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Effects of Time Delays on the Behavior of a Centralized Control System for Providing System Ancillary Services in an Active Distribution Network

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Abstract. – **An electrical distribution system with several dispersed generation (DG) units interconnected to the AC grid through PWM static converters is considered. The DG units can provide both energy and system ancillary services (e.g. voltage regulation, voltage harmonic distortion and unbalance compensation).**

The DG unit converters are coordinated through a centralized control system that provides in real time the reference signals to the control systems of the DG static converters allowing them to provide the aforementioned services. The centralized control system calculates the reference signals using an optimization procedure whose inputs are measurements from the distribution network busbars and whose outputs are the reference signals; thus, the compensation action is depending on the unavoidable time delays introduced in the whole process by data acquisition, digital processing and data communication.

With particular reference to the waveform distortion compensation, the paper proposes a new procedure to compensate them. Time domain simulations on an actual distribution system are reported in order to analyze the delay effects and show the effectiveness of the proposed compensation procedure.

Keywords

Active distribution systems, Ancillary services, Centralized control system, Time delay compensation.

1. Introduction

The deregulation of energy generation has significantly increased the presence of dispersed generation (DG) in electrical distribution systems; when connected to the grid through power electronic interfaces, the DG units can play a relevant role since they can provide both typical energy service as well as ancillary services, e.g., reactive power support, load following, peak shaving, back-up service, waveform distortion compensation [1-3].

In this frame, this paper considers an active distribution system where selected DG units with DC sources are interfaced to the network through DC/AC static converters (inverter). The considered DC sources include a primary source (solid oxide fuel cell (SOFC), and photovoltaic cells) and a storage system comprised of lead-acid batteries and supercapacitors. The DG units can operate in grid-connected mode or in island mode, typically depending on the distribution operating condition at the point of common coupling.

In grid-connected mode, a centralized control system coordinates the DG units control systems in order to optimally provide ancillary services.

In [4, 5] the centralized control system (CCS) of Fig. 1 was proposed; it allows the coordination of some selected DG units and permits more effective improvement of the operational conditions of the entire distribution system. In particular, the centralized control system coordinates the compensation of some PQ continuous disturbances (waveform distortions and unbalances) and allows obtaining a proper allocation of reactive powers that can be furnished by the selected DG units to improve the voltage profile at network buses.

However, as well known, the whole compensation action depends on the unavoidable time delays caused by the application of the CCS control strategy. The main delays are due to delays for analog-to-digital and digital-to-analog conversions, the delays for calculating the reference currents and additional time delays due to the communication between the involved distribution network nodes and the CCS or the DG units. These delays can lead to a non-ideal compensation action as well as limited dynamics.

In this paper, with particular reference to the waveform distortion compensation, we further analyse the effects of time delays due to the data acquisition and digital processing, considering negligible the delays due to the communication of distributed measurements and assuming synchronized measurements thanks to the presence of a GPS-based Synchronized Measurement system or a dedicated communication network. Moreover, a new technique is proposed to compensate the aforementioned time delays.

The paper is organized as follows. First, the components (SOFC fuel cells, photovoltaic cells, and storage systems) of each DG unit present in the active distribution system and their models are briefly described. Then, the centralized control system that allows the coordination of selected DG units is analysed and the time delays for the static converter reference current calculation are evidenced and discussed. Finally, a method to compensate these time delays is proposed and the results of computer time domain simulations on an actual distribution system are reported.

2. Dispersed generation unit

In this Section we analyse the DG unit components and their models.

The selected DG units are fuel cell-based and photovoltaic cell-based generation systems whose general scheme is shown in Fig. 2. In the most general case, their DC sources include a storage system (composed of supercapacitors and lead-acid batteries) and can supply a privileged load connected at the point of common coupling (PCC).

In the following sub-sections, the models of photovoltaic cells, fuel cells, and storage systems are described along with the inverter.

A. Photovoltaic cells

The photovoltaic field has been modelled using a controlled, DC voltage source. In practice, the photovoltaic system is represented by the characteristic relationship between the voltage and the current, so that the values of the DC voltage source are obtained from the current measured at the DC bus [6]. The characteristic relationship between the voltage and current is provided by the PV photovoltaic field (I-V curve) and calculated as reported in [7].

B. Fuel cells

Among the various fuel cells, the solid oxide fuel cell (SOFC) are considered that operates, as well known, at high temperatures (600 – 1000 °C) and thus have great potential for use in stationary applications.

The solid oxide fuel cell was modelled using an electrical dynamic model, which includes Nernst's voltage, a capacitor that simulates two ideally polarized metal plates separated by a thin plastic sheet, and parallel and series resistors to represent the losses. The model parameters for SOFCs were assumed to be equal to the parameters shown in [8].

The SOFC system were interfaced with the DC link through a DC/DC converter that allows the adaptation of the output voltage of the FC system to the voltage level required for the inverter input. Different topologies can be used for this converter. In this study, a simple, step-up chopper was used; the control of the DC/DC converter was aimed at furnishing the necessary reference current to satisfy the active power demand required by the inverter.

C. Storage system

As shown in Fig. 2, the DC source includes a storage system with supercapacitors (SCs) and lead-acid batteries. In the case of FCs, the storage system presence

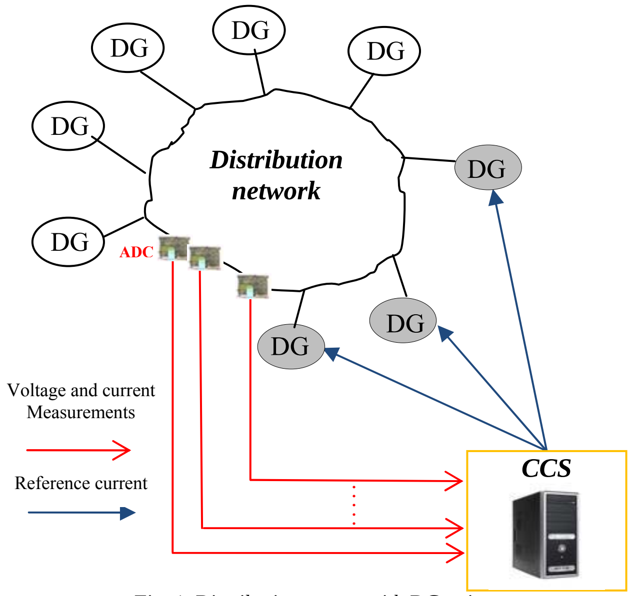

Fig. 1. Distribution system with DG units

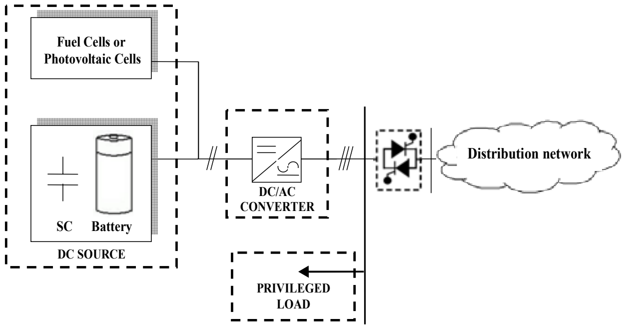

Fig. 2. The considered DG unit

is useful to balance the slow response of the FC system with rapid variations in the power to be furnished [10]. In addition, it also improves the efficiency of the entire system and reduces the capital expenses by allowing the systems to be sized more closely to the steady-state power requirements [4, 5].

In addition, in the case of photovoltaic-cell systems, the storage system is particularly useful for compensating uncertainties due to the primary energy source, mainly when back-up service is required.

The lead-acid batteries were modelled using the model proposed in [11].

Concerning the SCs, the model used was an RC-series with the electrical-equivalent circuit reported in [12]; in particular, the resistivity of the materials that forms the double-layer charge distribution is represented by R, whereas C is a fixed capacitor.

Lead-acid batteries and SCs were both interfaced with the DC link through a proper bi-directional DC/DC converter [20]. With reference to the DC/DC converter for the SC, the control was aimed at maintaining the DC voltage at a proper reference value. On the other hand, the DC/DC converter for the lead-acid battery is current controlled and was aimed at furnishing energy to cover power requirements without dramatically reducing the lifetime of the batteries.

D. Inverter

The DC/AC converter is a three-phase, PWM inverter that can operate in two modes: current control mode (grid-connected mode) or voltage control mode (island mode).

In *current-control mode*, the inverter inject a current that is the sum of two components. The first component allows a supply of power to the privileged load and to the utility (in particular, active and reactive power for the load-following service and reactive power for the voltage-regulation service). The second component compensates for waveform distortions and voltage unbalances, either at all system buses or in particular areas (compensation of system or area) [4, 5].

In *voltage-control mode* (V-f control), the DG unit can furnish the back-up service to supply the active and reactive powers required by the local privileged load in the case of grid disconnection.

3. Centralized control strategy

The centralized control system manages and coordinates the voltage regulation and the compensation of unbalances and waveform distortions.

With particular reference to the compensation of unbalances and waveform distortions, the centralized control system furnishes the reference currents to the DC/AC converters of the selected DG units applying a proper procedure. The scheme of the centralized control strategy, implemented in real time, is shown in Fig. 3 [4. 5].

At first, measurements in the distribution system are conducted. The values obtained are used as inputs to a disturbance-estimation algorithm that provides real-time estimation of the disturbances to be compensated (Kalman Filter). Finally, an optimization procedure was applied to obtain the reference current contributions for the selected DG unit converters. The optimization procedure is based on the optimal control theory in the frequency domain and allows the determination, in a closed form, of the reference currents.

The optimal procedure consists of minimizing a global index of quality while satisfying a constraint on the size of the compensator. In this way, the selected DG converters can allow compliance with additional PQ objectives, not only all over the network (system compensation),but also at a number of selected busbars (area compensation). For more details about this topic see the rferences [4, 5].

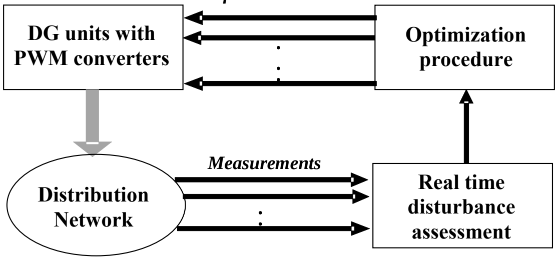

Fig. 3. Centralized control strategy for compensating for PQ disturbances.

4. Delay time for the calculation of reference currents

As obvious, the correct compensation action is depending on the unavoidable time delays caused by the application of the control strategy.

The main delays are due to the analog-to-digital and digital-to-analog conversions, calculation of the reference currents and communication between the involved distribution network nodes and the centralized control system and DG units. These delays can lead to a non-ideal and less dynamic compensation action.

In the literature, the effect of time delays on the reference signal for compensation of harmonic disturbances, due to data acquisition and digital signal processing, has been examined with reference to active filters [10].

With particular reference to the procedure previously described (Fig. 3), additional time delays due to the communication between the involved distribution network nodes and the centralized system should be considered; moreover, the problem of measurements synchronization has to be solved since more than one converter is included in the compensation action.

To better clarify the problem, in Fig. 4 a time diagram with the time delays involved in the centralized control strategy reported in Fig.2 is shown [5].

At first, the measurements of voltage and current are effected on the distribution network and sent to the centralized control system. This involves time delays for analog-to-digital conversion and communication time delays between distribution network and centralized control system. The time delays for measurements are due to the transducers that measure the currents and the voltages and to the analog-to-digital converter (ADC) whose operation consists in the digital signal processing which digitizes the current and voltage measurements effected on the distribution network. Thus, these last delays are depending on the type of ADC used.

The communication time delays between distribution system and centralized control system mainly depend on the extension of distribution system and the communication network considered.

Starting from the measurements, the centralized control system calculates the reference currents applying the real time disturbance assessment and the optimization procedure.

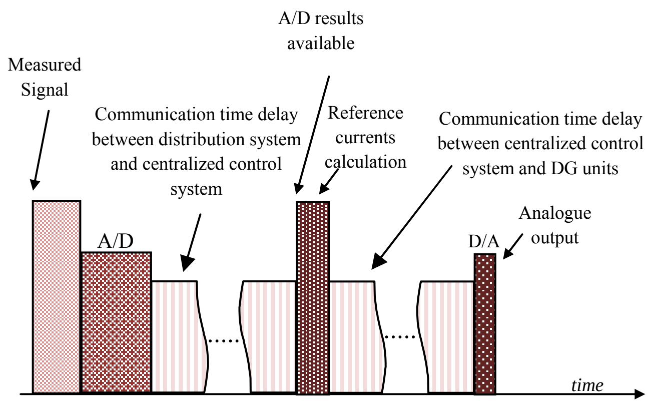

Fig.4. Time diagram.

These procedures involve time delays related to the application of the disturbance assessment algorithm (based on Kalman filter) and the determination in a closed form of the reference currents involving matrix calculations (reference currents calculation in Fig. 3). The reference currents have to be sent to the DG unit converters. This involves communication time delays between centralized control system and DG units. These time delays, once again, are depending on the extension of distribution system and the communication network considered. At the end, the converter control of the selected DG units uses digital-to-analog conversions (DAC) that causes a time delay that depends on the DAC used.

In the numerical applications, the influence of the time delays on the compensation actions is further analysed.

5. Time delays compensation

To introduce the logic on which the technique of the time delay **Δt** compensation is founded, for the sake of simplicity, only the compensation of waveform distortions is considered. Moreover, we assume that the measurements are slowly varying.

As shown in the previous Section, an *unknown* time delay **Δt** exists between the time instant when the disturbance measurements are effected and the time instant when the measurements become an input of the centralized control system (where the reference currents for the DG inverters are calculated).

The strategy of the time delay compensation is just based on a procedure aiming at determine the unknown **Δt**; this is obtained by minimizing an objective function equal to the difference between the mean values of the THDv evaluated in some busbars of the distribution system and a reference value of the THDv (THD_{VREF}), properly selected.

In particular, the whole procedure applied for the compensation of the time delay is represented in Fig. 5.

The difference between the mean value of the THDv, properly filtered, and the reference value THD_{VREF}, set to zero (theoretically, this is the ideal condition of waveform distortion compensation), represent the input of a PI regulator. In such a way, the output of the PI regulator, after a block of saturation, should just represent the actual time interval **Δt** by which (theoretically) the measurements should be anticipated to guarantee the time delay compensation (and, then, the minimization of the mean value of THD_V).

Once known the time interval **Δt**, under the aforementioned assumption that the waveform distortions are slowly varying, we assume that the measurements at time *t* to be sent as input to the real time disturbance assessment are the delayed measurements (Fig. 6b) *further delayed* of a time interval equal to the difference between the measurements' fundamental period $\mathbf{T_0}$ and the obtained time interval **Δt,** that is $t - \mathbf{T_0} + \mathbf{\Delta t}$ (Fig. 6c).

Obviously, if a certain time interval (>**Δt**) of the measurements are stored in a digital memory, then they can be *anticipated* of **Δt** with the same benefit on the compensation action (Fig. 6d).

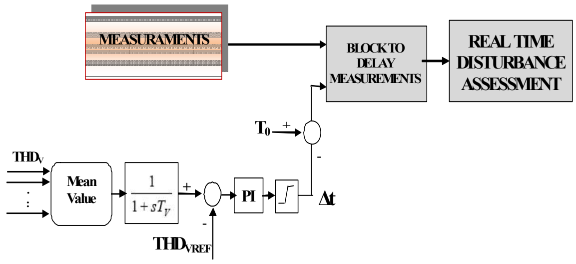

Fig.5. Procedure for the compensation of the delay time

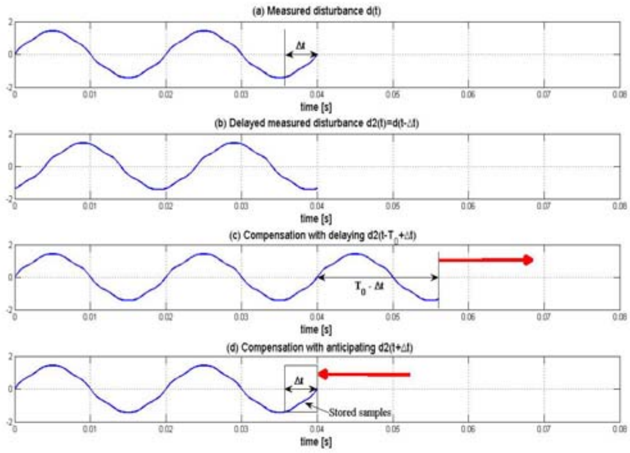

Fig.6. Waveforms in the procedure for the time delay compensation

6. Numerical applications

An actual low-voltage (LV) electrical distribution system with a number of DG units was simulated in time domain. The considered distribution system is shown in Fig. 7. This system contains 29 low-voltage busbars at 0.4 kV and a medium voltage bus at 20 kV. The three-phase short circuit power at the 20-kV bus is S_{sc} = 400 MVA; the MV/LV transformer is rated at 250 kVA with $v_{cc,\%}$ = 4.2%. The active powers of the loads are reported in [5] and in order to analyze the influence of the time delays only on the harmonic compensation action, for the sake of simplicity, three-phase loads all operating at cosφ = 0.9 are considered.

Two different types of DG units are present in the distribution system: photovoltaic and fuel cell systems (SOFC); they receive reference signals from the

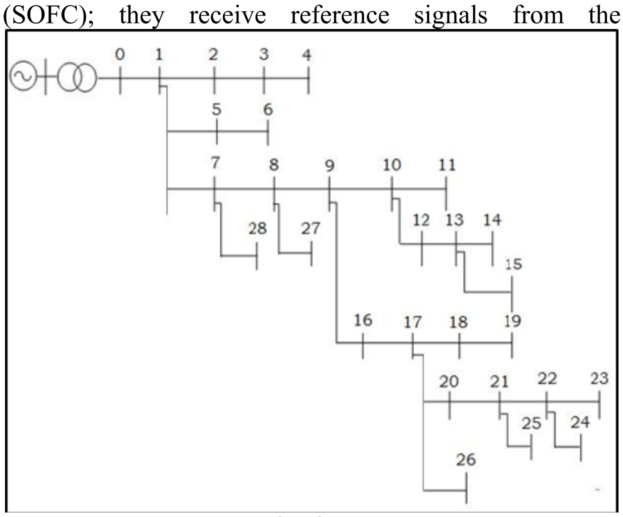

Fig.7 LV distribution system

centralized control system in order to perform adequate system ancillary services and in particular voltage waveform distortion.

In the following, two case studies considered for the application are reported.

A. Case 1

Two 10-kW DG units were installed; in particular, a SOFC fuel cell-based system at the bus #22 and a photovoltaic cell-based system at bus #7. All DG units contribute to the centralized compensation of voltage harmonic distortion, they also provide load-following service for their privileged loads. Non-linear loads are present in the system; they are two three-phase, AC/DC converters connected at busbars #14 and #25 and are characterized by firing angles of α = 40° and rated DC load powers of 2 kW and 11 kW, respectively. Different time delays (Tab.1) were applied in order to analyze their effects on the compensation actions.

	Time Delay [µs]
D_1	70
D_2	100
D_3	130
D_4	170

Tab. 1 Time Delays

Figs. 8 and 9 show the total voltage harmonic distortion THDv and the 11th voltage harmonic V_{11}/V_1 values at some significant network busbars obtained without any compensation action and by applying the centralized control strategy with and without the time delays (Tab. 1), respectively.

The analysis of Figs 8 and 9 clearly reveals that:

- without time delays, the reduction of the waveform distortions obtained is significant so demostrating the strength of the compensation action in an ideal condition;
- with increasing time delays, an increasing and not always negligible reduction of the compensation action arises.

It follows that a time delay compensation is necessary in order to avoid misoperation of the CCS. This is confiremed by the analysis of Figs. 10 and 11, in which the THDv and V_{11}/V_1 values are shown at bus #25 versus different time delay values.

B. Case 2

A 10-kW SOFC fuel cell-based system was installedat bus #25. The DG unit contributes to the centralized compensation of voltage waveform distortions. As a source of harmonic disturbances, a three-phase DC/AC converter is connected at busbar #25; it is characterized by a firing angle equal to α = 40° and a rated DC load power of 14 kW.

This simple case is used to analyse the effects on the harmonic compensation obtained by applying the technique for compensation of time delay shown in Section 5.

Fig. 12 shows the total voltage harmonic distortion THDv values at bus #25 in the following three cases:

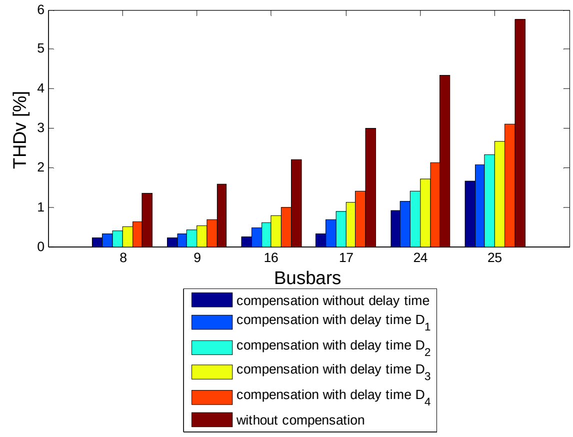

Fig.8 THD_v at some network busbars

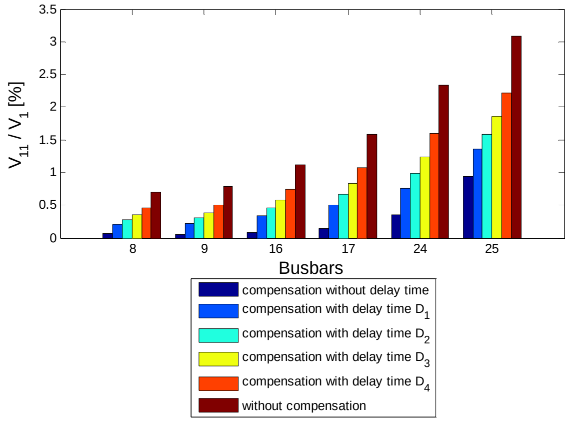

Fig.9 V_{11}/V_1 at some network busbars.

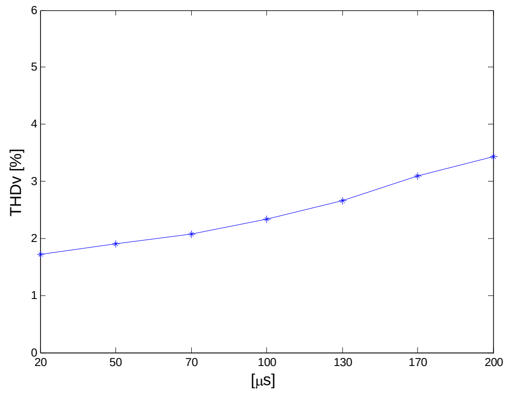

Fig.10 THD_v at bus 25.

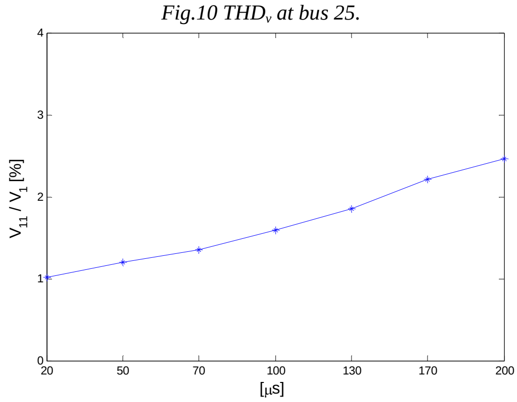

Fig.11 V_{11}/V_1 at bus 25.

- ideal compensation, without delays (red curve);
- in presence of a delay of 50 µs (green curve);

- in presence of a delay of 50 μs, but applying the new technique for compensation of time delay of Sect. 5 (blue curve).

From the analysis of Fig. 12 the benefits obtained thanks to the presence of the time delay compensation technique are evident. Similar results are obtained also with increasing values of time delays.

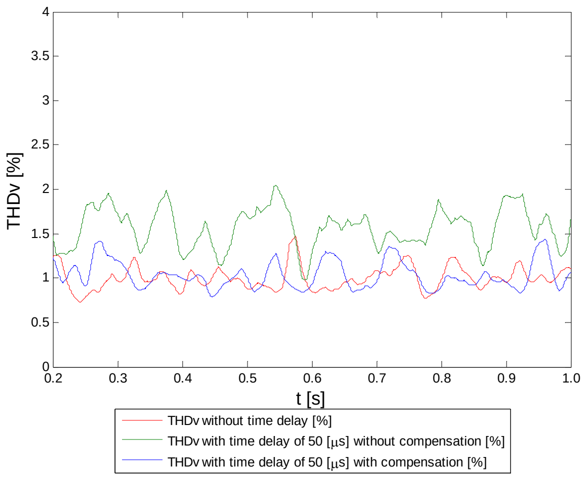

Fig.12 THD_v at bus #25

7. Conclusion

In this paper an electrical distribution system with several dispersed generation units interconnected to the AC grid through power electronic interfaces was considered. The DG units can provide both energy and system ancillary services, such as voltage regulation and voltage waveform distortion compensation.

In order to provide the aforementioned services, a centralized control system properly operates in order to furnish in real time the reference signals to the control systems of the DG power electronic interfaces. Since the correct compensation actions depend on the unavoidable time delays due to data acquisition, digital processing and data communication, the effects of the time delays have been deeply analyzed and a method to compensate them has been proposed. Several time domain simulations on an actual distribution system with different type of DG units are shown; the results obtained on the considered distribution system lead to the following main outcomes:

- increasing time delays can lead to an increasing reduction of the compensation actions;
- the proposed technique to compensate the time delays seems to operate satisfactorily and in a way that doesn't depend on the value of the time delays considered.

Work are in progress to verify the proposed technique in a more complex active distribution system characterized by the presence of several DG units (fuel-cell, photovoltaic-cells and wind-based systems).

Acknowledgments

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