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SIMULATION OF CURRENT INTERRUPTION AND POSSIBILITIES OF PROTECTION OF PHOTOVOLTAIC SOURCES

Ľudovít Hüttner — Igor Kertész — Martin Liška *

This article describes the importance of simulating the behaviour of current interruption. In the last years, computer simulation has obtained a significant position in the investigation and development of technical products and in the area of electrical devices. The results of simulation are presented of short-circuit current interruption for a miniature circuit breaker (MCB) and of interruption of the follow current in a lightning arrester with a spark-gap. The article treats also the issues of DC current interruption with switches and the behaviour of electrical devices during passage of impulse currents.

K e y w o r d s: simulation, short-circuits current, MCB, overvoltage protection, surge arrester, follow current, arcing chamber

1 INTRODUCTION

Electrical devices play an important role in the electrical energy distribution network and also in energy supply control (switching, overcurrent and surge protection, etc.). The operation of such devices must be reliable not only at rated network parameters but at failure conditions, too. The failure is often caused by short-circuit currents and overvoltages, when the magnitudes of currents and voltages can achieve multiples of their rated values. It is important to find ways how to limit the adverse effects of short-circuit current in the power grid and equipment. A specific and typical phenomenon for miniature circuit breakers (MCBs) and surge protection devices (SPDs) with a spark-gap is electrical arc which originates in fault current interruption. For extinguishing this arc, arcing chambers with deion sheets are usually used. Interruption of the follow current (up to 25 kA) on spark-gap SPDs, where ionised gases are released to the environment, can cause an unwanted ground short-circuit in the network. The growing number of photovoltaic power plants leads to a constant improvement of technology and these systems become more sensitive. One of the phenomenon which can damage equipment used in photovoltaic systems is a surge. Protection devices (SPDs, MCBs and fuses) must withstand the passage of impulse currents and interruption of follow currents. Very important is the interruption of DC currents in photovoltaic sources at about 1000 V.

2 ANALYSIS OF SHORT–CIRCUIT CURRENT LIMITING

The short-circuit current is a typical transient phenomenon in the power grid. The interruption of fault current with a high amplitude (up to 25 kA) without dangerous consequences is a task for protection devices (overcurrent, overvoltage). Analysis of short-circuit current breaking solves the time behaviour of the current in the low-voltage network. The simulation program solves the basic differential equation

$$u_s(t) = Ri + L\frac{\mathrm{d}i}{\mathrm{d}t} + U_0 \tag{1}$$

where $u_s(t) = U_m(\sin\omega t+\alpha)$ is the supply voltage, U_m is the amplitude, ω is the angular frequency, α is the initiation instant (switching angle) of the short-circuit current with respect to the foregoing zero value of the supply voltage, ϕ is the phase shift, R, L are the resistance and inductivity of the network. The solution is

$$\begin{aligned} i(t) =& \frac{U_m}{Z}\left[\sin(\omega t+\alpha-\phi) - \sin(\alpha-\phi)\exp\left(-\frac{R}{L}t\right)\right] \\ &- \frac{U_0}{R}\left[1-\exp\left(-\frac{R}{L}(t-t_1)\right)\right] \end{aligned} \tag{2}$$

with Z the impedance, t_1 and the rise time of the arc voltage maximum, while U_0 is the arc (constant) voltage. This equation describes the time behaviour of current during the interruption of the test circuit supplied with a generator [1].

The equation shows that the current vs time curve is influenced by the arc voltage (depending on the design of the extinguishing system of the particular device) and by the network parameters (R, L).

Simulation software gives the time behaviour of the limited current for a given time of arc voltage $u_0(t)$ and the value of the Joule integral JI$= \int i^2 \mathrm{d}t$ which is very important mainly from the breaking capacity and selectivity point of view. Individual parameters essential for the Joule integral and arc energy calculation (*eg*, the rise time of arc voltage, magnitude of arc voltage) can be changed in the software.

* Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Institute of Power and Applied Electrical Engineering, Ilkovičova 3, 812 19 Bratislava, Slovakia, ludovit.huttner@stuba.sk, igorkertesz@gmail.com

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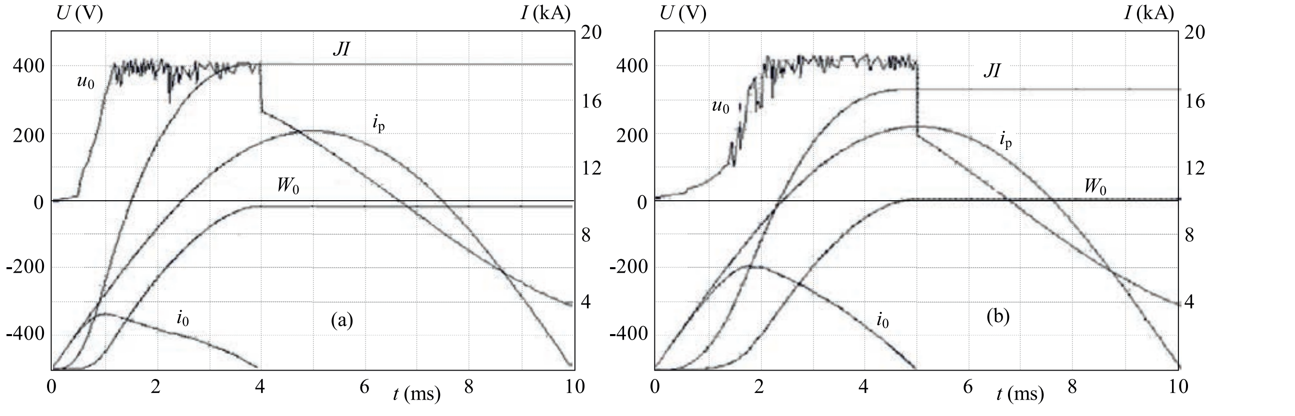

Fig. 1. Simulation with various times t_1: (a) – JI=5kA ^{2} s/d (d stands for grid division), W_0=0.5 kJ/d, (b) – JI=1 kA^2 s/d, W_0=0.25 kJ/d; Legend: u_0 arc voltage, i_p assumed current, i_0 limited current JI Joule integral, W_0 arc energy

Simulation experiments yield results displaying the dependences that would be very hard to obtain by traditional laboratory experiments.

The arc voltage can be defined either very simply, *eg*, as a step function just for very basic studies in a circuit with a capacitor battery as a short-circuit current source, or as a data file recorded from real arc voltage behaviour obtained experimentally using the test circuit with a generator.

3 CURRENT INTERRUPTION IN MCB

The arc voltage curve is determined by the characteristics of the sub-systems of MCB. The rate of rise of the arc voltage time t_1 depends on the speed of the electromagnetic release, on the properties of the mechanism and the behaviour of the arc after disconnection of the contacts until its entry into the arcing chamber. An important role in this part belongs to the aerodynamic properties of the extinguishing system. Ionized gases hamper the movement of the arc into the chamber and its division into partial arcs, Fig. 1(b). Time t_1 is extended as a result. If the air-flow of the internal environment supports the movement of the arc, time t_1 is reduced, Fig. 1(a). In the present MCB the optimum time should not be more than 1.5 ms. The speed of the electromagnetic release depends on the rated current and tripping characteristic [2]. For higher rated currents (over 63 A), C-type characteristics and all D-type characteristics MCBs the time is extended, Fig. 1(b).

For a comparable scale of the arc voltage approx. 400 V and time $t_1 = 1.1$ ms, the value of JI is 18 kA^{2}s and arc energy 2.4 kJ, see Fig. 2(a). For time t_1 approx. 2 ms, JI reaches 82 kA^{2}s and arc energy is 4.95 kJ. From the point of view of thermal effects such values are undesirable for the device and the distribution network as well.

The analysis also showed that the arc voltage below U_m extended the time of current flow and increased the values of JI and arc energy.

SADYS simulation software [3] was used for the initial considerations of how to solve this problem.

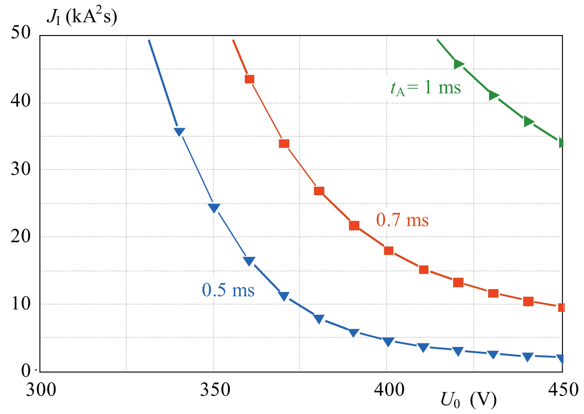

Fig. 2. Joule integral for different rise times

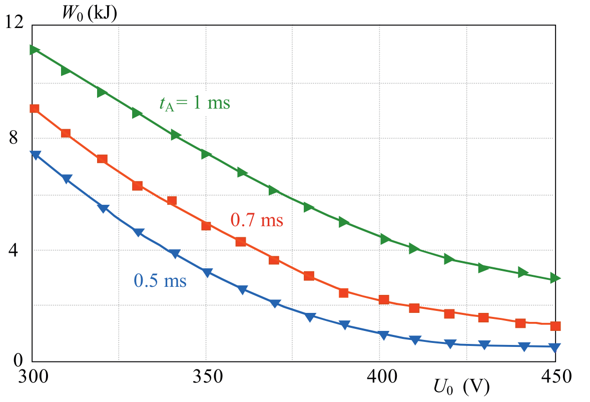

Fig. 3. Arc eneergy for different rise times

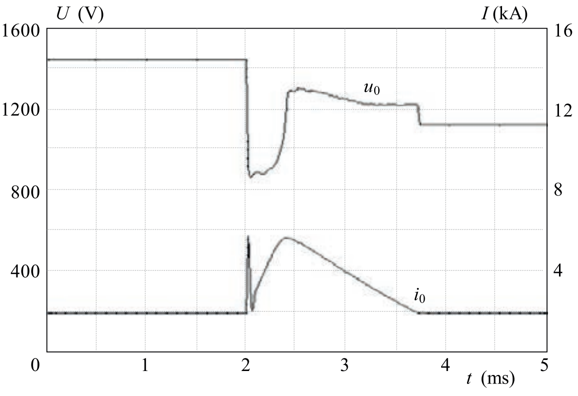

Fig. 4. Follow current limitation at capacitor test circuit

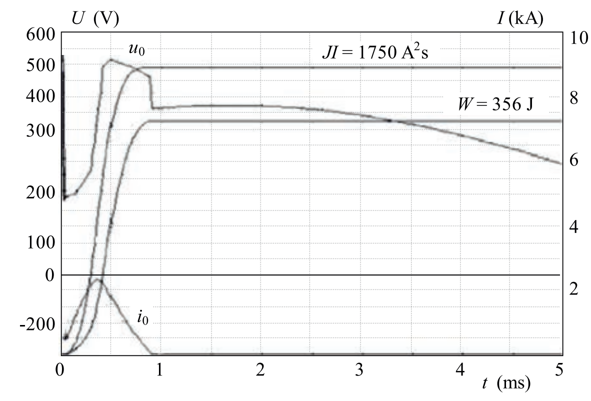

Fig. 5. Simulation of arc extinction at 255 V RMS

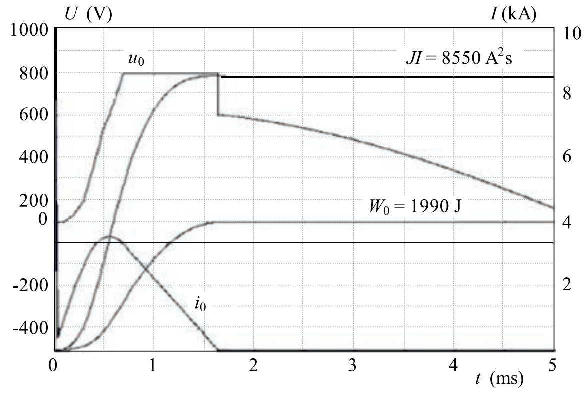

Fig. 6. Simulation of arc extinction at 440 V RMS

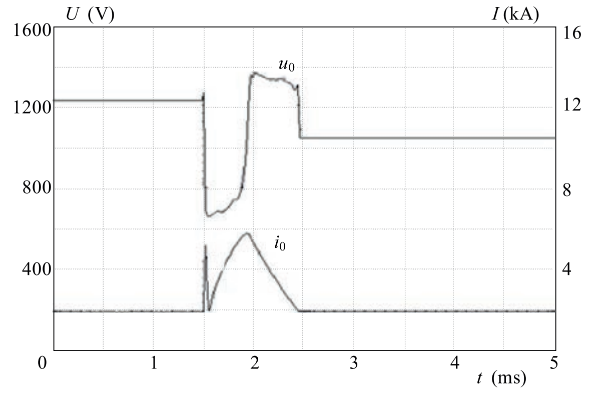

Fig. 7. Follow current limitation at capacitor test circuit

4 CURRENT INTERRUPTION IN LIGHTNING ARRESTER

Lightning current arresters used in low-voltage systems are rated for RMS voltage (U_N) of at least 255 V and follow current (I_p) up to 25 kA. The follow currents that occur following the discharge of impulse currents must be highly limited to prevent tripping of overcurrent protective devices. The let-through energy (Joule integral) of the limited follow currents should be below the melting integral of a fuse with a nominal current of 100 A (JI at 27 kA^{2}s). The simulation was based on experience with the interruption of short-circuit currents by means of circuit breakers with deion chambers [4].

The time characteristic of the follow current also depends on the instantaneous value of the voltage at which the impulse current occurs. This instantaneous value is characterised by the switching angle α. In the simulation, the switching angles α were varied from 30 to 150 deg. The maximum current steepness lies between switching angles 30 and 90 deg. The rise times t_A of the arc voltages are selected between 0.3 ms and 1 ms and the maximum value of the arc voltage between 300 V to 450 V for a nominal voltage of 255 V RMS.

From a practical point of view, the arc needs time t_A of about 0.5 ms to 0.7 ms for running from the place of arc formation into the arcing chamber and for arc splitting. In the case of long rise times, *eg* 1 ms, the desired let-through energy is significantly exceeded even for an arc voltage of 400 V

Figure 2 and 3 shows the dependence of the Joule integral and the arc energy on the arc voltage U_0 for different rise times t_A for a switching angle $\alpha = 60$ deg. It can be seen that voltages of about 380 V are required for a rise time of about 0.7 ms to safely achieve the desired Joule integral of 27 kA^{2}s.

However, if voltage U_0 is raised to above 400 V, the Joule integral is only slightly reduced. A further reduction of the rise time t_A to 0.5 ms significantly minimizes the let-through energy.

Figure 4 shows the current and voltage characteristics of the sample in a test circuit with a capacitor source. The rise time t_1 could be reduced to 0.5 ms on average due to the optimized internal gas circulation and the arc travel path.

Fig. 5 shows the simulation with a corresponding rise time t_1 of such an arrangement. The experiments with the arrester sample coincide well with the results of the simulation at a nominal voltage U_N of 255 V RMS and a follow current I_p of 25 kA $(\cos\phi = 0.25)$.

The simulation was therefore carried out with a nominal voltage of 440 V RMS. According to the simulation, an arc voltage of 800 V to 900 V must be achieved in 0.6

to 0.8 ms to ensure the same Joule integral of 27 kA^{2}s. Figure 6 shows a simulation with a rise time of 0.7 ms and an arc voltage of 800 V. For voltage 440 V RMS it is necessary to increase the number of deion sheets for the higher value of arc voltage (800 to 900 V).

The current and voltage characteristics in Fig. 7 show a measurement with the help of an adequate arrester sample in a test circuit with the capacitor source [5].

With the growth of the arc voltage, the value of the arc energy increases and overheating of the sheets in the arcing chamber exceeds the limited value. Therefore it is necessary to increase the thermal capacity of the arcing chamber. This will be achieved by increasing the width of the metal sheets but such a solution leads to an increase of the width of the module dimension of 1.5 times. For higher voltages a special arcing chamber was designed (Fig. 8). For optimization of gas flow, division of the arc and its stability the chamber was covered by plates for the arc entrance and between-the-sheets ventilation. Released gases are separately led into channels that are insulated against each other and recirculated, via recesses on the electrodes, into the arc travel path again. The total number of sheets is 19. For higher voltages up to 1000 V (for example in photovoltaic equipments) two chambers or a serial connection of two arresters is used.

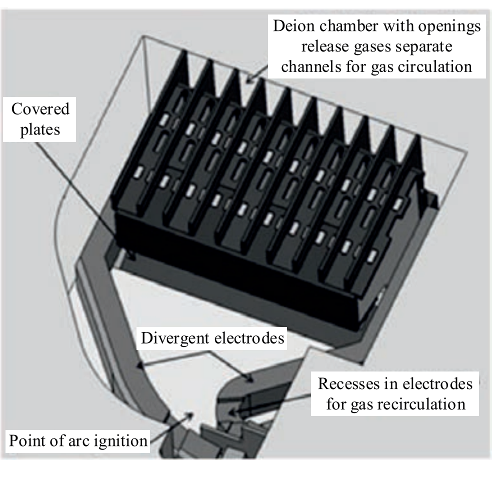

Fig. 8. Front view of the spark gap with optimized deion chamber and 19 sheets

5 PROTECTION OF PHOTOVOLTAIC SYSTEMS

Renewable energy sources are an important contribution to the protection of environment. They are significantly different from other sources of energy and obtain electric and thermal energy [6, 7]. The overvoltage and overcurrent protections are important arrangements for reliable and faultless service of energy devices. From this point of view the renewable sources of energy are very significant, especially the photovoltaic and wind power stations [8, 9, 11, 12].

Photovoltaic systems are installed in external ground spaces or on the building roofs. The photovoltaic panel requires, without the basic element, the voltage changer, which changes the DC voltage to AC and supplies the electric grid with the produced energy. It is also necessary to use surge arresters, switches and circuit breakers [3]. A general schematic of a photovoltaic source cooperating with the electric grid is shown below, Fig. 9, [8]. Single strings are connected in series and parallel to reach higher values of voltage and current. In such a case the strings must be protected against reverse currents with the possibility of disconnection. The usage of surge arresters is important for both sides DC and AC behind the voltage converter. The manufacturers offer surge arresters for DC voltage from 150 V up to 1200 V. The surge arresters on DC side are solved with a metal oxide varistor as a basic element. The main reason for this solution is the problem with the spark gap system and the breaking of the DC current after overvoltage elimination. The surge arresters on AC side represent usual types for AC grids (spark gap, varistor). There is also necessary to solve the overvoltage protection for signal and communication circuits.

The switching and circuit breaker devices must be able to secure reliable breaking of the DC current. This request requires a specific solution because the disconnection of higher DC voltages (1000 V) is substantially difficult. The reason is the shape of the current chart at the switching off mode because the photovoltaic source behaviour is not the same as that of a DC source [10]. The curve of the classic source current is linearly descending but the shape of the photovoltaic source current is constant for almost the whole time of switching off. The devices must be able to create the high arc voltage because the shapes of current at the switching off mode are dependent on the size of the device contact voltage.

The manufacturers reach a high arc voltage by breaking the current in multiply poles, using two arc chutes on a pole, fast switching off speed of contacts, adequate distance between contacts in off mode, using permanent magnets, *etc*, [13].

6 BEHAVIOUR OF ELECTRICAL DEVICES DURING PASSAGE OF IMPULSE CURRENT

The system for overvoltage protection consists of electrical devices such as modular circuit breakers and surge protective devices. These devices must withstand besides short circuit currents also impulse currents which flow via them during operation of the system for protection against surges. Surge protective devices (SPD) are default constructed for these high currents. Surge protection devices used in photovoltaic systems are based on metal-oxide varistor technology. The current I_i which a SPD can withstand depends on the dimensions of the varistor [14,15].

A different situation arises during the passage of impulse current through the fuse or modular circuit breaker

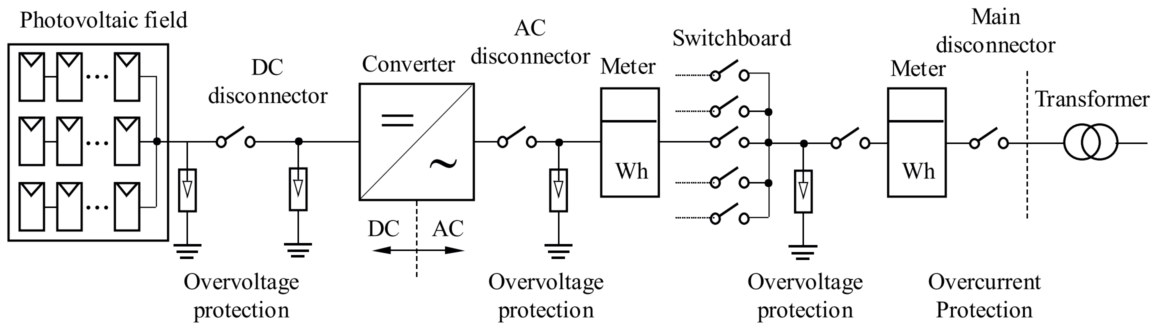

Fig. 9. Circuit diagram of photovoltaic source

(MCB). These devices are constructed to brake short-circuit currents. The impulse current which flows through them can cause their undesirable tripping. This is mainly due to electrodynamic forces that are induced by the passing current or huge energy that flows through the device. In the fuse the impulse current causes interruption of the conductive track and in some cases this can cause its explosion. In Fig.10 one can see the values of fuse impulse current I_i withstand capability. Current values in the red zone cause explosion and currents in the yellow zone cause melt down of the fusible element.

Passing of impulse current through MCB is accompanied by the formation of electrodynamic forces between contacts that are separate/disconnected and an electric arc is created between them. The electric arc has devastating effects on the contact and also on the arcing system. The arc causes erosion and welding. To prevent this effect, the circuit breaker should have a proper construction of the current track and especially of the contact system.

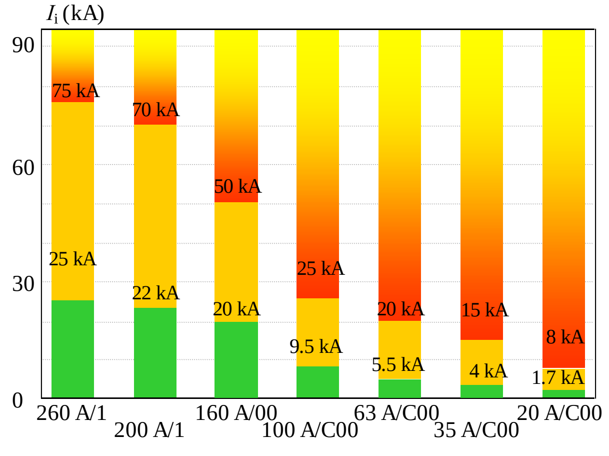

Fig. 10. Impulse current values

7 SUMMARY

The use of simulation software allows solving theoretical problems, optimization of device design and support of development. The presented analysis shows the influence of various factors on current limiting. An important role belongs to the arc voltage curve the magnitude of the arc voltage and the rise time. The simulation was made for MCBs with short-circuit currents 6 kA and for SPDs with follow current 25 kA interruption and line voltages 255 and 440 RMS V. The simulation allows saving construction and sample preparation costs. It is possible to avoid damage of photovoltaic systems by appropriate selection of fusing, switching and protective devices.

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Ľudovít Hüttner (Doc, Ing, PhD), born in Bratislava, Slovakia, in 1946, graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, in 1969. He gained the PhD degree in electrical machines and devices in 1988. At present he is Associate Professor of the Institute of Electrical Power Engineering and Applied Electrical Engineering. The main field of his research and teaching activities are switching and protective low-voltage apparatus and the use of computers in education.

Igor Kertész (Ing) was born in Šaľa, Slovakia, in 1986. He finished engineering study at the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, in 2010. At present he is an external PhD student and his field of research are overvoltage protection systems for low voltage wiring. At present he works as a technical support for a company producing surge protection devices. SALTEK s.r.o.

Martin Liška (Ing, PhD) was born in Trenčín in 1984. He graduated from the Faculty of Electrical Engineering and Information Technology at Slovak University of Technology in Bratislava in 2009 and gained his PhD title in 2013. From October 2011 to August 2013 he worked as a researcher at the Department of Electrical Engineering at the University of Bologna. At present he is a researcher at the Institute of Power and Applied Electrical Engineering, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava. His research activities are in the area of smart metering and smart grid systems, modelling and simulation of power systems and renewable energy sources. He also cooperates with transmission and distribution system operators on many scientific projects in the area of power engineering.