Transient behaviour of non-conventional multi-circuit power lines with different voltages levels at the same tower

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Abstract—**Expanding overhead transmission system is becoming a difficult task due to environmental concern and exiguity of land. Recent researches, aiming to also reduce the Right of Way, have been focused on the use of non-conventional multi-circuit transmission lines with different voltage levels at the same tower. In this paper, optimized non-conventional multi-circuit lines with up to four circuits are studied for typical switching, such as faults, auto-reclosing, and load rejection. The coupling overvoltages are more severe when voltage level difference is higher. However, important voltage coupling is observed when same phase sequence is applied to different circuits, even when they are not the closest ones. The current signals also experience strong coupling. Therefore, future researches should be focused on overvoltage mitigation methods and protection scheme for those special lines.**

Keywords—**Auto-reclosing, coupling overvoltages, electromagnetic transients, multi-circuit transmission lines, multi-voltage transmission lines, switchings.**

I. Introduction

WITH the continuous growing of population density and power demand, transmission line projects need to use the land in a more efficient way. Increasing the natural power of the line, or Surge Impedance Loading (SIL) [1], allows to transmit more power using a very similar Right of Way (ROW) of conventional lines. Russian researches proposed in 1991 the use of transmission lines with closer phases (compact lines) and non-conventional bundles, i.e., conductors non-uniformly separated in a circular geometry [2]. Based on this, several approaches to increase the SIL [3]–[7] were developed.

Another approach to make a better use of the land is the use of multi-circuit overhead power lines, i.e., several circuits in the same tower sharing the same ROW. The largest overhead double circuit transmission line, built in 1999, is the Kita-Iwaki power line, operating at 500 kV with a height of 108 m and a ROW of 38 m. The use of multi-circuit transmission lines is increasing in the last years. In several countries such as Germany, India, Japan and China the use of double or quadruple circuits is common, and in rare cases six circuit lines can be built.

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The behavior of conventional multi-circuit transmission lines has been characterized in several researches [8], [9]. Specific topics as protection [10], [11], lightning performance [12]–[16], electromagnetic behavior [17], [18], transient behavior [19] and secondary arc current extinction [20] have been studied for overhead multi-circuit AC power lines. Even researches on multi-circuit DC lines have been made [21]. Currently, some attention has been focused on hybrid AC/DC multi-circuit transmission lines [22]–[24].

The present document intends to provide additional information related to transient response of non-conventional multi-circuit multi-voltage lines.

II. Non-conventional multi-circuit lines

The present study analyses a transmission system composed of a 350 km multi-circuit multi-voltage transmission line (MCMVTL). The basic approach is that all transmission circuits will have the same length and will be connected at terminals' substations to equivalent systems of different short-circuit ratio (SCR).

The lines used in this research were created by an optimization process that modifies the bundle geometry, and searches for ideal wire and phase sequence through evolutionary computing. The mathematical model has four objective functions that maximize SIL and minimize: costs, ROW and tower's height. Zero sequence optimization was not taken into account in the present research.

Since the focus of this research is only the transient study of non-conventional multi-circuit lines, no details on the optimization process is given. However, the process is based on [7] extended to multi-circuits lines.

The multi-circuits lines were modeled with real transposition cycles (1/6, 1/3, 1/3, 1/6). All circuits were transposed at the same location (tower), resulting in coincident transposition cycles. This approach is not the regular one. The compensation level for all voltage level circuits was 70%. The whole systems is shown in Fig. 1.

Four systems were analyzed. System one is composed of just the single circuit line presented in Fig. 2; in system two the double circuit transmission line in Fig. 3 with phase sequence ABC CBA was used; in system three the triple transmission line in Fig. 4 with phase sequence CBA BAC ACB was used; finally, in fourth system the quadruple transmission line in Fig. 5 with phase sequence ABC BCA CAB ABC was used.

In all cases the designed phase sequence corresponds to the one with the lowest electric field under the transmission lines (E_{soil}). However, it is a consequence of optimizing the objective functions and not a specific goal. Fig. 6 shows as an example E_{soil} obtained with the charge calculation applied in the 4 circuit transmission line for different phase sequences. E_{soil} reduction is important and the influence on electromagnetic coupling is analyzed in the following sections.

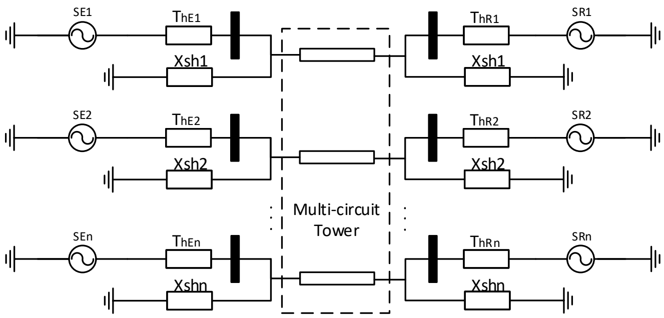

Fig. 1. Equivalent system for n circuits.

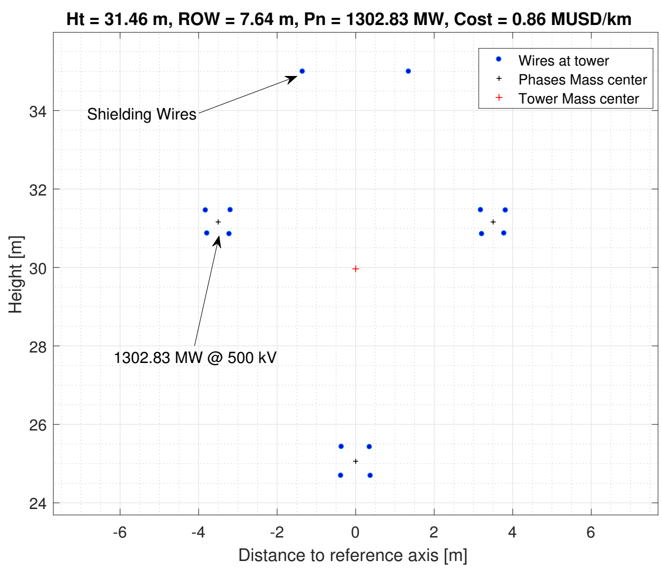

Fig. 2. Single-circuit transmission line.

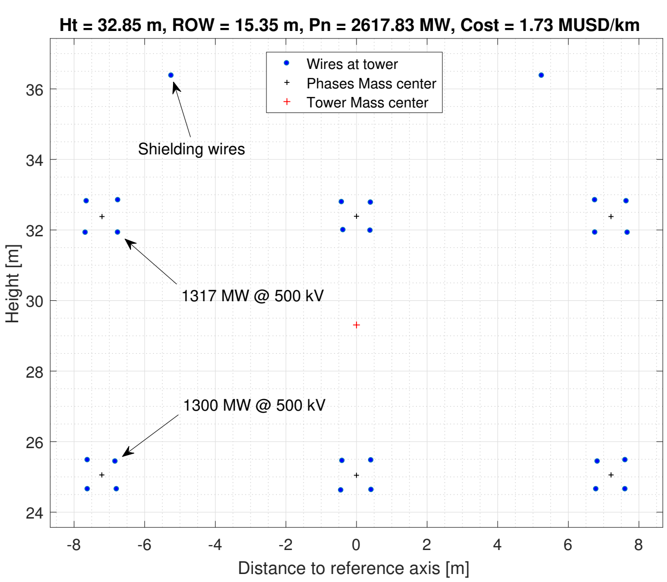

Fig. 3. Double-circuit transmission line.

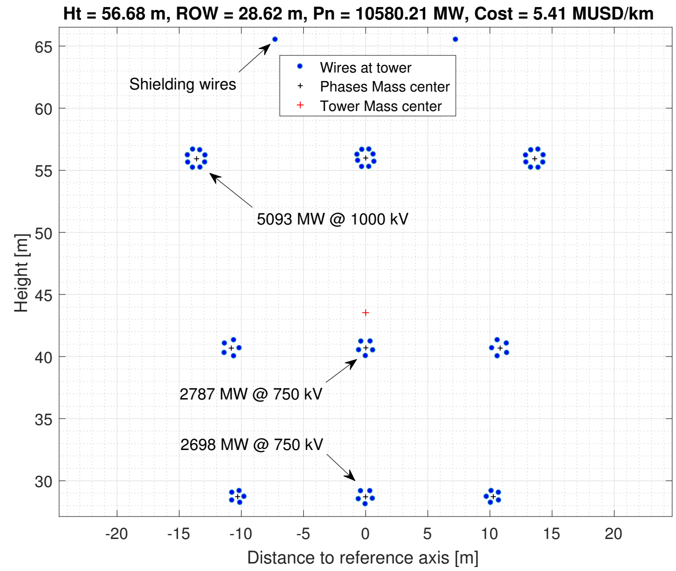

Fig. 4. Triple-circuit transmission line.

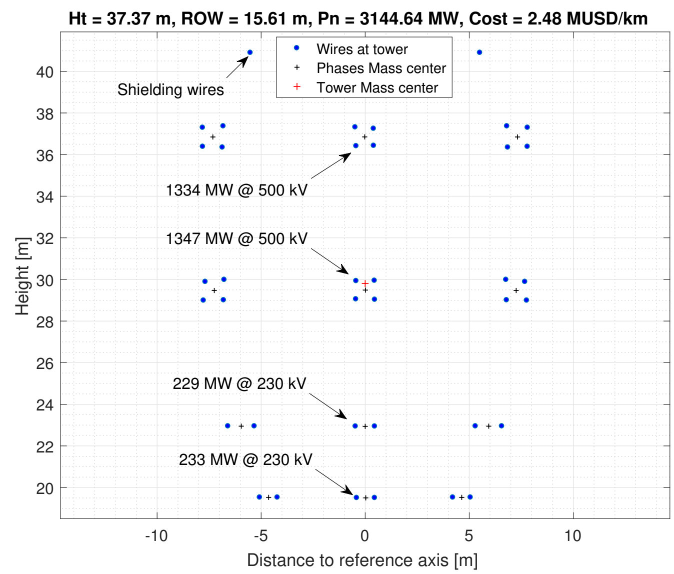

Fig. 5. Quadruple-circuit transmission line.

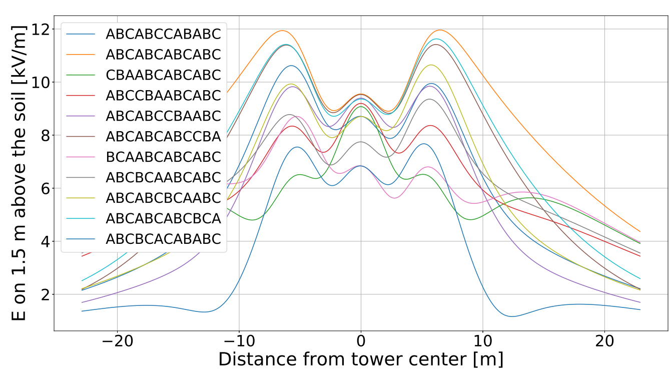

Fig. 6. E_{soil} in the 4 circuit transmission line with different phase sequence.

III. Systems under Study

The parameters of the tested systems were calculated using the two-port networks theory considering a loading condition of 90% of the SIL of each circuit (SIL_{ci}), and a SCR of 10 kA in the reception equivalents, 20 kA in the sending equivalent of 230 kV systems and 40 kA in 500 kV systems and above.

Also, a neutral reactor is added between the common point of each reactor bank and the ground, producing a four-legged reactor. The neutral reactor aims to eliminate or minimize the capacitive coupling between phases within each circuit, because it is the main source for secondary arc during single-phase tripping. The coupling between circuits was not focused in this paper. Eq. (1) was used to obtain neutral reactor value. We used typical Brazilian reactor quality factors, being 400 for phase reactor and 40 for neutral reactor.

$$X_{n_{ci}} = \frac{r_0 X_{c_{ci}} - 1}{3} \tag{1}$$

Where:

- $X_{c_{ci}}$ Compensation reactance of transmission line of circuit ci in $[\Omega]$.
- $X_{n_{ci}}$ Neutral reactor reactance of transmission line of circuit ci in $[\Omega]$.
- r_0 X_0/X_1 ratio of reactor zero and positive sequence components assumed as 1.5 for optimal results [25].

Accordingly, the parameters of the systems are presented in tab. I, whereas the line parameters for balanced line condition in tab. II.

TABLE I
PARAMETERS OF THE SYSTEMS.

Circuit	SE V [kV]	SE angle [°]	SR V [kV]	SR angle [°]	Compensation $R_c[\Omega]$	Compensation $X_c[\Omega]$	Neutral React. $R_n[\Omega]$	Neutral React. $X_n[\Omega]$
Single-circuit line								
1	545.16	22.92	493.43	-7.72	3.03	1210.96	15.13	605.14
Double-circuit line								
1	543.69	23.29	493.44	-7.68	2.99	1197.99	14.97	598.66
2	544.77	23.41	493.40	-7.80	2.93	1171.94	14.64	585.64
Triple-circuit line								
1	815.83	23.92	739.97	-10.69	3.25	1300.39	16.14	645.57
2	814.73	24.12	740.17	-11.29	3.08	1230.86	15.38	615.10
3	1088.70	24.93	991.42	-15.23	3.06	1222.82	15.27	611.08
Quadruple-circuit line								
1	255.29	22.69	228.34	-2.96	3.49	1394.52	17.42	696.93
2	254.79	22.79	228.39	-2.83	3.63	1450.26	18.12	724.79
3	546.54	23.43	493.38	-7.89	2.89	1154.59	14.42	576.96
4	547.21	23.39	493.36	-7.98	2.86	1143.31	14.28	571.32

TABLE II
LINE PARAMETERS CALCULATED FOR 60 HZ.

Circuit	$R_{l_0}[\Omega/km]$	$X_{l_0}[\Omega/km]$	$Y_{l_0}[\mu S/km]$	$R_{l_1}[\Omega/km]$	$X_{l_1}[\Omega/km]$	$Y_{l_1}[\mu S/km]$
Single-circuit line						
1	0.48	1.59	2.87	0.022	0.24	6.62
Double-circuit line						
1	0.43	1.56	4.18	0.019	0.25	6.73
2	0.47	1.53	4.11	0.019	0.25	6.73
Triple-circuit line						
1	0.35	1.53	3.92	0.017	0.27	6.20
2	0.37	1.50	4.18	0.015	0.25	6.53
3	0.41	1.43	3.84	0.011	0.25	6.54
Quadruple-circuit line						
1	0.41	1.70	4.02	0.043	0.29	5.78
2	0.42	1.67	4.39	0.043	0.31	5.54
3	0.43	1.56	4.83	0.022	0.24	6.96
4	0.48	1.54	4.07	0.022	0.24	6.93

Notes
$_0$: zero sequence
$_1$: positive, negative sequence

IV. SIMULATED CASES

A typical transient study was performed, considering specifically the following cases: line-to-ground fault (LG) with three-phase and single-phase reclosing, three-phase fault and load rejection. The lines were modeled with frequency-dependence representation of series parameters (phase-domain model) and PSCAD software was used. The actual transposition cycles were modeled and a soil resistivity of 4000 Ω.m was considered. This is a mean value in Brazil.

For the fault cases we have faults applied at 90% of the line length of each circuit. The sequence for fault studies is the following: 1) A fault with a resistance of 10 Ω is applied during 300 ms near to the maximum voltage value of one phase; 2) The nearest breaker opens after 100 ms of fault occurrence; 3) The remote breaker opens 20 ms after leader terminal; 4) After 500 ms dead-time the line reclosing is performed. For fault extinction we considered either the imposed fault duration or removed the fault when the fault current was lower than 30 A in 230 kV systems; 50 A in 500 kV and 750 kV systems and 80 A in 1000 kV systems.

In the case of load rejection there is no fault, only the breaker at reception substation opens and there is no reclosing.

In all cases a statistical breaker operation is considered with 100 cases using Gaussian distributions with standard deviation of 2 ms.

Since the quantity of simulations performed is high, we present only the graphical response of the quadruple transmission line for a LG fault applied in the fourth circuit with single-phase auto-reclosing. Similar simulations were implemented for the other systems/circuits. For the remainder cases we are presenting the results in tables.

Figs. 7 to 9 show the voltage response at both line terminals and fault point. Note that during the fault in c_4 the voltages at the sending terminal of the healthy circuits present a small disturbance that disappears after protection actuation. We can also observe another disturbance in the healthy circuits when the reclosing is performed. On the other hand, higher disturbances are experienced at receiving terminal at the same instants. This is derived both due to fault proximity and weaker remote equivalent. The strongest coupling is sensed at the fault location, where higher coupling overvoltages were produced in the others circuits.

It is interesting to observe the strong coupling between circuits 1 and 4 that have the same phase sequence (ABC BCA CAB ABC). Circuit 1 overvoltage is higher than the ones in circuits that are closer to the faulted circuit, the 4^{th} one.

Fig. 10 shows the current in the fault point. The events of fault occurrence, breaker operation, secondary arc extinction and reclosing are marked. Only successful reclosing was simulated.

Although secondary arc current minimization was not focused in the present study, a regular neutral reactor optimization was implemented, considering each circuit stand-alone. A more complete study is necessary to mitigate circuit coupling, and high-speed grounding switches may be an interesting alternative. However, we have observed that the phase sequence plays an important role in secondary arc current minimization, as a consequence of the electric field produced by each circuit. With the conventional ABC sequence in the quadruple transmission line a secondary arc current of 120 A is obtained for a fault in c_4, meanwhile with

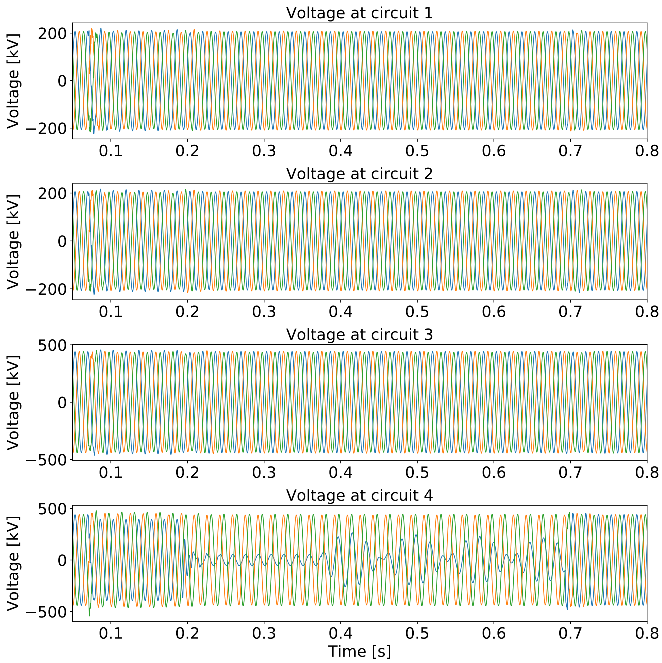

Fig. 7. Voltage at sending terminal for a LG fault at circuit 4 with single-phase reclosing in the quadruple line.

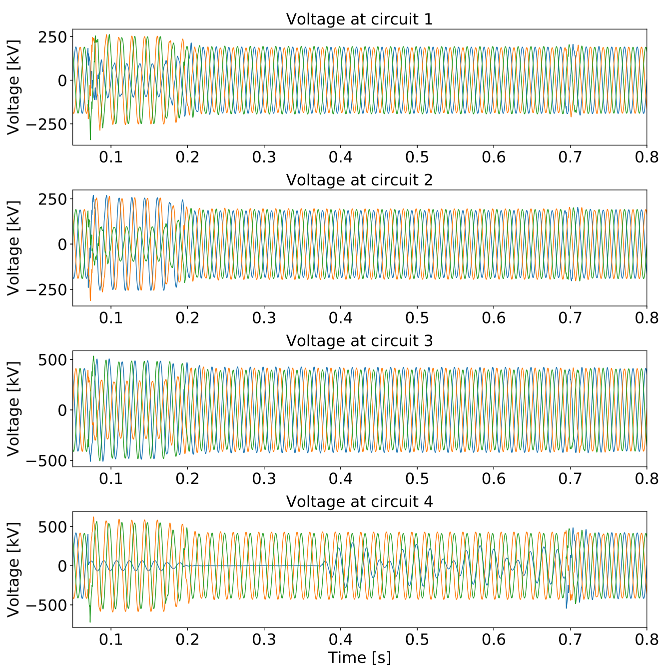

Fig. 8. Voltage at fault point for a LG fault at circuit 4 with single-phase reclosing in the quadruple line.

the proposed phase sequence the value decreased to 85 A. This shows the importance of the phase sequence design to decrease the secondary arc currents.

Figs. 11 to 12 show the current wave-forms at both line terminals. Note that although the voltage of healthy circuits were not severely affected by the fault, due to terminal systems' strengths, the current sensed it most. This is because in the present tested system the voltage is imposed by the terminal equivalents, but the current is not. Thus, when a fault occurs in one circuit, overcurrents will be coupled in

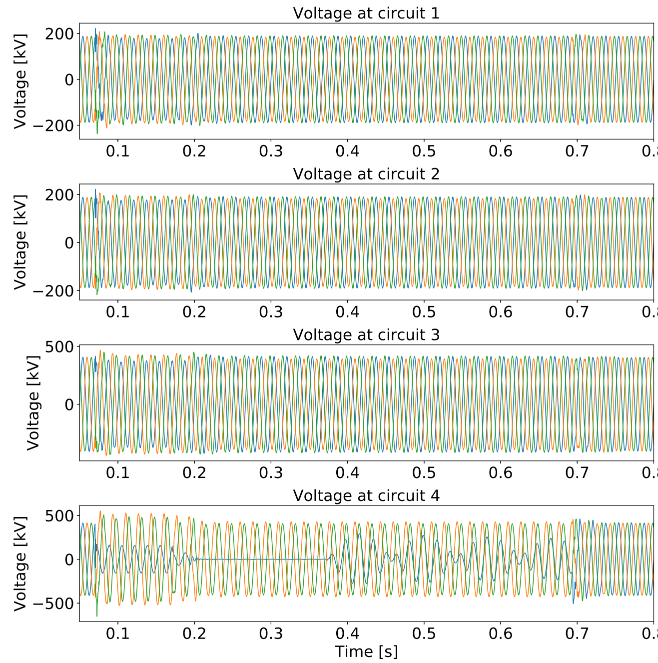

Fig. 9. Voltage at receiving terminal for a LG fault at circuit 4 with single-phase reclosing in the quadruple line.

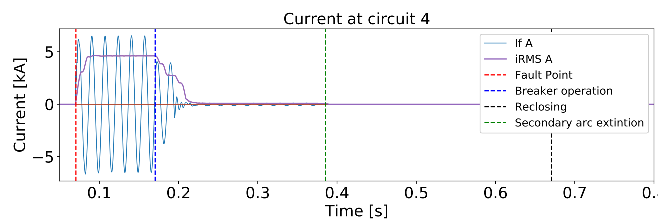

Fig. 10. Current at fault point for a LG fault at circuit 4 with single-phase reclosing in the quadruple line.

near circuits. Because of this, the protection scheme has to be properly designed to cope with multi-circuit lines.

Again, a very important result is the influence of phase sequence. Thus, the strongest coupling is observed between circuits 1 and 4. Therefore, circuit 1 suffers a strong unbalance throughout the single-phase opening period, that is even higher than the one experienced by the 3^{rd} circuit. This is not an expected result, but it is explained by the selected phase sequence.

The other tested systems behave in similar way as in the quadruple line, inducing overvoltages and overcurrents in near circuits during disturbances.

Tables III to VI summarize the overvoltages presented in circuit one at 90% of line length when a disturbance occurs in the others c_i circuits. The system with a single-circuit transmission line was simulated in order to present a comparison basis to the multi-circuit transmission lines. The fault location was selected to reduce the terminal equivalent interference.

Note that the higher overvoltages occur generally in the case of a LG fault with three-phase reclosing. Although the highest overvoltage is observed in the circuit where the fault occurred, the coupling overvoltage varies as analyzed above.

From tables IV to VI it is possible to note that when a fault

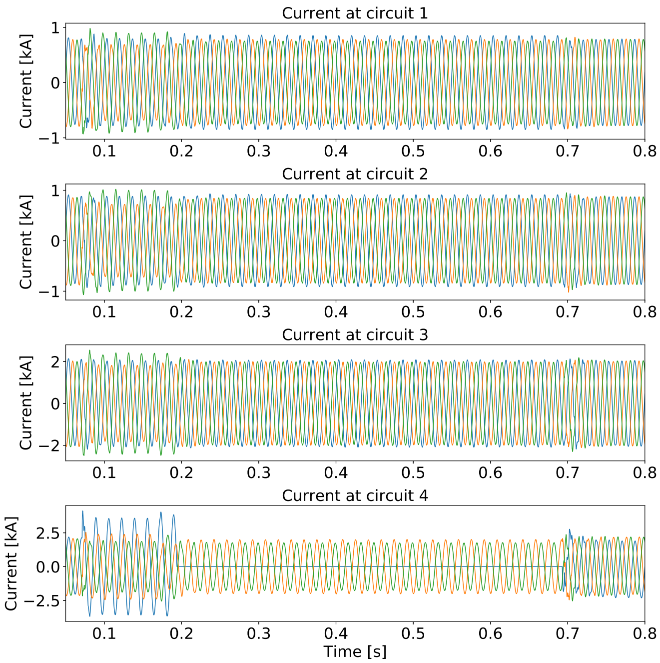

Fig. 11. Current at sending circuit-breaker for a LG fault at circuit 4 with single-phase reclosing in the quadruple line.

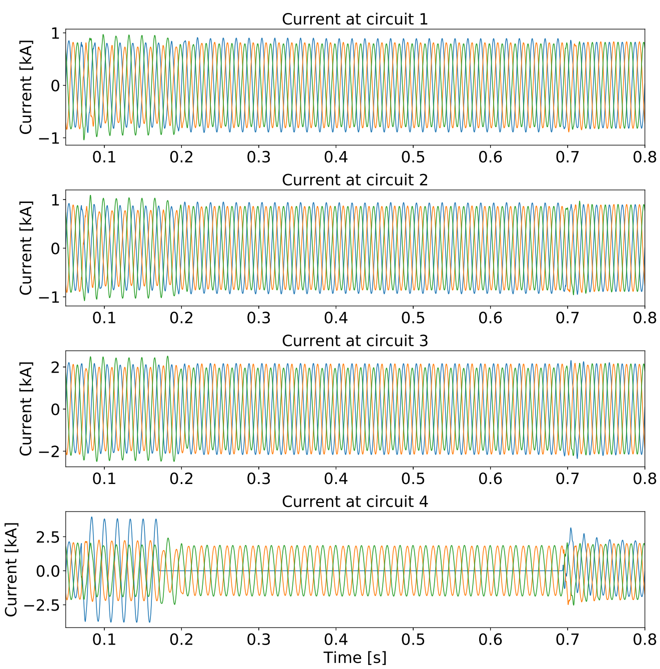

Fig. 12. Current at receiving circuit-breaker for a LG fault at circuit 4 with single-phase reclosing in the quadruple line.

occurs in one circuit the other circuits suffer disturbances on their voltage. Also, note that the coupled overvoltages were pratically the same for single-phase and three-phase reclosing.

Another important point to highlight is that in some cases the most remote circuits had higher influence on circuit one than the closest circuits. This behaviour can be seen more clearly in table VI where the higher overvoltage was caused by the fault in circuit 4. One could expect that the closest circuit with higher voltage (i.e. circuit three in the quadruple line) would cause the highest induced overvoltage due to the

TABLE III
OVERVOLTAGE FOR EVENTS IN A SINGLE TRANSMISSION LINE AT 90% OF LINE LENGTH.

Voltage in [pu]	Line-to-ground fault with: Three-phase reclosing	Line-to-ground fault with: Single-phase reclosing	Three phase fault	Load rejection
Min.:	1.98	1.45	1.93	1.78
Max.:	2.33	2.17	2.16	1.80
Mean:	2.14	1.71	2.06	1.79

TABLE IV
OVERVOLTAGE IN CIRCUIT 1 FOR EVENTS AT CIRCUIT c_i IN A DOUBLE TRANSMISSION LINE AT 90% OF LINE LENGTH.

Voltage [pu]	Line-to-ground fault at circuit with: Three-phase reclosing		Single-phase reclosing	
	c_1	c_2	c_1	c_2
Min.:	1.97	1.27	1.50	1.27
Max.:	3.25	1.42	1.85	1.42
Mean:	2.47	1.32	1.76	1.32
Voltage [pu]	Three-phase fault at circuit		Load rejection at circuit	
	c_1	c_2	c_1	c_2
Min.:	1.94	1.34	1.70	1.09
Max.:	2.81	1.54	1.83	1.09
Mean:	2.25	1.47	1.75	1.09

stronger coupling. However, since a non-conventional phase sequence (e.g., ABC BCA CAB ABC in the quadruple line) was used, in the fault instant phase A of circuit one and four are in phase, meanwhile phase A of circuit three is delayed. Therefore, a higher overvoltage is induced by the circuit 4 and not by the third circuit. Note in table V that the circuit three also induces higher overvoltage than circuit two. However, in this case the higher value is caused by the higher nominal voltage in circuit three (1000 kV), as the phase under fault is not in phase with circuit one (CBA BAC ACB).

Also, note that the switching with lowest influence on the other circuits was the load rejection, in which the highest induced overvoltage was only 1.13 pu. Additionally, note that load rejection was the only switching that did not suffer a significant change when the maneuver was presented in the own circuit. In almost all cases the value was near to 1.8 pu.

As expected, higher overvoltages were produced for faults in their own circuits, obtaining important overvoltages near to 3.5 pu in some cases. No surge arrester were modeled in order to obtain the maximum overvoltages. In the present study no Corona effect was considered, what would result in lower overvoltages. However, as the same linear line model was

TABLE V
OVERVOLTAGE IN CIRCUIT 1 FOR EVENTS AT CIRCUITS c_i IN A TRIPLE TRANSMISSION LINE AT 90% OF LINE LENGTH.

Voltage [pu]	Line-to-ground fault at circuit with: Three-phase reclosing			Single-phase reclosing		
	c_1	c_2	c_3	c_1	c_2	c_3
Min.:	2.22	1.22	1.30	1.44	1.22	1.30
Max.:	3.16	1.36	1.44	1.87	1.35	1.44
Mean:	2.61	1.27	1.39	1.62	1.26	1.39
Voltage [pu]	Three-phase fault at circuit			Load rejection at circuit		
	c_1	c_2	c_3	c_1	c_2	c_3
Min.:	2.21	1.39	1.36	1.74	1.10	1.08
Max.:	2.75	1.44	1.46	1.85	1.11	1.10
Mean:	2.48	1.42	1.40	1.78	1.11	1.08

TABLE VI
OVERVOLTAGE IN CIRCUIT 1 FOR EVENTS AT CIRCUIT c_i IN A QUADRUPLE TRANSMISSION LINE AT 90% OF LINE LENGTH.

Voltage [pu]	Line-to-ground fault at circuit with: Three-phase reclosing				Single-phase reclosing			
	c_1	c_2	c_3	c_4	c_1	c_2	c_3	c_4
Min.:	2.30	1.27	1.49	1.50	1.46	1.27	1.49	1.50
Max.:	3.54	1.32	1.66	**1.83**	2.21	1.32	1.65	**1.83**
Mean:	2.72	1.29	1.58	1.73	1.75	1.29	1.58	1.74
Voltage [pu]	Three-phase fault at circuit				Load rejection at circuit			
	c_1	c_2	c_3	c_4	c_1	c_2	c_3	c_4
Min.:	2.14	1.31	1.39	1.32	1.74	1.12	1.13	1.12
Max.:	2.54	1.40	1.49	1.38	1.79	1.13	1.13	1.13
Mean:	2.29	1.33	1.43	1.35	1.77	1.12	1.13	1.12

applied to all simulations, no conflict in the present analysis is foreseen.

Finally, note that comparing system one and two (both with 500 kV lines and similar SIL) the overvoltages for faults in their own circuits in the double transmission lines were higher. Therefore, having a close circuit will increase overvoltages even when the fault occurs in their own circuit.

Future researches should be focused on the protection and overvoltage mitigation for the multi-circuit transmission lines.

V. CONCLUSION

Multi-circuit multi-voltage high SIL transmission lines are good alternatives to transmit high blocks of energy in a narrow space. However, some challenges as the overvoltage coupling must be faced.

The current in neighbour circuits experienced much severe coupling, posing important requirements for protection system. It is important to highlight that the phase sequence has an important influence on the systems, helping to mitigate the induced overvoltage and secondary arc current in some cases. Additionally, phase sequence can promote higher coupled overvoltages than voltage difference between circuits. However, no important effects were observed for load rejection.

An important result is that during fault events the multi-circuit line overvoltages will be higher than the ones in single-circuit line. This was not observed for load rejection.

Therefore, the multi-circuit multi-voltage non-conventional lines produce several benefits and they could be used in actual projects after some additional researches related to protection and insulation coordination.

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