the line surge impedance by reducing the series impedance and increasing the shunt capacitance. The SIL consequently increases without affecting stability margins.

Fig. 4 shows the percentage variation of line parameters calculated for one conductor per phase (Table I) when a second conductor is added to form a bundle. Assumed conductor separation is 45cm. It can be seen that positive and zero sequence magnitudes are not affected in the same proportion. The C_{ph-ph}/C_{ph-gr} ratio increases with the addition of new conductors per phase and consequently the resonant

points are shifted to areas with lower compensation degrees. This effect is shown in Fig. 5 for the flat tower design. Vertical and delta configurations follow the same trend and are not included due to space limitations.

Increasing the conductor diameter slightly moves the resonant peaks to areas of lower compensation degrees but the effect is hardly noticeable, as shown in Fig. 6.

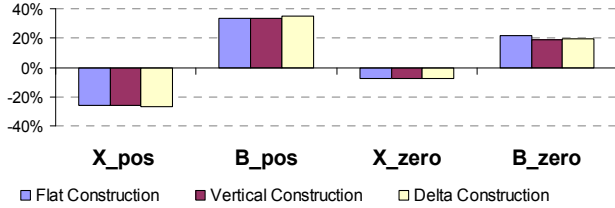


Fig. 4 Variation of power frequency line constants due to bundle conductors with respect to single conductor parameters (2 x 600SCA. Distance = 45cm).

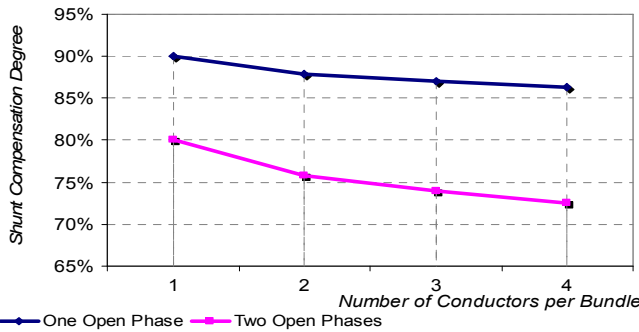


Fig. 5 Location of resonant peaks in a “Flat Construction” Transmission Line as a function of the number of conductors per phase.

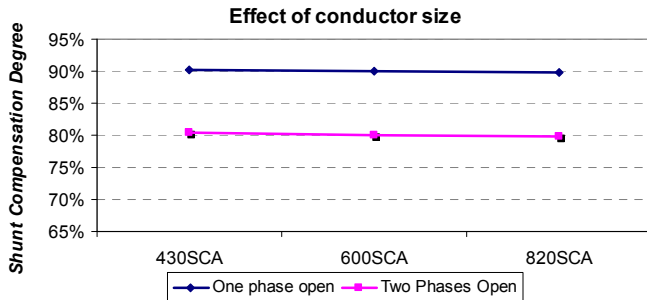


Fig. 6 Location of resonant peaks in a “Flat Construction” Transmission Line as a function of phase conductor size.

C. Effect of Shield Wires

Although shield wires are normally justified only in areas with medium or high isokeraunic level from an economic point of view, they may be necessary in other areas with very high soil resistivity in order to reduce effective tower footing resistances and guarantee correct operation of earth-fault protection relays.

The main effect of the shield wires on the line parameters is an increase between 5% and 10% of the zero sequence capacitance. As a consequence, resonant peaks are shifted towards an area of higher compensation degrees. As an illustration, Fig. 7 compares open phase voltages as a function of shunt compensation degree for the flat configuration with and without shield-wires. It can be seen that the amplitude of open-phase voltages is reduced by the presence of the shield-wires.

Shunt compensation degrees that cause resonance at power frequency are included in Table II for each tower construction. It can be seen that in all cases the resonant peaks are moved towards higher compensation degrees than in their equivalent unshielded configurations.

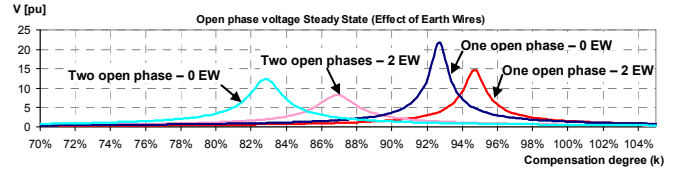


Fig. 7 Open Phase Voltages in Single Circuit Transmission Lines with and without earth-wires (Flat Construction) as a function of Shunt Compensation degree. Shunt reactors neutral is solidly grounded.

TABLE II

LOCATION OF RESONANT POINTS FOR ONE AND TWO OPEN PHASES

Construction	Shield Wires	k	
		One open phase	Two open phases
Flat	0	92.75%	82.80%
Vertical	0	89.88%	77.42%
Delta	0	90.19%	77.91%
Inverted Delta	0	89.40%	76.15%
Flat	2	94.78%	86.91%
Vertical	1	90.89%	79.25%
Delta	2	92.34%	82.16%
Inverted Delta	1	91.35%	80.00%

D. Effect of Neutral Reactors

Neutral reactors are normally used in conjunction with phase reactors in long transmission lines to reduce the amplitude of the secondary arc current and increase the reliability of SPAR schemes [2], [3]. Successful application of SPAR schemes relies on extinction of secondary arc within the selected dead time. Operation near a resonant peak may result in excessive recovery voltages causing secondary arc re-ignition.

Since the origin of the resonant circuit formed during the open-phase conditions in shunt compensated lines is the unequal compensation of positive and zero-sequence line capacitance, it seems reasonable to think that it can be avoided by the introduction of an adequate neutral impedance. This neutral impedance needs to be selected in such a way that both positive and zero sequence line capacitances are equally compensated by the combination of phase and neutral reactors, as per (4).

$$\frac{L_N}{L_{Phase}} = \frac{1}{3} \cdot \left(\frac{C_+}{C_0} - 1 \right) \quad (4)$$

where L_N is the neutral reactor inductance, L_{phase} is the shunt reactor inductance per phase, C_+ is the positive sequence line capacitance and C_0 is the zero sequence line capacitance.

Simulation results confirm that resonance does not occur for a range of shunt compensation degrees from 0% to 100% when the neutral reactor is selected using (4). These results apply both to the unshielded and shielded constructions.

A parametric analysis was performed to investigate the effect of different neutral reactor sizes on open-phase voltages. The following parameters are defined:

$$\text{Positive seq. compensation degree: } k_+ = \frac{1}{\omega^2 \cdot L_{\text{phase}} \cdot C_+} \quad (5)$$

$$\text{Zero seq. compensation degree: } k_0 = \frac{1}{\omega^2 \cdot (L_{\text{phase}} + 3 \cdot L_N) \cdot C_0}$$

As previously discussed, $k_+ = k_0$ results in the neutral reactor defined in (4) and series resonance is not possible for practical shunt compensation degrees. Two other situations have been considered: $k_0 > k_+$ and $k_0 < k_+$.

Small values of neutral reactors result in overcompensation of zero sequence capacitance (the extreme is when no neutral reactors are present) and resonance occurs for compensation degrees k below 100%. On the other hand, when larger neutral reactors are used, the zero sequence capacitance of the line becomes under-compensated and resonance is shifted to compensation degrees exceeding 100%. As an example, two cases are compared in Fig. 8: overcompensation by 25% and under-compensation by 25% of zero sequence capacitance in relation to positive sequence. It is interesting to note that undercompensation (i.e. neutral reactor larger than (4)) results in resonance for two open phases at higher compensation degrees than for one open phase, just the opposite that the overcompensated case.

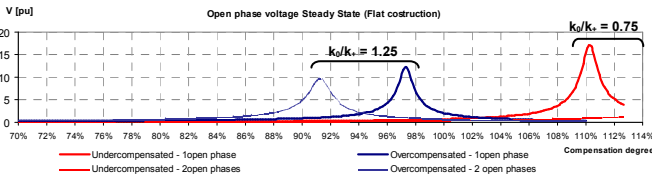


Fig. 8 Open Phase Voltages in Single Circuit Transmission Lines with undercompensation ($k_0/k_+=0.75$) and overcompensation ($k_0/k_+=1.25$) of C_0 with respect to C_+ .

III. 400kV SYSTEM EXPANSION

A practical example of a system expansion is presented here to illustrate the effects of line design options in the performance of a transmission line under unbalanced conditions. Fig. 10 shows the 400-kV system under study. The existing transmission system consists of two fully transposed 400-kV lines connecting a 1000-MW power plant with a large load centre. Both lines have a permanently-connected 80-MVAR shunt reactor (60% compensation) at the load end. The reactor's purpose is to compensate the charging MVAR of the line and to control voltage in the event of load dropping. It also provides a means of connecting a neutral reactor, needed for the extinction of secondary arc current in single-phase-to-ground faults and essential for the successful operation of the single phase tripping and reclosing. A new 400/220-kV substation has been planned along the route of one of the existing 400-kV lines (at about 60% of its length) to be looped into the 400-kV system. This configuration will split the line into two new sections, one being 102% compensated and the other without any shunt compensation. In addition, both new line sections will become partially transposed. Extensive system studies have been performed to investigate the line performance under the new configuration.

In the original network arrangement with full line transposition, open-phase resonant peaks would appear at shunt compensation degrees of 91.8% and 81.5% for one and two open phases respectively if the reactors' neutral was solidly earthed. The introduction of a neutral reactor shifted the resonant peaks beyond 110% shunt compensation degree, providing thus a very large operational safety margin for the selected compensation degree of 60%.

The new planned network development results in a 400kV line being 102% shunt compensated and partially transposed. The main consequence is that resonant peaks are slightly different for each phase. A frequency scan analysis revealed resonant frequencies around 48Hz and 45Hz for one and two open phases respectively when the neutral reactor remained in service and 54Hz and 57Hz respectively if the neutral reactor was removed from the circuit. It can be appreciated that both configurations present a high risk of near-resonant oscillations at power frequency.

As an example, Fig. 9 shows simulation results for induced voltage on an open phase during line energization with a stuck breaker pole. This represents the most onerous scenario in terms of amplitude and duration of near-resonant overvoltages. It can be seen that overvoltages of 5pu can stress line insulation if the neutral reactor remains in service. Removing the neutral reactor and grounding directly the phase reactors' neutral can reduce temporary overvoltages to 1.45pu, which does not represent a hazard to the line connected equipment (instrument transformers, surge arresters, shunt reactors and open circuit breakers) for the duration of the unbalanced condition.

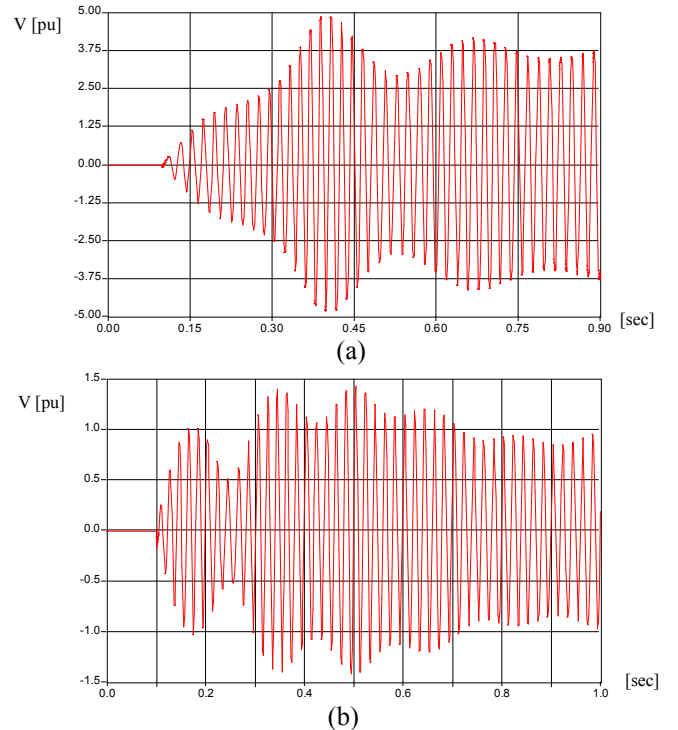


Fig. 9 Open Phase Voltages in partially transposed 400kV line (102% compensation) for stuck pole condition. (a) Neutral Reactor remains in service; (b) Reactors' neutral is solidly grounded.

IV. CONCLUSION

Series resonance can occur in single-circuit shunt compensated transmission lines due to the unequal compensation of positive and zero sequence line capacitances. Network conditions that can lead to series resonance are the result of single-phase operation of circuit breakers, which is normally a desired feature to enhance system transient stability. This paper has shown the effects of different design parameters on the voltages induced on de-energized phase conductors. Flat line constructions present resonant peaks at the highest compensation degrees whereas vertical and delta constructions present similar resonant peaks for equivalent phase clearances. Increasing the number of conductors per phase shifts the resonant peaks towards lower shunt compensation degrees. Additionally, the presence of shield-wires moves the resonant peaks towards higher compensation degrees areas. Analysis of four standard transmission line designs has revealed resonant peaks for shunt compensation degrees between 76% and 95%, with steady state voltages exceeding 1pu for a wider range of compensation degrees. It has been shown that resonance can be avoided by introducing a neutral reactor, properly dimensioned, so that positive and zero sequence line capacitances are equally compensated. An additional benefit of this scheme is the reduction of secondary arc currents and, in turn, improvement of system stability by means of a reliable SPAR scheme.

Simplified formulas can be used to quickly estimate the location of resonant peaks. These formulas, however, do not provide an indication of the resonance band-width. Parametric time-domain simulation has proved to be a very powerful tool for this kind of analysis.

Special attention must be paid when performing system expansions. In particular, incomplete line transpositions and inadequate selection of shunt or neutral reactors can result in severe overvoltages under unbalanced switching conditions.

Although [1] emphasizes the voltage limiting effect of corona and reactors saturation, authors' preferred design criteria is to minimize corona losses, which are highly dependant on ambient humidity and weather conditions, and to avoid saturation of magnetic cores, which may result in ferroresonance. Extensive system studies are recommended at the planning stage considering all the design parameter options and aiming for a cost-effective solution. Equipment manufacturing and structures construction tolerances should be kept in mind and an adequate safety margin should be introduced.

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VI. BIOGRAPHIES



Marta Val Escudero received her degree of Industrial Electrical Engineer from the University of Zaragoza, Spain, in 1994. From 1994 to 1997 she was with CIRCE (Centre of Research for Energy Resources and Consumption) in Zaragoza. In 1997 she joined ESB International in Dublin, Ireland, where she is currently employed full time in power system modelling and analysis. Her main working areas include electromagnetic transients, HV insulation co-ordination, short-circuit and load flow analysis, power transfer capability, voltage and frequency control and system stability analysis. She is currently pursuing Mphil studies at the University of Bath (UK) by research of resonant conditions in shunt compensated transmission lines.



Miles Redfern (M' 79) received his BSc degree from Nottingham University and PhD degree from Cambridge University in 1970 and 1976 respectively. In 1970, he joined British Railways Research, and in 1975, moved to GEC Measurements where he held various posts including Head of Research and Long Term Development and Overseas Sales Manager. In 1986, he joined Bath University with research and teaching interests in Power Systems Protection, Control and Industrial

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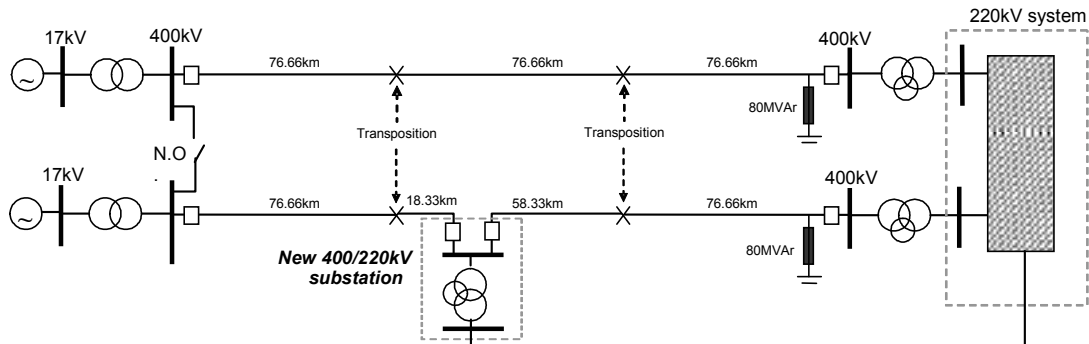


Fig. 10 400kV system expansion