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Numerical Modelling of Transient Phenomena in a Synchronous Machine

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Abstract. The present contribution deals with the idea of identification of electromagnetic transient phenomena pages in a synchronous machine – namely of distant short circuits – by numerical modelling. Phenomena in AC windings of a synchronous machine (stator) have a backswing effect on the phenomena in DC windings – namely the excitation one. Concerned is namely the current stress of the excitation circuit during the transient phenomenon. The computer model is created in the Famulus- vers. 3 – environment. The time behaviour of AC circuit currents in components d, q and the excitation circuit is monitored on the example of a 3-pole distant short circuit in a synchronous machine (via the impedances of connecting elements). The results are compared of models with a simpler structure (one damper circuit in the rotor) with those with a more complicated structure (two damper circuits in the rotor).

Key words: electromagnetic system, synchronous machine, transient phenomena, modelling.

INTRODUCTION

Specific problems appear in the process of creating mathematical models of physical systems. The most essential issue appears to be the description of mutual relations between individual elements of the system and their mathematical interpretation. An important aspect of the created model is the possibility of modifications in a form allowing elimination of potential inaccuracies or minimization of their effect. Simulation experiments allow creation of alternative forms of models and their structures which enable the results of models to be in closest agreement with the behaviour of real electrodynamic systems (e. g. a synchronous machine supplying an independent network). The tool used for this purpose is the Famulus programme environment created at Charles University. Compared with the globally used simulation programme Matlab, its advantage is that it requires less sophisticated hardware but on the other hand it requires at least a minor knowledge of programming. Modelling of synchronous machines is important for estimating their behaviour in various modes of operation. This is based on the fact that synchronous machines are used in a broad range of applications. For example, for research on the effect of the excitation system of a synchronous machine on the power engineering network Jonaitis (2013) used the Heffron-Phillips model. Transients on exciting and damper windings on synchronous machine during de-excitation are explored by Hořan (2015). Machines with permanent magnet exciting are frequently used for driving applications. The verification of modell-parametters for this construction of synchronous machine is described by Novák et al. (2012). Comparison of simulation results of Park-Gorevs model structures with a various number of damper circuits in the rotor is performed on a 3-pole distant short circuit in a synchronous machine.

MATERIALS AND METHODS

Theoretical Solutions

The model of a synchronous machine is created by means of the Park-Gorev transformation of coordinates into d, q, 0 components. Under conditons of linearity a similar model was created by T. Laible, described by Hora & Navrátil (1976) and Laible (1957) and modified according to Canay (1980). In the most basic case a description is necessary by means of systems of voltages (u), currents (i) and linked magnetic fluxes (ψ), possibly also by conversion relations of phase and component quantities. Another type of description can be performed either by means of physical quantities or proportional ones related to specific quantities of the investigated machine. Proportional (per-Unit) quantities (p. U.) were selected for further description.

The description of a synchronous machine in the d-q-0 system by means of proprotional (p. U.) quantities is performed in accordance with Fig. 1 by the system of equations (1) for voltages, currents and linked magnetic fluxes. It includes additional connecting elements with circuit parameters – resistance r_V and reactance x_V – between the machine and the short circuit location.

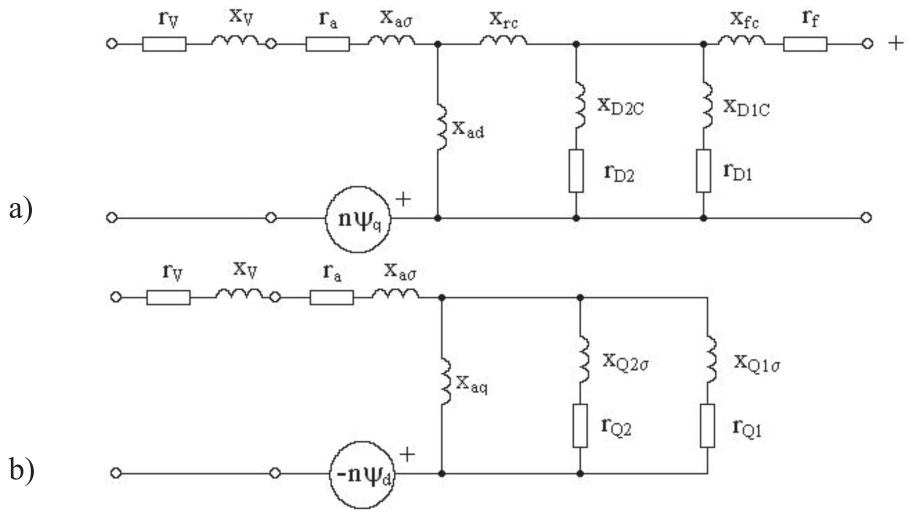


Figure 1. Schematic arrangement of equivalent circuits of a synchronous machine with two damper circuits: a) direct axis; b) transversal axis.

$$
\begin{aligned}
u_d &= -(r_V + r_a)\times i_d - \frac{d\psi_d}{dt} + n\times\psi_q \\
u_q &= -(r_V + r_a)\times i_q - \frac{d\psi_q}{dt} - n\times\psi_d \\
u_0 &= -(r_V + r_a)\times i_0 - \frac{d\psi_0}{dt} \\
u_f &= r_f \times i_f - \frac{d\psi_f}{dt} \\
0 = u_{D1} &= r_{D1}\times i_{D1} - \frac{d\psi_{D1}}{dt} \\
0 = u_{D2} &= r_{D2}\times i_{D2} - \frac{d\psi_{D2}}{dt} \\
0 = u_{Q1} &= r_{Q1}\times i_{Q1} - \frac{d\psi_{Q1}}{dt} \\
0 = u_{Q2} &= r_{Q2}\times i_{Q2} - \frac{d\psi_{Q2}}{dt}
\end{aligned}
\qquad (1)
$$

where r_V is the proportional resistance of the circuit connecting the machine and the short circuit location, r_a is the proportional resistance of the stator winding of the machine, r_{D1} & r_{D2} are the proportional resistances of rotor damper windings in the direct axis of the machine, r_{Q1} &d r_{Q2} = proportional resistance of rotor damper windings in the direct axis of the machine and n is the propotional magnitude of rpm of the machine. The indexes of circuit quantities (*u, i, ψ*) have the following meaning: *d* = relation to the direct machine axis, D_1 & D_2 = relation to damper windings in the direct axis of the rotor in corresponding sequence, *f* = relation to the excitation winding (in the rotor), *q* = relation to the transversal axis of the stator, Q_1 & Q_2 = relation to damper windings in the transversal axis of the rotor in corresponding sequence, *0* = relation to 'non-rotating' quantities of the stator, *a* = relation to stator windings, *V* = relation to connecting elements between the machine and the short circuit location.

In contrast with the system of forming linked magnetic fluxes, which has a certain variability, the decribed system of equations for the voltage of the system will not substantially change The system according to Canay (1980), which can use in a linear approximation with advantage a matrix notation, can be applied for comparison.

$$
\begin{bmatrix}\psi_d\\ \psi_{D1}\\ \psi_{D2}\\ \psi_f\end{bmatrix} =
\begin{bmatrix}
(x_V + x_{a\sigma} + x_{ad}) & x_{ad} & x_{ad} & -x_{ad}\\
x_{ad} & (x_{ad}+x_{rC}+x_{D1C}) & (x_{ad}+x_{rC}) & -(x_{ad}+x_{rC})\\
x_{ad} & (x_{ad}+x_{rC}) & (x_{ad}+x_{rC}+x_{D2C}) & -(x_{ad}+x_{rC})\\
-x_{ad} & -(x_{ad}+x_{rC}) & -(x_{ad}+x_{rC}) & (x_{ad}+x_{rC}+x_{fC})
\end{bmatrix}\times
\begin{bmatrix}i_d\\ i_{D1}\\ i_{D2}\\ i_f\end{bmatrix}
$$

$$
\begin{bmatrix}\psi_q\\ \psi_{Q1}\\ \psi_{Q2}\end{bmatrix} =
\begin{bmatrix}
(x_V + x_{a\sigma} + x_{aq}) & x_{aq} & x_{aq}\\
x_{aq} & (x_{aq}+x_{Q1\sigma}) & x_{aq}\\
x_{aq} & x_{aq} & (x_{aq}+x_{Q2\sigma})
\end{bmatrix}\times
\begin{bmatrix}iq\\ i_{Q1}\\ i_{Q2}\end{bmatrix}
\qquad (2)
$$

$$\psi_0 = x_0 \times i_0$$

where x_{ad} = proportional main reactance in the direct stator axis, $x_{a\sigma}$ = proportional leakage reactance of stator windings, x_{rc} = proportional coupling reactance of rotor windings in the direct axis with respect to the main flux according to Canay (1980), x_{D1c} and x_{D2c} = proportional leakage reactances of rotor damper windings according to Canay (1980), x_{fc} = proportional leakage reactance of the excitation winding, x_{aq} = proportional main reactance in the transversal axis of the stator, $x_{Q1\sigma}$ and $x_{Q2\sigma}$ = proportional leakage reactances of rotor damper windings in the transversal axis in corresponding sequence, x_0 = proportional reactance of the non-rotating stator component, x_v = proportional reactance of the connecting lead between the machine and the short circuit location.

$$
\begin{aligned}
\frac{d\psi_d}{dt} &= -u_d - (r_V + r_a)\times i_d + n\times\psi_q \\
\frac{d\psi_q}{dt} &= -u_q - (r_V + r_a)\times i_q - n\times\psi_d \\
\frac{d\psi_0}{dt} &= -u_0 - (r_V + r_a)\times i_0 \\
\frac{d\psi_f}{dt} &= u_f - r_f\times i_f \\
\frac{d\psi_{D1}}{dt} &= -r_{D1}\times i_{D1} \\
\frac{d\psi_{D2}}{dt} &= -r_{D2}\times i_{D2} \\
\frac{d\psi_{Q1}}{dt} &= -r_{Q1}\times i_{Q1} \\
\frac{d\psi_{Q2}}{dt} &= -r_{Q2}\times i_{Q2}
\end{aligned}
\tag{3}
$$

The method of solution is as follows: voltage equations (1) are modified into the form (3), where on one side of the equation are time derivatives of linked magnetic fluxes and on the other side the remaining parts. The fact is taken into consideration that linked magnetic fluxes do not variate suddenly compared with other circuit quantities. During the short circuit in a particular winding this winding tries to maintain a constatnt magnitude of the linked magnetic flux, which, however, changes its magnitude compared with that at the moment of the short circuit due to the rotation of the rotor. The time variations of the magnitudes of linked magnetic fluxes can be quantified by means of the system of equations (3).

Experimental Implementation

The implementation is carried out for a ŠKODA synchronous alternator with a typical 250 MVA output which is used for short circuit tests at the test plant of the former Heavy Current Electrical Engineering Research Institute (VÚSE) Prague-Běchovice. The parameters of the alternator are in Table 1.

Table 1. Parameters of synchronous machine Škoda (type HB 644862/2)

S = 250 MVA	U_{1n} = 13 kV	I_{1n} = 11.1 kA	X_d' = 0.0825 Ω	T_d'' = 0.026 s
n_n = 3,000 min^{-1}	f_n = 50 Hz	GD^2 = 19 t. m^2	X_d'' = 0.0635 Ω	T_d' = 0.647 s
U_f = 139 V	I_f = 700 A	R_f = 0.197 Ω	X_0 = 0.05766 Ω	T_a = 0.091 s
R_a =1.985 mΩ	Z_n = 0.67595 Ω	X_d = 1.0806 Ω	X_2 = 0.659 Ω	T_{d0}' = 8.473 s

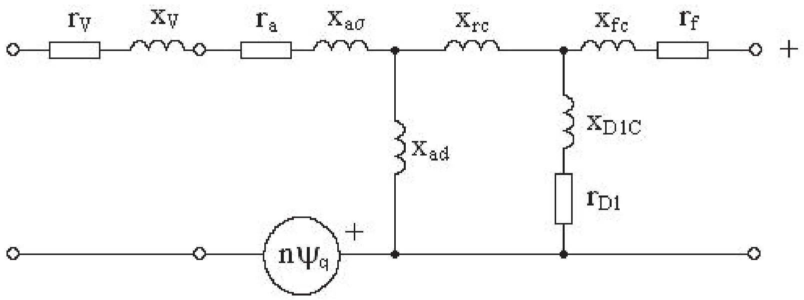
The parameters are transformed in the simulation programme into per-unit-quantities and all time quantities are transformed into angular ones in radians for the specific frequency and rpm of the alternator. The Runge-Kutta method according to Ralston (1978) usually gives more accurate results (standard procedure of the Famulus programme) is used for the calculation of the simulation. Another alternative is the Euler incrementation method, which is according to Ralston (1978) not as accurate as the Runge-Kutta method, but is easier in completing the model with further elements and effects.

The synchronous generator was connected with the short circuit location with connecting elements. The parameters of the connecting elements are in Table 2.

Table 2. Parameters of connecting elements for short circuit tests

Test – denotation	Connecting element – denotation	X_V (Ω)	x_V (P. U.	R_V (mΩ)	r_V (P. U.
62195	X45	0.65033	0.962032	10.10	0.014941
62198	X13	0.086168	0.1274749	1.44	0.0021303

a)



b)

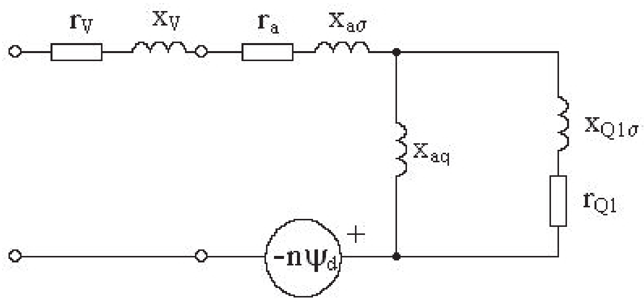


Figure 2. Schematic arrangement of equivalent circuits of a synchronous machine with one damper circuit in the rotor: a) direct axis; b) transversal axis.

RESULTS AND DISCUSSION

The calculations of currents during a transient phenomenon are performed assuming constant rpm of the machine ($n = n_S = const.$) and a constant magnitude of the excitation winding voltage applying connecting impedance X13 according to Test 62198 (more severe operating short circuit). For the analysis only a 3-pole symmetrical short circuit was considered, during which a non-rotating component i_0 of the stator windings current is not developed, and the whole calculation of the conditions for the current during a short circuit is as easy as possible.

Fig. 3 shows the time behaviour of equivalent stator currents in the direct and transversal axis and the excitation current after reduction into unit initial excitation values applying a more complicated model structure with two damper circuits according to Fig. 1. The result of the numerical calculation of a short circuit after approx. 0.1 sec. (i. e. at $\omega t \approx 30$ rad) diverges. The divergence primarily affects the transversal component of the stator currents, and in a further 0.2 sec (i. e. at *0.3 s*, or $\omega t \approx 120$ rad) affects also all other monitored currents. Experiments both with changes of circuit parameters and shortening of the calculation step did not lead to an elimination of this divergence. In fact the results are actually devalued and are absolutely different from those in the oscillogram of a real short circuit – comparing Figs 3 & Fig. 5.

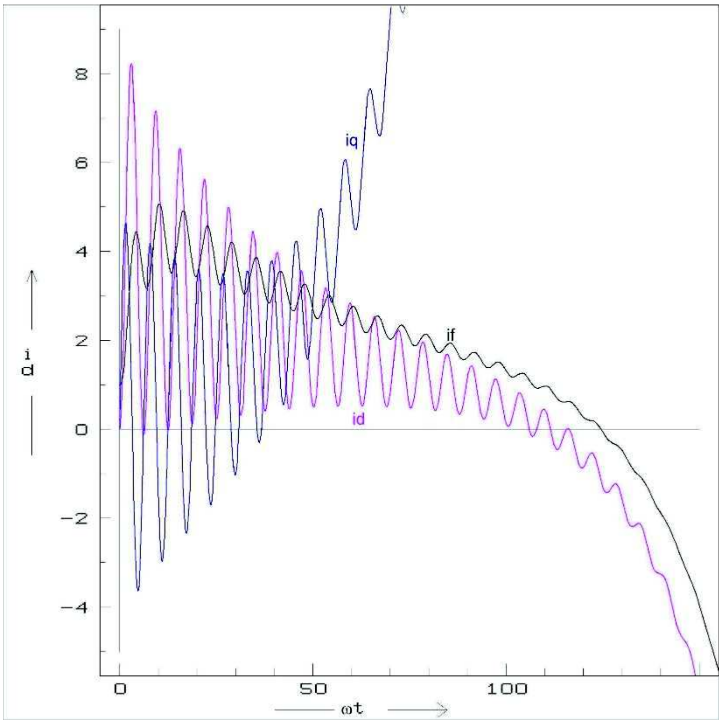


Figure 3. Result of numerical calculations of the time behaviours of currents in equivalent stator windings in the direct axis (i_d, i_q) and the excitation current (i_f) during a more severe operating short circuit applying a more complicated structure model.

Fig. 4 shows the time behaviour of excitation and equivalent stator currents in individual axes applying a simpler structure model according to Fig. 2. By comparison with the real behaviour of currents during the short circuit test on the oscillogram in Fig. 5 it can be observed that the calculated behaviour of the excitation cuurent is very similar to that on the real oscillogram. The magnitude of the maximum amplitude of oscillation of the excitation current shows a dissimilarity – in the calculation it is by 10.5% higher than the recorded reality. For the dimensioning of serial elements of the excitation circuit such a partial ‘overestimation’ of the expected magnitude of the excitation current compared with reality can be an advantage since it reduces the risk of damage of additional elements of the excitation circuit Also the identification of parameters of equivalent model diagrams, due to the above minimum difference of the simulation results from the real state appears to be correct.

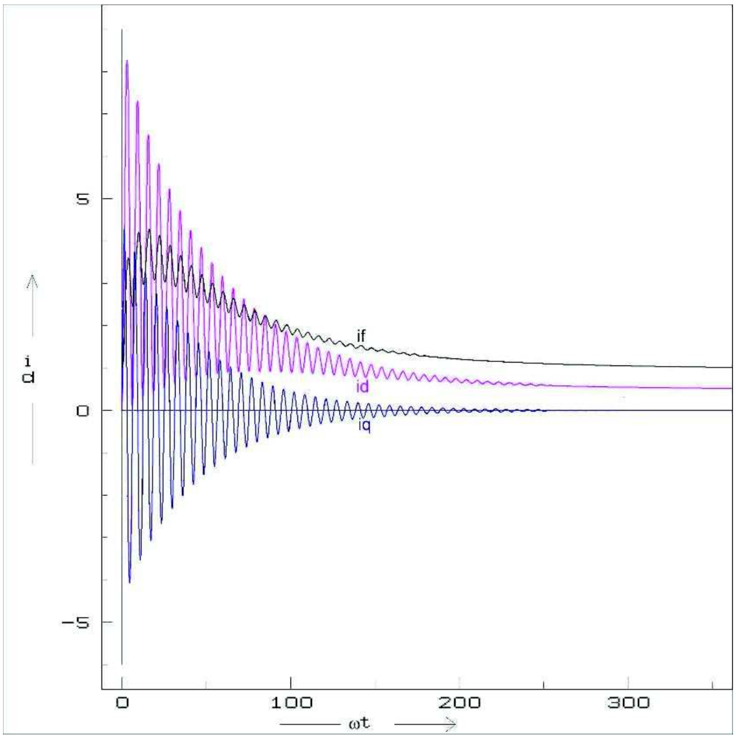


Figure 4. Result of numerical calculation of the time behaviours of circuits in equivalent stator windings in the direct and transversal axis (i_d, i_q) and the excitation current (i_f) during a more severe operating short circuit applying a simpler model structure.

By the application of a simpler structure of equivalent diagrams with one damper circuit in the rotor, paradoxically more correct results are obtained of the calculation of transient phenomena in a synchronous machine. The more complicated structure with a larger number of damper windings has a questionable calculation stability of long-term phenomena. Numerical divergence of a more complicated structure can be eliminated only with difficulty and hitherto has not been sucessfully accomplished.

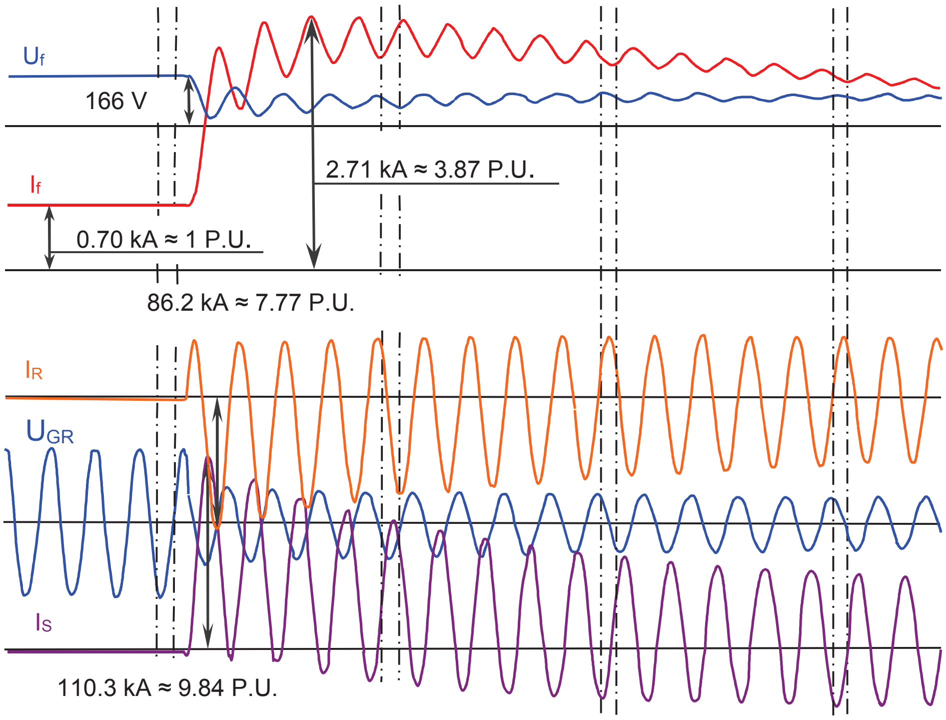


Figure 5. Real oscillogram of an exciting current (I_f) and stator windings curents (I_R, I_S) on more severe operating short circuit by speed 3,000 rpm (machine output frequency 50 Hz).

CONCLUSIONS

By the application of a simpler structure of equivalent diagrams with one damper circuit in the rotor, paradoxically more correct results are obtained of the calculation of transient phenomena in a synchronous machine meanly comparising between Fig. 4 and Fig. 5. The more complicated structure with a larger number of damper windings has a questionable calculation stability of long-term phenomena, see Fig. 3 and Fig. 5. Numerical divergence of a more complicated structure can be eliminated only with difficulty and has not been sucessfully accomplished.

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REFERENCES

Canay, M. 1980. *Equivalent Diagrams of a Synchronous Machine and Calculation of Characteristic Values with Examples*. Lausane, École polytechnique de l'Université de Lausane, 151 pp. (in German).

Dvořák, L., Ledvinka, T. & Sobotka, M. 1992. *Famulus Etc. – User Manuals of the Famulus 3.5 System.* Prague, Famulus Etc, 307 pp. (in Czech).

Hora, O. & Navrátil, S. 1976. *Controlling of Electrical Machines*. Prague, SNTL-Theoretical Engineers Library, 483 pp. (in Czech).
Hořan, M. 2015. De-Excitation Action of Synchronous Machine. In: *Elektrotechnika a informatika 2015 – Elektrotechnika, elektronika, elektroenergetika*. Pilsen, University of West Bohemia in Pilsen, pp. 59–62. ISBN: 978-80-261-0514-5. (in Czech).
Jonaitis, A. 2013. Impact of Increased Frequency Excitation System on Stability of Synchronous Generator. In: *Elektronika ir Elektrotechnika* **19**(4), 29–32.
Laible, T. 1957. *Theory of Synchronous Machine during Transients.* Moscow, Gosudarstvennoe energeticheskoe izdatelstvo, 169 pp. (in Russian).
Novák, M, Novák, J. & Chyský, J. 2012. Experimental verification of high-speed permanent magnet synchronous motor model. In: *20th International Conference on Electrical Machines*, *ICEM 2012*, 2435–2440. ISBN 978-1-4673-0143-5
Ralston, A. 1978. *Fundamentals of Numerical Mathematics*. Prague, Academia, 635 pp. (in Czech).
Vondrášek, Z. 2009. *Identification of Parameters of a Synchronous Machine*. Prague, Czech University of Life Sciences, doctoral dissertation, 91 pp. (in Czech).