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Comparison of the Intersystem Faults In Multi-Voltage Lines Working On the Lattice and Tubular Poles

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ABSTRACT: In this paper presents results of simulations of the intersystem faults in overhead transmission multi-voltage lines working on the lattice and tubular poles. Investigation carry out analysis of the electromagnetic transients during the many cases of intersystem faults. The multi-voltage tree-circuit 380 kV + 220 kV + 110 kV overhead line was analyzed.

KEYWORDS: Multi-voltage lines, intersystem faults, electromagnetic transients, tubular pylons, lattice towers.

I.INTRODUCTION

Modern rules of the new overhead lines investment are so restrictive. Build of the new linear sequences of overhead lines need to do many requirements - legal, social and environmental [1, 4]. The most important is the right of way of the overhead lines, whose width depends on nominal voltage of the line and number of circuit.

One of the solution to solve problems of build new lines investments is use the multi-voltage lines. Leading a few overhead lines with a different nominal voltages on the same towers (usually connecting different power subsystems) involves the danger of impacts circuits of the multi-voltage line due to the electromagnetic coupling [1]. In literature, there are many researches about electromagnetic field around multi-voltage lines. Also papers about multi-voltage lines in normal condition may be found easily. In other hand, only a little publications describe the condition of the power system during the intersystem faults in multi-voltage lines. What is more, the behavior of these special type of the overhead lines during the electromagnetic transients caused by intersystem faults can be found only in few publications [1, 2, 3].
In this paper presents results of simulations of the intersystem faults analysis in three-circuit multi-voltage 380 kV + 220 kV + 110 kV line. Results was compared with lattice and tubular poles.

II.MULTI-VOLTAGE LINES WORKING ON THE TUBULAR POLES

In the last few years was observed significant progress of production and processing the plate of large area, which resulted in the dynamic development of companies producing tubular poles [4]. More and more often use this kind of poles is particular importance in high and extra-high voltage networks. A significant reduction of the area occupied by the tubular pole foundation compared to lattice tower solution is often the decisive factor for the acceptance of line investment by landowners. In addition to the reduction of the area occupied by tubular poles it also allows a significant reduction in the intensity of the electromagnetic field [5]. Depending on the number of circuit of overhead lines and used type of conductor suspension (steel or insulating crossarm), reducing the electric field intensity may be up to approx. 30% and 38% of the magnetic field [5]. Tubular poles are also used in the multi-voltage lines. As in the case of lattice towers this kind of poles are often dedicated solutions to specific type of a multi-voltage line. One of the most common conductor configuration with this type of lines are [6, 7]:

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- horizontal configuration,
- vertical configuration,
- triangular configuration,
- zigzag configuration.

In practice, also meets mixed conductor configurations, e.g. vertical-horizontal or triangular-horizontal. The use of tubular poles allows a slight reduction in the electrical distance between the conductors of the various phases of the line compared to the lattice tower solution. The rest of the article examines the impact of reduced electrical distance between conductors working (by the use of tubular poles) for currents and voltages transients during the selected intersystem faults (faults between two or more circuits phase with different nominal voltage).

III.ANALYSIS OF INTERSYSTEM FAULTS IN MULTI-VOLTAGE THREE-CIRCUIT 380 KV + 220 KV + 110 KV LINE

Analyzed multi-voltage three-circuit lines high + extra-high voltage lines with a length of approx. 10 km:
- 380 kV: circuit No. 1 (designation '*T*1'),
- 220 kV: circuit No. 2 (designation '*T*2'),
- 110 kV: circuit No. 3 (designation '*T*3').

Fragment of the analyzed network system as shown in Fig.1. Conductor lines in the circuit No. 1 was modeled as a three-wire bundle, and in the circuit No. 2 as double-bundle.

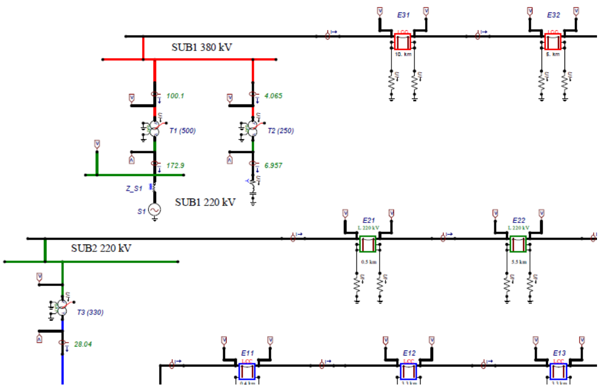

Fig. 1 Fragment of the analyzed network

The geometric parameters of a structures for multi-voltage line was determined on example-based towers of multi-voltage-lines and current standards [1, 7, 8]. The analyzes included two types of conductor configuration working in a multi-voltage line:
- horizontal configuration,
- triangular-horizontal configuration.

Comparison of support structures for horizontal conductor configuration work are compared in Fig. 2, and the triangular-horizontal conductor configuration in Fig. 3. In parentheses are the geometric parameters of the tubular poles. The use of tubular poles allowed to reduce the distance between the different phases of a multi-voltage line of 1.0 m for horizontal conductor configuration and 1.5 m for triangular-horizontal conductor configuration. Transient simulations were performed in ATPDraw (version 5.8), while the short-circuit calculation for determine initial symmetrical short-circuit power in the power supply nodes of each circuit of multi-voltage line was designated in the SCC Ind + kreator FW software (version 1 build 23).

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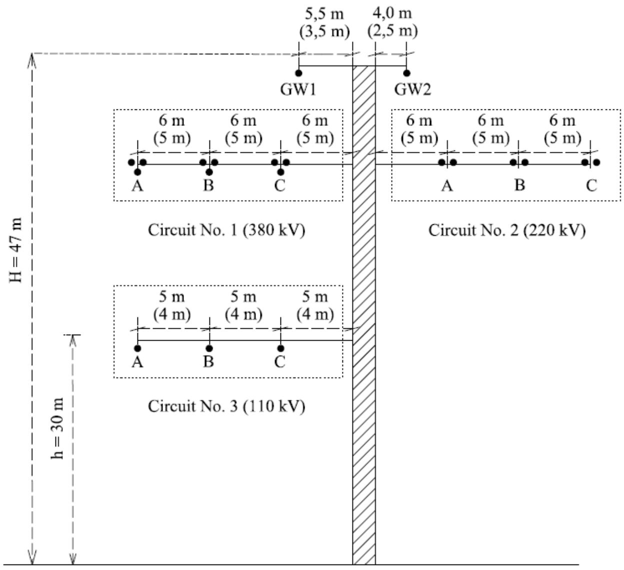

Fig. 2 The geometric parameters of the towers with horizontal conductor configuration

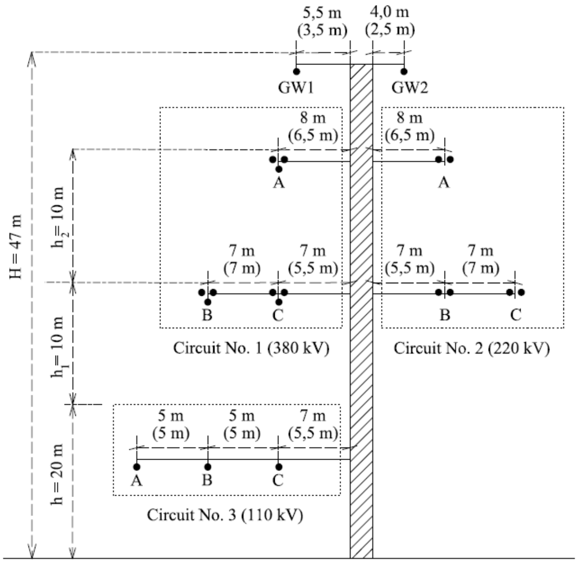

Fig. 3 The geometric parameters of the towers with triangular-horizontal conductor configuration

The simulation length was set to 100 ms, due to the application of the Marti model [3]. Due to the number of circuit of the multi-voltage line and practical experience, the following types of intersystem faults was simulated:

- intersystem fault between the two circuits *T*1-*T*2 (designation '*IF*1') - breaking one phase of *T*1 and fault with the selected phase of *T*2 at the time $t_f \sim 7$ ms,
- intersystem fault between the two circuits *T*1-*T*3 (designation '*IF*2') - breaking one phase of *T*1 and fault with the selected phase of *T*3 at the time $t_f \sim 7$ ms,
- intersystem fault between the two circuits *T*2-*T*3 (designation '*IF*3') - breaking one phase of *T*2 and fault with the selected phase of *T*3 at the time $t_f \sim 7$ ms,
- intersystem fault between the all three circuits *T*1-*T*2-*T*3 (designation '*IF*4'):

- breaking one phase of *T*1 and fault with the selected phase of *T*2 at the time $t_f \sim 7$ ms,
- breaking one phase of *T*2 and fault with the selected phase of *T*3 at the time $t_f \sim 13$ ms,

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- intersystem fault between the all three circuits *T*1-*T*2-*T*3E and the ground (designation '*IF*4E'):
- breaking one phase of *T*1 and fault with the selected phase of *T*2 at the time t_f ~ 7 ms,
- breaking one phase of *T*2 and fault with the selected phase of *T*3 at the time t_f ~ 13 ms,
- breaking one phase of *T*3 and fault to ground at the time t_f ~ 15 ms.

The study included an analysis of all possible combinations of intersystem faults between the different phases of a multi-voltage line. In addition to the faulted phases also verified currents and voltages transients in 'healthy' phases. For the purposes of intersystem faults analysis identified the following factors:

- surge factor for intersystem faults defining change the value of the instantaneous voltage of the phase during the intersystem faults:

$$k_{Tx} = \frac{u_{Tx}}{\sqrt{2}U_{nTx}} \qquad (1)$$

where k_{Tx} , is the overvoltage factor for intersystem fault ('*x*' indicates the number of the circuit). u_{Tx} , is the highest value of the instantaneous voltage during the intersystem fault in the circuit (kV). U_n , is the rated voltage of the circuit (kV).

- factor determining the growth of current in the 'healthy' phase:

$$g_{hTx} = \frac{i_{gTx}}{i_{hTx}} \qquad (2)$$

where g_{hTx} , is the ratio of the instantaneous current in the 'healthy' phase during the intersystem fault and instantaneous current in normal operating condition ('*x*' indicates the number of the circuit). i_{gTx} , is the highest value of instantaneous current in the 'healthy' phase during the intersystem fault (A). i_{hTx} , is the highest value of instantaneous current in the 'healthy' phase in normal operating condition (A).

Maximum instantaneous values of voltage and current, and calculated factors k_{Tx} and g_{hTx} for each circuit of multi-voltage line as shown in tables I.I...II.IV. Table I.V summarizes the instantaneous currents of intersystem faults (currents flowing between faulted phases of circuits).

TABLE I.I. THE HIGHEST VALUES OF THE INSTANTANEOUS CURRENTS OF THE OF SELECTED PHASES AND FACTORS DETERMINING THE GROWTH OF HEALTHY PHASE CURRENTS DURING THE INTERSYSTEM FAULTS - VARIANT ***IF*1**.

RZM/OZM: *T*1-*T*2/*IF*1						
RKW ↓	i_{T1} **(CB)**	i_{T2} **(CB)**	i_{T3} **(-)**	g_{hT1} **(CB)**	g_{hT2} **(AB)**	g_{hT3} **(AB)**
	kA	**kA**	**kA**	-	-	-
SK(P)	7,19	6,34	-	5,69	23,74	13,21
SS(P)	7,19	6,35	-	5,70	23,46	13,38
SK(TP)	7,26	6,45	-	5,76	25,43	13,20
SS(TP)	7,26	6,45	-	5,76	25,36	13,29

where RZM/OZM , is the kind/indicates of intersystem fault. RKW is the type of pylon: SK(P) - lattice tower with horizontal configuration, SS(P) - tubular tower with horizontal configuration, SK(TP) - lattice tower with triangular-horizontal configuration, SS(TP) - tubular tower with triangular-horizontal configuration. A, B, C , are the phases of multi-voltage line. *T*1 , *T*2 , *T*3 are the circuits of multi-voltage line: 380 kV (*T*1) , 220 kV (*T*2) , 110 kV (*T*3). i_{T1} , i_{T2} , i_{T3} are the highest values of the instantaneous currents during the intersystem faults (in the parentheses show sequence for highest value of each quantity).

TABLE I.II. THE HIGHEST VALUES OF THE INSTANTANEOUS CURRENTS OF THE OF SELECTED PHASES AND FACTORS DETERMINING THE GROWTH OF HEALTHY PHASE CURRENTS DURING THE INTERSYSTEM FAULTS - VARIANT ***IF*2**
.

RZM/OZM: *T*1-*T*3/*IF*2						
RKW ↓	i_{T1} **(AB)**	i_{T2} **(-)**	i_{T3} **(AB)**	g_{hT1} **(BC)**	g_{hT2} **(BC)**	g_{hT3} **(AB)**
	kA	**kA**	**kA**	-	-	-
SK(P)	7,51	-	6,91	6,21	10,49	70,44
SS(P)	7,52	-	6,92	6,22	9,73	70,36
SK(TP)	7,60	-	7,12	6,39	10,17	75,32
SS(TP)	7,61	-	7,12	6,39	10,33	74,69

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TABLE I.III. THE HIGHEST VALUES OF THE INSTANTANEOUS CURRENTS OF THE OF SELECTED PHASES AND FACTORS DETERMINING THE GROWTH OF HEALTHY PHASE CURRENTS DURING THE INTERSYSTEM FAULTS - VARIANT ***IF*3**.

RZM/OZM: *T2-T3/IF3*						
RKW ↓	i_{T1} **(-)**	i_{T2} **(AC)**	i_{T3} **(AC)**	g_{hT1} **(BC)**	g_{hT2} **(BC)**	g_{hT3} **(AB)**
	kA	**kA**	**kA**	**-**	**-**	**-**
SK(P)	-	9,30	9,51	1,44	23,17	75,79
SS(P)	-	9,30	9,53	1,44	23,60	75,73
SK(TP)	-	9,54	9,89	1,41	25,66	81,98
SS(TP)	-	9,54	9,90	1,41	25,83	81,12

TABLE I.IV. THE HIGHEST VALUES OF THE INSTANTANEOUS CURRENTS OF THE OF SELECTED PHASES AND FACTORS DETERMINING THE GROWTH OF HEALTHY PHASE CURRENTS DURING THE INTERSYSTEM FAULTS - VARIANT ***IF*4** AND ***IF*4*E***.

RZM/OZM: *T1-T2-T3/IF4*						
RKW ↓	i_{T1} **(BCA)**	i_{T2} **(BCA)**	i_{T3} **(BCA)**	g_{hT1} **(BCA)**	g_{hT2} **(BCA)**	g_{hT3} **(BCA)**
	kA	**kA**	**kA**	**-**	**-**	**-**
SK(P)	7,77	6,87	9,37	8,01	27,34	92,10
SS(P)	7,78	6,88	9,39	8,01	27,50	99,66
SK(TP)	7,83	6,97	9,66	8,24	25,40	92,04
SS(TP)	7,83	6,98	9,67	8,23	25,39	92,26
RZM/OZM: *T1-T2-T3E/IF4E*						
RKW ↓	i_{T1} **(BCA)**	i_{T2} **(BCA)**	i_{T3} **(BCA)**	g_{hT1} **(BCA)**	g_{hT2} **(BCA)**	g_{hT3} **(BCA)**
	kA	**kA**	**kA**	**-**	**-**	**-**
SK(P)	7,52	7,06	9,93 /5,30*	7,99	27,38	90,06
SS(P)	7,53	7,08	9,95 /5,31*	8,01	27,54	90,10
SK(TP)	7,56	7,12	10,31 /5,40*	8,23	25,33	80,90
SS(TP)	7,57	7,13	10,32 /5,42*	8,23	25,43	80,53

* indicates the part of short-circuit current in circuit *T*3 flowing to the ground.

TABLE I.V. THE HIGHEST VALUES OF THE INSTANTANEOUS INTERSYSTEM CURRENTS (ALL VARIANTS).

RKW ↓	i_{IF1} **(CB)**	i_{IF2} **(AB)**	i_{IF3} **(AC)**	i_{IF4} **(BCA)**	i_{IF4E} **(BCA)**
	kA	**kA**	**kA**	**-**	**-**
SK(P)	12,77	13,48	18,69	14,36 /18,39	13,58 /17,46
SS(P)	12,78	13,48	18,70	14,37 /18,42	13,59 /17,47
SK(TP)	12,83	13,59	18,97	14,41 /18,57	13,61 /17,53
SS(TP)	12,83	13,59	18,98	14,42 /18,56	13,62 /17,53

where i_{IFx}, is the highest values of the instantaneous intersystem current between two circuits of multi-voltage line. For the intersystem fault mark as *IF*4 and *IF*4*E* given two values - first for the intersystem current between circuits *T*1-*T*2 and second for intersystem current between circuits *T*2-*T*3.

For the all tables (I.I...I.IV) with results of the maximum instantaneous current in ‘healthy’ and faulted phases the differences between tubular and lattice towers are irrelevant. This situation is for all analysis type of intersystem faults. The same conclusion is for the intersystem currents value from table I.V. The largest difference between results for the tubular SS(P) and lattice towers SK(P) was noticed for the g_{hT3} factor -- about 8% (intersystem fault mark as *IF*4, table I.IV).

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TABLE II.I. THE HIGHEST VALUES OF THE INSTANTANEOUS VOLTAGES OF THE OF SELECTED PHASES AND OVERVOLTAGES FACTOR DURING THE INTERSYSTEM FAULTS - VARIANT ***IF*1**.

RZM/OZM: *T1-T2/IF1*						
RKW ↓	u_{T1} **(CB)**	u_{T2} **(CB)**	u_{T3} **(AB)**	k_{T1} **(CB)**	k_{T2} **(CB)**	k_{T3} **(AB)**
	kV	**kV**	**kV**	-	-	-
SK(P)	657,48	493,74	210,51	1,20	1,59	1,35
SS(P)	657,65	495,56	211,25	1,20	1,59	1,36
SK(TP)	656,06	486,39	203,77	1,20	1,57	1,31
SS(TP)	656,46	488,98	204,88	1,20	1,58	1,32

TABLE II.II. THE HIGHEST VALUES OF THE INSTANTANEOUS VOLTAGES OF THE OF SELECTED PHASES AND OVERVOLTAGES FACTOR DURING THE INTERSYSTEM FAULTS - VARIANT ***IF*2**.

RZM/OZM: *T1*-T3/*IF2*						
RKW ↓	u_{T1} **(CB)**	u_{T2} **(CB)**	u_{T3} **(CB)**	k_{T1} **(CB)**	k_{T2} **(CB)**	k_{T3} **(CB)**
	kV	**kV**	**kV**	-	-	-
SK(P)	645,47	369,17	552,1	1,18	1,19	3,56
SS(P)	645,38	369,87	553,2	1,18	1,19	3,57
SK(TP)	645,61	364,66	546,72	1,18	1,18	3,52
SS(TP)	645,37	365,84	548,10	1,18	1,18	3,53

TABLE II.III. THE HIGHEST VALUES OF THE INSTANTANEOUS VOLTAGES OF THE OF SELECTED PHASES AND OVERVOLTAGES FACTOR DURING THE INTERSYSTEM FAULTS - VARIANT ***IF*3**.

RZM/OZM: *T2-T3/IF3*						
RKW ↓	u_{T1} **(CB)**	u_{T2} **(CB)**	u_{T3} **(CB)**	k_{T1} **(CB)**	k_{T2} **(CB)**	k_{T3} **(CB)**
	kV	**kV**	**kV**	-	-	-
SK(P)	554,99	390,40	300,17	1,02	1,26	1,94
SS(P)	557,15	390,38	300,67	1,02	1,26	1,94
SK(TP)	555,48	389,98	298,09	1,02	1,26	1,92
SS(TP)	555,71	389,75	298,68	1,02	1,26	1,93

TABLE II.IV. THE HIGHEST VALUES OF THE INSTANTANEOUS VOLTAGES OF THE OF SELECTED PHASES AND OVERVOLTAGES FACTOR DURING THE INTERSYSTEM FAULTS - VARIANTS
IF*4** AND ***IF*4*E.

RZM/OZM: *T1-T2-T3/IF4*						
RKW ↓	u_{T1} **(BCA)**	u_{T2} **(BCA)**	u_{T3} **(BCA)**	k_{T1} **(BCA)**	k_{T2} **(BCA)**	k_{T3} **(BCA)**
	kV	**kV**	**kV**	-	-	-
SK(P)	694,07	579,60	442,49	1,27	1,87	2,85
SS(P)	693,50	578,84	443,57	1,27	1,87	2,86
SK(TP)	693,48	577,03	442,18	1,27	1,86	2,85
SS(TP)	692,82	576,05	442,47	1,27	1,86	2,85
RZM/OZM: *T1-T2-T3E/IF4E*						
RKW ↓	u_{T1} **(BCA)**	u_{T2} **(BCA)**	u_{T3} **(BCA)**	k_{T1} **(BCA)**	k_{T2} **(BCA)**	k_{T3} **(BCA)**
	kV	**kV**	**kV**	-	-	-
SK(P)	694,07	579,60	442,49	1,27	1,87	2,85
SS(P)	693,50	578,84	443,57	1,27	1,87	2,86
SK(TP)	693,48	577,03	442,18	1,27	1,86	2,85
SS(TP)	692,82	576,05	442,47	1,27	1,86	2,85

For the all tables (II.I...II.IV) with results of the maximum instantaneous voltage in ‘healthy’ and faulted phases the differences between tubular and lattice towers are minimal -- less than for current results (table I.I...I.V). For all analysis type of intersystem faults the difference between results for the tubular and lattice towers is less than 1% (k_T factors).

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The fig. 4...8 show the current and voltage transients in faulted and 'healthy' phases of multi-voltage line. Due to fault between all circuit of the multi-voltage, as a variant of intersystem fault *IF*4*E* was selected.

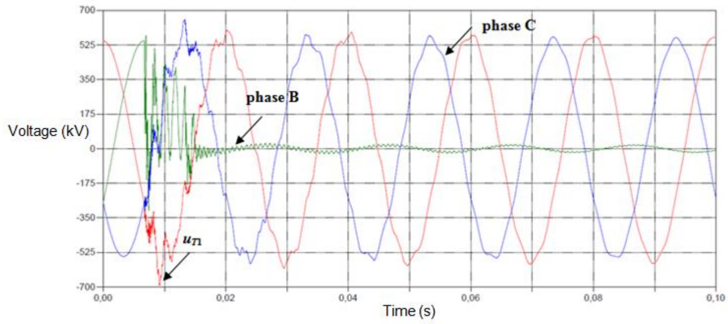

Fig. 4 The voltage transients in circuit *T*3 (380 kV) during the intersystem fault *IF*4*E*

In the fig 4, it shown influence of the intersystem fault in phase B for the 'healthy' phases of the 380 kV system. In the phase A, the largest increase of the voltage was observed. The reason of this situation is the moment of the simulated time of the intersystem fault. For the 380 kV system the instantaneous value of the 'healthy' phases are higher than faulted one (phase B). For the 220 kV and 110 kV systems situations are reverse.

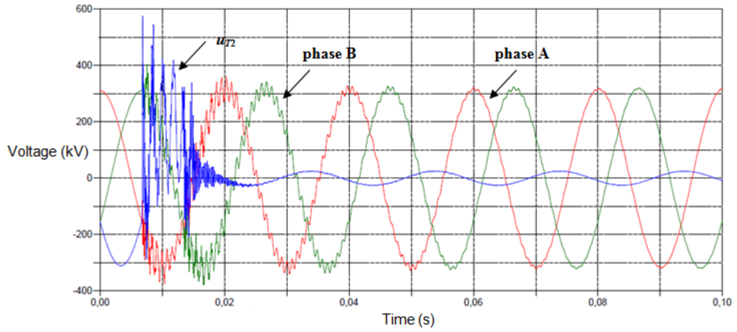

Fig. 5 The voltage transients in circuit *T*2 (220 kV) during the intersystem fault *IF*4*E*

Figure 5 presents voltage condition in circuit *T*2. For the 'healthy' phases (phases A and B) the high-frequency components are observed. The similar situation is for the faulted phase (phase C), but for this phase more high-frequency components were noticed. After four period (80 ms) this components are disappear.

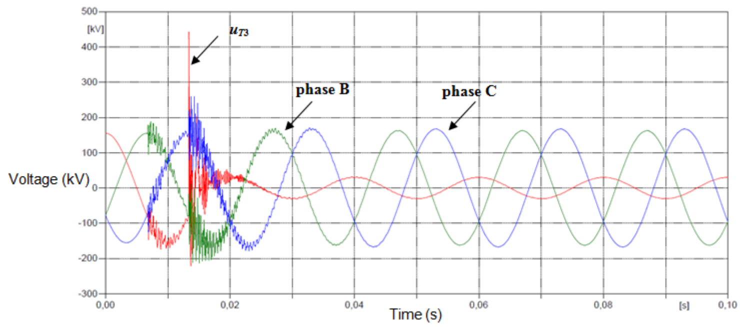

Fig. 6 The voltage transients in circuit *T*3 (110 kV) during the intersystem fault *IF*4*E*

The biggest overvoltages conditions were observed in circuit with the lowermost rated voltage - circuit T3 (110 kV). The value of the overvoltage factor is k_{T3} = 2.86. It's mean that instantaneous value of the voltage in faulted phase (phase A) is almost three times higher than rated voltage of the circuit. Figure 6 shows this situation.

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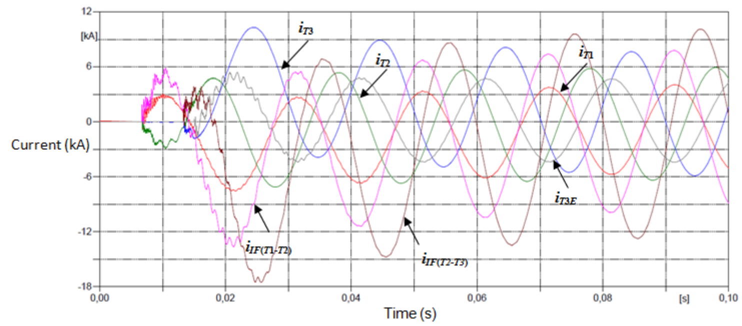

Fig. 7 The current transients in faulted phases of all three circuits during the intersystem fault *IF*4*E*

Maximum instantaneous value of the intersystem currents was noticed between circuits *T*1 and *T*2 ($i_{IF(T1-T2)}$). This current also has the biggest steady-state value. For the initial part of the transients the high-frequency components were noticed. Contents of the high-frequency components are the biggest in first period of the intersystem fault and is lower than in voltage transients. All the current transients in faulted phase is presented in the fig 7.

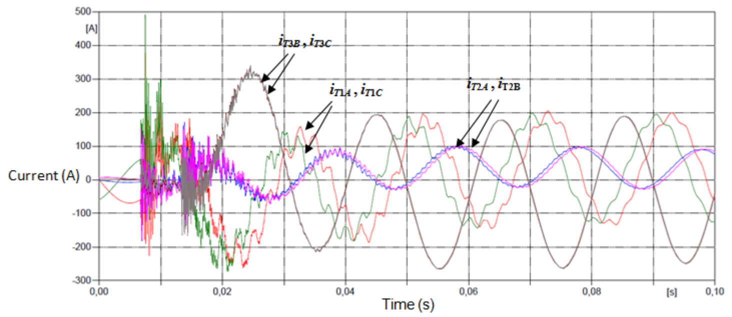

Fig. 8 The current transients in 'healthy' phases of all three circuits during the intersystem fault *IF*4*E*

During the intersystem fault between all three systems of the multi-voltage line also dynamically changes of the values were observed for the currents in 'healthy' phases. Because of the lower rated voltage, the most significant changes were appeared in 100 kV system. For the system with higher rated voltage (circuit *T*3, 380 kV) the time duration of the transient phenomena is much longer than in 220 kV and 110 kV systems.

VI.CONCLUSION

Based on the analysis on the comparison of the simulation of selected types of intersystem faults in the three-circuit multi-voltage 380 kV + 220 kV + 110 kV line working on lattice and tubular poles it is concluded that:

- from the standpoint of overvoltages factor k_{Tx} reducing the distance between the electrical conductors working doesn't matter. This property is confirmed in all the analyzed types of intersystem faults. The difference between value of the overvoltages for the line working on the lattice and tubular poles in any of the analyzed variants short circuit does not exceed 1%.
- reduce the distance between the conductors has no effect on the instantaneous values of intersystem fault currents i_{IF} and instantaneous currents i_{Tx} , independently of intersystem fault. Differences of less than 0.1% at these values of short-circuit currents range (from a few to several kA) have no meaning.
- from the standpoint of the overcurrent in the 'healthy' phases g_{hT1} noticeable difference between these values of the instantaneous current occurs for a intersystem fault *IF*4 (intersystem fault between all three circuit of multi-voltage line without the ground) and is approx. 8%. It should be noted, however, that with tens of times increase of current growth in this type of intersystem fault this difference does not matter. For other types of intersystem faults differences in the coefficients g_{hTx} of lattice and tubular poles does not exceed 2%.

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All the above listed applications refer to both conductors configuration i.e. horizontal and triangular-horizontal. Reduce the electrical distance between conductors by applying tubular poles does not affect to:

- overvoltages factor k_{Tx} ,
- instantaneous values of intersystem fault currents i_{IF} and instantaneous currents i_{Tx} ,
- overcurrent in the 'healthy' phases g_{hT1}.

However, from a practical point of view, the use of tubular poles construction significantly reduces the right of way of multi-voltage line. This is crucial in the era of restrictive legislations for the build of the new line investments. The use of tubular poles allows investments in areas, where use lattice towers - due to occupy a considerable area of the foundations of these structure - cannot be used. An additional factor in favor of the use of this type of construction is to reduce the intensity of the electromagnetic field near the line.

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BIOGRAPHY

Rafał Kumala (born in 1986) - received the M.S. degree in Electrical Engineering in 2011 from Silesian University of Technology in Gliwice, Poland. In the same year he has started working on PhD thesis about multi-voltage lines in the Institute of Power Systems and Control in Faculty of Electrical Engineering. His researches includes three main group:

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Paweł Sowa (born in 1947) - received the M.S. degree in Electrical Engineering in 1971, PhD in 1980 and professor in 2012 -- all in Silesian University of Technology in Gliwice, Poland. At the moment professor Paweł Sowa is the Dean of the Faculty of Electrical Engineering and Director of the Institute of Power Systems and Control in Silesian University of Technology. The main current research and interests are:

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