Measurement of the Efficiency of Electric Vehicle Charging Stations

George Milushev
Department of Electrical Measurements
Technical University – Sofia
Sofia, Bulgaria
gm@tu-sofia.bg

***Abstract*—The most important indexes while comparing the performance of the electric vehicles are: 1) the mileage for a single full charge and 2) the efficiency in km/kW.h or t.km/kW.h. As these indexes are deeply interrelated, we assume efficiency is a major specification in most practical cases.**

The efficiency of the charging stations is a direct multiplier calculating the total efficiency of electric vehicles. Its significant weight and importance draw special attention to measurement methods, measurement conditions and required accuracy in the measurement process to assess the efficiency of electric vehicle charging stations.

The paper aims to describe an applied methodology for assessment of Electrical Efficiency of the Charging Stations based on experience with Supercap Rechargeable Energy Storage System (RESS) and provides conclusions valid to all types of RESS.

Keywords—Efficiency, Energy, Electrical, Electricity, Vehicle, Charging, WLTP, NEDC, SORT, E-SORT

I. Introduction

Each Vehicle Homologation Procedure is based on driving cycles standardised according to the present and well-recognized standard World Harmonized Light-Duty Vehicles Test Procedure (WLTP) [6], the previous New European Driving Cycle (NEDC) [7] or UITP (Union Internationale de Transport Publique / International Association of Public Transport) SORT (Standardised On-Road Test Cycles) [3] etc. In the case of estimated range of Fully Electric Vehicles (FEV), sometimes additional standards as UITP E-SORT (Cycles for Electric Vehicles) [2] are applied. In all cases the most important indexes while comparing performance of the FEV are: 1) the mileage for a single full charge and 2) the efficiency in km/kW.h or t.km/kW.h. As these indexes are deeply interrelated, we assume efficiency is a major specification in most practical cases. From a professional and user-centric point of view, we assume the significance of the charging stations (CS) [5] as an important part of vehicle efficiency in general.

II. Electrical Efficiency of Charging Stations

A. Electrical Efficiency

According the definition for Energy Efficiency given by the International Standard EN ISO 50001 [1]: '*The energy efficiency is ratio or other quantitative relationship between an output of performance, service, goods, commodities, or energy, and an input of energy*'. In the case of charging stations, we are discussing not just energy efficiency but *Electrical Energy Efficiency,* as both the input and output energies are electrical energies. That means for CS: *The energy efficiency is the ratio between an output of energy, and an input of energy*.

B. Charging Stations Efficiency

The present paper is based on field experiments measuring the CS efficiency of Rechargeable Energy Storage System (RESS) type Supercap but the methodology is valid for all types of RESS, implemented in FEV (Note: The popular abbreviation BEF concerns only battery RESS).

The methodology adaptation of the SORT procedure, documented in the UITP E-SORT project paper [2] consists of two sequenced testing methodologies [4]:

1) Usable Energy Measurement of the RESS: the difference between SOC_M (Maximum level of State of Charge - SOC) and SOC_W (warning SOC corresponds to the minimum level allowed by the manufacturer during a normal operation).

2) Energy Consumption Measurement — aiming to determine the energy consumption of the vehicle on a given SORT cycle.

The methodology for 'Energy Consumption Measurement' is an object of a separate paper [4]. The 'Usable Energy Measurement' approach given by E-SORT [2], even dependable on the SOC_M and SOC_W is applicable to energy efficiency of CS.

C. Usable Energy Measurement

According E-SORT [2] the Usable Energy Measurement takes two steps:

1) 1ST STEP: BATTERY DISCHARGE. '*The aim of this step is to discharge the RESS close to the charging station until its warning SOC. The method employed to achieve this is the responsibility of the manufacturer (for example by driving the bus, using auxiliaries and so on)*' [2]

2) 2ND STEP: BATTERY CHARGE. '*Charge the RESS until SOC = SOC_M, with a power rate allowing a full charge of the RESS …*'. This step specifically is useful to measure the Energy Efficiency of the charging station.

D. Usable Energy Content

Two simultaneous energy measurements are necessary:

- Upstream from the charger - E_G, kW.h - Energy from the grid;
- Downstream from the charger - E_C, kW.h - Energy from the charger.

The Usable Energy Content assessment [2] is based on the approach shown on Fig. 1.

The author would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

978-1-7281-9719-7/20/$31.00 ©20XX IEEE

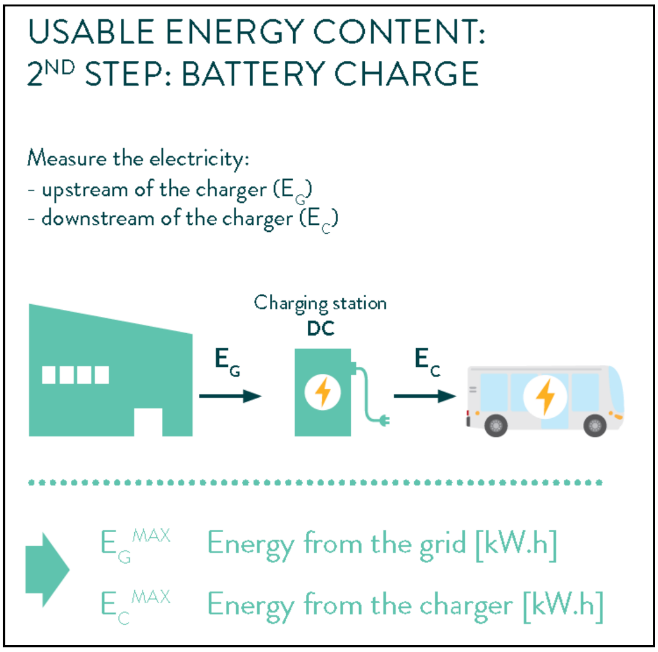

Fig. 1. Usable Energy Content. (Source E-SORT [2])

E. Charging Efficiency

E-SORT [2] refers to use the Charging Efficiency only for 'Information' purposes because:

- SORT [3] and E-SORT [2] are designated '... *to provide the bus sector a standardised way to compare the energy consumption of different buses.*' The performance of charging stations is not a subject of these two documents.
- The maximal range on SORT$_i$ d_i^{Max} (1) [2,4] which is one of the vehicle performance parameters in E-SORT [2] does not include CS efficiency but only the maximal energy measured downstream the charging station in kWh. The expressions in E-SORT are as follows:

$$d_i^{Max} = \frac{100.E_C^{Max}}{C_i} = \frac{E_C^{Max}}{E_i}\, d_i \qquad (1)$$

E_C^{Max}, kWh - energy measured downstream the charging station;
C_i, kW.h/100 km - energy consumption on SORT$_i$ (2);

$$C_i = \left[\frac{kW.h}{100.km}\right] = \frac{100.E_i}{d_i} \qquad (2)$$

E_i, kW.h - energy measured on SORT$_i$;
d_i, km - maximum range on SORT$_i$;
i - an index which marks the respective SORT profile.

Estimation of CS efficiency is based on (3) according to the already defined Electrical Energy Efficiency:

$$\eta_C, \% = \frac{E_C^{Max}}{E_G^{Max}}.100 \qquad (3)$$

A result obtained according to (3) for η_C is a single test result. The representative assessment for CS Energy Efficiency depends on many factors such as levels of SOC_W and SOC_M, the capacity of RESS, energy measurement method, voltage levels, measurement uncertainty factors etc.

The efficiency of the charging stations is a direct multiplier calculating the total efficiency of electric vehicles. Its significant weight and importance draw special attention to measurement methods, measurement conditions and required accuracy in the measurement process to assess the efficiency of electric vehicle charging stations.

The present paper aims to describe a proven methodology for assessment of Electrical Efficiency of the Charging Stations based on the experience with Supercap Rechargeable Energy Storage System and provides conclusions valid to all types of RESS.

All the results are obtained during an accredited testing procedure compliant to E-SORT, and are published with the knowledge and the consent of the applicant.

III. The Methodology

The applied methodology bases on two separate devices to measure respectively upstream E_G and downstream E_C energies (Fig. 2)

Fig. 2. Connection to a CS with two energy analysers.

Lack of designated devices for the purposes of variety of the cases for CS electrical energy efficiency measurement requires alternative approaches. The usage of energy analyzers designed to measure electrical power and energy through direct measurement of current and voltage has many advantages compared to multichannel recorders, scopes or other possible applications. There are, however, some inconveniences related mainly to synchronization between the two devices.

A. A variety of current probes and voltage ranges

The currents and the voltages are primary quantities and as such the values of their parameters are very important for correct measurement of power and energy. At the present, enough different producers of energy analyzers offer wide choice of the appropriate current probes and adjustable voltage ratios. High values of the output DC currents, different dimensions, numbers and accessibility of the cables and busbars are project advantages of the energy analyzers over other solutions.

B. Multidisplay visualisation

The opportunity to monitor both processes of the power flow of upstream and downstream energies assures the timely reaction the operator in the case of overcurrent, overvoltage, transients, phase sequences and enables the immediate discovery of the incorrect connection.

Fig. 3 (upstream AC 3 phase power) and Fig 4 (downstream DC power) show process recordings from one charging cycle.

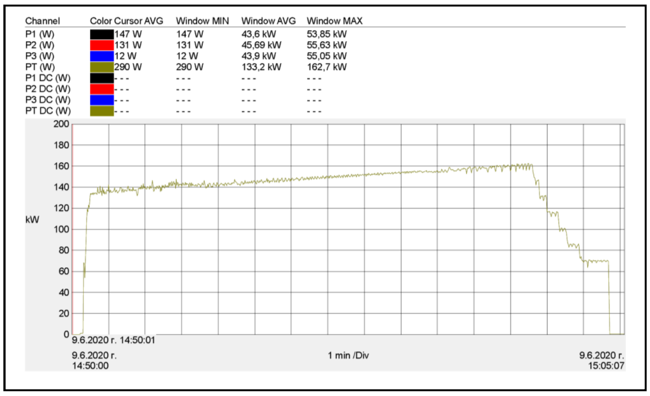

Fig. 3. Upstream AC power.

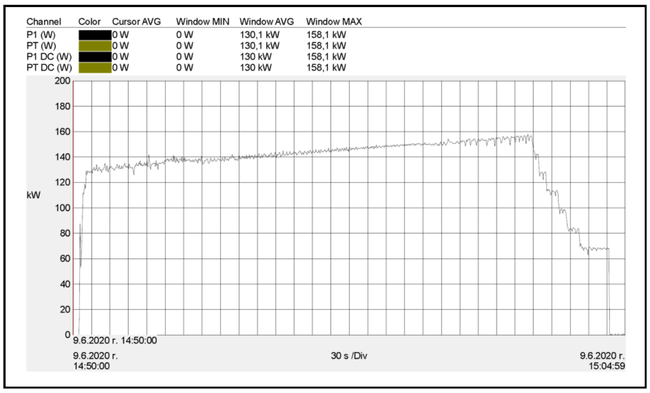

Fig. 4. Downstream DC power.

This is a big advantage of the applied methodology because wrong records lead to significant loses of time and money.

C. AC/DC and DC/DC cases

The usage of two energy analyzers significantly increases the functionality of the applied approach to both AC/DC CS where a variety of sensors and connections types exist Fig. 5 and DC/DC CS where the configuration is equal to a single phase connection Fig. 6.

In the case of DC/DC CS, due to the limited usage of channels, it is possible to make a record of the upstream and downstream DC power and respective energies with a single analyzer. Such an approach can be used only in the edge case of the mutual neutral and leads to dimensional limitations related with the length of measurement cables and probes.

Fig. 5. Upstream AC Connection to CS.

Fig. 6. Upstream DC Connection to CS.

D. Metrology and calibration

It is essentially important to meet the E-SORT [2] requirement for '*global accuracy of at least +/- 2 %*' and for '*calibrated data acquisition devices so that you can measure current and voltage on each cable*'. The calibration of energy analyzers is more convenient than that of any other possible device, so it is one more advantage to the analyzer's usage.

The metrology optimization needs to calibrate each device with the respective probes to each channel, to fix and to fit the three components: probe-channel-device.

E. Synchronization

The time synchronization between the two analyzers is the only issue under consideration with the used methodology. Some analyzers have the possibility for GPS time and Start/Stop synchronization, but this approach is costly and heavy.

Actually, the synchronization is important, but not critical. The internal clocks of the devices have acceptable temporary stability. A simple clock synchronization with a personal computer ahead of the measurements would satisfy the accuracy requirements.

More problematic could be the simultaneous Start/Stop when the two analyzers are too far away from one another to be manipulated by one operator. Critical in this case is to start the downstream record a bit after the upstream one. This would lead to a worse efficiency estimation, but satisfies the requirements from a methodical point of view. In practice, the downstream current absents before the start of the charging and stops immediately after the charge. At the same time, the short intervals recorded before and after the charge, don't really alter the process by more than 0.0001%, because the upstream current powers only the very low self-consumption of the CS for the periods out of charge.

IV. Results

The results necessary for the calculation of the CS Energy Efficiency (3) come directly from the energy registers of the analysers. Fig. 7 and Fig. 8 represent screenshots of the values from the upstream and in the downstream registers.

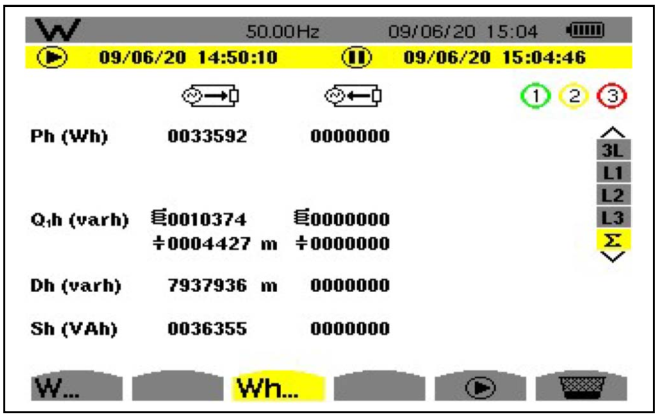

Fig. 7. Upstream AC Energy.

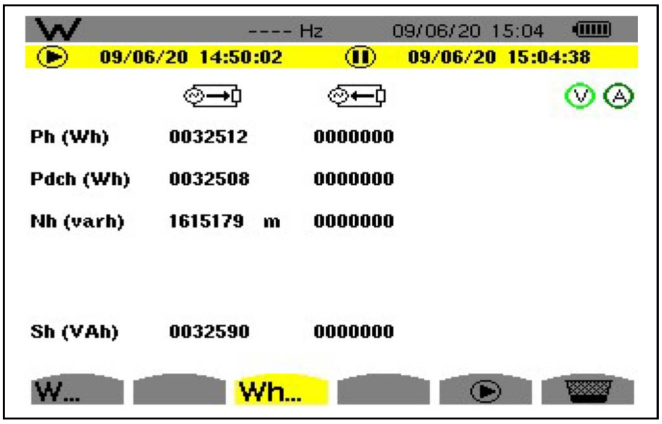

Fig. 8. Downstream DC Energy.

Sometimes, when taking into account the symmetry of the load consumption from the grid, a phase by phase register of the upstream energy is also useful (Fig. 9).

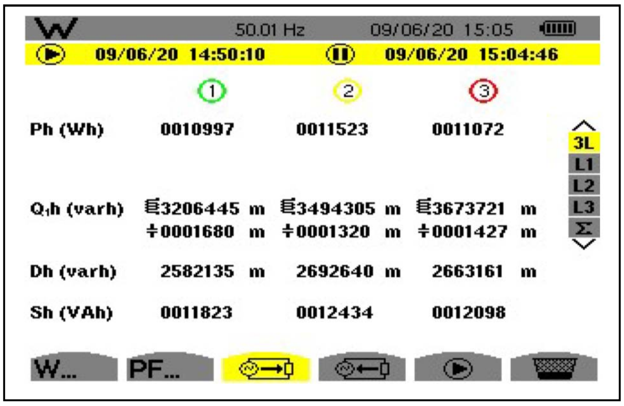

Fig. 9. Upstream AC Energy phase by phase.

For the concreate case the CS efficiency according to (3) is:

$$\eta_C, \% = \frac{32.508\ kWh}{33.593\ kWh}.100 = 96.77\% \qquad (4)$$

The following Table I represents the results obtained from several measurements of the efficiency of Charging Stations of Supercap FEV Bus.

TABLE I. CS Energy Efficiency

No	CS Type	SOC_W	SOC_M	U_{MAX}	Charge Duration	η_C
1	DC/DC 45kW 70A	439V 16%	579V 97%	585V	29 min 20 s	91.34%
2	AC/DC 100kW 150A	533V 19%	718V 96%	725V	20 min 57 s	96.69%
3	AC/DC 150kW 200A	565V 24%	715V 94%	725V	14 min 36 s	96.77%
4	AC/DC 45kW 70A	643V 58%	718V 95%	725V	23 min 05 s	96.74%
5	AC/DC 85kW 130A	598V 37%	661V 69%	725V	8 min 55 s	96.54%
6	DC/DC 400kW 600A	547V 19%	720V 97%	725V	9 min 24 s	95.65%
7	AC/DC 400kW 600A	531V 10%	718V 96%	725V	8 min 58 s	95.15%
8	AC/DC 50kW 80A	663V 69%	719V 97%	725V	12 min 40 s	96.97%

V. Conclusions

The applied methodology for measurements of the efficiency of charging stations based on two separate devices is appropriate and proven in the practice. The usage of energy analyzers designed to measure electrical power and energy through direct measurement of current and voltage is cost effective, appropriate for on-site applications and optimal from metrology considerations.

The Start/Stop procedure requires special attention during the records of upstream and downstream electrical energy.

The CS energy efficiency depends on the setup mode of the charging stations. Better results are obtained with AC/DC stations (compared to DC/DC type) with optimal load near the upper limits of the station range.

REFERENCES

[1] EN ISO 50001, "Energy management systems — Requirements with guidance for use", Second edition 2018-08, Reference number ISO 50001:2018(E), ISO copyright office CP 401, Ch. de Blandonnet 8, CH-1214 Vernier, Geneva.

[2] UITP PROJECT E-SORT, "Cycles for electric vehicles", International Association of Public Transport (UITP), Rue Sainte-Marie 6, B-1080 Brussels – Belgium, Legal deposit: D/2017/0105/9.

[3] UITP PROJECT SORT, "Standardised on-road test cycles", New edition UITP 2014, International Association of Public Transport, Rue Sainte-Marie 6, B-1080 Brussels – Belgium, Legal Deposit: D/2014/0105/1.

[4] G. Milushev and K. Kirilova-Blagoeva, "Accredited testing of energy consumption of electrical vehicles according to E-SORT protocol", Proceedings of 28th International Scientific Symposium "Metrology and Metrology Assurance 2018", pp. 220-225, September 10-14, 2018, Sozopol, Bulgaria.

[5] G. Milushev, K. Kirilova and K. Stanev, "Method for assessment of the consumption of electrobus using load profile of the charging stations", Proceedings of XXV National Scientific Symposium with International Participation 'Metrology and Metrology Assurance 2015', pp. 620-625 September 7-11, 2015, Sozopol, Bulgaria.

[6] WLTP, "Worldwide harmonised light vehicles test procedure", https://en.wikipedia.org/wiki/Worldwide_Harmonised_Light_Vehicles_Test_Procedure

[7] NEDC, "New European Driving Cycle", https://en.wikipedia.org/wiki/New_European_Driving_Cycle