DISTURBANCE LOAD MODELLING WITH EQUIVALENT VOLTAGE SOURCE METHOD IN GRID HARMONIC ASSESSMENT

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ABSTRACT

The subject addressed in this paper is to recommend using equivalent multi-frequency voltage source method, instead of conventional current source method, in assessing harmonic aspect of some new nonlinear loads. In grid harmonic assessment, we suggest to model the disturbance load by multi-frequency voltage source. This approach can bring about some interaction between disturbance source and grid parameters such as impedance and background harmonics. In fact, new disturbance loads are mainly built with transistor-based converters, ie, voltage source converters.

Another advantage of proposed method is to study power quality issues inside micro grid, even in island mode the equivalent multi-frequency voltage source can be used to study power quality behaviour when switched in to voltage/frequency control (VF) mode.

In the end, two case studies have been carried out with acceptable results compared to on-site measurements.

Keywords: *Harmonic impedance, high frequency harmonics, voltage source converter, micro grid.*

INTRODUCTION

In grid harmonic assessment, disturbance load was often modelled as constant multi-frequency current source. This simplified approach had resulted in acceptable result in the past. In fact, disturbance loads were mainly built with thyristor-based converters, ie, line-commuted converter with current source nature. Current harmonics at the input of this type of converter are mainly defined by DC bus filter, only a little bit influenced by grid voltage and impedance. For this reason, disturbance load could be modelled by constant multi-frequency current source in simplified harmonic assessment (Fig. 1).

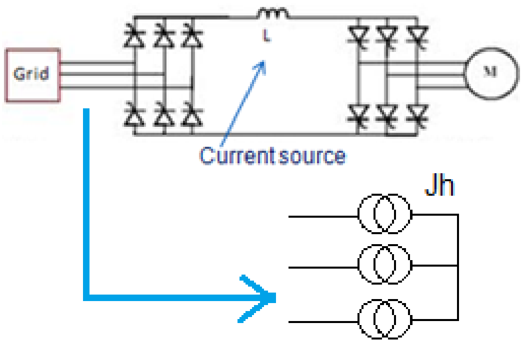


Fig. 1: Equivalent harmonic current injection method

For recent utility and end-user power quality studies, some harmonic issues show that equivalent current injection is not suitable to reveal actual disturbance behaviours such as harmonic interaction. For instance, this type of equivalent model can't interact with the back ground voltage harmonics from upstream grid as the equivalent current source is modelled with infinite internal impedance.

Furthermore, the load type changes today: more and more voltage source converters based on transistors are used in MV and LV equipment such as switching power supplies, Adjustable-Speed Drive (ASD), EV, PV, Voltage Source Converter (VSC)-HVDC, etc. The behaviour of these new nonlinear loads changes considerably: they act no more as current source, but as voltage source with input passive Electromagnetic Compatibility (EMC) filter. For example, a general LV switching power supply is composed of a rectifier with DC capacitor that acts with voltage source behaviour (Fig. 2). The input ac current harmonic is considerably influenced by grid voltage and impedance. Apparently, the harmonic injection of this device shouldn't be modelled by constant equivalent current source. Especially for transient response, some interaction with grid impedance or background harmonics should be taken into account. Therefore, we should change modelling methods according the nature of actual non linear loads.

The subject addressed by this paper is to recommend using equivalent voltage source method in harmonic assessment of some new nonlinear loads. The following figure shows the voltage source method which may be used to model the new power electronic devices such as ASD.

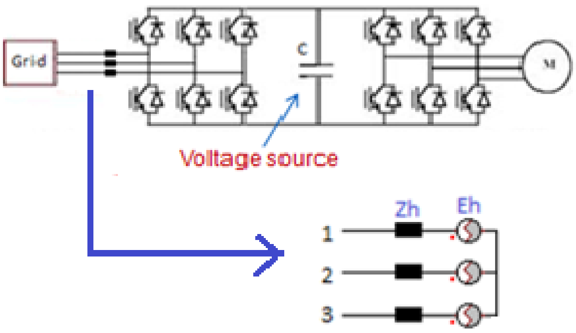


Fig. 2: Equivalent harmonic voltage source method

EQUIVALENT VOLTAGE HARMONIC SOURCE METHOD

Why using voltage source method

A frequency domain simulator can carry out power quality assessment in a large scale grid with a low computing burden; therefore, this approach has accuracy issues while dealing with time-varying and non-linear loads such as power electronic equipment with equivalent current injection method.

As mentioned above, today, there are more and more new types of power electronic devices connected to the grid. Although harmonic injection level is under control by different international and national standards, the presence of some high frequency harmonic currents > 2kHz in these new devices is not yet limited efficiently by current standards and grid codes. In practice, the impact of high frequency harmonics should not be neglected. They may reduce lifespan of other electronic devices and even disturb grid communication based on PLC (Power Line Carrier). In other side, new electronic devices are also sensitive to grid back ground high frequency voltage harmonics. The figures 3 and 4 below show the current wave shapes of a PV inverter when it is powered by different voltage supplies. Fig. 3 is with sinusoidal voltage supply. Fig. 4 is with a grid voltage disturbed by harmonics (voltage THD=5.053%, < 9 kHz). The measurements show that this inverter is very sensitive to the harmonic voltages. The input current THD changes from 5.225% to 24.75% in case of disturbed power supply voltage.

The above laboratory tests indicate the necessity to represent by simulation the interaction between grid background voltage harmonics and the current harmonic emission from nonlinear load.

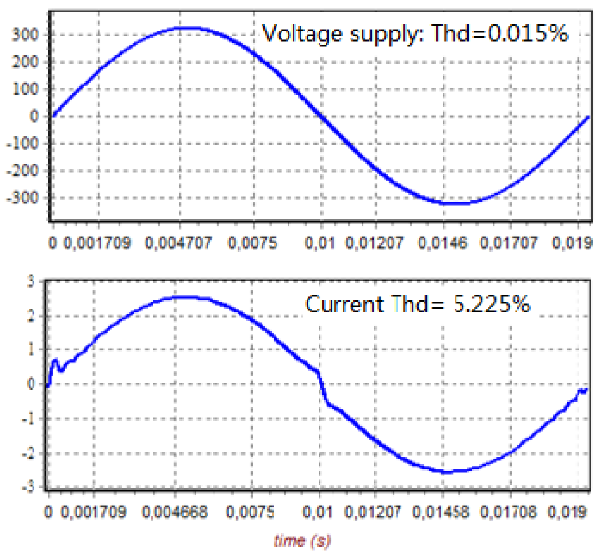


Fig. 3. Current of PV inverter with sinusoidal power supply voltage

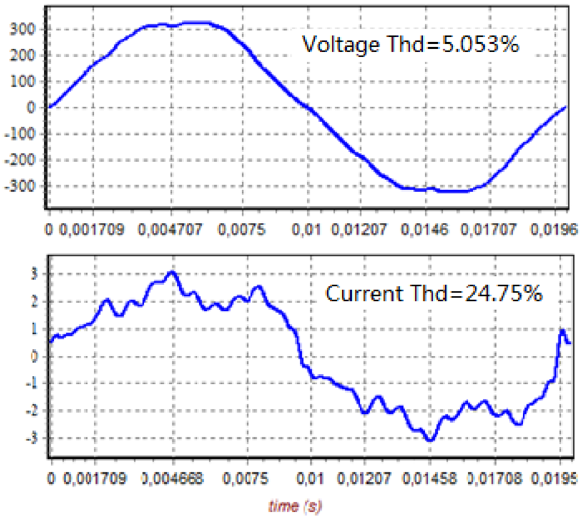
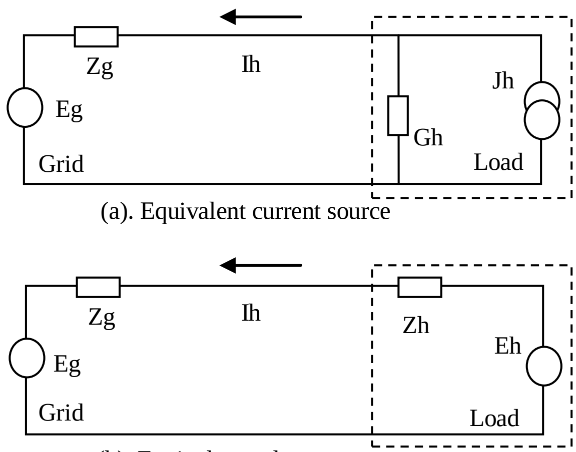


Fig. 4. Current of PV inverter with non-sinusoidal power supply voltage

It is possible to estimate the above phenomenon by the proposed voltage source method. In recent practical applications such as PV and energy storage system integration, the grid-connected converters are almost all voltage source type. Furthermore, in micro grid working mode, these converters may play a role of power supply as VF node. It is thus reasonable to model these devices by equivalent harmonic voltage sources. According to Thevenin/Norton transfer theory, a nonlinear load can be theoretically represented by either current source or voltage source method at each studied frequency in terms of external equivalent behaviour (Figure 5). But in practice, a pure current source was used as it is difficult to define the parallel admittance of the current source. When connecting these models to an electric power grid for power quality assessment, the results may be very different for these two equivalent methods such as in internal harmonic interaction and harmonic impedance assessment, etc.



(b). Equivalent voltage source

Fig. 5: Two reciprocal modelling methods of disturbance loads

In comparing the above equivalent circuits, it is observed that in voltage source equivalent circuit (b), it is easier to model the disturbance source impedance, and the disturbance load acting as voltage source may become power supply in micro grid mode. That means, we can use the same source to carry out power quality assessment even in island mode.

Relations in proposed modeling method

In Fig. 5 (b), at each harmonic frequency, the harmonic injected into the grid is defined as follow:

$$\mathrm{Ih} = \frac{\mathrm{Eh} - \mathrm{Eg}}{\mathrm{Zh} + \mathrm{Zg}}$$

This formula indicates that the current injection of a nonlinear load has no more current source behaviour; it depends on the equivalent harmonic voltage source values and the impedance values. There are two cases to define harmonic source:

- If Eh is known, the current injection Ih can be assessed by the above formula.
- If Ih is known by equipment supplier's information or by limited values, the internal voltage harmonic source Eh can be computed by Ih, Eg and Eh.

Grid impedance Zg and background harmonic Eg

For simplifying actual case, it is possible to use grid short circuit power to define grid impedance Zg, or for more accurate case to simulate Zg frequency curve based on grid data base. The grid back ground harmonic Eg may be also assessed by on-site measurement or by planning levels.

Internal harmonic source impedance Zh

Generally, Ih may be set by limited harmonic values or defined by manufacturer's data sheet. The difficulties are how to determine internal impedance Zh and Eh.

<u>By dynamic short-circuit power ratio</u>

For very simplifying actual case, we can set either constant ratio Zg/Zh according to short-circuit levels or use predefined impedance curves of Zg and Zh from manufacturer's data if available. This ratio is one of the key parameters to quantify the short-circuit power level when Eh is used as power supply in island mode of micro grid.

For example, the nonlinear load is 50kVA PV inverter with 150kVA dynamic short-circuit power. It is connected to 400V LV grid with short-circuit power of 3MVA at the PCC. The grid impedance Zg is about Z1=0.031525 + j0.0441. For starting a frequency domain simulation, the harmonic source impedance can be estimated as:

Zh = Zg*3000/150 = 0.631 + j0.882.

This method is very simple approach, it may conduct some error compared to the reality, but it is more realist than equivalent constant current source method.

It is also recommended to take into account input EMC filter for power quality assessment (Fig.6).

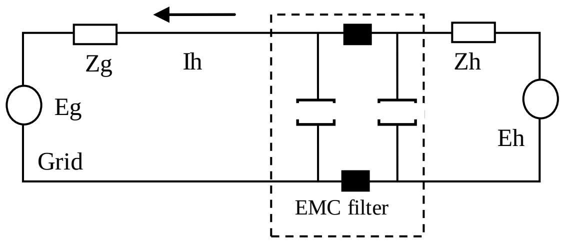


Fig. 6: Voltage source method with input EMC filter

Generally, it is easy to get EMC filter's technical parameters. This filter has an important impact in HF harmonic study. It is suggested to deal with EMC filter as an independent added-in part on the impedance Zh. This filter is normally designed for radio frequency attenuation, but it may contribute, especially its parallel capacitors, to the HF frequency harmonic magnification, from 2 to 150 kHz for example.

<u>By harmonic measurement (island mode for example)</u>

In case of micro grid case, it is relatively easy to quantify frequency depended impedance Zh of the nonlinear load. If the nonlinear load is served as power supply in island mode, it is recommended to connect a harmonic source to the circuit (Fig.7). Because the rated power is generally small in micro grid, it is possible to use a disturbance generator as the variable harmonic source.

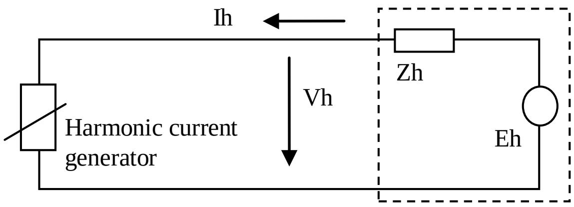


Fig. 7: Harmonic source identification

By varying frequency of harmonic generator, it is possible to identify the impedance Zh by computing Vh/Ih at each measured frequency. If there exists same harmonic frequency from Eh side, we can shift a little generator's frequency $f_h+\Delta f$ and $f_h-\Delta f$ in order to avoid the influence resulted from Eh's harmonics. The harmonic impedance can be defined by linear mean values of the impedances at these two frequencies:

$$z_h(\mathrm{f_h}) = \left[\frac{z(f_h-\Delta f)}{f_h-\Delta f} + \frac{z(f_h+\Delta f)}{f_h+\Delta f}\right] \times \frac{f_h}{2}$$

<u>By time domain simulation</u>

In particular case if the power electronic structure of nonlinear load is known, it is also possible to define impedance Zh=Vh/Ih by time domain simulation + FFT computation for each harmonic frequency.

Harmonic assessment by iteration

As per above proposed method, the harmonic impedance is defined by simplified processes. For a concrete power quality simulation, voltage source Eh should be finalized by iterations. With iteration algorithm in advanced power quality modelling, the source Eh should be further modified in order to get accurate results. The iteration process is suggested as follow:

- Start load flow computation: the studied nonlinear load is modelled by its actual powers P and Q;
- Update the source Eh at fundamental frequency by load flow result and the preset impedance Zh;
- Replace the equivalent load PQ by Eh and Zh;
- Re-simulate the circuit by iteration until get correct and converged Ih;
- Launch frequency domain simulation to study power quality issues.

CASE STUDIES

Micro grid application

The proposed equivalent voltage source method has been applied in micro grid power quality assessment. The energy storage system in this micro grid is served as either nonlinear load (charging mode) or power supply (discharging mode). It is modelled by multi frequency voltage source Eh and its harmonic spectrum is set on basis of on-site measurement (Fig. 8). Even though the current spectra > 2kHz are not nominated as harmonic by IEC standards, here we still use the term harmonic for general representation of Fourier frequency components.

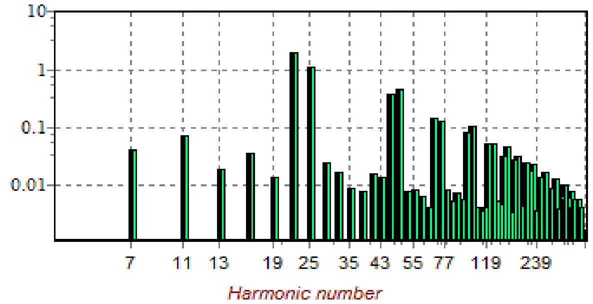


Fig. 8: Equivalent voltage spectrum (magnitude in %)

The impedance of source Eh is approximately defined by the grid impedance and the ratio Zg/Zh set to 0.1. With this voltage harmonic source, two simulations have been carried out: the storage is controlled as PQ node in grid connected mode and as VF node in island mode. The voltage source model of this nonlinear load has been implanted into EDF's power quality simulation software and this application case study is focused on micro grid power quality study.

Fig.9 shows the phase voltage and line current at the input of the energy storage model in two modes. In island mode, the harmonic source worked as voltage control mode and the power is defined by all loads of the micro grid. The result of this simulation is near the results from on-site measurements of micro grid powered by battery energy storage system.

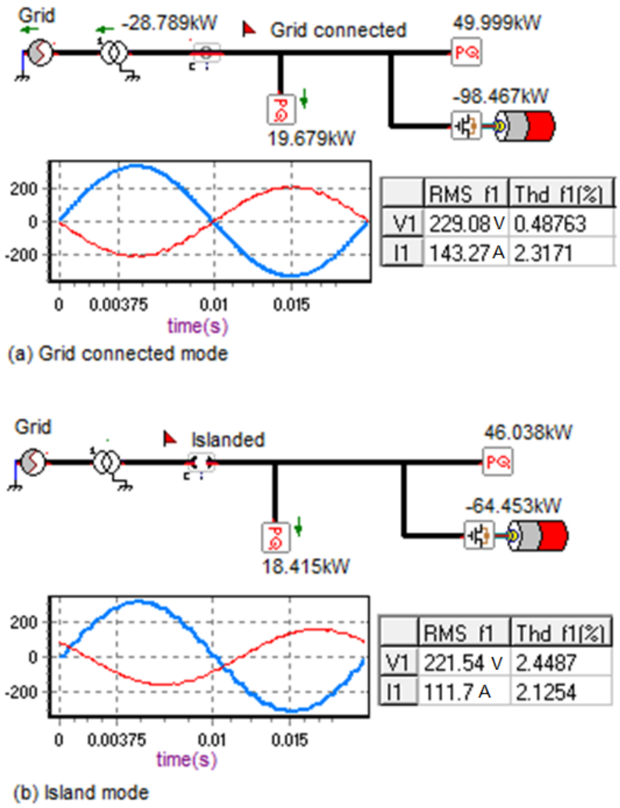


Fig. 9: Voltage and current at the input of energy storage unit of the micro grid

Harmonic resonance between grid impedance and EMC filter

This case study concerns a 21kW bidirectional EV charging system. Laboratory tests show the HF harmonic magnification phenomenon around 6kHz. This harmonic magnification is caused mainly by a resonance between LV grid impedance and the capacity of EMC filter of EV charger (Fig.10). The simulation result is very near that obtained from laboratory tests.

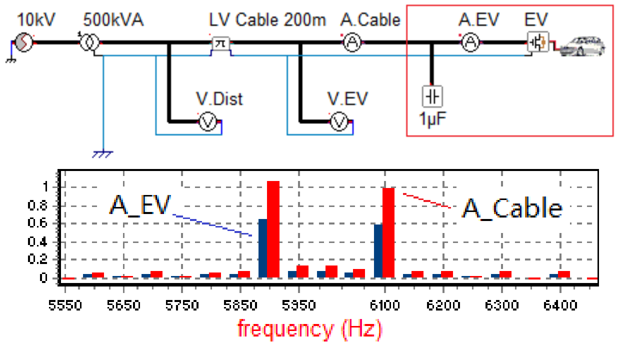


Fig. 10: HF harmonic magnification (current harmonic values in %)

CONCLUSION

The proposed multi-frequency voltage source method in disturbance load modelling is naturally compatible with voltage source converter used in new power electronic equipment such as ASD, PV, EV, energy storage, etc. It is possible to simulate certain harmonic interaction between nonlinear loads and upstream grid.

Another important advantage of this method is capable to represent nonlinear load both in grid connected and island modes. It is thus adaptable to represent distributed source simulation in micro grid as it works correctly as power supply in island mode as VF node.

With proposed method, it is possible to enhance some commercial simulation tools in disturbance assessment as these tools still use equivalent constant harmonic current method in disturbance load modelling.

FURTHER WORK AND PERSPECTIVES

The key step in using proposed multi-frequency voltage source method is to define correctly internal source parameters. The method is not perfect yet, but it gives the possibility to deal with certain harmonic interaction with upstream grid and represent harmonic sources with voltage behaviours.

In the future, other advanced harmonic methods should be taken into account in power quality studies:

Hybrid approach between time & frequency domains
For well-known structure of nonlinear load, it is recommended to create embedded time domain modeling unit [5] inside a frequency domain simulation tool. The non-linear load such as power electronic device can ban be modeled by time domain [5] or by crossed frequency admittance matrix extracted from steady-state differential equations [2][3][4] and the results will be exported to frequency domain power quality studies. This approach makes it available to deal with directly an actual distribution grid database including more than thousands of nodes.

Frequency coupling admittance matrix by laboratory tests
The crossed frequency admittance matrix proposed by [2][3][4][6] result from analytical resolution of well-known steady-state differential equations. This approach gives very good result in harmonic assessment. Therefore, it is impossible to be used on unknown nonlinear load modeling. That is why we suggest building frequency coupling admittance matrix by laboratory tests.

The modeling methods "linear" are quite unsuited to define the behavior of non linear devices like inverters. That's why we tested a model with a neural network method.

A neural network can be seen as a function between its inputs and outputs that has several parameters set by a learning algorithm. It is then able to predict the value of the output variables whatever input values.

As the figure below shows with laboratory tests, this method gives much better results than linear regression methods. In addition, the power delivered by the inverter can be counted as an input parameter.

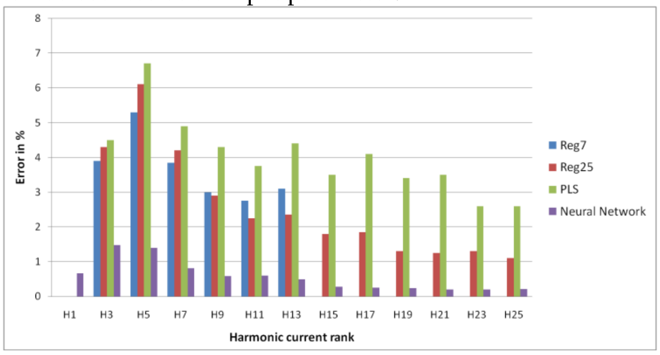


Fig. 11: Relative errors to the fundamental current obtained with the different modeling methods

We will use this modelling method as part of our harmonic impact studies of new uses on the French DNO networks.

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