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Influence of the Secondary Arc on the Operation of Single Phase Auto-reclosure of the 400 kV interconnection between Hungary and Croatia

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SUMMARY

Faults on EHV lines are generally single-phase-to-ground ones and not permanent in the majority of cases. Thus single phase auto reclosure (SPAR), at which the faulty phases are tripped for a short time, eliminates the predominant part of the faults [1,2]. The secondary arc, which follows the high power arc after tripping the faulty phases at both side of the line may endanger the successfulness of reclosing if the duration of the switched off interval (dead time) is not long enough to ensure the extinction of the arc. The secondary arcing times recorded on different EHV lines or measured in laboratory tests show significant spread, consequently, to select a dead time according to the longest experimental secondary arc extinction time is not feasible.

During commissioning of the double circuit 420 kV interconnection between Hungary and Croatia several staged faults were initiated to analyze the arc extinction performance. Initially the line was in operation by connecting the two circuits in parallel along the 1/3rd of the full length. In this configuration the longest secondary arc extinction time was 4 seconds and the secondary arc has not extinguished in 27s in one of the tests, so the line had to be tripped out to clear the staged fault. Later on, the length of the Croatian section of the line has been significantly shortened after putting a new substation into service. The increased performance of SPAR of the new arrangement has been proved with field tests.

A realistic representation of the secondary arcs is essential in determining the auto-reclosure performance of EHV transmission lines. As shown in the paper, the random variation of the arc parameters influences significantly the arc extinction time. The results of the field tests confirmed the importance of the distributed nature of the transmission line and the nonlinear characteristic of the arc resistance in the intermittent region of arcing, where temporary extinctions and sudden re-ignitions in the arc channel produce transient wave processes along the line.

KEYWORDS

Line fault, secondary arc, reclosing, simulation, measurement, EMTP-ATP.

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1 INTRODUCTION

To find a new right-of-way is rather difficult today. Using compact tower construction and upgrading existing lines offer a possibility to overcome these constraints. However reducing the phase-to-phase clearances has a strong impact on the lightning and switching performance of the line. The increasing number of faults contradicts an other key expectation of the public today: the *quality of supply*. These conditions emphasize the importance of reclosing efficiency, which may compensate the less favourable lighting performance of compact line designs of reduced insulation clearances [3,4,5,6].

The successfulness of SPAR is endangered by long duration secondary arcs and reclosing overvoltages that can re-ignite the arc at the place of the fault. Single or three-phase reclosure produces high switching overvoltages and the heaviest stresses in line insulation. These overvoltages may endanger in particular those lines running in polluted areas or operating in foggy zones. Contamination usually extends to a large area, and it can be presumed that an intensive partial arc activity is going along the surface of many line insulators. The fault occurs when one of them flashes over by the normal operating voltage stress. As a rule, the heating effect of the primary arc dries out the faulted insulator, but a high reclosing overvoltage is able to initiate partial arcs on some other insulators. The temporary overvoltage and the normal operating voltage which follows the reclosing transient may then sustain and elongate the partial arcs further till a full flashover occurs.

Increasing number of unsuccessful reclosing can be observed especially at winter period in operation of the Hungarian HV and EHV lines. Table 1. shows aggregated data for a 4-year period. The ratio of the unsuccessful reclosing to the total ones is 0.26 in summer and 0.53 in winter. Transmission line faults originate mainly from lightning in summer and predominantly from foggy weather in winter. Considering that the ratio of unsuccessful/total reclosing is twice as high in winter as in summer, a significant limitation of the reclosing overvoltages is recommended for the lines containing polluted or foggy sections to keep the line operating performance high.

Table 1: Number of reclosings on the Hungarian HV/EHV lines within a 4-years period.

Voltage level	Summer		Winter		Line length (km)
	successful	unsuccessful	successful	unsuccessful	
750 kV	5	0	1	2	479
400 kV	48	20	28	9	1530
220 kV	83	28	23	47	1687
∑	136	48	52	58	3696

2 SECONDARY ARC AND RECLOSING EFFECTIVENESS

The fault arc can be classified according to the fault state: *primary arc* is effective after fault inception till single-phase tripping of the faulty phase. The *secondary arc* follows the primary arc in the ionized, hot plasma channel after isolating the fault by single-phase tripping and is sustained by the capacitive and inductive coupling to the sound phases. The secondary arc self-extinguishes usually, but its life-time may have a strong influence to the reliability of the operation of the line. On the one hand a non self-extinguishing secondary arc endangers the efficiency of the single-phase reclosing; on the other hand prolonging the dead time (switched-off interval of the faulty phase) is limited by dynamic stability constraints. This limit is usually less than 1.5 - 2 seconds for a long EHV/UHV interconnection. Considering that line faults are mostly non-permanent ones, a significant percentage of them can be cleared by single-phase auto-reclosure. In particular for compact lines with reduced clearances the smaller phase-to-phase clearances make the capacitive coupling between conductors more substantial, which may result in higher secondary arc currents and longer arcing times.

3 EXPERIMENTAL DATA ABOUT SECONDARY ARC EXTINCTION TIMES

The secondary arcing times recorded on real lines and laboratory tests show a significant spread [1,14]. This spread can be explained by the extremely random character of the arc formation and the strong influence of many parameters (wind velocity, the movement of the hot plasma generated by the primary arc, magnetic force due to the current, convection of the plasma cloud and surrounding air, presence and degree of shunt compensation –if exists-, etc.) to the arcing time.

3.1 Staged fault tests on the 400 kV double-circuit interconnection between Croatia and Hungary

As part of commissioning of the new interconnection, the secondary arc extinction parameters have been checked by initiating staged faults with and w/o primary arc in different meteorological conditions at both end of the line. The one-line schema of the corresponding 400 kV network is given in Fig. 1. Initially, the operating length of the line was 230 km without shunt compensation, connecting Heviz 400/132 kV and Tumbri 400/110 kV substations in Hungary and Croatia, respectively. Currently, the line connects Heviz and Žerjavinec 400/220/110 kV substations. At the beginning of operation the interconnection has been operated by connecting the two circuits in parallel along the 1/3rd of the full length to reduce transmission losses. The remaining sections of the second circuit had been operated then at 220 kV or were grounded. Seven staged faults have been carried out, aiming to predict the secondary arcing times. The measuring arrangement and the length of the faulty phases are shown in Fig. 2. The location of the staged fault is indicated by a grounding symbol.

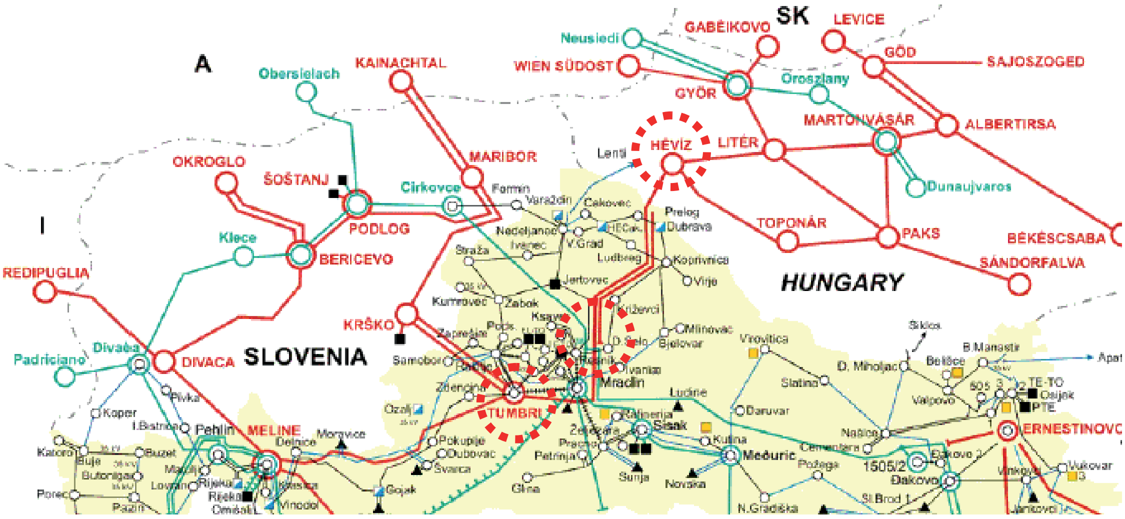


Fig. 1 – Overview of the 400 kV interconnection between Hungary and Croatia

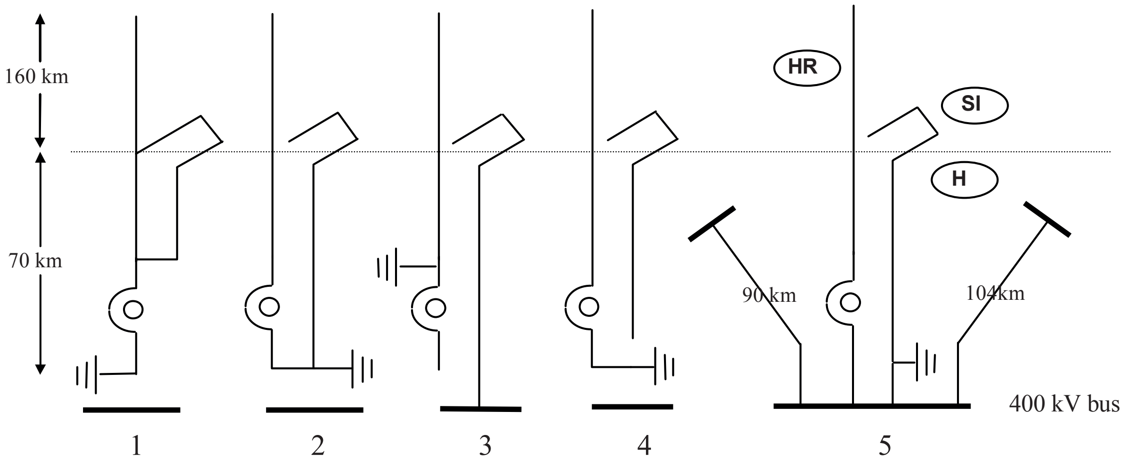
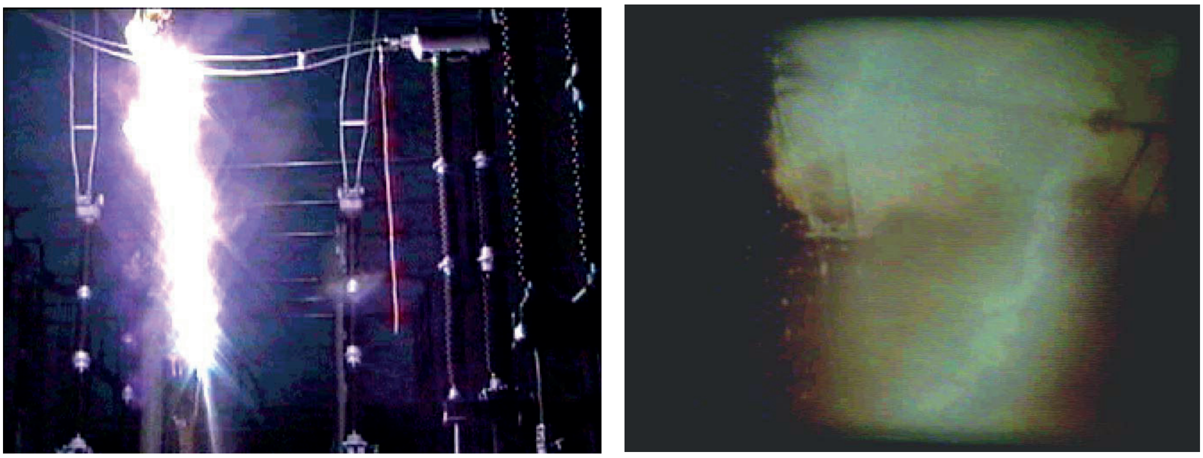


Fig. 2 – Measuring arrangements at fault tests. 1-4 fault w/o primary arc, 5 with primary arc.

In majority of tests the arc has been initiated by a thin wire connecting the phase conductor of an already isolated phase to the substation ground or to metallic structure of transmission line tower, i,e, the primary arc has been omitted in these tests. According to [14] such an arc ignition technique provides comparable results to tests with primary arc if the expected secondary arcing time exceeds 700 ms because the plasma cloud of the primary arc certainly has strong influence to quickly extinguishing secondary arc. However such a self-extinguishing short duration arc does not endanger the SPAR successfulness.

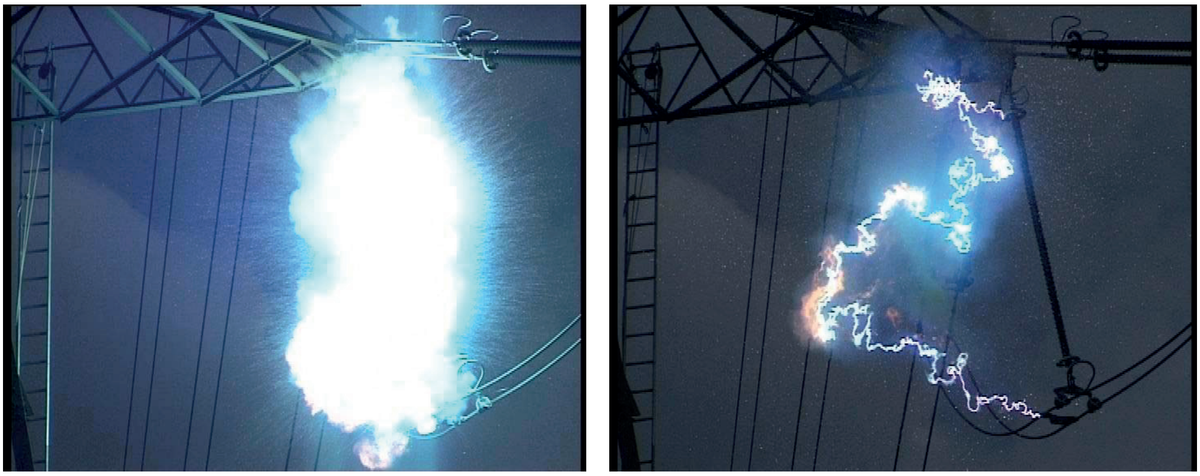
3.2 Test results

The shortest arc extinction time was 0.05 s and the longest one was 4 s during the tests. The secondary arc did not extinguish during 27 s at one of the tests. 4 s and 27 s extinction times have been measured in arrangement “1” of Fig. 2 where the fault was created inside the substation at calmness. As Fig. 3 shows, at calmness no significant arc channel elongation is seen. Ions generated during the intermittent arc interval remain in the environment of the arc. These circumstances make the self-extinction time very long. The secondary arcing times recorded at moderate (3 - 4 m/s) wind velocities were in the range of 0.05 s – 0.69 s. As Fig. 3/d shows the elongation of the arc is slow and many loops occur in the arc channel due to the electromagnetic forces. The big spread of the extinction times and very long arcing times experienced in two cases correspond to the data about extinction times published in former papers containing generalized diagrams [1].



a)
non-self extinguishing secondary arc at calmness

b)
formation of the secondary arc inside the plasma cloud



c)
primary arc

d)
self extinguishing secondary arc

Fig. 3 - Pictures taken at the staged fault tests.

3.3 Secondary arc extinction

The main condition of the spontaneous extinction of the secondary arc is a strong air movement, which makes the arc to elongate quickly. The hot plasma generated by the primary arc moves upward with a high velocity, resulting in an initial vertical component for the secondary arc elongation (Fig. 3/b/d). Wind has the same effect on the secondary arc.

The elongation of the secondary arc causes a linear increase of arc voltage. If the arc elongation is rather smooth without steep rise then the secondary arc extinguishes as the arc voltage reaches the magnitude of recovery voltage [7]. A steep rise of arc length can be caused by a gust of wind. In that case the arc may extinguish sooner. Consequently, the arc duration may be estimated by the elongation speed of the arc.

Besides the arc elongation, re-ignitions inside the arc channel may have a significant role in the process. The speedy elongation of the arc separates the conducting plasma clouds by high resistance channel zones. When number of high resistance zones increases, the amplitude of the operating frequency component of the current decreases and high amplitude impulses occur as a consequence of the growing re-ignition voltage. If the recovery voltage is sufficient to produce a breakdown bridging these high resistance zones, the arcing process may return to the steady-state condition, remarkably prolonging the self-extinction time as shown on Fig. 4. The final extinction of the secondary arc is very often preceded by an intermittent interval, when high current impulses are superimposed on the low amplitude operating frequency component of the current. As can be seen on Fig. 4 the amplitude of these impulses is much higher than the peak value of the steady-state current.

The sudden re-ignitions in the arc channel initiate electromagnetic wave phenomena along the line. The length of the current impulses depends on the place of the fault. For the predominant part of the fault displacement, the duration of these impulses is twice of the line travel time. The superposition of the reflected waves produces a current zero in the arc channel resulting in partial arc extinction. The amplitude of these current impulses are sufficiently high to re-ionize a large amount of plasma, resulting in a fallback into the quasi-sinusoidal phase of the arcing process which elongates the secondary arc duration.

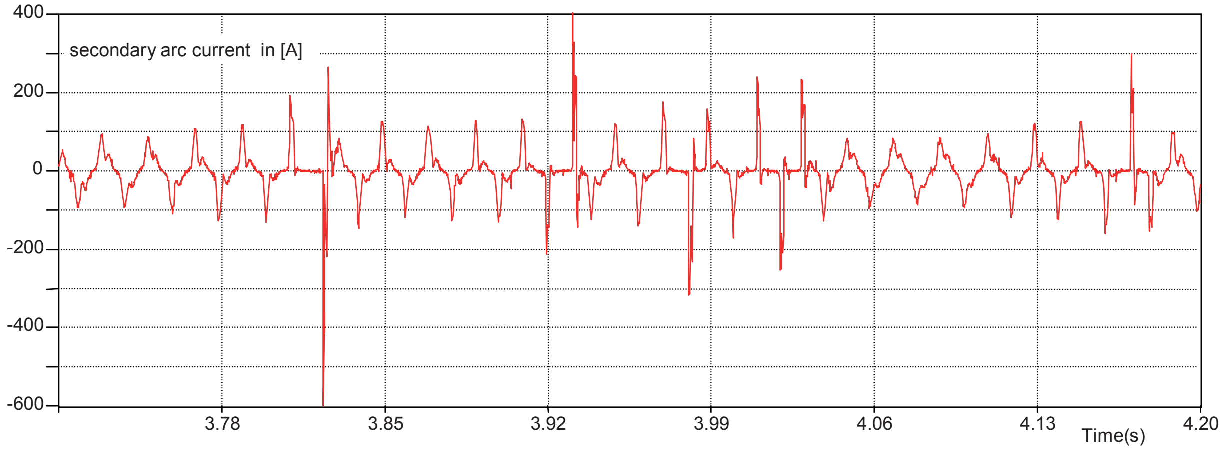


Fig. 4 - Secondary arc current (measurement).

4 EMTP-ATP MODEL OF THE 400 KV INTERCONNECTION

The ATP-EMTP model of the interconnection has been assembled by using ATPDraw graphical preprocessor [16]. The model has been elaborated to prove the main characteristics of the recorded signals at the staged fault test. Initially the model corresponded to the measuring arrangement "case 5" of Fig. 2. Later the model has been improved by completing it with an arc model based on identification of arc parameters [17, 18]. And finally, after commissioning Žerjavinec substation, the model has been further improved to take into consideration the new arrangement of the line and to represent the supply network configuration and influence of the magnetic voltage transformers at both end of the line in more detail. The complete model is shown on Fig. 5.

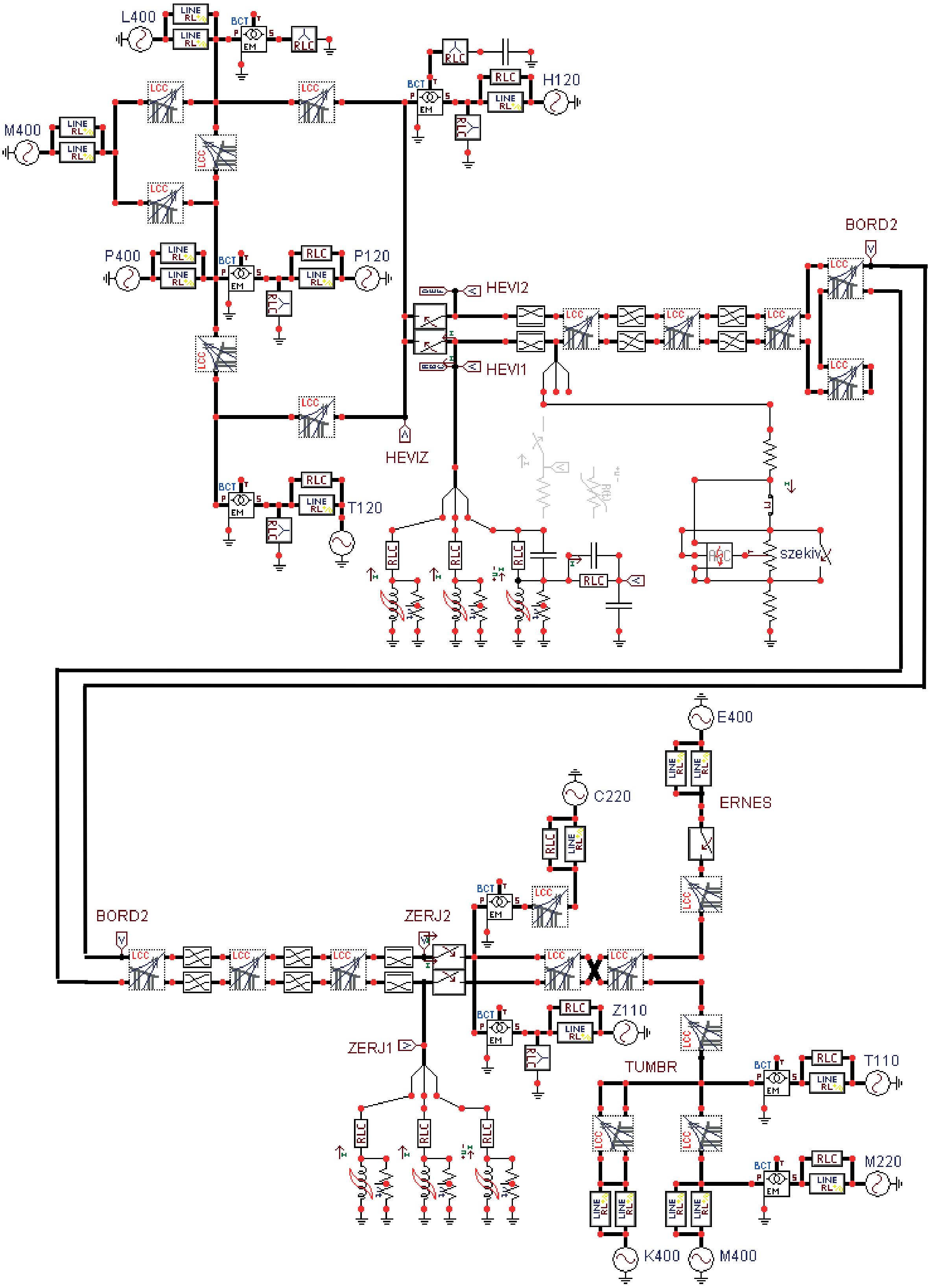


Fig.5 – EMTP simulation of the Heviz - Žerjavinec 400 kV interconnection.

4.1 Fault arc modelling

Whereas the primary arc shows generally a deterministic behavior as observed at field and laboratory tests [7, 8, 9, 10, 11], the secondary arc has extremely random characteristics effected by the external conditions around the arc channel like ionized surrounding air, wind, thermal buoyancy and electrodynamic forces. A numerical arc model may be a useful tool to identify the main influencing factors and the interaction of the arc with the electric circuit, and to estimate the worst-case arcing time.

The arc model used in this work is based on the energy balance of the arc column and describes an arc in open air by a differential equation of the arc conductance g [7, 15, 17]:

$$\frac{dg}{dt} = \frac{1}{\tau}(G - g) \tag{1}$$

where τ: is the arc time constant, g: instantaneous arc conductance,
G: stationary arc conductance.

The stationary arc conductance is defined as:

$$G = \frac{|i_{arc}|}{u_{st}} \quad \text{with} \quad u_{st} = u_0 + r_0\,|i_{arc}| \tag{2}$$

where i_{arc}: instantaneous arc current, u_{st}: stationary arc voltage,
u_0: characteristic arc voltage, r_0: characteristic arc resistance.

Arc parameters u_0 and r_0 are dependent on arc length l_{arc}, The dependence of the arc time constant τ on $l_{arc}(t)$ can be defined by the inverse relation

$$\tau = \tau_0 \cdot \left(\frac{l_{arc}}{l_0}\right)^{\alpha} \tag{3}$$

where τ_0: initial time constant, l_0: initial arc length, α: coefficient of negative value.

4.2 Arc representation in EMTP - ATP

The arc as a nonlinear dynamic element can be represented by the *Thevenin type*, Type-94 component in the ElectroMagnetic Transients Program EMTP-ATP [12]. The arc is described in MODELS language [13]. The interaction of the electric arc with the remaining circuit is shown in Fig. 6. The use of Type-94 component in EMTP-ATP enables simultaneous solution of arc equations together with the equivalent system of the electric network.

Since the arc parameters are expressed as functions of the instantaneous arc length, the random arc behavior can be reproduced by varying the arc length in a random way. It is physically reasonable to describe a global arc length increase – either piecewise-linear or any predefined function – superposed by a local random length variations that should imitate the local breakdowns along the elongated secondary arc.

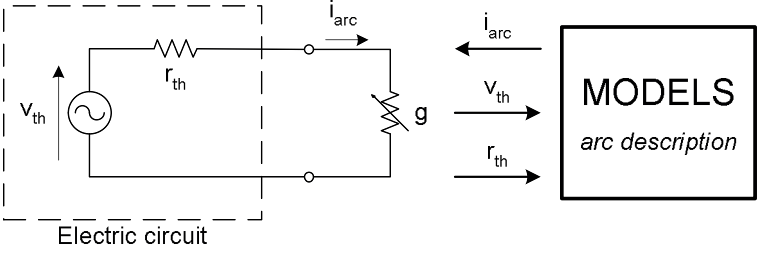


Fig. 6 - Interaction between the electric circuit and the arc model.

4.3 Simulation results

Measuring arrangement "5" of Fig. 2 has been selected to compare the simulation results with measurements. In this test the phase-to-ground fault has been cleared by disconnecting phase *a* of circuit breakers at the receiving end of the lines connected with the 400 kV busbar of Heviz substation.

Piece-wise linear arc length variation superimposed by a random signal has been used in the simulation [18]. Fig. 7 and 8 show the measured and computed arc voltages and currents, respectively.

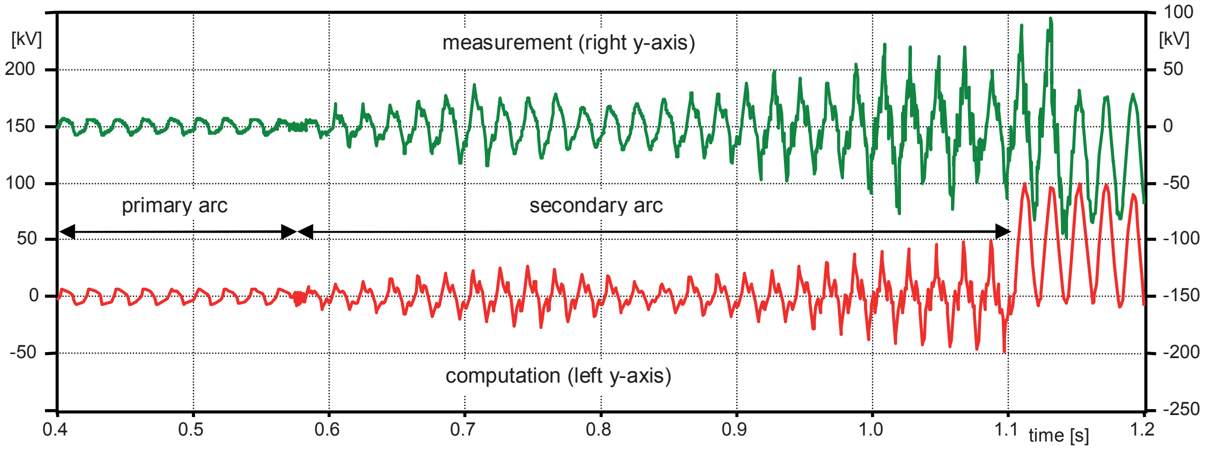


Fig. 7 - Measured and computed arc voltages.

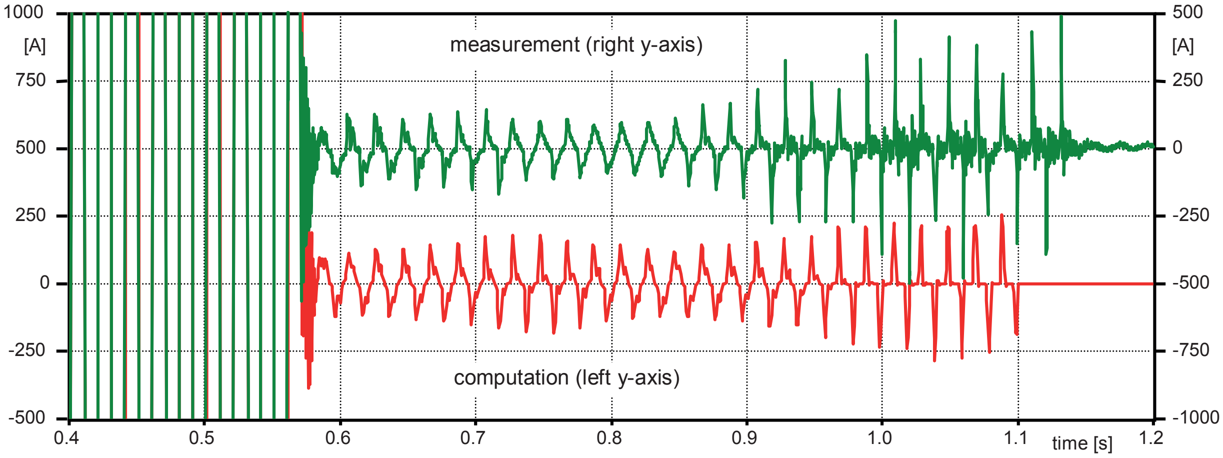


Fig. 8 - Measured and computed arc currents.

5 CONCLUSIONS

Secondary arcing times recorded at field tests spread to a great extent due to the differences in the wind velocities, arc initiation technique, line construction etc. Recording the wind velocity in the environment of the secondary arc and a detailed description of the way of arc initiation would reduce the spread of the experimental data.

The staged fault tests proved that the distributed nature of the transmission line plays an important role during the intermittent stage of arcing and that the final extinction of the secondary arc is often preceded by an intermittent interval, when high current impulses are superimposed on the power frequency component of the secondary arc current. The extinction time of the secondary arc is affected by the shape and amplitude of the recovery voltage arising in the transient current zeros at the place of the fault.

Due to highly random behavior of the secondary arc it is difficult to reproduce exact arc duration by digital simulations. The speed of arc elongation plays a significant role regarding arc duration and extinction. In addition the arc time constant depends inversely on arc length. The arc tends to extinguish faster as the arc time constant becomes smaller. This behavior is based on the fact that the arc is an energy storage element. In spite of these uncertainties in the modeling, the arc model can be successfully utilized to find main factors influencing the secondary arcing process.

6 ACKNOWLEDGEMENT

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