IMPACT OF ELECTRIC VEHICLE CHARGING ON UNBALANCE AND HARMONIC DISTORTION – FIELD STUDY IN AN URBAN RESIDENTIAL AREA

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ABSTRACT

The paper presents the impact of a high penetration of plug-in electric vehicles (EVs) on the Power Quality in an urban residential low voltage grid. It discusses in detail the impact on unbalance, harmonics and supraharmonics (2 kHz to 150 kHz). The results are based on an as best as possible field study, where ten EVs were provided to ten households (penetration of almost 100%), which are connected to one feeder of an urban public distribution grid. Measurements were carried out at three different conditions. While the measurement without EVs serves as reference, during coordinated charging the EVs were connected and disconnected according to a defined schedule. Finally during a weekend the customers could use and charge the EVs as they wanted, which represents a realistic usage behavior. The measurements have shown that EV charging has a significant impact not only on Power Quality but also on the fundamental load flow.

INTRODUCTION

At present most EVs in Germany have a single phase onboard charger. Depending on circuit topology and control algorithm, the power electronics used in the charger rectifier can cause considerable distortion in the low and higher frequency range. Usually the rectifiers are equipped with an active power factor correction, which can result in a considerable emission at switching frequency, commonly in the range of several 10 kHz. Moreover, this circuit topology generates low order harmonic currents if the supply voltage is distorted, which is usually the case in public grids. This is e.g. not covered by the present test conditions according to IEC 61000-3-2. Finally, an impact on the unbalance is expected because of the single-phase connection.

Due to the political framework, the number of electric vehicles is expected to grow significantly during the next years, which can result in a considerable impact on the Power Quality in distribution grids. This problem is currently researched by modelling EV chargers in terms of the mentioned Power Quality phenomena and simulating different future scenarios of EV penetration.

Several papers study the impact of car charging on Power Quality, especially harmonics [1] - [3]. In most cases the verification of the models based on realistic field measurements is missing. This paper shall close the gap. In order to get a realistic data source for the model verification, a realistic field study with a high EV penetration has been carried out in a feeder of an urban low voltage (LV) grid supplying a residential area. As one key issue, the measurements take the interaction between EV charging and other household loads into account.

The first part of the paper provides detailed information about the grid and the measurement set-up. After that the used EVs are characterized. The main part of the paper discusses the impact of EVs on unbalance, harmonics and supraharmonics.

MEASUREMENT FRAMEWORK

Grid details

For the field study a LV grid, which supplies an urban residential area in Dresden, Germany was chosen.

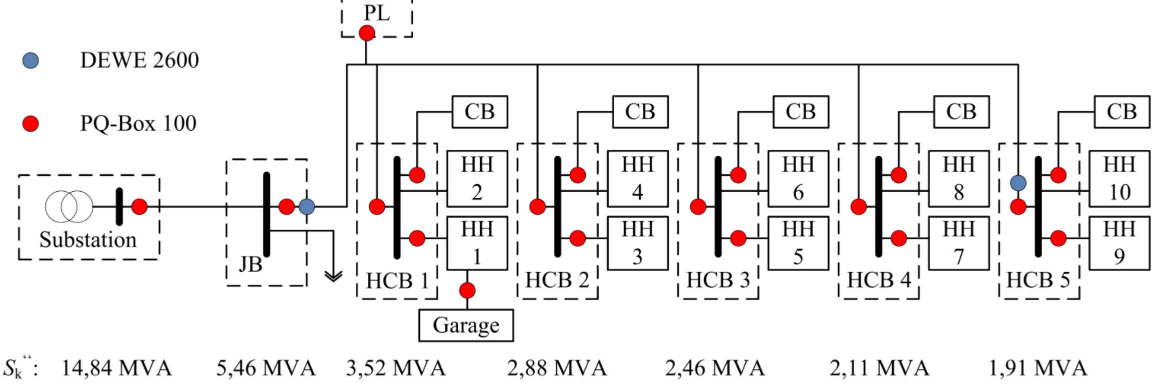

Figure 1: Single line diagram and short circuit power of the studied low voltage grid

The MV/LV transformer has a rated power of 630 kVA and supplies four feeders with more than 400 households (three phase connection). Five two-family houses and a public lighting system (PL) are connected to a junction box (JB) in one of the feeders. A single phase charging EV was provided to every household (HH) for one weekend. While the EV of HH 1 was connected to a socket in the garage, all other EVs were supplied by dedicated charging boxes (CB). To every CB two EVs can be connected. The CBs were connected to the house connection boxes (HCB). Fig. 1 shows the single line diagram including the short circuit power for different HCBs. It is a strong grid, because the lowest short circuit power in the studied grid is still four times greater than the power that corresponds to reference impedance.

Measurement details

The measurement sequence is divided into three parts; a coordinated charging (half day) following a pre-defined connection of the EVs to the phases, an uncoordinated (random) charging with a uniform distribution of the charging boxes to the three phases (one weekend) and a measurement without EVs for one week (reference). During the uncoordinated charging the residents used the EVs as they liked. During the coordinated charging, every two minutes a car was connected to its CB. The state with nine cars connected to one phase was kept for ten minutes. After that the EVs were disconnected step by step with a delay of 2 minutes.

The following measurement devices were used. The measurements up to 150 kHz were carried out by two Dewe 2600 and the harmonic measurements up to 2.5 kHz with 19 PQ-Box 100. The measurement interval of the PQ-Box is three seconds during the coordinated charging and one minute for all other measurements. Due to its dimensions the Dewe 2600 could only be used for the coordinated charging measurements. It was operated at a sampling rate of 1MS/s. The PQ Box 100 measured magnitude and phase angle up to the 50^{th} harmonic current and voltage. The connection points of the measurement devices are shown in Fig. 1.

INDIVIDUAL EV CHARACTERIZATION

For the field study ten EVs of four different types were used, namely one EV of type 1, two EVs of type 2, six EVs of type 3 and one EV of type 4. At least one sample of each type was extensively measured at a laboratory test stand which was especially designed for EV characterization [4].

Table 1: Switching frequency and emission level for diffrent types of electric vehicles

Type	Switching frequency		Emission level	
	Lab	Grid	Lab	Grid
EV1	27,2 kHz	27,3 kHz	335,1 mA	337,7 mA
EV2	-	-	-	-
EV3	37 kHz	35,4 kHz	84,7 mA	111,0 mA
EV4	100 kHz	100 kHz	7,3 mA	10,3 mA

All car types charge single phase with a constant charging current until the energy content of the battery has reached 95 % of the maximum energy content. At this point the charging current starts to decrease exponentially. Further details on the charging behavior and load modelling can be found in [4]. The EVs of type 3 interrupt the charging procedure for some minutes depending on the energy content of the battery at the beginning of the charging. This behavior can be seen in Fig. 7 (left) for EV_A (interruption) as well as EV_E and EV_F (switch off earlier than being disconnected). The charging current depends on the used charging cable and varies between 10 A and 17 A.

Regarding the harmonic emission Fig. 2 shows that the supply voltage waveform has a significant impact on the harmonic currents. While the sinusoidal waveform is usually used for the verification of emission limits, the flat top waveform is typical for residential low voltage grids. For some EV types and harmonic orders the difference in current magnitude between both voltage waveforms is relatively high. Therefore, future standardization work should take test waveforms into account, which are more realistic than the sinusoidal one. Further details about the harmonic emission of EVs are provided in [1].

The largest supraharmonic emission occurs at the switching frequency of the active PFC circuit of the charger. Table 1 presents the switching frequency and the corresponding emission level of the four different EV types. A detailed characterization of the supraharmonic behavior of EVs is given in [5]. EV 2 does not show recognizable supraharmonic emission. Therefore, neither an emission level nor a switching frequency is given in

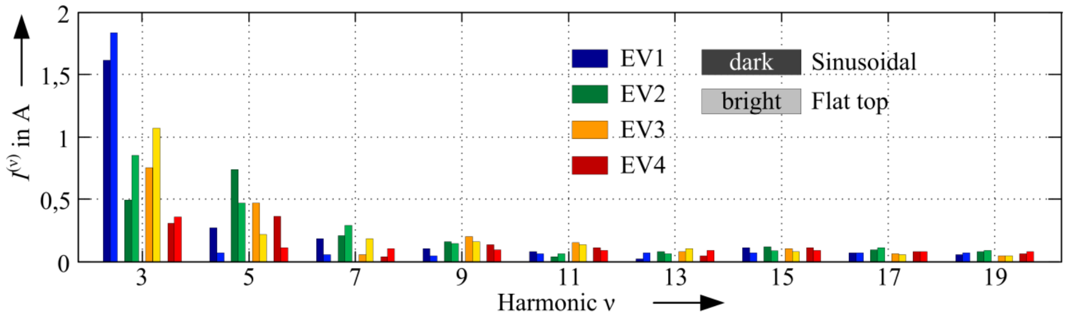

Figure 2: Magnitude of harmonic currents at different voltage distortion

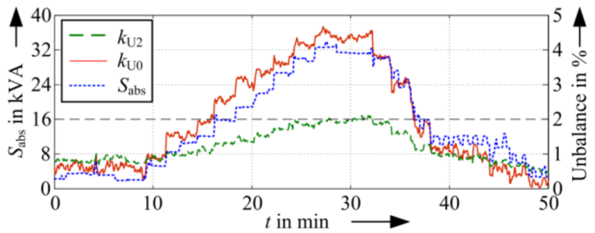

Figure 3: Voltage unbalance and absolute apparent power during coordinated charging

Table 1. It should be noted that the supraharmonic current emission for some EV types significantly depends on the impedance at the connection point of the EV (cf. grid vs. lab in Table 1).

IMPACT ON UNBALANCE

Based on the theory of symmetrical components for the fundamental frequency a negative sequence voltage unbalance factor k_{U2} and zero sequence voltage unbalance factor k_{U0} are defined as follows:

$$k_{U2} = \frac{|\underline{U}_2|}{|\underline{U}_1|} \qquad k_{U0} = \frac{|\underline{U}_0|}{|\underline{U}_1|} \qquad (1, 2)$$

Limits are only defined for the negative sequence unbalance. Fig. 3 presents both voltage unbalance factors at the household connection box HCB5, the limit for the negative sequence unbalance according to DIN EN 50160 and the total apparent power measured at the junction box JB during the coordinated charging, while all EVs were stepwise connected and disconnected to phase A. Unbalance increases proportional with the apparent power. Without connected EVs a background unbalance exists, which is caused by the other unbalanced loads and the unbalanced voltage in the upstream MV grid. When eight and nine EVs are connected, the limit of the negative unbalance is exceeded (green dashed plot in Fig. 3). In order to minimize the impact of car charging on the unbalance, the charging boxes were uniformly distributed to the three phases during the uncoordinated charging. However, due to the different usage behavior, the uniform distribution of the charging boxes is no guarantee for a symmetrical drawn charging current. Fig. 4 shows the number of EVs in every phase, the apparent power and the voltage unbalance for a Saturday with and without EV charging. Most cars were charged during the evening hours, some around noon. This behavior is also reflected in the apparent power. In the time between 7pm and 9pm there are three EVs connected to phase A and only one to phase B and C, respectively. For this case the negative sequence voltage unbalance has a peak of 1.6 %, which is lower than the limit but still 0.5 % higher than during the reference day without EV charging. This shows that even by uniform allocation of charging points to the phases unbalance levels can increase considerably. Therefore, further techniques are required in order to minimize the impact of single phase charging on unbalance.

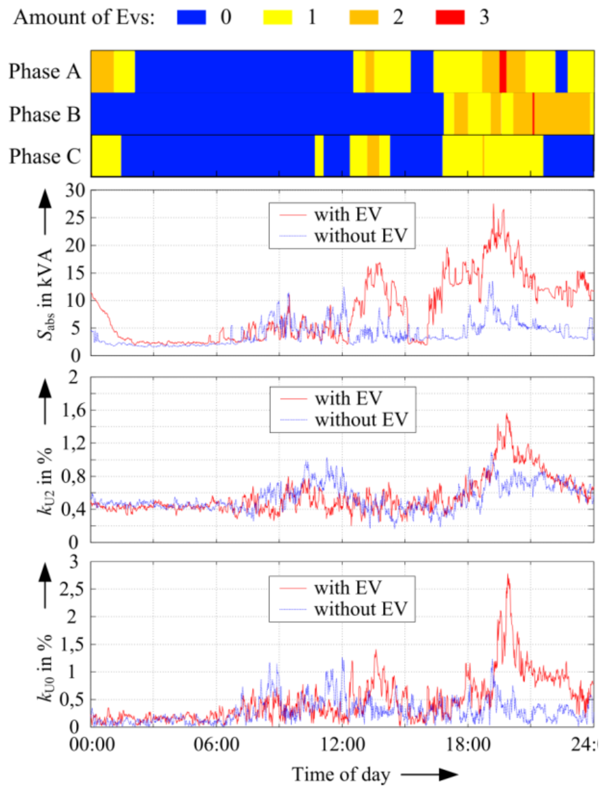

Figure 4: Amount of EVs, voltage unbalance and apparent power during a day (uncoordinated charging)

IMPACT ON HARMONICS

Every harmonic current and voltage can be described by magnitude and phase angle. Depending on the topology of the power electronic circuit the harmonic currents are nearly constant or they depend on the voltage distortion. Lab measurements have shown that the harmonic currents of EV charging further depend on the voltage magnitude and the charging state of the battery [1]. Fig. 5 and Fig. 6 (left polar plots) show the measured individual emission of the EVs for the third and fifth harmonic (realistic voltage distortion) in the complex plane. The EV types are distinguished by colors. The prevailing phase angle of the households is highlighted by the blue hatched sectors. The plots in the middle show the path of the harmonic current for the stepwise connection of the EVs to phase A during the coordinated charging. Finally, the right plots show the time characteristic of the magnitude of the harmonic current and the difference of the harmonic voltage between the last household connection box (HCB 5 / Fig. 1) and the junction box JB.
For the third harmonic the prevailing phase angle of the household loads and the EVs are almost in phase (Fig. 5). Therefore, the third harmonic current and voltage increase with increasing number of EVs. The current increases from about 1 A to 8 A. The magnitude of the third harmonic voltage at the household connection box 5 is higher than at the junction box, it is "amplified" along the feeder.

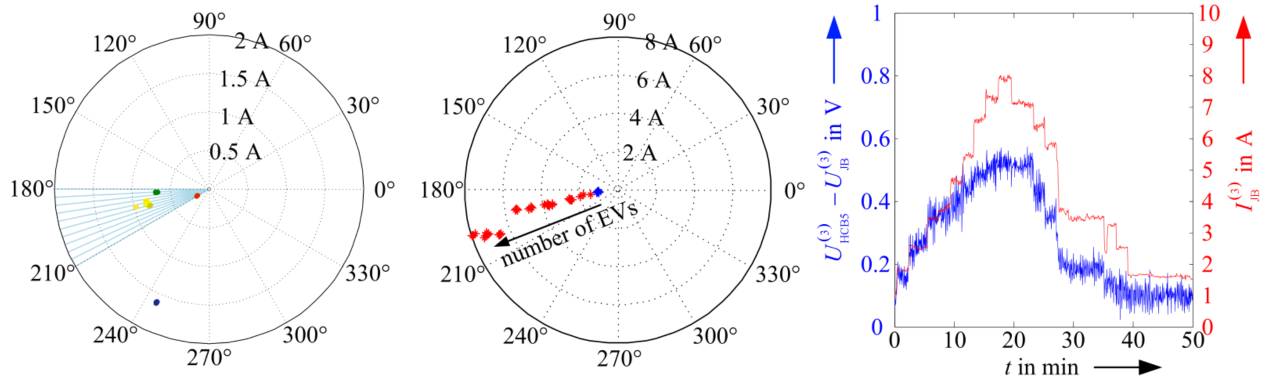

Figure 5:Third harmonic current of EVs and houshold loads and theirimpact on the third harmonic voltage

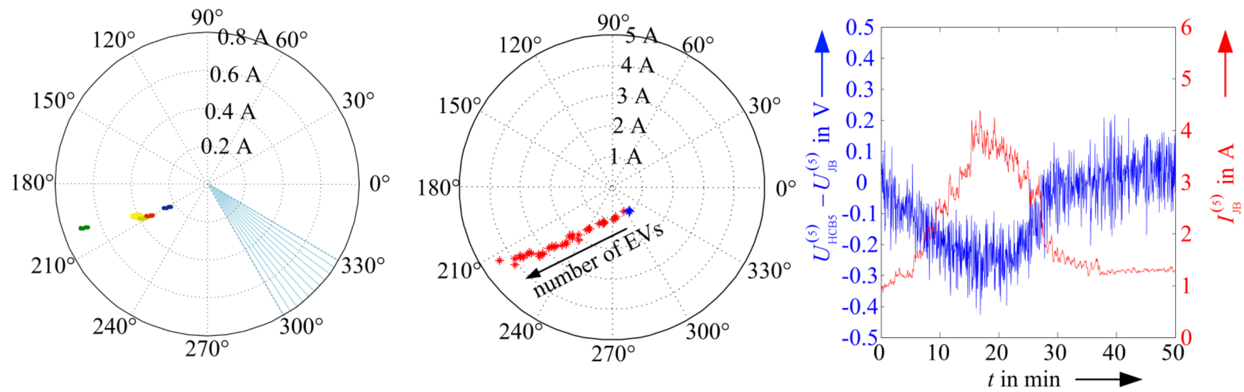

Figure 6:Fifth harmonic current of EVs and houshold loads and their impact on the fifth harmonic voltage

The prevailing phase for the fifth harmonic current of household loads differs by about 90° to the phase angle of the EVs (Fig. 6). This shifts the fifth harmonic current from fourth to third quadrant and consequently, it results in a slight compensation effect in the fifth harmonic voltage along the feeder. The harmonic current increases from 1 A to 4.5 A. Fig. 5 and Fig. 6 show that the emission of the EVs dominates the total harmonic emission of the feeder. Furthermore the impact on the harmonic voltage levels can be positive or negative and is not consistent for different harmonic orders. General conclusions about the impact on the harmonic emission are therefore virtually not possible.

IMPACT ON SUPRAHARMONICS

Fig. 7 (left) shows the charging current for each individual EV during their stepwise connection during the coordinated charging. As already mentioned all EVs with the exception of EV_B are connected to phase A.
The middle diagram in Fig. 7 presents the spectrogram of the charging current that was measured at the junction box JB. The Y-axis represent the frequency, the X-axis the time and the intensity of the color represent the magnitude of emission. The right diagram shows the corresponding voltage emission. The supraharmonic emission of the EVs can be clearly recognized. Based on the switching frequencies in Table 1 it is possible to identify which EV type is charging.

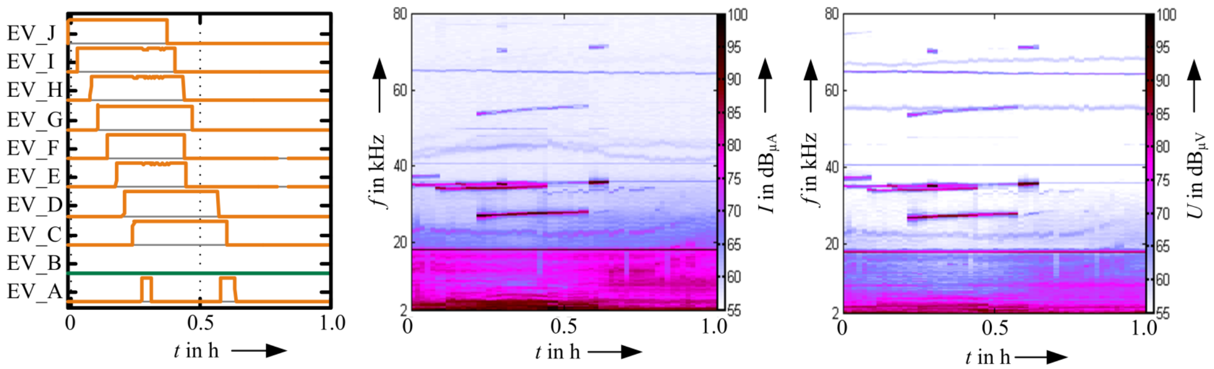

Figure 7:Overview of individual EV charging cycles and the current and voltage supraharmonics (coordinated charging)

An additional emission can be observed at 18 kHz. This emission is caused by a PV-installation, which is connected to one of the houses. Because of the grid impedance, the current supraharmonics generate significant voltage distortion at switching frequencies. It seems that the current emission between 4 and 25 kHz slightly decreases as a result of the EV charging. The reason for this effect is the input impedance of the EVs, which operate as a filter for this frequency range. Most of the supraharmonic current flows between individual devices and does not propagate very far in the grid [6]. In many cases the magnitude of supraharmonics at switching frequency decreases quickly with increasing distance from its source.

CONCLUSION

In a realistic field study the impact of electric vehicle charging on unbalance, harmonics and supraharmonics (2-150 kHz) in an urban low voltage grid was analyzed. A high penetration with EVs was simulated and the results show a considerable impact on the above mentioned PQ parameters.

Single phase connected EVs can have a significant impact on *unbalance*. The effect on the zero sequence unbalance is higher than on the negative sequence unbalance, because the zero sequence impedance at connection points away from the distribution transformer is higher than the negative sequence impedance. If the EVs are not equally distributed to the phases, the limit of negative voltage unbalance is likely to be exceeded. Because of the user behavior even an equal distribution of the charging points to the three phases is no guarantee for a low unbalance. Only a three-phase charging can reliably ensure that voltage unbalance is not affected.

The impact on *harmonics* considerably depends on magnitude and phase angle of the charging current harmonics. The voltage distortion can have a significant impact on the charging harmonic currents. In urban grids with residential customers the third harmonic current of EV is almost in phase with the existing harmonic current emission. Consequently, the third harmonic voltage increases with the number of EVs. The phase angle of the fifth harmonic current of EVs and house hold loads are different. As a result the fifth harmonic current shifts from the fourth to the third quadrant. The fifth harmonic voltage is slightly reduced by the EVs. This will turn, if the penetration of EVs dominates the third harmonic emission in LV grids on large scale.

Measurements of *supraharmonics* show that most of the switching frequencies of EVs are in the range between about 10 and 100 kHz. The emission level of the current supraharmonics can become 1 A and even more. A standardization framework, especially compatibility levels and emission limits in the range between 2 kHz and 150 kHz are urgently required.

The paper shows that a high penetration of EVs can have a significant influence on Power Quality and research in this field is still required. The lab measurements of individual EVs are available in the equiPment hArmoNic DAtabase (PANDA), which can be accessed via the Internet under http://panda.et.tu-dresden.de. Further information can be found in [7] or on the website.

A key issue for realistic simulations is a sufficient accurate modelling of the interaction between the EVs and the other equipment connected to the public LV grid. Case studies play an important role in the verification and further improvement of models.

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REFERENCES

[1] F. Möller, J. Meyer, P. Schegner, 2014, “Load Model of Electric Vehicles Chargers for Load Flow and Unbalance Studies”, *Electric Power Quality and Supply Reliability Conference (PQ)*, Rakvere, Estonia, June 2014

[2] S. Müller, J. Meyer, P. Schegner, 2015, “Characterization of Electric Vehicle Chargers for Harmonic Modeling in Frequency Domain”, *International Conference on Renewable Energies and Power Quality (ICREPQ)*, La Coruña, Spain, March 2015

[3] C. Jiang, R. Torquato, D. Salles, W. Xu, 2014, “Method to Assess the Power-Quality Impact of Plug-in Electric Vehicles”, *International Conference on Harmonics and Quality of Power (ICHQP)*, Bucharest, Romania, May 2014

[4] A.J. Collin, S.Z. Djokic, H.F. Thomas, J. Meyer, 2011, “Modelling of Electric Vehicle Chargers for Power System Analysis”, *International Conference on Electrical Power Quality and Utilisation (EPQU)*, Lisbon, Portugal, October, 2011

[5] S. Schöttke, J. Meyer, P. Schegner, S. Bachmann, 2014, “Emission in the Frequency Range of 2 kHz to 150 kHz caused by electrical vehicle charging”, *International Symposium on Electromagnetic Compatibility (EMC Europe)*, 2014, Gothenburg, Sweden, September 2014

[6] S. Rönnberg, M. Wahlberg, M. Bollen, A. Larsson, M. Lundmark, 2009, “Measurement of Interaction between Equipment in the Frequency Range 9 to 95 kHz”, *International Conference on Electricity Distribution (CIRED)*, Prague, Czech Republic, June 2009

[7] A. M. Blanco, E. Gasch, J. Meyer, P. Schegner, 2012, “Web-based Platform for Exchanging Harmonic Emission Measurements of Electronic Equipment”, *International Conference on Harmonics and Quality of Power (ICHQP)*, Hong Kong, China, June 2012