HARMONICS ANALYSIS USING SEQUENTIAL-TIME SIMULATION FOR ADDRESSING SMART GRID CHALLENGES

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ABSTRACT

This paper presents the sequential-time simulation mode for harmonics recently included on EPRI's OpenDSS program. This development was made for a graphical version of this software called DSSim-PC/RT, which adds some other advanced features to OpenDSS. This simulation mode is used for evaluating the behaviour of harmonics at a certain point when the load changes in time. Additionally, the model of the load is modified by adding a parallel R-L at different percentages in three different scenarios. The results delivered in this paper can be used by users of OpenDSS for considering which load model is more adequate for performing their own harmonics studies.

INTRODUCTION

Harmonic distortion is an operational characteristic of the power distribution system that has become more relevant considering proposed smart grid characteristics. Harmonic distortion originates primarily on the load side and the magnitude and phase angle of its components depends on the load type [1]. For this reason, this phenomenon directly affects the utilization sector more than the utility power delivery sector. The inclusion of electronic power converters, variable-frequency drives, arc furnaces, among other devices at the industrial level increases the harmonic distortion in the current signal. The current distortion can also distort the voltage signal and lead to the malfunction of interconnected low power devices and power quality deviations throughout the system [2].

To improve the power factor locally, usually the distribution planners include capacitor banks. This solution may cause fall into resonance at certain frequencies, which will dramatically increase the distortion level [3]. In addition to these cases, the present smart grid scenario brings a new variable: The system and load become more dynamic in time [4].

Activities such as reconfiguration, islanding operation and the presence of devices like electric vehicles (EV) interconnected within the power system, provide new challenges to address. When the distribution system is separated in islands the power system's capacity and short circuit capability generally decrease, which will often increase harmonic voltage distortion. Also, the random connection or disconnection of the EVs; even when there are some trends associated with this behavior; is controlled by the consumer. So, the distribution planner must address many of the possible scenarios [5].

To handle these unconventional problems, the distribution planner needs unconventional tools. This work describes the use of DSSim-PC [6], which is a simulator based on EPRI's OpenDSS program [7], to perform harmonics studies using sequential-time harmonic simulation.

In this study the EVs are modeled in two different ways: First as a Norton equivalent (current source) and then as a more detailed model using a series resistance and inductance. Both models are included in the OpenDSS and can be configured and modified dynamically from DSSim-PC.

The dynamic behavior of the micro-grid is addressed in three different scenarios and the connection/disconnection of the EVs are modeled by a Monte Carlo algorithm programmed in the simulator. The aim is to evaluate which of the modeling approaches is more accurate and to show how the sequential-time simulation of DSSim-PC can help address the proposed problems.

This paper is divided into four sections:

1. Theoretical concepts behind the load model and sequential-time simulation mode for harmonics.
2. Study scenario descriptions.
3. Study results.
4. Discussion of this work.

THE LOAD MODEL AND SEQUENTIAL-TIME SIMULATION

Since March 2013 the load model for harmonics studies can be modified by the user in OpenDSS. Additionally, in February 2014 the sequential-time simulation for harmonics mode was introduced to OpenDSS through DSSim-PC, which is the PC version of DSSim-RT. Both items are described as follows:

The Load model in OpenDSS

A one-line diagram of the OpenDSS Load model in harmonics mode is shown in Figure 1. It is conceptually a multiphase Norton equivalent with the shunt admittance in the model consisting of a parallel R-L part and a series R-L part. The values for the variables G, B, R, and X are nominally determined from the specified load kW and kvar values at 100% rated voltage. The current source value is determined from the fundamental frequency power flow solution of the distribution system. The current in the load computed from the power flow, I_{fund}, is modified by the multiplier in the Load object's assigned

Spectrum object at each frequency. The phase angle of the I_{fund} is rotated appropriately for each frequency in the harmonic solution [8]. OpenDSS automatically populates the values in this model when it switches from a power flow mode to harmonics mode.

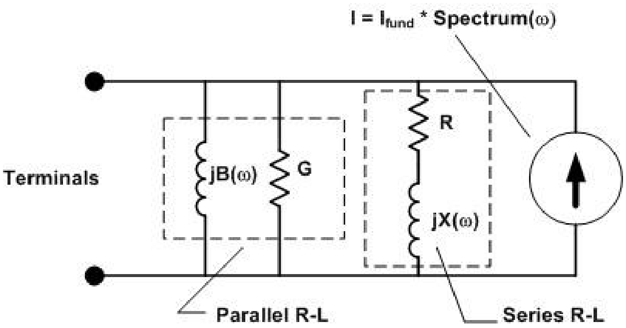

Figure 1. Load Model in Harmonics Mode

By default, 50% of the load is assumed to be represented by the parallel R-L model and 50% by the series R-L model. One generally does not know exactly how a particular load should be modeled and this 50/50 mix has proven to be a good compromise. The mix can be changed by setting the *%SeriesRL* property. Setting this to 100% (all series R-L) will tend to predict conservatively high values of harmonic distortion. Setting it to 0% (all parallel R-L) yields lower distortion by providing more damping of system resonances.

Rotating machine load is best modeled by a series R-L model for harmonic analysis. However, when determined from specified power (kW, kvar) values used in the power flow, the series R-L branch is generally too highly resistive. The machine model should be more reactive with the reactance determined from the blocked rotor impedance for asynchronous motors. There is an option to specify the reactance of the series R-L branch in per unit of the kVA of the load to accommodate this. If there are many such loads on the distribution system the impact of employing this modeling approach is to shift system resonances to slightly higher frequencies.

There is also an option in the program for neglecting the shunt admittance in the load model entirely. The harmonic current from the source is directly injected into the system. This is generally acceptable unless the system is in sharp resonance. Then the model will predict impossibly high voltage distortion due to attempting to drive a current into the very high impedance of a system that is in parallel resonance. The main reason for using a Norton equivalent for the load model is to avoid this problem.

When the distribution system is not in resonance at a given frequency the mix assumed for the shunt admittances is of less importance. The system impedance is much less than the shunt impedance of the model and nearly all of the current source output is injected into the distribution system model.

The sequential-time simulation mode

DSSim-PC is a Graphical User Interface (GUI) for OpenDSS that offers some extra features. This software was developed by using the actor model as framework in NI LabVIEW and is available for free on the internet.

The incorporation of the sequential-time simulation mode results from the question: What happens to the power system when harmonic loads get connected/disconnected in time? This is because nowadays loads like EVs are more common and their energy exchange with the power system is dynamic in time.

This behaviour corresponds to a dynamic Total Harmonic Distortion (THD) present in the system, which requires a dynamic response of control devices for ensuring the reliable operation of the power system.

The sequential-time simulation mode for harmonics is inspired by the existing sequential-time modes of OpenDSS. The software solves the power system for all frequencies separately at each time step. This is repeated sequentially and can demand quite significant amounts of computation time as the system's size and number of harmonics or interest grow.

In DSSim-PC/RT the system's solution is performed by connecting the OpenDSS in-process COM server, OpenDSSEngine, as actor. An actor is a queue-driven state machine (QDSM). This means that actors are independent algorithms that can be executed concurrently [9]. These can be cloned and communicate with other actors by issuing messages.

In harmonics simulation mode the processing times for each time step increases because the solver can only solve one frequency at the time. In the DSSim-PC/RT architecture the OpenDSS actor (ODH) is composed of several other actors, thus minimizing the processing time to solve the system at multiple frequencies as shown in Figure 2. The number of ODHs depends on the hardware's available cores for processing.

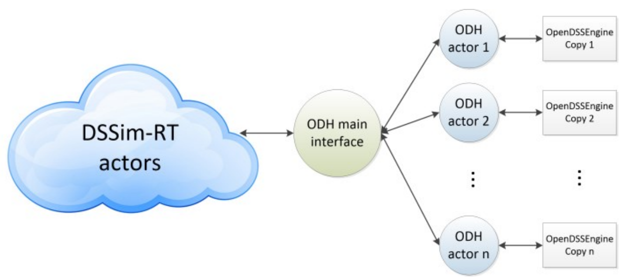

Figure 2. Distributed actors for solving the power system in harmonics mode.

When a load changes in time its representation as a current source is updated before the next time step. This way, the effects on the power system's harmonics after the connection/disconnection of loads can be simulated in time.

Additionally, harmonic meters and THD meters can be

added by the user to the Graphical User Interface (GUI) for monitoring. These meters can be placed anywhere on the system and are updated at each time step.
The maximized frontal panel of the harmonics meter is shown in Figure 3.

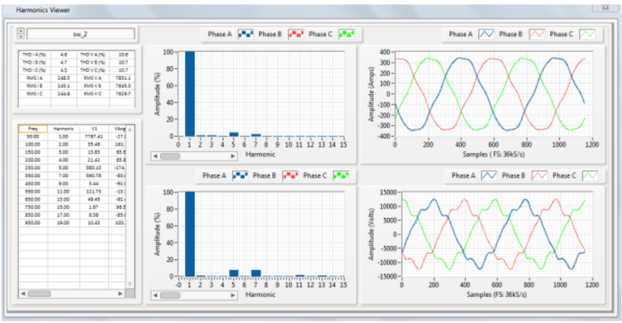

Figure 3. Graphical Harmonic meter placed in the power system using DSSim-PC/RT.

THE SYSTEM UNDER TEST

For evaluating the performance of the load in harmonics mode when configured as either a series or parallel R-L or a weighted combination of both; the power quality park proposed by EPRI for creating a micro-grid is used [10]. This is shown in Figure 4.
In this system there are 6 zones where the demand is concentrated. Two of these zones consist of a set of small businesses representing a demand of 200 kW and 250 kW. These two zones are configured by grouping 50 kW loads. For simulation purposes these loads represent EVs that are connected/disconnected randomly from the power system.
The spectrum for the EVs is the same used for representing a 6 pulse rectifier. The aim with this spectrum is to simulate the harmonic contribution of the EV when interacting with the power system.
In this power system there are also small factories (1 MW, 1.5 MW and 2 MW), a hospital (1 MW), 2 photovoltaic (PV) cell arrays (250 and 750 KW), 1 wind generator (250 kW) and a synchronous generator (4 MW).
The color of the switches in Figure 4 represents their status: The green ones are closed and the red are open. The harmonics meter is placed at the beginning of the upper feeder (SW_2). The simulation is performed for 1 week taking samples each hour. The EVs are connected/disconnected from the power system randomly according to a uniform distribution function.

THE RESULTS

The proposed scenario is used for performing 3 different simulations: In the first the EVs are represented 100% as R-L parallel, in the second 50% R-L parallel and 50% series, and in the third 5% parallel and 95% series.
The connection/disconnection of the EVs is performed from an external application that controls the simulation using the TCP/IP server included in DSSim-PC/RT.
Then 5 days are simulated and each simulation plotted for analysis as shown in Figure 5.

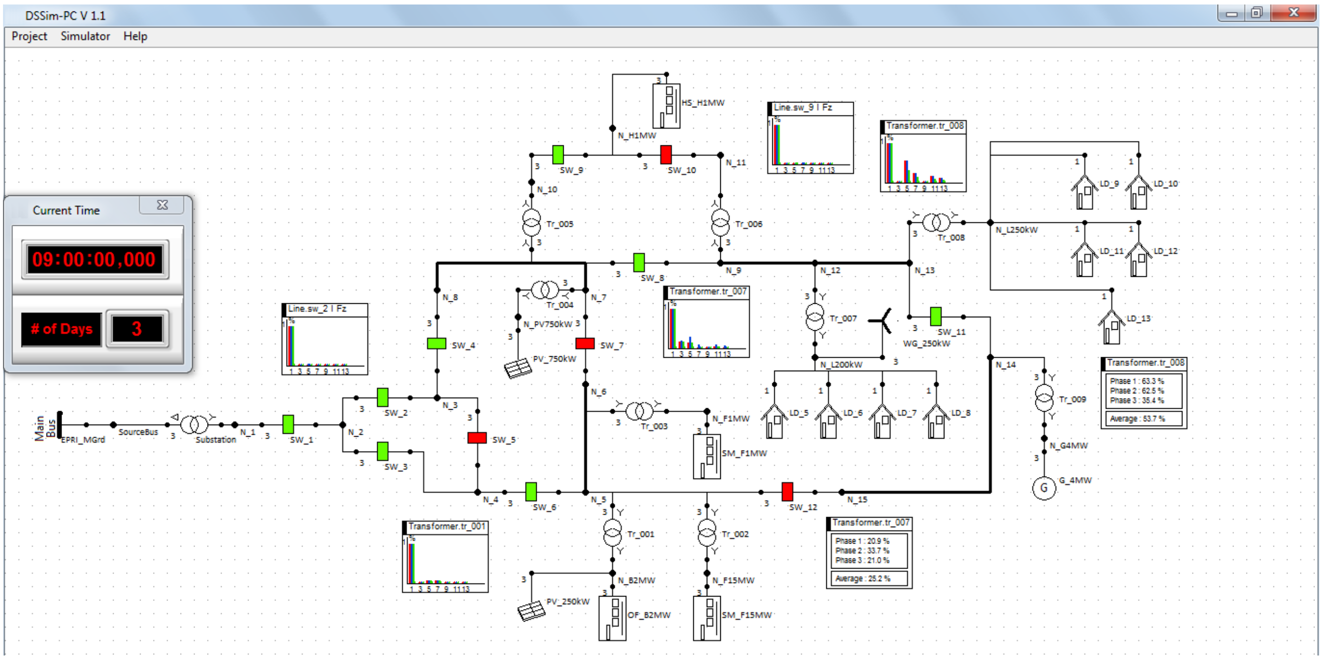

Figure 4. EPRI's power quality park for creating micrograms implemented on DSSim-PC.

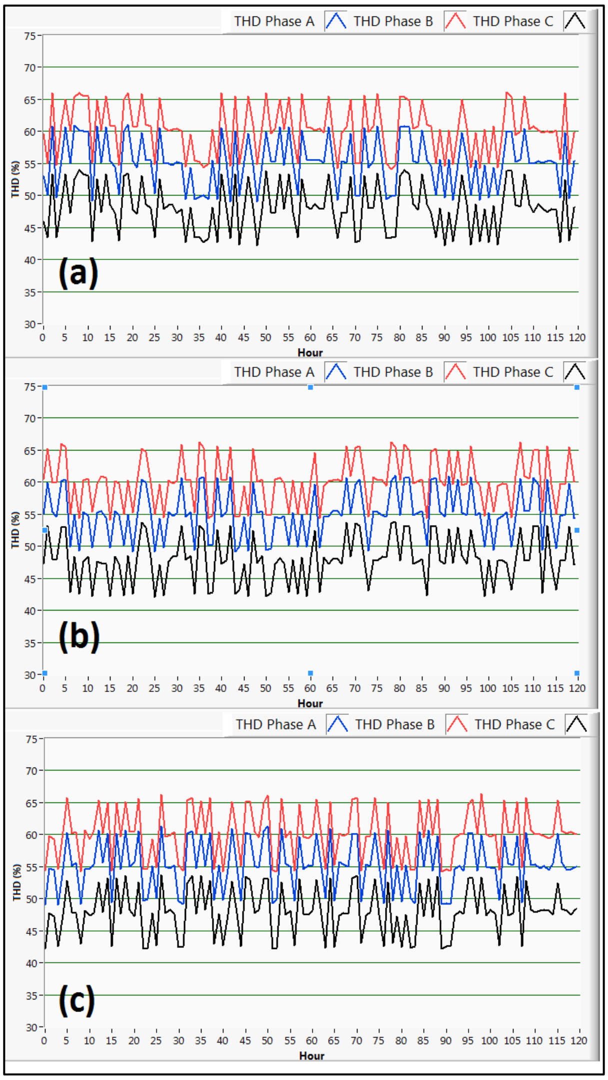

Figure 5. Harmonic simulation in sequential-time mode. (a) EVs 100% parallel R-L, (b) EVs 50% parallel and 50% series R-L, (c) EVs 5% parallel and 95% series R-L.

Note that the three phases are not balanced. For evaluating these results the average THD is calculated for each case. Additionally, the THD's standard deviation is calculated to study its behavior. These results are presented in Figure 6. The numerical values are presented in TABLE I.

The percentage of series/parallel representation of the load is modified by setting the %SeriesRL properties of the Load element models in OpenDSS.

As can be seen in TABLE I the lower THD is reached on simulation 1, the 100% parallel R-L model. The maximum difference is between values of simulation 1 and 3 and is 1.77%. The simulation with the lower deviation is simulation 3 compared with the other two simulations. These results reveal the damping effect of the parallel R-L and how this can be used for adjusting harmonic currents. In fact, as explained above this is the purpose of combined series and parallel R-L within the model.

TABLE I
Standard Deviation and average THD for each simulated scenario

Phase	Value	% Series RL 0.1%	50%	95%
A	Std. Dev.	3.78805	3.90677	3.66948
A	Average THD	54.73	55.116	55.235
B	Std. Dev.	3.74558	3.83326	3.73367
B	Average THD	60.0218	60.3064	60.3333
C	Std. Dev.	3.70308	3.72272	3.73367
C	Average THD	47.7769	47.9105	47.985

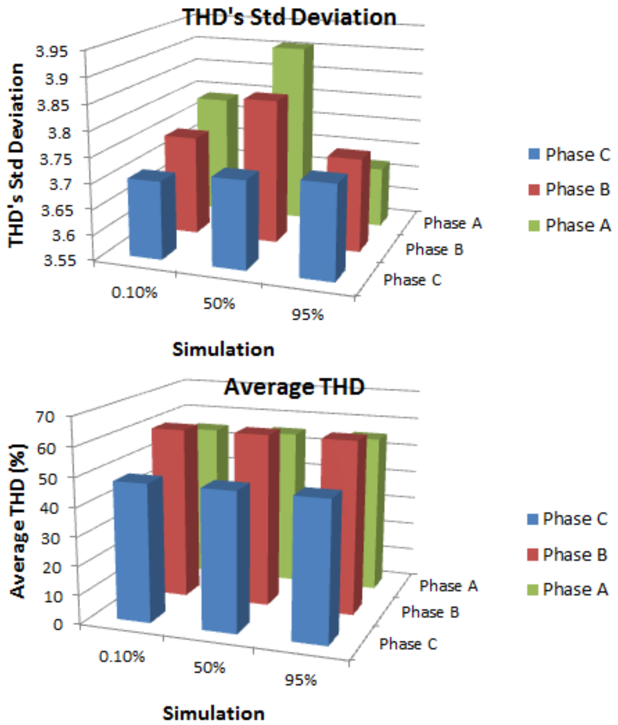

Figure 6. Average Total Harmonic Distortion and standard deviation for each simulation.

On the other hand, the simulation 3 gives the higher THD. The behavior of the THD in Figure 6 and in TABLE I suggest that the damping in the load model plays an important role. Basically this is because the damping effect of the parallel R-L allows a more stable simulation to be performed. The question here is how big should be the damping component for a more accurate simulation approach.

The results delivered by the simulation when %SeriesRL is equal to 50 reveal a balanced and conservative simulation. In this case the difference in terms of deviation and THD between simulation 2 and 3 are very low (0.98% and 0.68% respectively).

These results suggest that %SeriesRL=50 is an adequate value for almost all simulations. However, it could be some special types of loads that requires adjusts in this relationship.

Because the system under test has no power factor capacitors causing resonance in the harmonic range of interest, the differences between the load models are relatively small. In systems where there is harmonic resonance, the damping caused by the load model will have a significantly larger effect.

DISCUSSION

We have taken an open-source general-purpose tool and enhanced it considerably by exploiting another platform (NI LabVIEW) to make a new useful tool. Several new features have been added to the original version of OpenDSS including new simulation modes (sequential-time simulation for harmonics). Additionally, the GUI helps users to exploit in a wider way the simulation platform.

This new mode of simulation can be used for several purposes. We demonstrated the value of sequential-time simulation in this paper by computing the harmonic distortion predicted due to the connecting and disconnecting of EVs at random times over a 1-week period. The value of the parameter %SeriesRL of the Load model was varied to achieve different models of harmonic damping due to loads. The value of this parameter can have an impact on the harmonic distortion predicted by the model and users should understand the impact of different load damping assumptions.

Three different scenarios have been modeled and their behaviors have been presented as the loads vary in time. With these results OpenDSS users can infer the impact of the parameter %SeriesRL on load modeling for their harmonic simulation needs.

However, some other considerations like resonance conditions should be taken into account for the model. In these cases, capturing the affects of rotating machines on the resonant frequency could require the modification of the reactance of the series part of the load model based on a per-unit value of the load kVA as permitted in OpenDSS. Modeling such loads in this manner will tend to shift resonant frequencies higher, which can significantly change the model's prediction of harmonic distortion.

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