Ultra fast charging station harmonic resonance analysis in the Dutch MV grid

24th International Conference & Exhibition on Electricity Distribution (CIRED)
12-15 June 2017
Session 2: Power quality and electromagnetic compatibility

Ultra fast charging station harmonic resonance analysis in the Dutch MV grid: application of power converter harmonic model

ISSN 2515-0855
doi: 10.1049/oap-cired.2017.1074
www.ietdl.org

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Abstract: This article introduces an advanced converter harmonic model that can be used to study harmonic resonance when the ultra-fast charging station (UFCS) is connected to the medium-voltage (MV) grid. A small demonstration network is created to verify the effectiveness of the converter harmonic model in the harmonic resonance interaction study compared with the traditional ideal current source model approach (all benchmarked to the detailed Electromagnetic Transient PSCAD® model). A case study is performed on the Dutch Bronsbergen MV grid when a UFCS is connected. The harmonic resonance is calculated with both the ideal current source model and the converter harmonic model. When the converter harmonic model is used for the impedance sweep calculation, its output filter capacitance plus control circuit gain creates one extra parallel impedance resonance peak at 1250 Hz providing good insight for harmonic resonance risk investigation. To conclude, this article highlights the risk of harmonic resonance when a voltage source converter such as an UFCS is introduced in a MV grid. The advanced converter harmonic model, as applied in the Dutch MV grid, delivers the required level of insight for the distribution network operators when it comes to large-scale integration of UFCS in the future.

1 Introduction

The plug-in electric vehicle (PEV) is steadily gaining interest as they offer an economically viable and environmentally friendly transportation solution when compared to their gasoline-powered counterparts. Despite the improved travel range offered by several popular PEV models (e.g. Tesla Model S, Nissan Leaf, General Motors Bolt etc.) the battery charging facility nowadays does not offer the same level of convenience for the PEV owners when compared to the extensive gasoline station network. Even though the level 1 household plug can easily recharge the battery overnight, it does not offer the PEV owner the freedom for long distance travel and relief of ‘range anxiety’. The Tokyo Electrical Power Company (TEPCO) study published in 2008 and BMW research project ‘Mini E’ conducted in the cities of Los Angeles, Berlin, and London [1] both confirm that the public charging infrastructure such as the ultra-fast charging station (UFCS) plays a key role in the development of the electromobility and transition towards E-mobility. In a report [2] revealing the historical lessons learnt from Norwegian experiences in deploying electric vehicles, a decent charging station network coverage has been identified as the main enabler for the adoption of PEV. Therefore, the availability of UFCS is not only a technical prerequisite but also a key enabler for the consumer acceptance to bring the electric mobility to the next level.

Next to the future demand for the extensive UFCS network coverage, the existing power grid infrastructure must be carefully reviewed in all necessary technical aspects to smooth out the integration of UFCS. Despite numerous studies covering the impact of UFCS in the literature [3–6], to the best knowledge of the author, the impact of UFCS on the medium-voltage (MV) grid harmonic resonance is not covered in any literature, but will be addressed here in detail. An UFCS offering several level 3 direct current (DC) charging slots connecting to the MV grid could easily reach MW (250 kW × 4) demand power levels, the harmonic emission to the MV grid of the converters should be assessed carefully. The widespread deployment of UFCSs with its AC connected power electronics can also adversely impact the local MV grid impedance resonance point causing an increased harmonic resonances risk to the distribution network operator (DNO). This article focuses on the proper modelling of an UFCS active front end (AFE) power electronics interface in a harmonic resonance study and discusses the impact of a UFCS on the network impedance resonance point in a case study of a MV grid in Bronsbergen, the Netherlands.

2 Ultra fast charging station topology and model

A vast amount of innovative UFCS converter topologies exist in the literature as well as manufacturer’s product offers [7]. For this study, it is not possible to capture all the UFCS topologies mentioned in the literature. To illustrate the impact of a typical future UFCS impact on the power grid resonance behaviour, a simple two-level AFE with stationary battery storage topology has been chosen for this study due to its prevailing presence in the literature [8, 9] and technology readiness for mass production. Fig. 1 illustrates that the AFE (1 MW) is coupled to the MV grid via a 10/0.4 kV transformer while each level 3 DC charging slot (250 kW × 4) is connected to the UFCS DC bus via a DC/DC converter. The stationary battery storage device is then connected to the UFCS DC bus bar via a dedicated DC/DC converter to reduce the static impact (power grid congestion, component overloading etc.) of the UFCS on the local MV grid.

Once the typical UFCS topologies have been determined, an electromagnetic transient (EMT) model of UFCS in PSCAD® can be made to facilitate the derivation of the converter harmonic model. Since the UFCS transient dynamic electrical characteristic

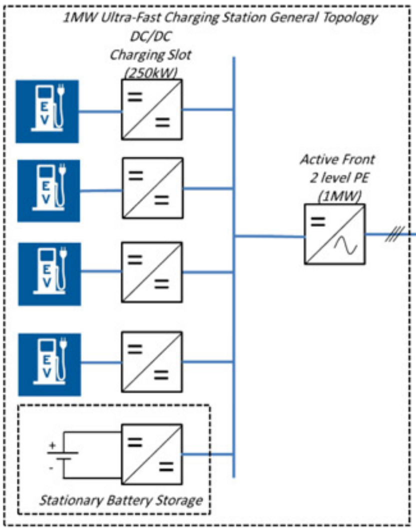

Fig. 1 *Typical UFCS topology with two level AFE and stationary battery storage*

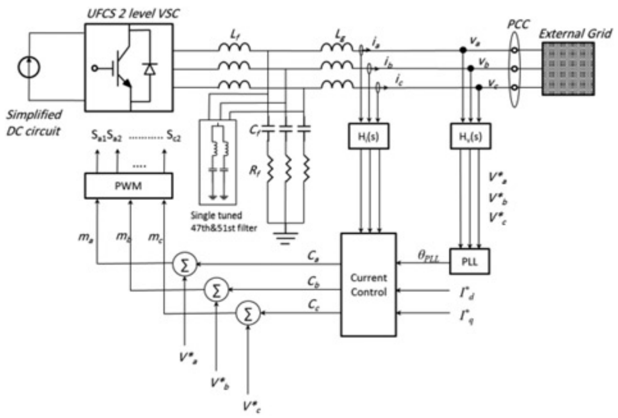

Fig. 2 *UFCS two-level AFE with simplified DC circuit*

seen from the power grid is mainly dictated by the AFE, the DC side charging slot and stationary battery storage DC/DC circuit can be simplified to an ideal DC current source connected to the DC bus of the AFE for the EMT model, as shown in Fig. 2. A popular synchronous frame *d*–*q* decoupled current control loop is adopted for the 1 MW generic UFCS model used here. Current and voltage are measured at the grid side inductor, L_g, as indicated in Fig. 2. Then the current set-points for both *d*-axis and *q*-axis are compared with the measured *d*- and *q*-axis currents (transformed from abc frame to dq frame). Through the proportion integral (PI) controller, reference dq frame voltage is fed into the dq to abc transformation block. Reference voltages on the abc frame are passed to the sinusoidal pulse width modulation (SPWM) control block, which in turn generates the gating signals for the individual semiconductor switches.

Table 1 summarises the basic electrical design parameters of the 1 MW UFCS AFE modelled in PSCAD®:

Table 1 Summary of 1 MW UFCS design parameters

Electrical characteristic	Value
rated grid voltage (phase-to-phase RMS)	0.4 kV
rated grid side converter power	1 MW
AC grid frequency	50 Hz
DC-link voltage	0.7 kV
DC-link capacitance	20.000 μF
switching frequency	2.450 Hz
power converter topology	two-level half bridge
L_f (converter side inductor)	130 μH
L_g (transformer leakage inductance $U_k = 6\%$)	30 μH
C_f (filter capacitance)	1000 μF
R_f (filter damping resistance)	0.04 Ω

3 Converter harmonic model

The detailed EMT model in PSCAD® not only serves as the basis for the derivation of the converter harmonic model but also used as the benchmark to validate the effectiveness of the converter harmonic model compared to the ideal current source model. This section starts with a short introduction on the evolution of the power system harmonic distortion calculation and the associated harmonic source model, followed by a discussion of the issues related to the ideal current source model. Then the state-of-the-art modelling approach in representing the voltage source converter (VSC) type of power converter as a converter harmonic model is given. A verification between the time domain electromagnetic model and its equivalent frequency domain converter harmonic model for the 1 MW UFCS concludes this section.

3.1 Background on the harmonic modelling development

The typical method used for the modelling of harmonic-generating devices is the ideal (constant) current source model as shown in Fig. 3. This approach originated from times when line commutated harmonic-generating devices (i.e. load-commutated converters and diode rectifiers) dominated, which could be modelled by an ideal current source model. It has since been proven to be inaccurate for the modelling of self-commutated devices (e.g. VSC high-voltage direct current, doubly fed induction generator (DFIG), photovoltaic, full converter-based wind turbine and UFCS). Even though it is common practice to document harmonic current emission at the grid connection point, such harmonic current emission measurements should not be used for the representation of VSC-based power electronics as an equivalent ideal current source in the harmonic resonance analysis [10], as will be substantiated next. The reasons are three folds: firstly, the measurement is not performed in a clean grid environment, i.e. without background harmonic distortion. Secondly, an ideal current source fails to capture the converter control reaction to the background harmonic voltage. Lastly, for the network impedance scan, an ideal current source does not present the frequency dependent inner current control loop and the passive output filter resulting in an inaccurate network resonance point.

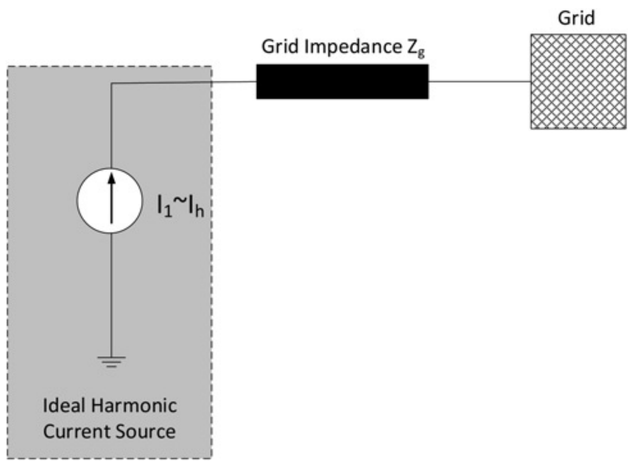

Fig. 3 *Ideal harmonic current source illustration for network harmonic distortion calculation*

CIRED, Open Access Proc. J., 2017, Vol. 2017, Iss. 1, pp. 879–882

3.2 Converter harmonic model

To fix the aforementioned issues with the simple harmonic current source model, a converter harmonic model is proposed to describe the harmonic behaviour of self-commutated converter based generation [11]. Properties of the converter harmonic model are:

- The converter harmonic model removes the influence of the connected grid from the measured self-commutated converter characteristics.
- The converter harmonic model includes the converter reaction to the background harmonic voltages in the connection grid.
- The converter harmonic model includes the influence of the connection grid impedance on the harmonic emission from the converter.

It is common practice to represent the converter harmonic model (Fig. 4) as Norton/Thevenin equivalent circuit [10].

The converter equivalent harmonic sources and impedances are highly dependent on the grid-side converter control strategy [12]. Regarding Fig. 5, the Norton equivalent impedance in the model represents both the converter reactor and the converter control frequency response which describes the converter interaction to the background harmonic disturbances. The equivalent voltage source/current source in the model represent the disturbances which are caused by the PWM switching, the non-ideal properties of the converter hardware and control.

3.3 Model verification – time domain versus frequency fdomain

Verification is performed against the large signal EMT model built in PSCAD®. An external grid, connected to the MV terminal of the UFCS transformer, with 5% fifth harmonic and 5% seventh harmonic background voltage distortion is used to confirm the validity of the derived converter harmonic model in the frequency domain. The single line diagram in Fig. 6 illustrates this simplified simulation test network.

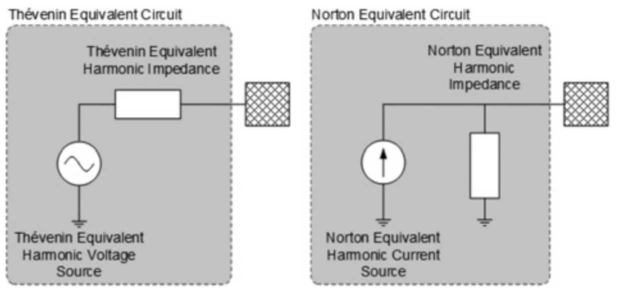

Fig. 4 *Converter harmonic model as Norton/Thevenin equivalent circuit*

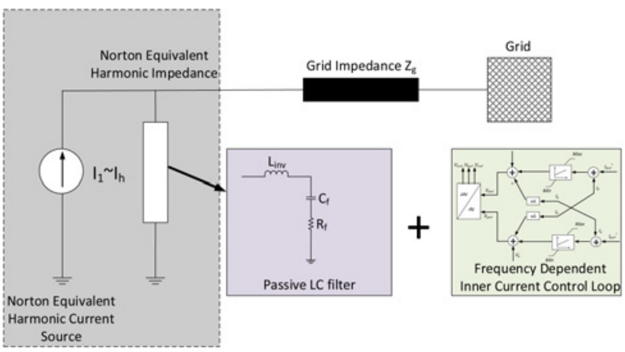

Fig. 5 *Norton equivalent harmonic current source illustration for network harmonic distortion calculation*

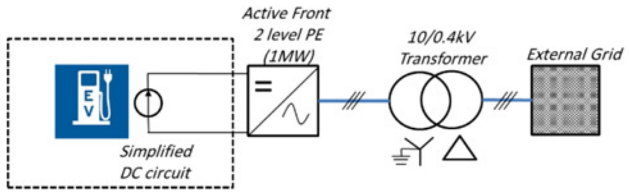

Fig. 6 *Test network with 5% fifth and 5% seventh background harmonic voltage distortion*

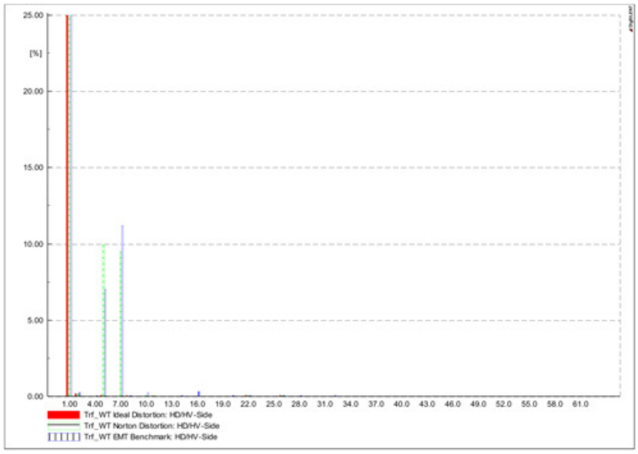

Fig. 7 *Comparison of harmonic interaction results for ideal current source model (red), converter harmonic model (green) and EMT time domain simulation (blue)*

The results are shown in the bar diagram in Fig. 7. On the fifth and seventh harmonic current results: results from the detailed switching model has been considered as the benchmark (blue curve); for the low order harmonic interaction because of the background harmonic voltage distortion (5% seventh harmonics, 5% seventh harmonics), the converter harmonic model (green curve) successfully captured the low order harmonics interaction while the ideal current source model (red curve) did not. In summary: the converter harmonic model correctly represents the power converter output impedance as well as the low order harmonics interaction when the background voltage is distorted.

4 Case study on Dutch MV grid

A typical Dutch MV grid in Bronsbergen (Fig. 8) operated by Alliander (Dutch DNO) has been selected for the case study to reveal the harmonic resonance impact of the UFCS connections. The UFCS is connected at MV bus 12 (Roelofs), where its downstream low-voltage grid is represented in detail as shown in Fig. 9. The impedance sweep is calculated at MV bus 12 for three scenarios: original without UFCS connection, UFCS connection with ideal current model, UFCS connection with converter harmonic model.

Fig. 10 presents the results of the impedance sweep for all three scenarios (green – original case without the UFCS connection, red – UFCS connection with ideal current source model, blue – UFCS connection with converter harmonic model). It is clear from the impedance sweep results that the red and green curves are overlapping. This provides almost no insight into the harmonic resonance behaviour when the ideal current source model is used. When the converter harmonic model is used in the harmonic impedance sweep calculation, its output filter capacitance plus control circuit gain creates one extra parallel impedance resonance peak at 1250 Hz while shifting the original resonance peak to a higher frequency, despite a reduced magnitude. The

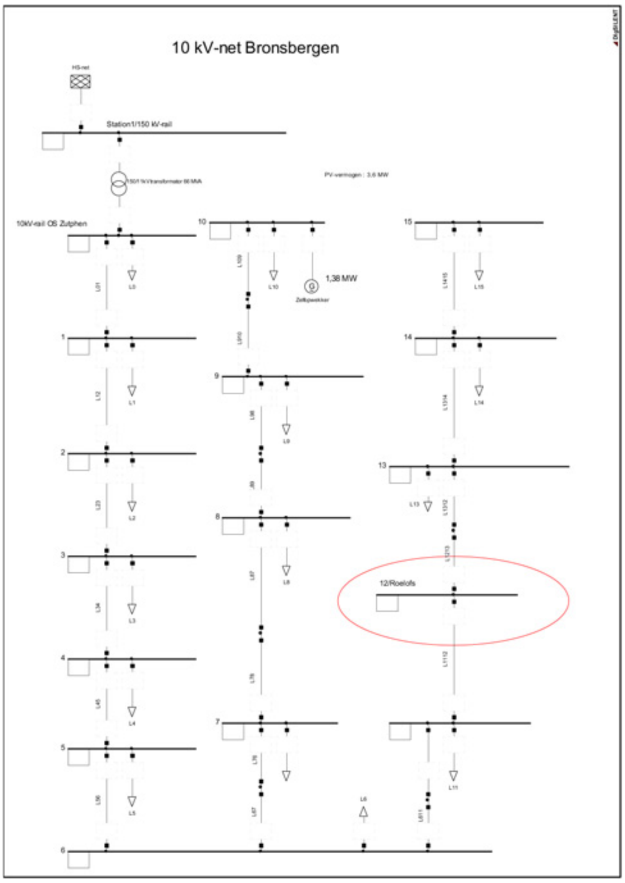

Fig. 8 *Bronsbergen MV grid single line diagram*

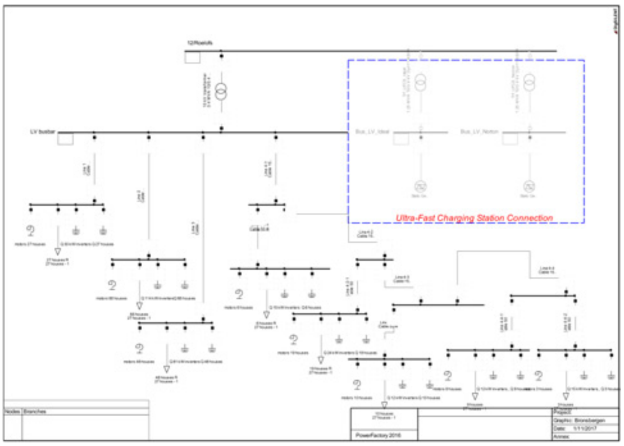

Fig. 9 *Role of 12 MV connection point detailed single line diagram*

extra parallel impedance resonance peak at 1250 Hz is of interest to the DNO as it could potentially create unacceptable harmonic voltage distortion due to neighboring equipment's harmonic emission near 1250 Hz.

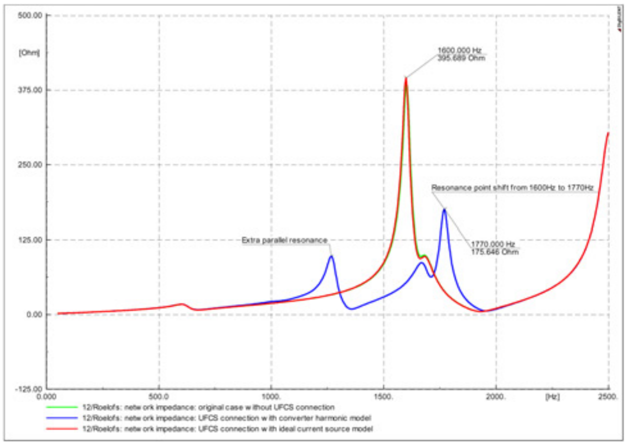

Fig. 10 *Impedance frequency sweep at 12/role of MV connection point*

5 Conclusion

This article highlights a harmonic resonance risk when a VSC-based power converter, such as a UFCS, is introduced in a MV grid. The advanced converter harmonic model, as applied in the Dutch MV grid, delivers the required level of insight for the DNOs when it comes to large-scale integration of UFCS in the future.

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