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Analysis and modelling of failure states in electric vehicle charging infrastructure

***Abstract**: This paper presents modeling methodology and simulation results of failure states and transients in electric vehicle (EV) charging infrastructure for investigation a potentially dangerous phenomenon that might appear during a typical operation. Transients can occur during normal work and during faults in EV Chargers. The trend in the electric cars suggests that in the future ultra-fast chargers would be the dominant one, therefore the focus is put-on high-power chargers (> 50 kW). During failure states of EV chargers' transients occurred in network can impact on other chargers or can propagate along power lines and affect other electrical power equipment. Studies and simulations have been carried out using EMTP-ATP software package on the test model circuit especially prepared for this paper purpose.*

***Streszczenie.** W pracy przedstawiono metodologię modelowania i wyniki symulacji stanów awaryjnych oraz stanów nieustalonych w infrastrukturze ładowania pojazdów elektrycznych (EV) w celu zbadania potencjalnie niebezpiecznego zjawiska, które może wystąpić podczas eksploatacji. Trend rozwoju pojazdów elektrycznych sugeruje, że w przyszłości będą dominowały ultraszybkie ładowarki, dlatego w artykule nacisk położony jest na analizę ładowarek dużej mocy (> 50 kW). Podczas awarii ładowarki stany przejściowe występujące w sieci, mogą oddziaływać na inne ładowarki lub mogą rozchodzić się wzdłuż linii zasilania i wpływać na inne urządzenia elektryczne. Badania i symulacje przeprowadzono przy użyciu pakietu oprogramowania EMTP-ATP w modelowym układzie stacji ładowarek. (**Analiza i modelowanie stanów awaryjnych w infrastrukturze stacji ładowania pojazdów elektrycznych**).*

Keywords: Electric vehicle (EV) charging, transients, EMTP-ATP, modelling, simulation
Słowa kluczowe: pojazdy elektryczne, ładowanie, przepięcia, EMTP-ATP, symulacje

Introduction

Electric vehicles (EV) are now the most promising and attractive alternative to combustion engine cars. This trend is caused by very fast evolving of this technology. Multiple car companies are providing in theirs' offer electric models. Standardization and growing infrastructure are fueling demand – EV technology is becoming popular and its price is falling. Thanks to modern technology the electric motors are comparable or even, in some cases, better than gasoline engines. The main weakness of EV is battery. There are big, heavy, and probably most expensive in production and usage part of vehicle. Typical Lithium-Ion battery is 25÷40 kWh, this type of battery is most popular due to its use in laptops and consumer electronics, the amount of electric power allows driver to travel 100-200 km on the single charge [1], [2]. That gives 50÷100 charging in a year, or one-two in a week in a city [1], [3]. Charging of electrical vehicles can be made in electrical vehicle charging stations, due to its power several types can be distinguished [1], [4] [5]. Charging station infrastructure should be dense enough to satisfy the demand for charging EV while the battery is discharged. Growth of the EV charging stations grid can affect on the work of power system due to local higher demand for electrical power, bidirectional power flow in case of storage of electrical power and issues related to malfunction of car charger [1].

Many researches are done in areas showing the impact of EV charging loads on the distribution network in cases like voltage stability [6–10] and power quality [11–13],

The purpose of this paper is to present an approach (methodology) for simulation of transients in Electric Vehicle charging stations and to investigate a potentially dangerous transient that might appear during a typical operation and transition between states. Transients can occur during normal work and during faults in EV Chargers [14–16]. The trend in electrical cars research area suggests that in the future ultra-fast chargers would be the dominant one, therefore the main focus is put-on high-power chargers (> 50 kW) [1], [4],[e17].

The paper presents simulation results of overvoltages occurring during simulated fault or emergency switching and short circuit currents flowing in DC circuit. Overvoltages were measured at selected points of EV charging station.

Charger topology

This section provides issues related to typical EV charging infrastructure (Fig. 1) specially focused on fast DC chargers and its influence on the grid. This technology is most likely used in commercial public charging stations. Today charger manufacturers have many different charging [5], [17–19] and infrastructure standards. There are many different solutions depending on charger's destiny work plan. However, there are some elements similar in every solution. Figure 1 shows typical charger topology. Fast DC charger consists of two main parts: AC/DC converter and DC/DC converter, the buck-boost converter. Each Charger station should be isolated form AC network. This can be achieved by a typical isolation transformer before AC/DC converter or as HF transformer (Fig. 3) [1], [17]. Depending on voltage level and capability to work in reverse power flow (Smart grid application – [20]), these devices are made using some different technologies [1], [4].

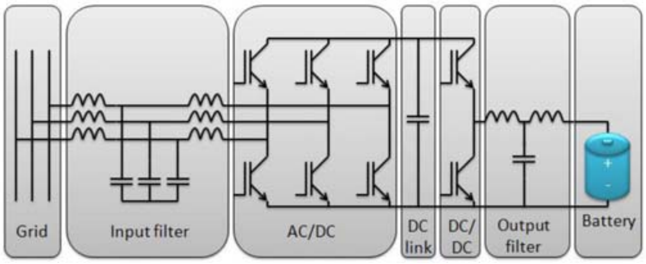

Fig.1. Typical charger topology [21]

Charging station topology

Chargers can be connected into charging stations [1], [4]. Two most common topologies are used. First configuration is simple connection of multiple chargers by single AC line to the step-down transformer [21]. This situation is shown on picture Fig. 2a. In second configuration charger topology is divided in two parts: Base station and charging points Fig. 2b [21].

Modeling of Electric Vehicle Fast Charger

Direct-current (DC) charging is a method of charging EV that provides rapid energy transfer from the network to the vehicle batteries. This method of charging allows to provide a significantly higher current to the vehicle compared to a smaller rated current in AC systems. Vehicles which can accept high-current DC charge and the DC supply equipment that provides it are described as “fast charging”. [8], [17–22].

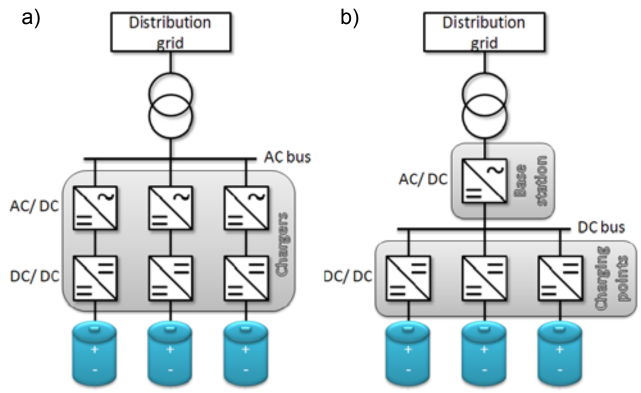

Fig.2. Charging station topology: (a) multiple chargers, (b) base station and charging points [21]

DC charging and AC charging vary by the location at which AC current is converted to DC current. For typical DC charging, the current is converted at the off-board charger, which is separated from the vehicle. For AC charging, the current is converted inside the vehicle, by means of an on-board charger. DC charger topology and its impact on the electrical network is widely analysed [17–19], [23], [24].

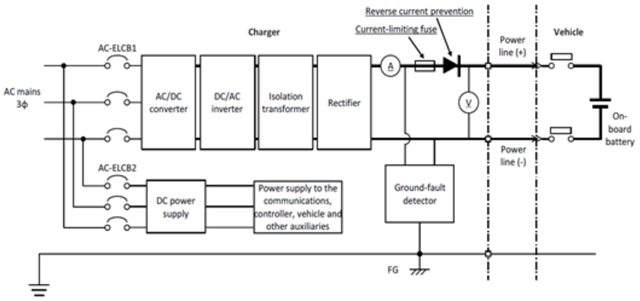

Fig.3. Typical configuration of EV Fast Charger [17]

Typical circuit configuration of EV Fast Charger is defined in IEEE Standard [17] (Fig. 3). It can be seen that power supply is usually 3-phase low voltage. Branched circuits should have circuit breakers (AC-ELCB1 and AC-ELCB2, Fig. 3) that protect from short-circuit or overcurrent and earth fault. Main assumptions are that if a fault occurs on the main power supply circuit, the control power supply circuit should remain active to maintain the control/communications function with the vehicle, as well as the function for protecting and monitoring the charger itself.

Proper work of EV charger is determined by algorithms implemented in logic controlling the power electronic switches. Control of Voltage at DC output and current in AC part of network was realized by voltage-oriented control of active rectifier [4] with additional phase locked loop algorithm [25]. Simulated control block scheme is presented in Fig. 4. This single line diagram presents AC/DC converter with DC link and control algorithm scheme where PLL – is a phase locked loop block, ABC-DQ – transformation from phase voltages to DQ space, PI – proportional-integral controller, U_{ABC} – 3 phase measured feeding voltage, U_{DC} – voltage at DC link, V_{ref} – Reference voltage, i_{ABC} – current measured at AC side, I_d,I_q – current components in DQ space, U_d,U_q – voltage components in DQ space, I_{qref} – reference current in Q axis, φ – phase shift, f_{sw} – switching frequency

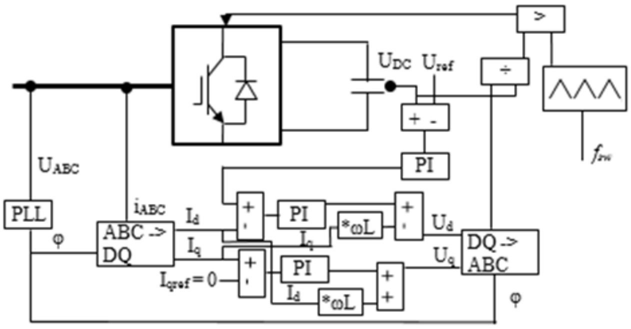

Fig.4. Simulated voltage control algorithm,

EMTP-ATP modeling details

Analysis presented in this paper based on computer simulations results. Every simulation should be performed with adequate digital models of every element in analyzed circuit. Proper selection of model type should be made due to current state-of-the-art and for fulfilling the requirement of imitation of physical properties of real object. In performed simulations charging station system and its control algorithms for single charger were simulated with additional power objects in model system. Studies and simulations have been carried out using EMTP-ATP software. This section presents description of models used in simulation in this environment.

Elements used in the simulations

Overhead line connecting the power system to medium voltage transformer was modelled as a part of power system, with LCC Overhead line Bergeron model [26], with horizontal configuration of conductor alignment. Length of the line was set to 5 km.

Power transformer in MV/LV substation was modeled as hybrid transformer model, with linear core and with capacitive couplings between phases. This type of power transformer model allows to model overvoltages transferred to other coupled windings. The parameters 15.75/0.4 kV and 2.5 MVA were selected [27]. Neutral point at LV side was grounded through resistor R = 0.01 Ω. The 50 Hz isolation transformer placed before AC/DC converter was also modeled as hybrid model with 0.4/0.4 kV and 400 kVA transformer parameters [27]. Neutral points at primary and secondary sides were not grounded.

LV cable lines were modelled for suppling electrical energy to EV charging stations form power transformer switchgear. LCC Single Core Cable model with JMarti procedure [26] was used. The cable YKY, 0.6/1kV and 240 mm was used in simulations [28]. Length of cables was variable.

Main AC LV Switch is modelled as three phases switch with chopping current set to 10 A.

IGBT switch was modelled with usage of ideal TACS switch and parallel ideal diode. Additionally, *RC* snubber was connected parallel to switch to prevent numerical oscillations, *RC* Snubber parameters were set to R = 250 Ω and C = 0.25 μF, additionally R elements with resistance value 1 mΩ were placed to prevent numerical problems [29]. Control algorithm of voltage-oriented control was simulated in model’s language.

Vacuum circuit breaker (Fig. 5) at MV side of distribution transformer was simulated. Main assumption of this model was to provide restrikes during switching-off operations, which were source for overvoltages propagating along the lines [30].

Slope of breakdown voltage curve was set to 1 kV/ms (Fig. 5), chopping current at which arc was distinguished was set to 3 A. Additionally open contacts was simulated as *RLC* branch with *R* = 50 Ω, *L* = 1.6 nH and *C* = 200 pF. Algorithm in this model closes contacts (arc is appearing) when voltage difference between contacts exceed actual dielectric withstand, resistance change its value from 10^{16} Ω to 0.5 Ω which was set as an arc resistance, this control was implemented in MODELS [31].

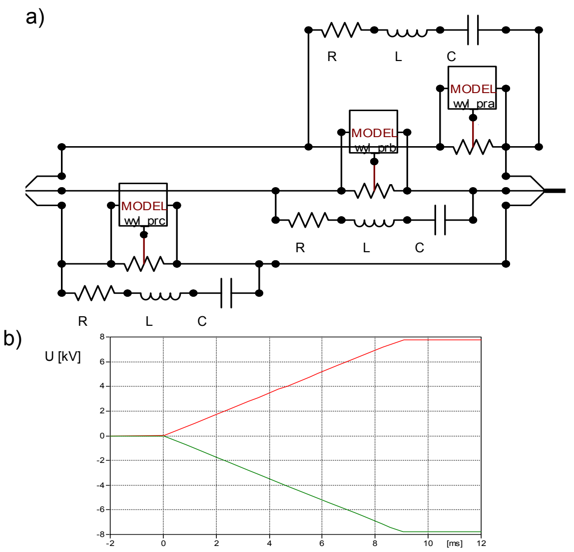

Fig.5. Scheme of 3-phase VCB model and simulated electrical breakdown voltage curve between contacts [30]

EMTP-ATP circuit

EMTP-ATP model of single charger is presented in Fig. 6, this charger consists of active bridge with voltage-oriented control algorithm. Voltage at DC output was set to 700 V, load is applied as resistor with controlled switch. Main AC circuit breaker is placed after isolation transformer. While AC switch is switched off the control algorithm is inactive.

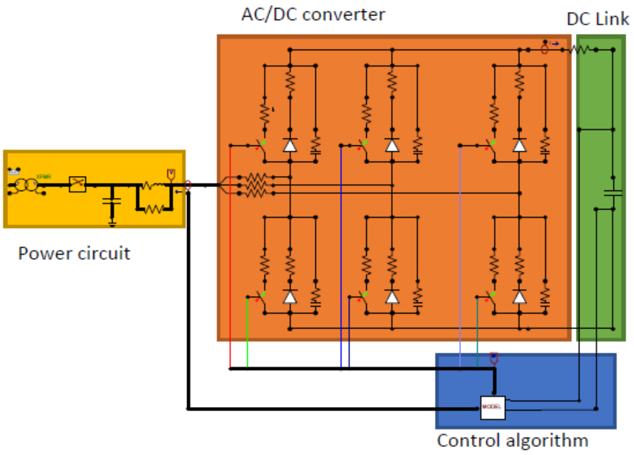

Fig.6. Single EV charger model

Model of the full charging station is shown in Fig. 7. This model consists of 3 single EV chargers (Fig. 6), connected to MV power transformer with LV cables with lengths: 20 m (Charger no. 1), 25 m (Charger no. 3) and 30 m (Charger no. 3). Star point of LV side of MV Transformer is grounded. MV transformer is connected with power system through 5 km overhead line. Every analyzed case assumed no-overvoltage and overcurrent protection in circuits.

Simulations and study cases

Scope of simulation work covers 3 cases:

- CASE 1: Emergency switch-off of EV chargers during its work – analysis of voltage transient impact on work of non-failure EV chargers,
- CASE 2: Emergency shutdown of MV transformer feeding whole analyzed station. Analysis of restrikes process during turning off VCB,
- CASE 3: Short circuit at cable connecting the EV charges to EV vehicle, analysis of overcurrent flow in DC and AC part of EV charger

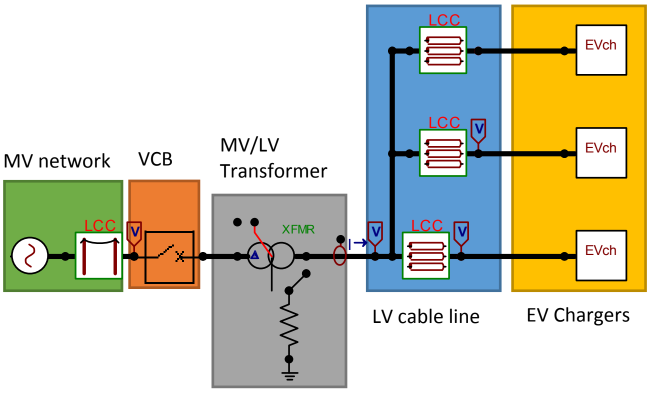

Fig.7. EV charging station model consisted of 3 charges in topology from fig. 2a

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Case 1: Emergency switch-off of EV chargers during its work

This section presents results of analysis a potentially dangerous transient that might appear during emergency switching and its influence on other chargers. Analyzed case cover failure state, emergency switching of two chargers (Charger no. 2 and Charger no. 3), at time 35 ms, (maximum current) chopping current of emergency switch model was set to 100 A, Charger no. 1 works normally. Analyses of transients influencing on Charger no. 1 and MV transformer were simulated. Results are presented in Fig. 8÷11.

Simulation results show that emergency switching of charger does not influence on voltage at DC link of normal operating charger (Charger no. 1, Fig. 8). Voltage measured at charger which is shutdown doesn't exceed nominal values (fig. 9). Overvoltages related with chopping current (Fig. 10 and Fig. 11) are observed and propagate along power lines, acting on other power equipment insulation system. The maximal overvoltages at selected points in the circuit are presented in Table 1. In the worst-case overvoltage level of k_p = 12.95 p.u. was reached (charger 2 phase b at the secondary side of isolation transformer).

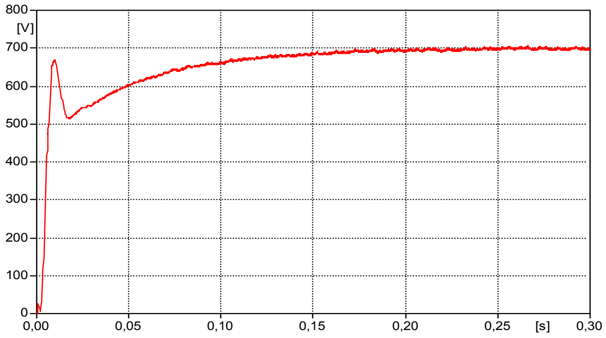

Fig.8. Voltage at DC output during normal work, (Charger no.1)

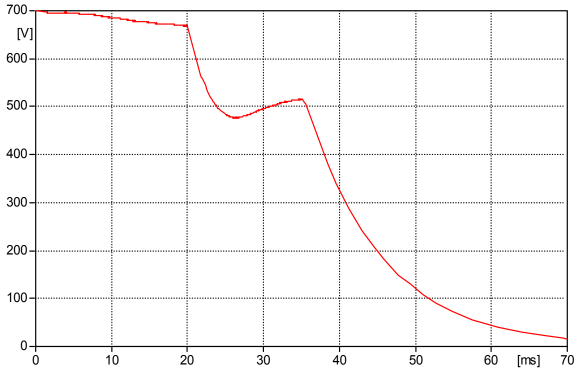

Fig.9. Voltage at DC output, load on t = 20 ms, emergency shutdown at t = 35 ms, I_{mar} = 100 A, (Charger no. 2)

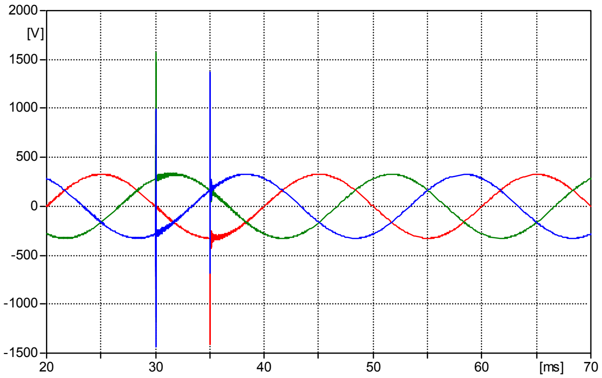

Fig.10. Voltage at charger terminals, AC side, Charger no. 1

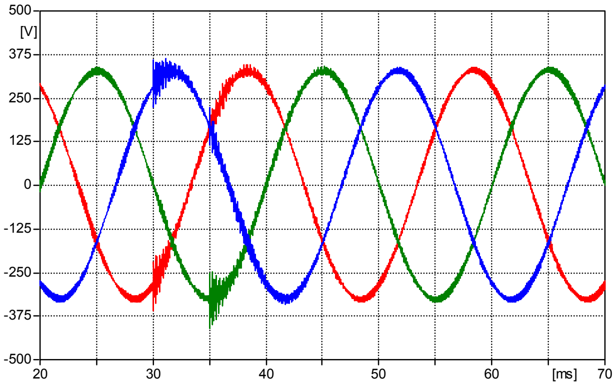

Fig.11. Voltage at EV charger at secondary side of isolation transformer, Charger no. 1

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Case 2: Analysis of VCB switching impact on overvoltage in the model

This section presents results of analysis failure state switching-off circuit breaker (VCB) at MV side of distribution transformer, while EV chargers are at normal operation. Analysis covered overvoltages appearing at distribution transformer MV terminals and overvoltages transferred to LV side which are influencing on EV charger system. Results are presented in Fig. 12 and Fig. 13.

Simulation results show that emergency switching of VCB located at MV side of power transformer provides transient overvoltages caused by restrikes between circuit breaker contacts. Overvoltages are influencing on feeding distribution transformer terminals (Fig. 12) and are transferring in to LV side reaching isolation transformers of EV chargers (Fig. 13). In the worst case restrikes are source for overvoltages which can reach at MV side up to 52 kV (overvoltages factor k_p = 4.23 p.u.) transferred overvoltages at EV chargers reach level of k_p = -6.06 p.u..

Summary results of maximal overvoltages at selected points in circuit are presented in Table 1.

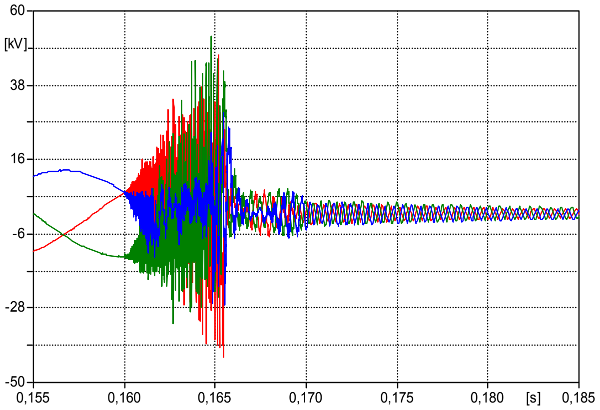

Fig.12. Voltage after VCB at MV transformer terminals, time at which contacts starts to move t = 0.116 s

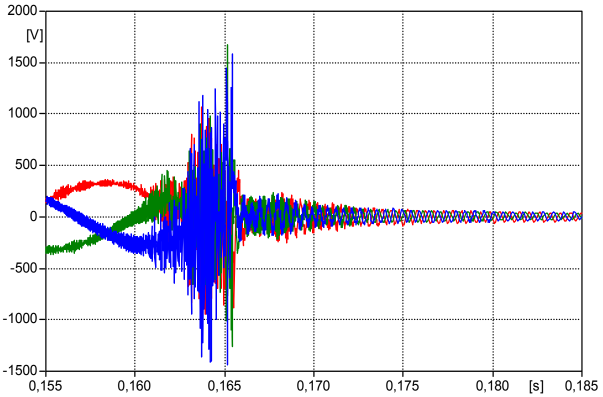

Fig.13. Voltage after isolation transformer (Charger no. 1), time at which contacts starts to move t = 0.116 s

Case 3: Analysis of short-circuti at connector cable

Third case refers to emergency state which can occur while short-circuit in the connector cable between electrical vehicle and charger post. Current flowing in DC and AC part of EV charger is presented in Fig. 14 and Fig. 15, additionally overvoltages at primary side of isolation transformer were measured (Fig. 16). Short circuit was simulated as a transition to small resistance load in time of 0.4 s.

To simplify the simulation and take in to the consideration the worst-case scenario all power electronics switches were simulated as an ideal diode without control algorithms (PE switches assumed closed).

Analysis of the results shows that during short circuit at connector cable high DC current starts to flow, the maximum overcurrent for this analyzed case is up to 4.5 kA (Fig. 15) this current transmits in to AC side and cause current flow equal to 4.9 kA.

Table 1. Simulation results of the maximal overvoltages at selected points of model circuit (Fig. 7 and Fig. 8)

	LV side of MV transformer (Fig. 7)			At the EV charger terminals (Fig. 7)			Secondary side of isolation transformer (Fig. 8)		
point	Phase A [V]	Phase B [V]	Phase C [V]	Charger 1 [V]	Charger 2 [V]	Charger 3 [V]	Charger 1 [V]	Charger 2 [V]	Charger 3 [V]
Case 1	1571	1507	-1461	1575	-2701	-2812	-410	4202	3735
Case 2	1070	1321	-891	-1320	-1384	-1385	1669	-1650	-1965

Elimination of short circuit at DC side by usage of DC switch can be problematic due to physical phenomena related to DC high current switching, usage of fuse in DC circuit can protect equipment from overcurrent, additionally protection of the circuit can be made by AC switches or implementation of proper control algorithms despite its disadvantages. Overvoltages measured in this case reach up to 1.2 kV (Fig. 16).

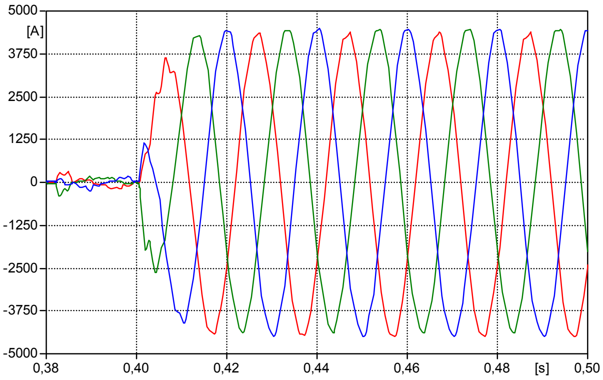

Fig.14. Current flow at AC side in isolation transformer winding while short circuit at connector cable

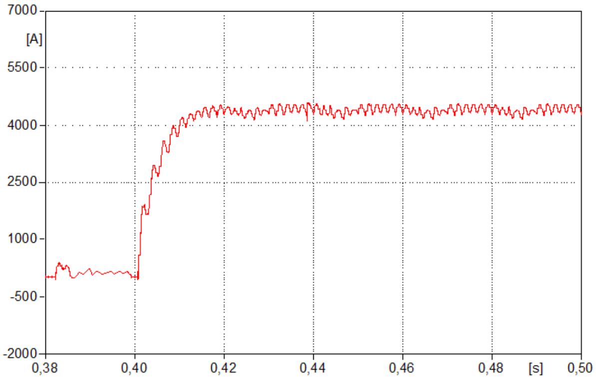

Fig.15. Short circuit current in connector cable

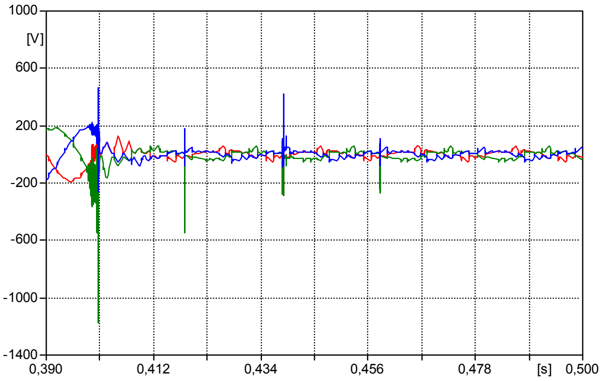

Fig.16. Overvoltages at secondary side of isolation transformer

Summary and conclusions

Analysis of fault states especially emergency shutdown of EV charger by its main AC switch shows strong influence on voltages and currents in LV network of whole charging station. Voltage transients occurring at EV charger propagates along cable lines and reach other EV chargers and distribution transformer. Overvoltage appearing in EV charger results from energy oscillations between DC output, smoothing inductance and input filtering capacitance. These transients pass isolation transformer with damped maximal value. Overvoltages appearing at HV side of distribution transformer have different shape than transients at LV side. Operation of VCB provides restrikes during opening process, this overvoltages are transferring on LV side and propagate along cable lines reaching EV chargers. Short circuit at cable connector between charge post and electrical vehicle leads to problematic high DC current in DC circuit of EV charger.

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