

## The Power Load Model for Electric Vehicle Charging Modelling and its Utilisation for Voltage Level Studies and Cables Ampacity in Distribution Grid

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When electrical energy is drawn by electric vehicles from charging stations at charging process the voltage drops and increased current loading of cable lines in distribution grid occur. Inasmuch the electrical grid is insufficiently dimensioned or at large amount electric vehicles concurrently charges without controlled charging system, the voltages could decrease under desired level in grid points. This leads to the deterioration of voltage quality in given grid. The higher cables current loading leads to active power losses increase and decrease their service life. The paper describes the utilisation of modelling the electric vehicles when charging by power load model in physical diagram implemented into alternative simulation software. The created charging station load model is used for solving of voltage studies in distribution grid and for the analysis of cable lines ampacity. The grid contains a small number of points and low penetration of charging stations. Voltage levels are solved when random operation of charging stations during the working day without controlled system. For other loads, the typified daily loads diagrams of households are used.

**Keywords:** Electric Vehicle Charging, Electric Vehicle Charging Modelling, Voltage Level, Cables Ampacity, Typified Daily Load Diagram

### 1 Introduction

When electric vehicle (EV) charging from public electric vehicle charging stations (EVCSs) the electric distribution grid is significantly affected. Consumed currents reach level of several tens of amperes, leading to influence the grid operation. The voltage deviations occur especially which can reach an undesirable level leading to deterioration the voltage quality parameters [1-10]. The voltage unbalance arises in non-symmetrically loaded grids and also during the unbalanced charging process of EVs [1,3,7]. At significant current or active power grid loading the level of active power losses also increases [1,2,5-8], consequently leading to the decreasing of electrical devices service life [1,2,5,7]. The most affected devices are transformers and cable lines. Ampacity of cables is also influenced by increased active power loading when EV charging and is limited mainly in poorly dimensioned grids.

Authors in [2] deal with the influences of EV connection to the electrical grid in 13-nodes distribution grid of small area size at various penetrations of chosen EVs and time of their connection to the EVCSs. They solve mainly voltage levels and active power demands. Voltage levels in grid nodes solve also authors in radial distribution grid with 12 loads in [6]. Analogical issue solve authors for the larger distribution grid

containing several radial lines, where each contains approximately 100 loads in [3], for the 33-nodes IEEE grid in [5], and for the large area city distribution grid in [4]. Authors in [2] deal with the active power demand which directly corresponds to the active power losses level in grid. In a paper [5], authors solve increased active power demand caused by installed given types and number of EVCSs, active power losses and economic losses. Total energy consumption and total losses are solved for radial distribution grid by authors in [6]. Active power losses at uncoordinated and coordinated charging process solve authors in [8]. An impact of high current loading of cables on cables ampacity at EV charging has been solved by authors in [11,12]. The same problem is solved by authors in [13] with respecting the influence of additional losses caused by harmonics.

It is clear from all mentioned studies that when EV charging, the significant voltage drops arise, mainly in poorly dimensioned distribution grids or their parts with strong current or active power loading. An influence on voltage deviations has number of charged EVs, location of EVCSs in network, desired level of charging power given by EVs and types of charging processes, charging times given by battery states and desired levels for battery states after charging. When

applying the controlled charging process or EVs charging in night times, the significant loading could be limited and therefore reduced the voltage drops.

Currently, the effort is to charge the EV batteries in the shortest possible time and in accordance to their capacities at maximum power. New EVs with high battery capacities have been charged by power in tens kW during a short time within one hour. This corresponds to the EVCSs placement within distribution grid, where sufficient active power level is available and the grid is well dimensioned. Therefore, the usage of one-phase households long lasting charging or charging by low level power is not preferred nowadays and in the future. This leads to usage the modelling of EV charging processes predominantly as loads connected to the distribution grid only for high consumed powers and charging from public charging stations.

## 2 Modelling of EV charging

Many authors have dealt with the influence of EV charging processes on the distribution grids, mainly with the voltage deviations. They have used for the voltage studies especially commercial softwares as Neplan [2,6] DlgSILENT [4] or MATLAB-Simulink [14-16].

On the real measured data base, it was found out that the consumed active power by charging station (CS) changes not only according to the voltage, but also according to battery state of charge (SOC). It was determined that for the EV charging modelling is the most advantageous to use a model containing impedance, current and power part, i. e. ZIP model [17,18], see equation (1). The problem of usage the ZIP model is its non-universal. For any type of EV and charging process, the parameters in ZIP model take different values. This also applies to the charging state, when for controlled current charging (CCC) or controlled voltage charging (CVC) coefficients and parameters levels are also various [17,19,20]. Therefore, no one universal ZIP model is possible to use for all EVCSs or types of EVs and EVs charging states.

$$\frac{P}{P_n} = a_1 + a_2 \cdot \left(\frac{V}{V_n}\right)^1 + a_3 \cdot \left(\frac{V}{V_n}\right)^2, \quad (1)$$

Where:

$a_1, a_2, a_3$ ...Constants for power, kurent and impedance part [-],

$P_n$ ...Nominal consumed active power [W],

$P$ ...Actual consumed active power [W],

$V_n$ ...Nominal rms voltage [V],

$V$ ...Actual rms voltage [V].

However, mathematical ZIP load model used by authors is not suitable for modelling by a physical diagram when EVCS has to be defined simply at charging

for any type of charging and also the charging process. In this paper, authors deal with the load modelling by using a physical diagram, which is based on the real behaviour of EVCS placed in strongly and generally loaded distribution grid. Therefore, the authors' created power load model should closely correspond to the real behaviour of EVCS at voltage changes. In this case, the load model should respect the battery SOC, battery management system operation and also working of power electronic devices inside charger. Simultaneously, it is also verified in the paper that active power load model is sufficiently accurate for solving the reverse influences on the grid at small EVCSs penetration in the well dimensioned grid.

## 3 Analysis of active power consumption by EVCS

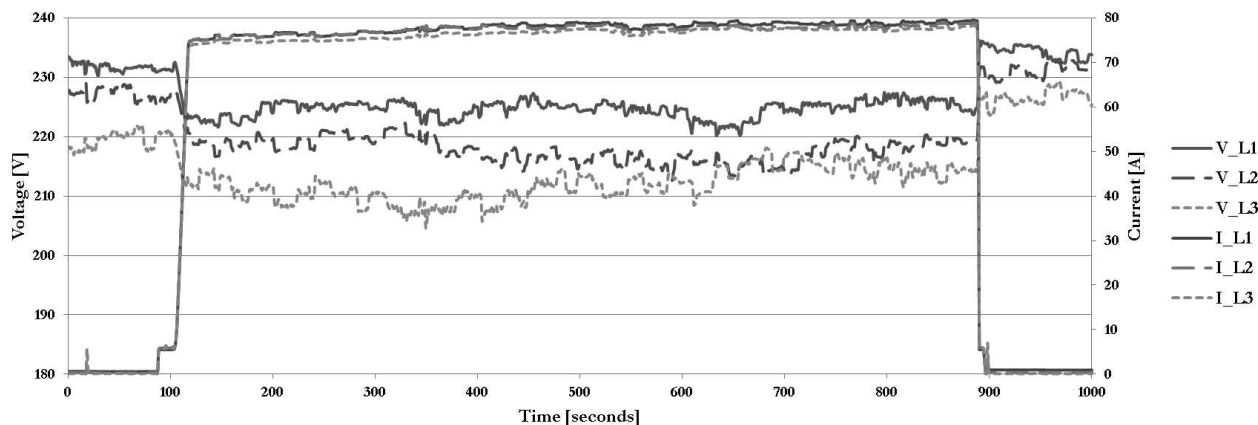
To verify the behaviour of the EVCS at EV charging, the measured data have been used from a public EVCS city distribution grid. The grid topology is radial and contains several loads which correspond to households and small companies. As a chosen example of typical behaviour CS when active power consuming from the grid, the voltage and current profiles are shown in Fig. 1. The chosen profiles correspond to the DC charging with maximum power level 50 kW. While charging, the consumed current does not have to be at the maximal level (current at phase L3 is the lowest). Such behaviour is caused by EVCS operation based on the communication with the battery management system and also by non-symmetry of supplied voltage (as seen on voltage at phase L3).

Voltage deviations caused by switching the various loads in the grid are seen on all voltage profiles (see Fig. 1). The most visible is the voltage steep decrease at the start of charging (approx. at time 100 s) and also voltage sharp increase at the end of charging (approx. at time 890 s). A huge current consumption causes voltage drops on all phases until the charging is completed in value approximately 7 V. The consumed current profile is almost constant except for small deviations as seen in Fig. 1.

Upon closer examination of current and active power profiles (Fig. 2), behaviour of CS when charging can be assessed. In case of DC charging, current profile should be approximately constant or rise slightly. Voltage, current and active power profiles are zoomed for chosen phase, in this example for phase L1. For the better scale the active power profile is three times magnified. It is evident, that active power profiles correspond to the current profile and also EVCS tries to preserve the active power consumption when voltage is changing. For example, if the voltage changes the current consumption changes with small deviations and active power remains approximately constant – bounded by a solid line. If the voltage

decreases, the current profile increases and power remains constant – bounded by a dashed line. Otherwise, if the voltage descends, the current is rising and active power is constant again – bounded by a dot

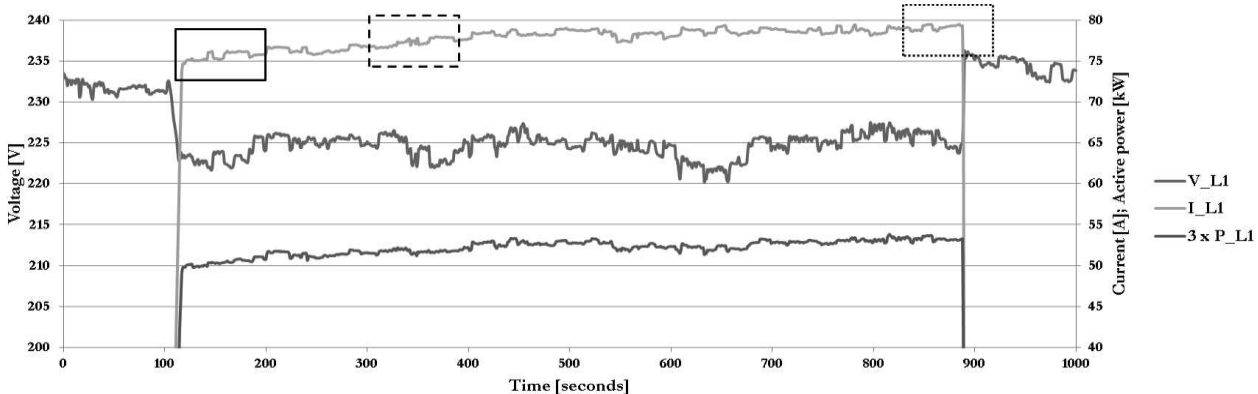
line, see all cases bounded for current in Fig. 2. However, the voltage deviations are very small, and therefore the preservation of active power level is not completely seen.



**Fig. 1** Typical voltage and current profiles when EV DC charging 50 kW

According to the voltage, current and active power profiles and also conclusions mentioned above, the EVCS behaves as a load with the approximately constant power consumption for small voltage changes when operating CS, thus as a power load. However, the changes are not sudden. The inertia of consumed current changes and small deviations on active power

profile are seen in Fig. 2. The active power profile doesn't change sharply in any of the bounded areas from Fig. 2. This suggests that CS when charging behaves as a power load at small voltage deviations. Similar behaviour has also CS for the AC charging, where the current and active power profiles are different at final part of battery charging process which correspond to the value higher than 80 % SOC.



**Fig. 2** Zoomed voltage, current and three times magnified active power profiles

Authors in [21] compare power load EVCS model with current one on the voltage-soft grid with the strong power loading. If the EVCS was given as power load, the consumed active power should be correct but not occurring current relations and thus neither voltage relations. If the load was given as current load, the current and voltage relations would be more accurate, but power flows would be fully incorrect. Since the EVCSs are not placed into voltage-soft locations in the distribution grid, the conclusions cannot be taken strictly. In the case of relatively voltage-stiff grid and use of power load model for EVCS when operating, the current deviations will be very small when

charging and thus with small errors determined active power losses, voltage drops and also examined cables ampacity.

#### 4 Simulation software for EV charging modelling

For the EV charging modelling the simulation software DYNAST was chosen. DYNAST is a software package for efficient and easy modelling, simulation and analysis of multidisciplinary nonlinear dynamic systems. It can be applied for numerical calculations in classical mechanics, heat transfer, energy transformation, electronics, electro-mechanics and other

technical fields. Therefore, DYNAST can become a universal tool for various technical disciplines. DYNAST enables the user to define the models by a set of algebraic-differential equations, block diagrams, physical models using a multi-pole diagram or by a combination of all mentioned approaches. The multi-pole diagram also allows us to define actual physical structures and links among individual elements of the real system without deriving any equations or constructing any graphs [21–24].

The internal structure of power load model in alternative simulation software DYNAST is introduced in a paper [25]. The EVCS model in physical diagram is defined by physical elements which consume predefined level of active power during the specified time. Active power level is inserted into the model by a tabular function. The initial increase of consumed power, constant power consumption up to demanded SOC, and also power decrease up to final SOC are respected in the model. The EVCS is then presented by resistance with the appropriate behaviour in the physical diagram. In this case, the EVCS load model consumes only the active power. There are no respected abnormalities, which could occur when charging. Phases switch-off or non-symmetrical active power consumption could be such abnormalities. They are results of EVCS searching for the optimal charging process.

## 5 Case study

For the case study the 21-nodes part of the distribution grid is selected with one distribution feeder and three radial lines. There are 17 household loads and four public EVCSs, where every radial grid part contains one EVCS and the last one is connected directly to the feeder output. The parameters of EVCSs are derived from the measured data. For the simulation, the theoretically maximal value of EVCS power is considered (AC 22 kW and DC 50 kW). The charging process is random during the day and is also balanced for consumed powers. Scenario of EVs connection to the CSs is described in Tab. 1. It takes in consideration the fact, that users can charge their EVs simultaneously, to start the charging process at different hours and also respecting the various battery capacities. Zero battery energy is assumed at the start of charging. Then the battery is charging up to approx. 80 % SOC by constant power for AC, and the next exponential decrease of power is up to 100 % SOC (the longest time charging process, i.e. the worst possible state). For the DC charging, the consumed power level reaches constant value for the whole charging time interval. The battery capacity is assumed 16 kWh or 36 kWh for AC and 50 kWh or 75 kWh for DC. The charging efficiency is considered as ideal and the start and completing of charging process in one minute duration.

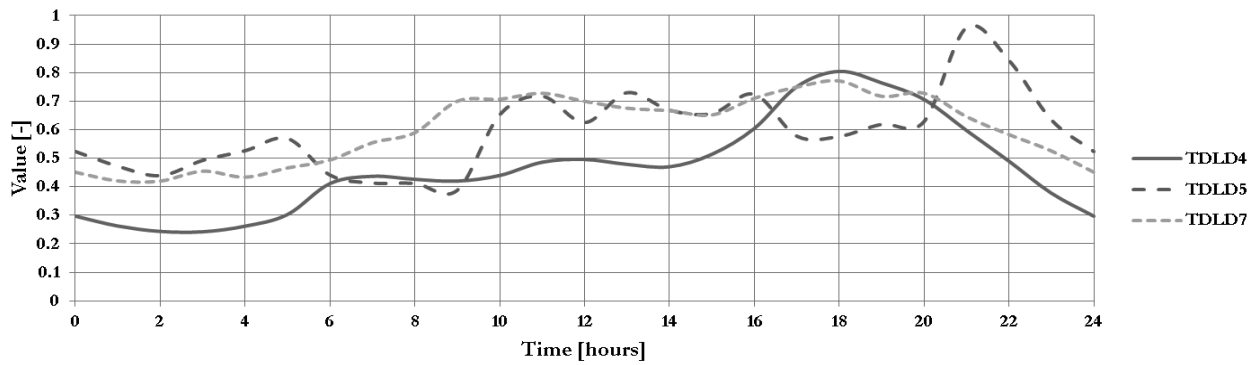
**Tab. 1** Scenario of EVs connection to CSs

CS – node	Connection time	Battery capacity	Connection time	Battery capacity
DC – 20	9:30	50 kWh	11:00	75 kWh
	15:00	75 kWh	18:30	50 kWh
AC – 5	8:00	36 kWh	14:30	16 kWh
	16:00	36 kWh		
AC – 12	15:00	36 kWh	20:00	16 kWh
AC – 19	7:30	16 kWh	12:00	16 kWh
	19:00	36 kWh		

The other loads in distribution grid are PQ, and their level is derived from typified daily loads diagrams (TDLD) of electrical energy. The chosen TDLD are among the most common types of loads with respecting the installed three-phase circuit-breakers 32 A or 25 A, and also less common 20 A. A winter season for TDLD, when the electrical energy consumption in the Czech Republic is the highest during the year, is considered. The chosen date was Monday, January 6, 2020 [26]. The time-profiles of TDLD for the chosen date are shown in Fig. 3. The consumers belong to the category “D”, i.e. households [27]. Three types of TDLD have been used. The first one is type 5 (consumption with heat accumulation load and circuit-breaker 25 Amps or 32 Amps), the second one is type 4 (consumption without heat accumulation

load and circuit-breaker 25 Amps or 20 Amps), and the last one is type 7 (consumption with direct heater system and circuit-breaker 32 Amps), see source [27].

All three types of TDLD are converted to physical values of consumed active powers which draw the physically defined loads. The active power parameters are inserted by a tabular function into the load, and its behaviour is entirely passive, i.e. it is recalculated into impedance. The load structure is closer described by authors in [28]. The reactive power load consumption is considered as constant and corresponds to the power factor 0.95 calculated from a minimum of the relevant TDLD. As the household loading is relatively high, it is possible to assume that the every load is the sum of two or more loads supplied from the given node.



**Fig. 3** Typical daily load diagrams for household active power consumptions

For the distribution grid the standardly used aluminium cables AYKY 3 x 120 + 70, AXKE 4 x 150 and AYKY 4 x 70 are considered. Individual consumers and EVCSs are mostly looped. CSs placed among houses are also connected directly to the consumers supply points. The lengths of cables are random and correspond to the standard lengths among connection

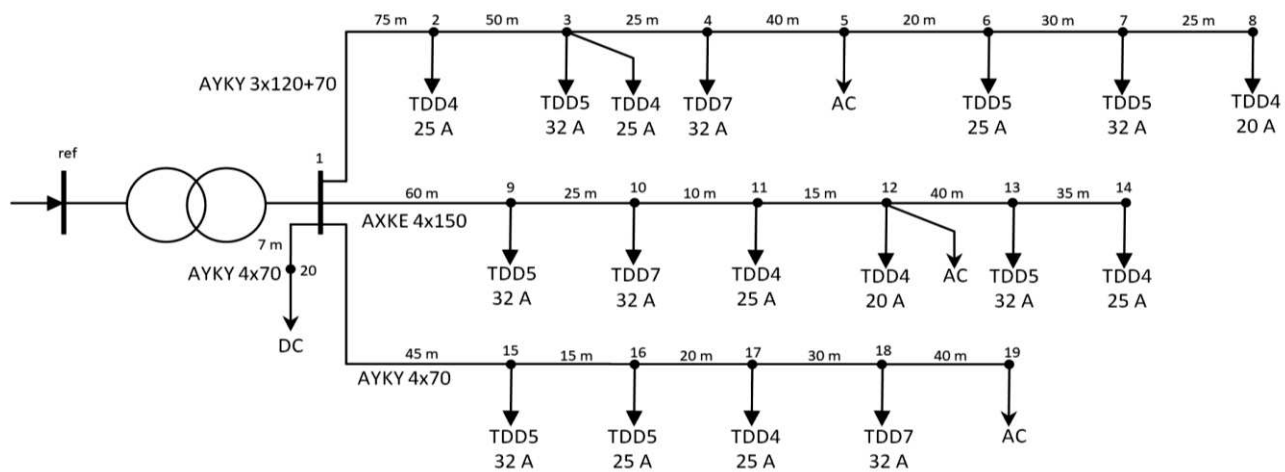
points of consumers. Cables passive parameters and their ampacities are taken from a catalogue [29], see Tab. 2. For the cables, none ambient influences are taken in account and influence of temperature on their resistivity is neglected. The feeder is the distribution transformer and its parameters from [30] are listed also in Tab. 2.

**Tab. 2** Parameters of elements used in distribution grid [29,30]

Distribution element	Parameters		
Transformer	22/0,4 kV, 50 Hz	$u_k\% = 4\%$	$\Delta p_{k\%} = 1,15\%$
	400 kVA	$i_0\% = 0,19\%$	$\Delta p_0\% = 0,1075\%$
Cable AYKY 3 x 120 + 70	$R_p = 0,253 \Omega \cdot \text{km}^{-1}$	$L_p = 0,228 \text{ mH} \cdot \text{km}^{-1}$	$I_{\max} = 253 \text{ A}$
Cable AXKE 4 x 150	$R_p = 0,206 \Omega \cdot \text{km}^{-1}$	$L_p = 0,219 \text{ mH} \cdot \text{km}^{-1}$	$I_{\max} = 331 \text{ A}$
Cable AYKY 4 x 70	$R_p = 0,443 \Omega \cdot \text{km}^{-1}$	$L_p = 0,236 \text{ mH} \cdot \text{km}^{-1}$	$I_{\max} = 186 \text{ A}$

The distribution grid is composed of three radial lines where each is made up of one cable type. The first and the second line include 7 and 6 household

loads respectively. The third one contains only 4 household loads. The loads placement is random, see diagram in Fig. 4. A Placement of EVCSs is mostly at the end of lines or in the middle of their lengths.



**Fig. 4** Diagram of 21-nodes distribution grid

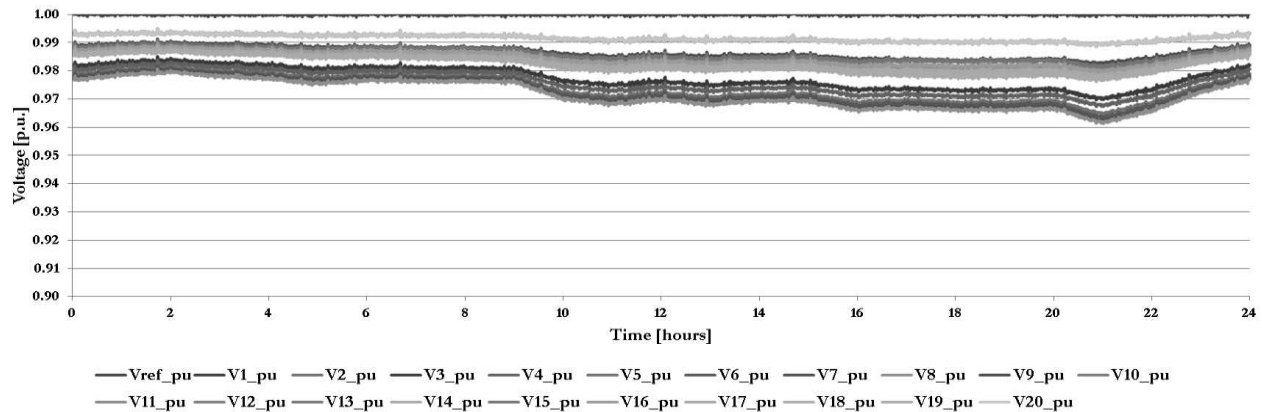
The simulation time is adjusted to a suitable scale, when one hour of real time corresponds to the one second of simulation time. The simulation time is adjusted to a suitable scale, when one hour of real time corresponds to the one second of simulation time. All shown profiles, i.e. voltages, currents and active power

losses, contain small deviations during the whole simulation time. These deviations are caused mainly by numerical calculations of solved system in given software. The circuit contains a large amount of regulation circuits, which are parts of submodels, namely loads and indicators of physical quantities. The close

description of operation the mentioned submodels to introduce authors in [23,28].

Voltage profiles in p.u. for distribution grid nodes without EVs during the day are shown in Fig. 5. The voltage at any node does not decrease under desired level. Voltage magnitudes fully correspond to the grid loading given by consumers TDLDs and does not

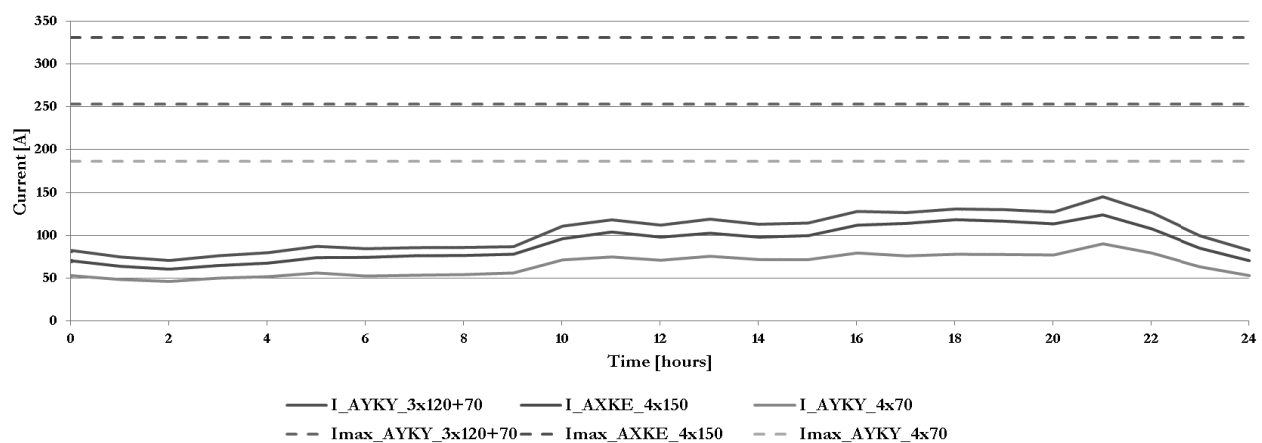
come down under desired level ( $\sim 10\%$  of  $V_n$ ) in any grid node. The highest grid loading occurs in afternoon and evening hours, when the highest voltage drops arises mainly in the furthest grid nodes. Setting of tap-changer on transformer is not considered. Thus, all voltages are lower than nominal value except for the reference voltage.



**Fig. 5** Voltage profiles during the day without EVs charging

Current loading of cables connected directly to the transformer are shown in Fig. 6. As the power loading is similar to all three grid branches, the current loadings have also similar profiles. It is seen, that cables ampacity is higher than real current loading. All cables are loaded around one halve or one third of maximal loading. The highest current loading occurs in the evening hours around 9 p.m. Loadings of remaining cables are not shown, because of their lower loading in

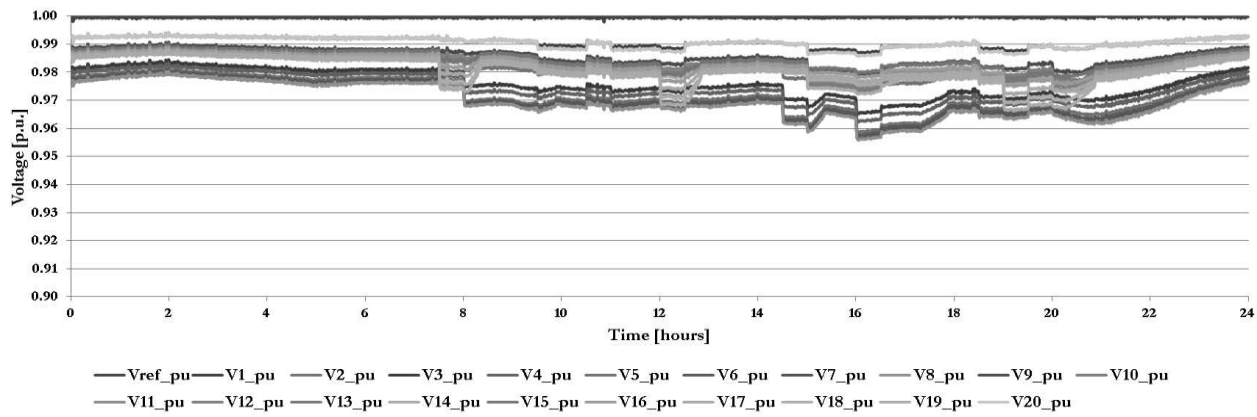
grid branches. As the DYNAST software connects each of two points by linear function in the graph, the current curves are not smooth. The current profiles are also influenced by amount of TDLDs inserted points, which are 24 in this case. The maximal daily loading of distribution transformer is around 62 %. It can be said that the grid is well dimensioned and is made with large reserves for cables loadings.



**Fig. 6** Current loading and ampacities of cables without EVs charging

The voltage magnitudes in distribution grid nodes for the chosen EVs charging scenario are shown in Fig. 7. If the EVs are charged, the current loading of cables is increasing and the voltage drops are also rising. The most significant voltage drops occur during the concurrent active power consumption by EVCSs. This case occurs in afternoon hours. The EVs charging during night hours is not assumed, therefore the

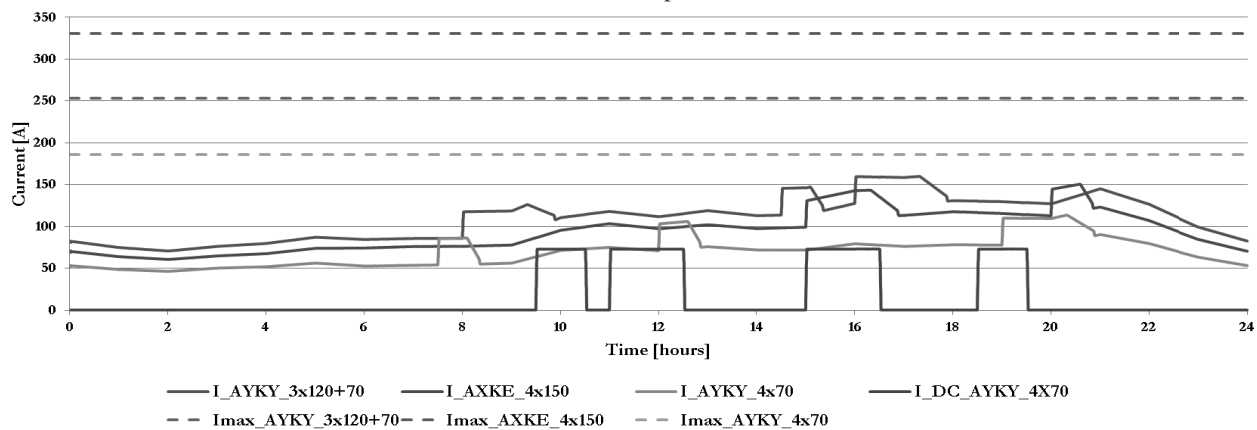
voltage drops are not changed in that time. As the proposed grid is well dimensioned, the voltage drops do not fall under demanded level in any node. The maximal voltage drop occurs around 4 p.m. and reaches approx. 6 % of  $V_n$ , i. e. the voltage is approx. 220 V in point 8. For the standard grid operation the voltage magnitude is low and therefore undesirable. Assuming setting the taps on transformer tap-changer, such voltage low level could be eliminated.



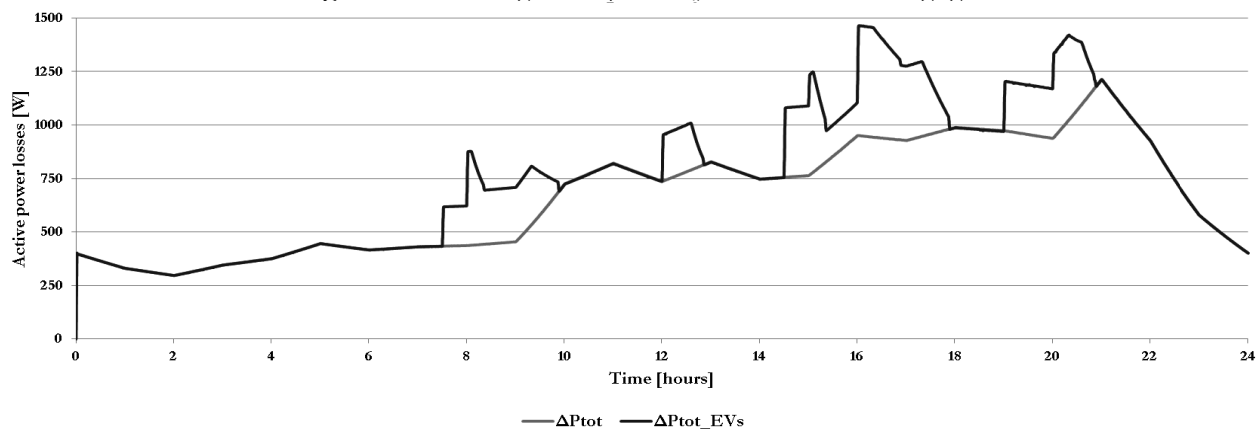
**Fig. 7** Voltage profiles during the day with EVs charging

The current profiles and cables ampacities for EVs charging are shown in Fig. 8. As the EVs charging is not in a high number and is also assumed only for medium-sized batteries and low concurrent charging, the maximal current loadings do not reach ampacity levels. The highest cable ampacity is around 63 % for the line with AYKY 3 x 120 + 70. It could be said, that for the well dimensioned distribution cables the

EVs charging would be no problem through their ampacities. Respecting the ambient conditions, large amount of power consumers, and also more intense charging processes, cables ampacities could be limit elements for installing the EVCs in distribution grids. The loading of transformer reaches approximately 79 %. In the case of respecting the same assumption as mentioned above, the transformer undoubtedly represents the weakest element in network.



**Fig. 8** Current loading and ampacities of cables with EVs charging



**Fig. 9** Total active power losses on cable lines without and with EVs charging

The total active power losses on cables without and with EVCs scenario are both shown in Fig. 9. The highest level of active power losses without EVs

charging reaches level around 1.2 kW at 9 p.m. That time correspond to the evening load peak. When charging during the day the active power losses increase

and maximal level reach around 4 p.m., when the total current loading is the highest. The level of power losses is about 1.5 kW. It can be seen, that the consumed powers by EVCSs have a significant effect on the total active power losses. As the penetration of EVs charging is low, the losses do not reach the extreme values. Respecting the ambient conditions, namely temperature of conductors, larger amount of power consumers which is typical for radial lines in distribution grids, and also more intense charging processes, the active power losses could reach undesirable levels which could limit the installing of public EVCSs.

Results introduced in Fig. 9 do not include the active power losses on distribution transformer. These losses are the same major attribute as other factors. Higher losses on transformer decrease its service life and reduce a possibility of installing the CSs in distribution grid.

## 6 Conclusions

On the real measured data of the EVCS at various charging processes was verified, that it is possible and sufficiently accurate to model the EVCS by active power load. While voltage changing at EVCS the consumed current is also changing in such a way when consumed active power remains approximately at constant level. It can be therefore said that it is possible to model the EVCSs efficiently accurate when operating by a physical diagram, which consumes the predefined power level during the time. However, this assumption applies only to voltage-stiff and well dimensioned grids. At voltage-soft grids, where high voltage drops occur, power load model behaviour does not correspond to the real data.

The active power EVCS load model was tested on the small 21-nodes well dimensioned grid which was composed of 17 households and with the 4 public EVCSs. Even in the case of concurrent power consumption by EVCSs the significant voltage drops do not occur. The lowest voltage level fell to 220 V corresponding to the 6 % of nominal voltage. The current loading of cables, namely connected directly to the transformer, does not reach their ampacity in any time during day for the chosen scenario. The highest current loading takes level around 63 %. EVs charging process causes increase of active power losses and can reach high levels if simultaneous charging process of EVs occurs at daily load peak demand.

The limiting elements of CSs expansion to the existing networks are transformers and cables. For the well dimensioned distribution grids should by a possible growth of public EVCSs. Cables having large cross-sections enable high current loading caused by EVCSs operation. This problem is mostly solved by ongoing renovation of distribution cable lines. As the modernization of distribution grids includes also

transformers replacement for larger and less lossy ones, their current or power loading could not also limit the expansion of EVCSs.

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