# HOW TO DEAL WITH ELECTROMAGNETIC DISTURBANCES CAUSED BY NEW INVERTER TECHNOLOGIES CONNECTED TO PUBLIC NETWORK

Xavier YANG
EDF R&D - France
xavier.yang@edf.fr

Ludovic BERTIN
EDF R&D - France
ludovic-g.bertin@edf.fr

## *ABSTRACT*

*This paper is intended to give first an overview of power quality simulation methods. A proactive approach for non-linear load modelling is then studied as adequate method for assessing power quality issues resulted from new inverter technologies. Different modelling methods of nonlinear loads are considered for various power quality phenomena such as voltage fluctuation, flicker, harmonic and HF disturbances (f> 2 kHz). Particularly, local time domain modelling method is proposed to evaluate the interaction between disturbance sources.*

*According to disturbance frequencies and profiles, different modelling approaches are presented and studied: parameter variation, equivalent multi-frequency current and voltage source, local time domain modelling, hybrid simulation, built-in statistical functions.*

*In the end, a case study is carried out with proposed modelling methods in order to deal with on-site observations: 1). disturbance interaction between nonlinear loads, 2). increase of HF disturbances caused by aging issues of electrical appliances, that may become potential issues for communication based on power line carrier.*

***Key words:*** *Nonlinear load modelling, RMS transient, hybrid simulation, HF disturbances, local time domain model, power quality deterioration by aging issues.*

## INTEGRATION OF ELECTRONIC DEVICES WITH NEW INVERTER TECHNOLOGIES

The main subject addressed in this paper is to deal with electromagnetic disturbances caused by new inverter technologies connected to public grid including microgrid and local networks. One of the important power quality signatures of these new devices is the non-characteristic HF disturbances that lead to more and more difficulties in assessing distribution grid power quality. In fact, disturbance loads were traditionally considered as multi-frequency constant current source representing mainly thyristor-based converters which are less sensitive to grid background harmonics. Therefore, since the recent decade and thanks to power electronic achievements, new electric appliances are built with modern inverter technologies and directly connected to public distribution network. These new devices are generally composed of input LC filter, rectifier, capacitive DC bus and controllable inverter. Consequently, they are intrinsically sensitive to voltage quality in the point of connection (POC). Fig.1 shows some recent electric devices with their input current wave shapes and spectra. New phenomena are observed: a). Important disturbance with wide frequency range. b). Presence of spectra around the chopping frequencies of embedded inverter and the resonance frequencies between the upstream grid impedance and the device input filters.

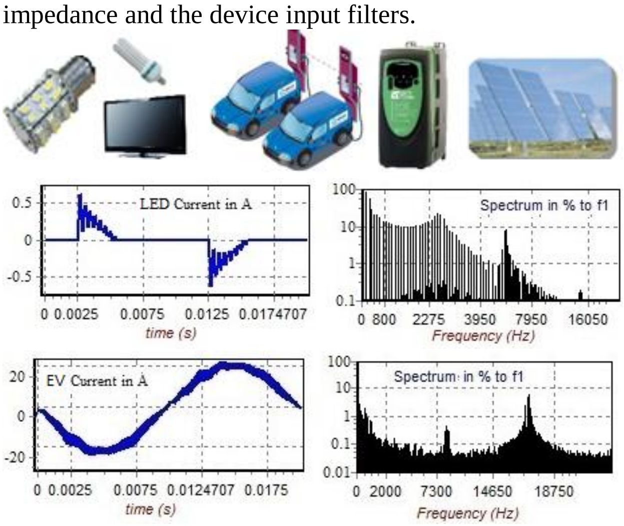


**Fig. 1 – New electronic devices: their frequency range may largely exceed 2 kHz**

The integration of some new electronic devices to the distribution grid may cause new power quality issues. From our on-site investigations, it is observed there exist important current spectra > 2 kHz at the inputs of some new LV appliances such as LED lamps and electric vehicle (EV) charger (Fig.1). The integration of these new devices is thus one of the important challenges in smart grid development.

In the past, some engineers thought there were no power quality issues at all in future DC electric network. One of our recent studies on a concrete DC micro grid witnesses that even in DC distribution network. In reality, the integration of new nonlinear loads is not so easy, there always exist transient disturbances and even HF issues. Furthermore, disturbances may propagate easier in DC grid than in AC because there are no attenuation components, AC transformers for instance.

Today, there are less and less linear and purely resistive loads directly connected to the grid, i.e. less damping effects on electromagnetic disturbances. The integration of the new inverter technologies may conduct to different consequences on distribution grid and arise the needs of new modelling method, simulation tools and laboratory testing facilities. It is emphasized that modern inverter technologies have following power quality behaviours:

- They are both dynamic disturbance sources and sensitive loads regarding to grid background voltage disturbances.
- They behave as multi-profiles such as consumer, generation, nonlinear and transient loads.
- New EMC issues resulted from non-characteristic disturbances (>2 kHz) besides conventional low harmonic frequency disturbances (<2 kHz): lack of international standards and regulations.
- They bring more capacitance between phase and ground to the grid, so more issues concerning zero sequence voltage and current, common mode disturbances for example.

## DEALING WITH POWER QUALITY ISSUES WITH DEDICATED MODELING METHODS

Power quality assessment covers important research topics [1] [2] from grid simulation to nonlinear load modelling. Our research team has carried out a number of on-site investigations, laboratory tests and modelling works for years. Particular attention has been paid on the issues mentioned above and different actions have been accomplished when dealing with the new power quality issues and developing research competences. Simulation platform and laboratory testing facilities have been built in order to study adequate modelling methods and fit them with laboratory tests.

Different methods of nonlinear load models are studied for power quality analysis. Fig.2 represents 5 main modelling approaches used for power quality assessments according to the relevant technical topics.

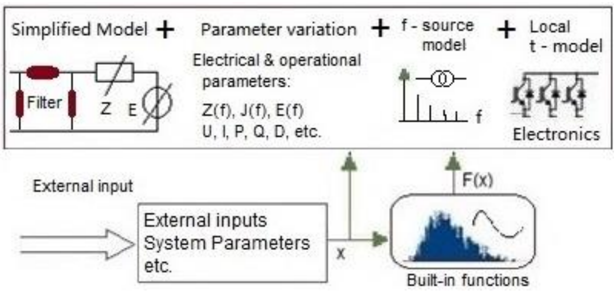


**Fig. 2 – Proposed model of nonlinear load based on new power electronic technologies**

The above model structure is detailed in the following sub-sections in accordance with actual application areas.

### Approach 1: RMS parameters variation for analysing voltage fluctuation and flicker (f < 50/60Hz)

The disturbances under 50/60 Hz may be studied by means of modifying dynamically different parameters of the equivalent RMS model of nonlinear loads. Parameter variations or RMS transient can represent voltage, current and power behaviours within each working states of modelled loads. In fast voltage fluctuation and flicker modelling, the sampling cycle should be less than one period of fundamental frequency, 10ms for instance in 50Hz system. It is possible to reproduce time-based RMS value evolution of active and reactive powers by varying the relevant parameters Z and E in Fig.2 of a nonlinear load model representing photovoltaic (PV) inverter or energy storage system.

The curves in Fig.3 are the PV active and reactive powers modelled by parameter variation based on on-site recordings (one typical day curve of 400kVA system). This model was used in local distribution voltage level assessment and grid planning studies.

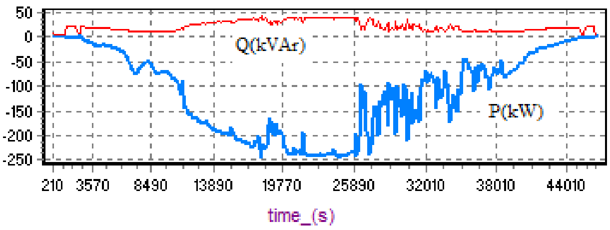


**Fig. 3 – Dynamic PV power evolution modelled by variable electrical parameters (grid connected mode)**

Applications: working cycle simulation of washing machine, air conditioner, heat pump, welding machine, oven for thermal processing, wind turbine, PV, etc.

### Approach 2: Equivalent frequency domain source model (f>50/60Hz)

In majority of cases, the harmonic distortion assessments are done in the frequency domain. Therefore, for new power electronic inverter, it is not always adequate to represent a nonlinear load by an equivalent current source (or Source J in Fig.4). In modelling energy storage system or renewable energy source, dedicate equivalent voltage source model (Source E in Fig.4) should be used when assessing harmonic interaction between grid and disturbance loads [6], especially in island mode.

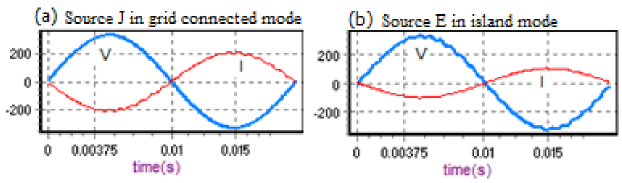


**Fig. 4 – Frequency domain equivalent source models**

Particular attentions must be paid when using individual equivalent harmonic source method in order to get reasonable disturbance summation effects on the whole electric grid:

- All frequency spectra have to be synchronized with fundamental frequency of the power supply.

- Three-phase harmonic source model must follow the grid voltage sequences.
- Take into account upstream grid equivalent model at the point of connection (POC) in order to build adequate disturbance spectra for steady state study.
- Representation of all losses for f > 50/60 Hz.

In modelling power quality issues caused by new power electronic inverters especially for f > 1 kHz, frequency behaviours should be taken into account such as skin and proximity effects. The skin effect depends directly on frequency [3], and proximity effect concerns the alternating flux in a conductor caused by the current of the other nearby conductors. This flux produces a circulating current or eddy current in the conductor which results in an apparent increase in the resistance of the wire and; thus, more power losses in the windings. This kind of eddy current is basically due to the frequency components of PWM current generated by electronic-based inverters.

Heat in the electrical distribution system is a major source of electrical losses in facilities. Wires in power lines and transformers are major sources of heat in distribution system. High frequency noise > 1 kHz is responsible for both skin and proximity effects which are important contributors to heat. In key grid component modelling such as power transformer, line or cable, skin and proximity effects should be taken into account. Fig.4 gives the real part *Re* of the impedance in Ohm of the model of 1MVA, 20/0.4kV power transformer and 0.5 km overhead line. At fundamental frequency f1 = 50Hz, *Re* is 0.18 Ohm, the skin effect is very apparent for f > 1 kHz. In high frequency disturbance studies, frequency-depended modelling should be used.

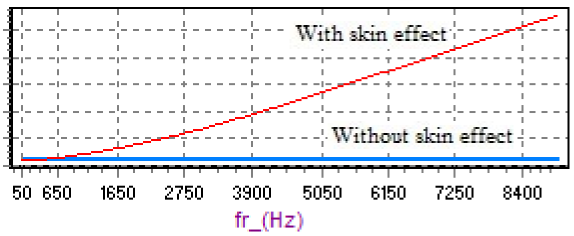


**Fig. 5 – Real part of the impedance of transformer + overhead line (values in Ohm)**

Applications: Studying the disturbances resulted from electronic converters installed in electrical appliances: adjustable speed drives (ASD), decentralized energy sources (DES), energy storages, electric vehicles (EV).

### Approach 3: Local time domain model of nonlinear load within hybrid simulation platform

When assessing accuracy harmonic behaviours and disturbance interactions, time domain modelling methods are employed. But the practical constraints of this method are the heavy computation burden and the knowledge of detail disturbance load structures, especially if analysing a whole electric power grid (> 1000 nods for instance) with the integration of different nonlinear loads.

For important nonlinear loads based on power electronic devices with variable disturbance profiles, one of the interesting approaches is to represent the equivalent power electronic structure (grid-connected part) by time domain modelling and dedicated solver. This method includes the development of local time domain solver for the solution of the equivalent time domain load structures such as PV inverters. The time domain models can be obtained by converting frequency domain equations into time domain ones with appropriate discretization methods [4]. This allows on easy mapping from the s-plane to the z-plane. The frequency domain nodal equations are thus discretized into to a time domain matrix. Another method is to create directly time domain differential equations for a given power electronic device structure [5]. Fig. 6 illustrates the phase current of a PV inverter simulated by local time domain module based on the first method with sampling frequency of 204.8 kHz. The spectra obtained by this method are much more adequate compared to the relevant grid impedance used. The spectrum around 5 kHz is the chopping frequency and 2.8 kHz is resonance frequency of input filter and the grid.

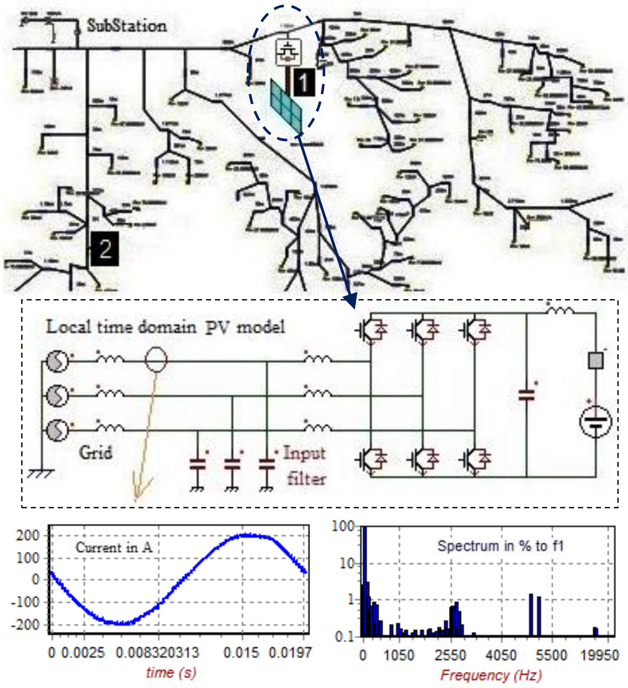


**Fig. 6 – Phase current and spectrum of the PV inverter simulated on local time domain platform**

The proposed local time domain method can represent the interaction between nonlinear load and upstream grid parameters (background disturbance and grid impedance) with acceptable accuracy. Another advantage of this method is to integrate as many as possible nonlinear loads in the overall grid simulation based on grid data base. If an important number of nonlinear loads is connected to the same grid, parallel simulation may be carried out. It is possible to assess the disturbance interactions among different nonlinear loads if an iteration algorithm is used.

In the example of Fig.6, the upstream grid at point 1 is represented by equivalent multi-frequency Thevenin network extracted from grid data base. Generally, Thevenin network should be used to represent the relevant upstream grid at the POC where each local time domain model is connected.

A number of common local time domain models have been created in our simulation platform to simulate rectifiers and inverters used in general LV appliances.

Applications: dealing with the harmonics resulted from new inverter technologies such as diodes and transistors rectifiers + inverters (switching power supplies, ASD, EV, PV, wind generators and energy storages).

**Approach 4: Model with built-in statistical functions**

For the purpose of improving energy efficiency and controllability, more and more closed-loop control algorithms are embedded in new converters. These algorithms make extra difficulties in harmonic assessment as they work almost always in dynamic regulation. Consequently, harmonic magnitude and phase angle become variable, so combined deterministic and probabilistic models should be considered. That is the reason why we have developed built-in statistical functions in all generic nonlinear load models in order to assess overall disturbance level with adequate summation effects. According to the actual load control patterns, standard Normal or Weibull distributions may be applied to represent symmetrical and unsymmetrical phenomena. On-site recording shows for example that grid voltage harmonic distortion doesn't always follow the standard Normal distribution. In most cases, it distributes likely asymmetrical distribution. Fig.7 shows the voltage distortions (Thd-U) measured during 1 week by 10min values: curve (a) for LV bus bar of a tertiary building, curve (b) for a household 230V outlet. One of the physical senses of asymmetrical distribution is that the Thd_U of LV grid is rarely very small even no there is local disturbance loads because of the presence of background disturbances from upstream grids.

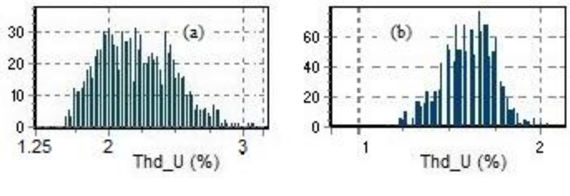


**Fig. 7 – Probability densities of Thd-U measurements**

The proposed built-in statistical functions include both symmetrical normal distribution with well-known Box-Muller method and asymmetrical Weibull distribution. The last one may be used to represent on-site recordings and create an equivalent statistical model of nonlinear loads. The probability density is as:

$$f(x;k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}$$

Where $k > 0$ is the shape parameter and $\lambda > 0$ the scale parameter of the distribution.

Applications: 1). Assessment of overall harmonic levels from different disturbance sources along with different time scales. 2). Post-data processing in order to obtain general rules on disturbance propagations and impacts on the grid. 3). Evaluation of the contribution of each disturbance source.

**Approach 5: The transfer function method for whole grid power quality assessment**

When assessing the impact on the whole grid resulted from different disturbance sources, we recommend using frequency domain transfer function methods to obtain the overall influences caused by nonlinear loads. Three type transfer functions may be computed:

- From harmonic current to harmonic voltage (local impedance method) at POC: to evaluate local power quality impact.
- From harmonic current at the POC to harmonic voltage at the substation or the point of common coupling (PCC), i.e. global impedance method: to assess the impact on the whole grid.
- From harmonic current at the POC to harmonic current at the substation or PCC: to assess the impact with absolute values and magnification effects.

The transfer function method is very simple to be set in a simulation tool and it is possible to evaluate the degree of impact and identify the optimised physical location where a nonlinear load may be connected. Furthermore, it is also possible to quantify and compare the magnification and damping coefficients at each disturbance frequency.

Applications: Optimization of the integration of nonlinear loads among different points on the grid, identification of resonance frequencies, and quantification of disturbance magnification coefficients.

## CASE STUDY

The case study (see Fig.6 for electric circuit) is about the integration of nonlinear loads (400kVA PV inverter and 10W USB charger) to the distribution grid. The PV inverter generates two principal sets of disturbances around 2.8 and 5 kHz. The main purpose of this case study is to verify the phenomena observed by on-site measurements: HF current increases at the input of USB charger (particularly for aged one) when PV works in day time. Two local time domain models are used in Fig.4: position 1 for PV inverter and position 2 for power supply of USB charger. Four different working states have been simulated by proposed methods (input charger's currents are shown in Fig.8):

(a) No presence of the PV inverter, charger is normal
(b) No presence of the PV inverter, charger is aged (DC capacitor C1 value decreases by 4 times)
(c) Presence of the PV inverter, charger is normal
(d) Presence of the PV inverter, charger is aged (DC capacitor C1 value decreases by 4 times)

In the above four situation, active power of the charger is PID-regulated as constant value by variable R1.

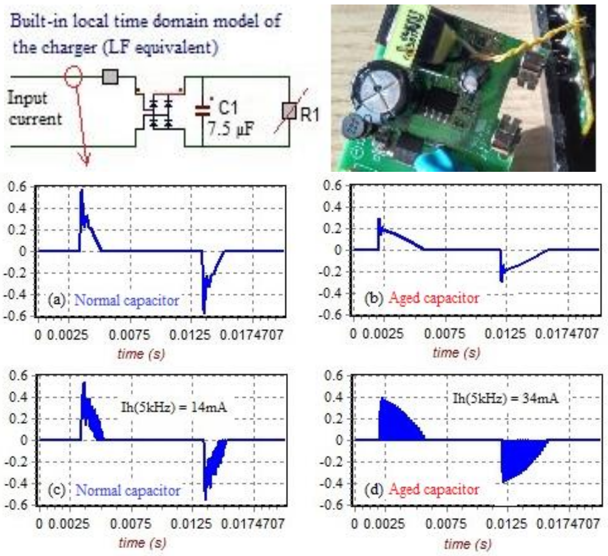


**Fig. 8 – Charger input currents in A simulated with local time domain models for different working states**

Here are the main outcomes from the above case study and the proposed methodologies:

The hybrid time and frequency domain modeling method can assess the interaction between the background grid voltage disturbance and the current interference generated by local nonlinear loads. In Fig.8, input currents of the charger (a) (b) are near the results obtained from equivalent current source modelling method (with or without the PV inverter), and curves (c) (d) from proposed local time domain model. The equivalent current source method leads to important errors.

The aging issue (devaluation of DC capacitor in switching power supply of LV appliances) increases the resonance frequency with grid from the initially designed value. This may magnify HF disturbance (>2 kHz). From the curves (c) and (d), it is observed that the disturbance current at 5 kHz is amplified from 14 to 34 mA. This phenomenon may cause potential problem for communication systems based on power line carrier.

## CONCLUSION

Different nonlinear load modelling approaches are put in force for power quality assessment.

For power quality studies f < 50/60 Hz such as sag, surge, voltage fluctuation and flicker, parameter variation is one of the simplest methods that are easy to integrate in general power grid simulation tools with RMS transient.

For harmonic issues caused by conventional disturbance sources based on Thyristor power electronic installations, equivalent multi-frequency current source method can be used. Furthermore, if nonlinear load is composed of decentralized generation, equivalent voltage source method should be used, especially in island mode.

For harmonic issues and disturbances (f > 2 kHz) caused by new inverter technologies, it is recommended to use time & frequency hybrid simulation with embedded local time domain models for main nonlinear devices. This method can well reproduce disturbance spectra and represent the disturbance interaction among different sources. The simulation in the case study verified the on-site observation as well as identified one of the potential HF disturbance magnification which may be further deteriorated by aging issues of customer appliances.

## PERSPECTIVES

If many nonlinear loads are modelled by local time domain modelling method for time domain (transient) & stability hybrid simulation within a large scale electric grid, stability studies are necessary to guarantee the reliable results and minimize computation time.

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