A Simulation Tool for Extended Distribution Grids with Controlled Distributed Generation

G. C. Kryonidis, E. O. Kontis, A. I. Chrysochos, C. S. Demoulias*
School of Electrical & Computer Engineering
Aristotle University of Thessaloniki
Thessaloniki, Greece
*corresponding author's email: chdimoul@auth.gr

D. Bozalakov, B. Meersman, T. L. Vandoorn, L. Vandevelde
Electrical Energy Laboratory
Dept. of Electrical Energy, Systems and Automation
Ghent University, Ghent, Belgium

***Abstract*—In this paper, a new software tool is presented for the simulation of electrical networks under steady-state conditions. Its distinct advantage is the robust integration of distributed generation droop controls, while offering the ability to simulate extended networks fast and reliably. The proposed simulation tool is based on the combination of two well-known software products, namely MATLAB and OpenDSS. The latter is employed as an unbalanced power flow solver, whereas the former implements the droop control of DG units. Simulation results for a simple and extended low-voltage network show the effectiveness of the proposed tool and mainly the reduction in the execution times over other conventional time-domain-based software products.**

***Index Terms*—Distributed generation, droop control, MATLAB, OpenDSS, simulation tool.**

I. INTRODUCTION

Over the last decade, the amount of distributed generation (DG) connected to the distribution system has been increased significantly due to a number of technical, economic, and environmental benefits it provides [1]. However, the advent of DG has gradually changed the power delivery system from a downstream unidirectional to a bidirectional operation, introducing various challenging technical issues, with the voltage rise being considered as the most substantial one [1], [2]. New control schemes have been proposed and integrated in DG units via grid-interfaced inverters in order to mitigate these issues [3]. Regarding the voltage regulation problem, droop control of DG unit output power is considered as the most widespread and effective solution [4], [5].

Therefore, the ability to simulate electrical networks that comprise DG units with such integrated control schemes is essential for further work and investigation on this research topic. Although the research community has focused on developing software products to analyze, plan, and simulate electrical networks, the efficient incorporation of the developed control techniques still remains an open issue [6], [7].

Assuming the simulation of power system networks under steady-state conditions, the existing software products are divided into two main categories. The first one employs algebraic equations by means of phasors, thus presenting short execution times in the simulation of extended networks. However, such models become cumbersome when incorporating additional DG control schemes, e.g., droop control [8]. The second category simulates the network in the time-domain by using differential equations, thus providing the ability to integrate DG control schemes in a more straightforward manner. However, this category is quite inefficient in the simulation of extended networks due to the excessive execution times [9].

In this paper, a flexible simulation tool for extended distribution grids with controlled DG units is proposed, comprising the benefits of both software categories, i.e. short execution times and robust integration of DG control schemes. The proposed tool is based on the combination of two software products, namely MATLAB and OpenDSS. The latter is used as an unbalanced power flow solver, employing phase-domain analysis of the network. MATLAB is utilized for the modeling of the developed control schemes and especially the incorporation of droop control for the injected active power of each DG unit.

The performance of the proposed simulation tool is demonstrated by comparing it with well-known software products. More specifically, the high flexibility and accuracy of the incorporated power flow routine over other commercial software, e.g. NEPLAN, is highlighted, whereas the efficiency of the presented tool is compared with the corresponding of MATLAB/SIMULINK time-domain software in order to indicate the improvement in execution times. Finally, results for an extended 79-node low-voltage network with time series unbalanced loads are also presented.

II. SIMULATION TOOL OVERVIEW

A. Main components

1) OpenDSS

OpenDSS forms the core of the developed tool. It is a comprehensive, open-source simulation tool for electric distribution systems, developed and distributed by the Electric Power Research Institute (EPRI) [8], [10]. OpenDSS can be implemented as either a stand-alone executable program or an in-process COM server DLL, designed to be driven from a variety of existing software platforms, including MATLAB, thus offering great flexibility compared to most commercial simulation tools. Through the COM interface, the user is able to design and execute custom solution modes and features

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from an external program and perform the functions of OpenDSS, including the definition of the model data.

Considering the power flow feature, OpenDSS can handle unbalanced networks. Specifically, it employs the full phase-domain circuit model and adopts a generalized admittance formulation of the examined circuit. The conceptual design of the power flow scheme is depicted in Fig. 1. Each element of the system is represented by a primitive nodal admittance matrix ($\boldsymbol{Y_{prim}}$) which is then coalesced into one large system admittance matrix ($\boldsymbol{Y}$). Therefore, the distribution network is represented by a system of equations according to:

$$\boldsymbol{I} = \boldsymbol{Y} \cdot \boldsymbol{V} \tag{1}$$

where $\boldsymbol{I}$ denotes the vector of injected currents from the power conversion elements connected to the network, e.g. loads, generators, etc., and $\boldsymbol{V}$ is the vector of phase-to-ground bus voltages. Sparse matrix solvers are employed to solve (1), while the power flow procedure is described as follows:
An initial guess of the voltages is obtained by performing a zero-load power flow computation. The iteration cycle starts by obtaining the injected currents and adding them into the appropriate slots in the current vector. The sparse set is then solved for the next guess of the voltages, whereas the cycle repeats until the voltages converge according to the user-defined tolerance. It is worth mentioning that the adopted iterative solution converges quite well for most distribution systems.

OpenDSS has been selected over other commercial tools, e.g. NEPLAN, as a power flow solver, due to its superior performance and flexibility [11]-[13]. More specifically, unlike OpenDSS, most commercial tools adopt the symmetrical-components approach. This approach is based on transformations from phase- to symmetrical-components-domain and vice versa, which can introduce significant round-off errors in the calculation procedure [14].

2) MATLAB

MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming. In this paper, it is employed in order to incorporate various control techniques of DG units in the power flow calculation scheme and particularly the droop control of the injected active power with respect to the voltage at the Point of Common Coupling (PCC) [3]-[5]. The implementation of droop control is actually performed in

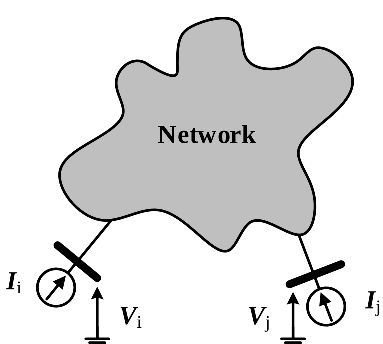

Figure 1. Conceptual design of OpenDSS power flow scheme.

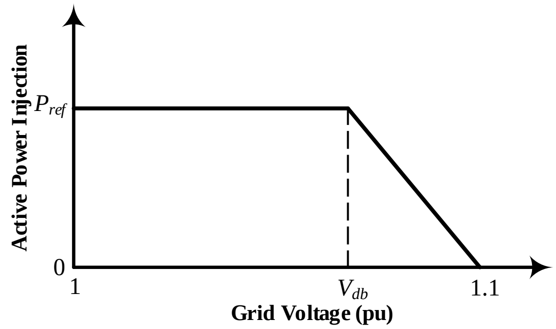

Figure 2. Droop curve of controllable DG unit. The maximum of the three phases is considered as Grid Voltage.

MATLAB environment, whereas the DG units are modeled as constant PQ generators with unity power factor in OpenDSS.

B. Droop control

The principal objective of the adopted droop control is the curtailment of the injected active power of DG units in order to prevent overvoltage problems. This control is based on the voltage at the PCC of the DG unit, since a strong linkage between active power and grid voltage is generally considered in low-voltage networks due to their resistive nature [5]. This avoids turning off the DG units due to over-voltages, while the voltage profile of the distribution feeder is actively controlled.

However, low-voltage networks also suffer from voltage unbalance due to the presence of single-phase loads and sources [15]. Thus, the maximum among the three phase-to-neutral voltages at the PCC is taken into account for the implementation of droop control in order to ensure that the operating voltage in each phase will not exceed the upper voltage threshold, i.e. 1.1 pu according to Standard EN 50160 [16]. The adopted control is implemented via a droop curve depicted in Fig. 2, where V_{db} indicates the voltage threshold for the activation of active power curtailment. In this paper, V_{db} is considered equal to 1.06 pu, whereas 1.1 pu is chosen for the zeroing of injection. P_{ref} denotes the maximum active power the DG unit can deliver at a specific time instant, which is explicitly defined from the available power of the primary source.

C. Calculation procedure

The simulation process of an electrical network can comprise several time instants. A time instant corresponds to the operating point for a specific time period where consumption, generation and network characteristics remain constant. This period may vary from few seconds to minutes depending on the provided measurements and data.

The calculation procedure for a given time instant includes successive power flows, taking into account the droop curves of DG units, until equilibrium, and thus a new operational state is achieved. The whole procedure involves four steps and is illustrated in Fig. 3 by means of a flowchart.

Step 1: Initial power flow. Initially, the network data such as loads, generators, etc., related to the specific time instant are loaded to OpenDSS through the COM interface. Each DG unit injects the active power of the previous time instant and

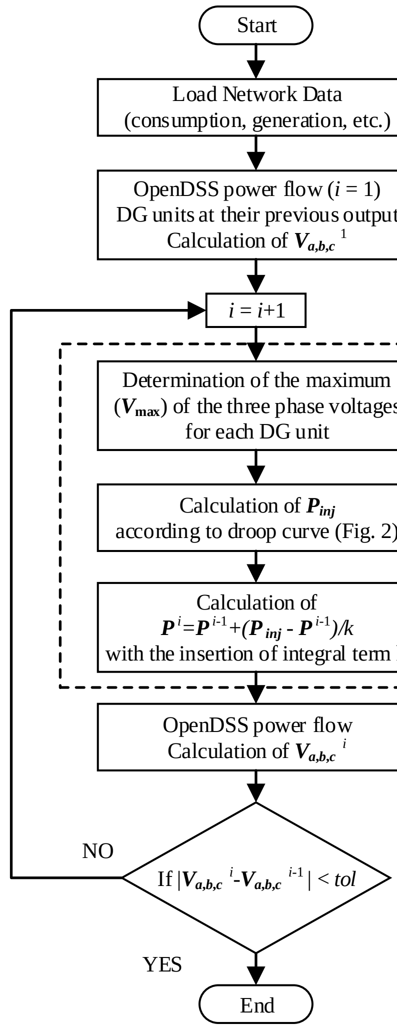

Figure 3. Simulation flowchart for one time instant. The procedure inside the dashed box is implemented in MATLAB.

OpenDSS solves the power flow equations calculating the phase-domain voltages at each node. If this process is performed for the first time instant, DG units are considered to inject their maximum available power denoted by the vector $\boldsymbol{P}_{ref}$.

Step 2: Calculation of DG unit injected active powers. This procedure is implemented in MATLAB. According to the results of the previous iteration, the maximum among the three phase-to-neutral voltages at the PCC is determined for each DG unit. Then, the injected active power of each DG unit is calculated taking into consideration the corresponding droop curve of Fig. 2.

Step 3: New power flow. Considering the new active power injections, a power flow is activated and new phase-domain voltages are calculated by OpenDSS.

Step 4: Convergence check. A comparison of voltages at each node between the last and the previous iteration is made. If the tolerance criterion *tol*, which has been set to 0.01 V, is satisfied for all nodes, convergence has been achieved and the simulation procedure for this time instant terminates moving to the next one. Otherwise, the procedure moves to the next iteration (*Step 2*).

The presented droop curve is expressed mathematically by a piecewise function comprising three regions. In the first region, the injected active power is kept constant to $\boldsymbol{P}_{ref}$ irrespective of the grid voltage. In the second region, droop control is implemented, and in the third one, the injection is considered zero. Therefore, the transition among the regions between two consecutive iterations may result in numerical oscillations of the injected active power and thus of grid voltage. In order to avoid these spurious oscillations, the injected active power $\boldsymbol{P}^{i}$ of the i-th iteration is calculated taking into account the value of the previous iteration $\boldsymbol{P}^{i-1}$ and using the integral term k as shown in (2):

$$\boldsymbol{P}^{i} = \boldsymbol{P}^{i-1} + (\boldsymbol{P}_{inj} - \boldsymbol{P}^{i-1}) / k \quad (2)$$

where $\boldsymbol{P}_{inj}$ denotes the vector of the injected active powers calculated according to the droop curve of each DG unit.

The value of k can generally vary from small values, which accelerate convergence and oscillations, to large values, which lead to slow convergence, but more robust results. A trade-off between convergence rate and damping of oscillations should be made for the right choice of the integral term. The effect of the integral term on the convergence rate and the mitigation of the numerical oscillations are thoroughly analyzed in the next section.

III. Simple Low-Voltage Feeder

The proposed simulation tool is demonstrated in the low-voltage feeder of 0.4 kV, shown in Fig. 4. The line characteristics of the test network are listed in Table I. The network includes three-phase balanced constant PQ loads and DG units with different nominal ratings, as presented in Table II. The transformer connection is Dyn5 and has a nominal power of 250 kVA, short-circuit voltage of 4%, while the no-load losses and on-load losses are 325 W and 3250 W, respectively. The transformer voltage ratio is equal to

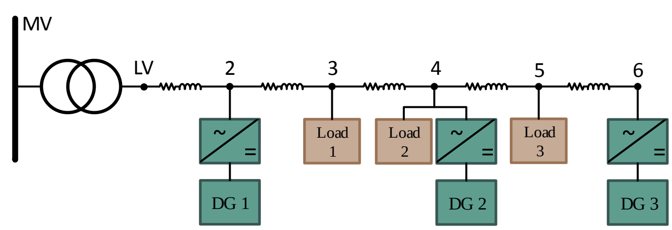

Figure 4. Simple low-voltage feeder topology.

TABLE I
LINE CHARACTERISTICS

LINE	R (Ω/km)	X (Ω/km)	C (nF/km)	Length (km)
LV-2	0.456	0.088	250	0.057
2 - 3	0.468	0.085	250	0.094
3 - 4	0.48	0.08	250	0.025
4 - 5	0.462	0.083	250	0.132
5 - 6	0.924	0.076	200	0.066

TABLE II
POWER GENERATION AND CONSUMPTION

	Rated Active Power (kW)		Active Power (kW)	Reactive Power (kVAr)
DG 1	20	Load 1	4.5	2.25
DG 2	40	Load 2	3	1.5
DG 3	35	Load 3	6	3

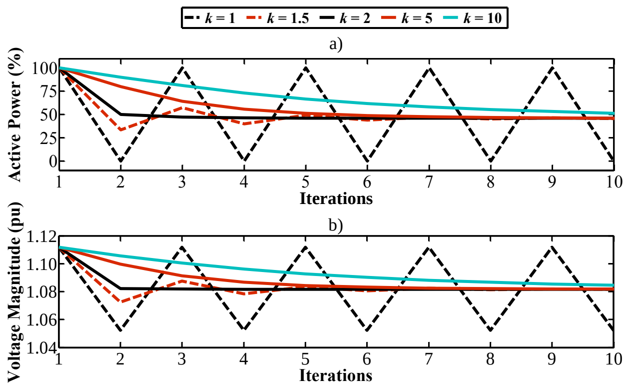

Figure 5. Numerical oscillations of the calculation procedure. (a) Injected active power of DG 3 and (b) voltage magnitude at node 6.

20/0.4 kV and the voltage at the slack bus is set to 1.05 pu (21 kV) in order to ensure that the voltages along the network are larger than 1.06 pu, and thus the activation of droop control. In practice, this is often the case as the ratio of the transformer is manually set to avoid undervoltages in high load conditions without taking into account the increasing penetration of DG.

Initially, the effect of the integral term on the convergence of the calculation procedure is examined. For this purpose, the injected active power of DG 3 and its voltage at the corresponding PCC are illustrated in Fig. 5 for different values of the integral term. For k equal to 1, (2) is simplified and the output power of each DG unit is calculated according to the corresponding droop curve ignoring the results obtained from the previous iteration. As a result, the calculation procedure presents an oscillatory behaviour and it cannot converge to equilibrium.

The incorporation of the integral term in (2) intends to reduce these oscillations. It is evident that values greater than 1.5 mitigate this numerical instability. However, an increase of the integral term also results in a slower but more robust convergence of the calculation procedure to equilibrium. More specifically, the necessary number of iterations in order to achieve convergence for values of k equal to 1.5, 2, 5, and 10 are 19, 10, 16, and 30, respectively. It is also noted that the final equilibrium point is irrelevant to the exact value of the integral term, guaranteeing that a unique solution exists which remains unaffected by the introduction of the integral term in (2). In this paper, the value of the integral term is selected equal to 5.

In order to validate the developed simulation tool, a comparison is made with the implementation of droop control in the MATLAB/SIMULINK time-domain software. In Table III, the injected active power of each DG unit is presented in the case of no droop control as well as in the case where droop control is implemented by both the proposed simulation tool and MATLAB/SIMULINK. Results from both implementations are in very good agreement. The maximum error on the injected active power is less than 36 W, thus 0.15 % which corresponds to a near-zero mismatch.

In Fig. 6 the voltage profile along the feeder is illustrated, where the activation of droop control mitigates overvoltages quite effectively. The two curves corresponding to both implementations of droop control, overlap (blue curve fits the red-dashed curve). Furthermore, the superior performance of the proposed simulation tool over time-domain simulations is evident by the fact that the total execution time for the proposed simulation tool is only 100 ms, whereas the corresponding time for MATLAB/SIMULINK is almost 1 min.

The injected active power of DG units referred to their rated power is depicted in Fig. 7. From their final values in the 16-th iteration it is concluded that there is an unequal curtailment of active power. The DG unit located at the end of the feeder is curtailed more than the other ones. This is the main drawback of the incorporated droop control which occurs due to the increased voltage along the feeder, as shown in the voltage profile of Fig. 6.

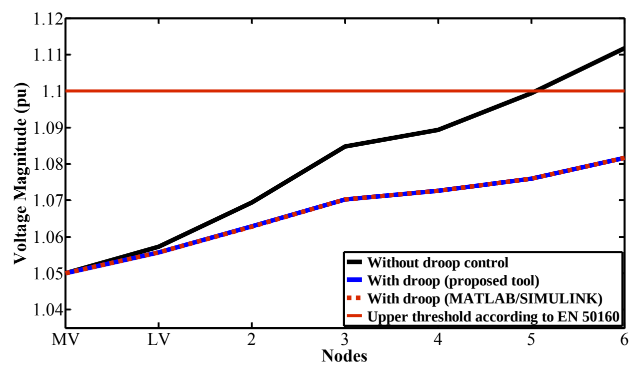

Figure 6. Voltage profile along the feeder.

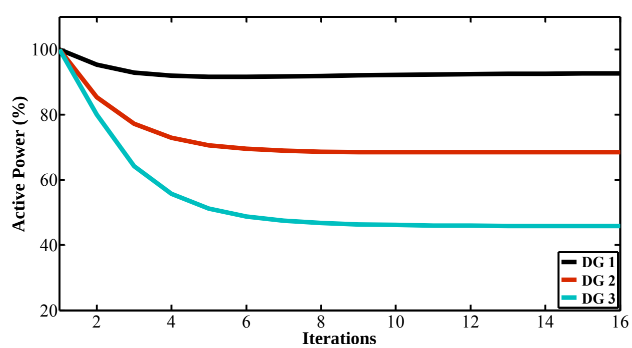

Figure 7. Injected active power of DG units.

TABLE III
INJECTED ACTIVE POWER (KW) OF DG UNITS

	Rated Output	With droop (proposed tool)	With droop (Simulink)
DG 1	20	18.526	18.561
DG 2	40	27.375	27.411
DG 3	35	16.041	16.055

IV. Extended Low-Voltage Network

The high performance of the proposed tool is further investigated by simulating an extended low-voltage network of a Slovenian Distribution System Operator, namely Elektro Gorenjska. The single-line diagram of the network is depicted in Fig. 8. This complex network consists of 10 feeders and 79 nodes, where 70 inductive unbalanced loads and 6 DG units are connected. The rated power of the DG units and their connection points are provided in Table IV. The characteristics of the medium- to low-voltage transformer have been presented in the previous section. Finally, the cross-sections of the 4-wire distribution lines range from 4x16 mm^2 to 4x150 mm^2 with their lengths varying from 10 m up to 176 m. More details considering this network can be found in [17].

In this section, the simulation process comprises 10 time instants. For each time instant, the P_{ref} is kept constant and equal to the rated power of the DG units, whereas the load varies. The variation of the aggregated load in each phase is depicted in Fig. 9. The load is unevenly distributed along the network and among phases in order to simulate the actual conditions of the network. Each load is considered with constant power factor equal to 0.9.

The total execution time for the proposed tool is approximately 2.2 s, i.e. 220 ms per time instant. In comparison with the simple network, the increase in the execution time is negligible compared to the increase in the number of nodes, highlighting the superior performance of the proposed tool. The simulation of the network with MATLAB/SIMULINK is infeasible due to the excessive execution time.

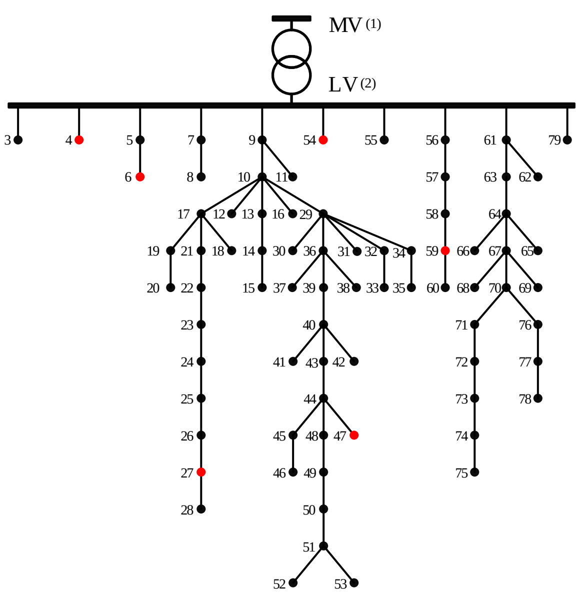

Figure 8. Single-line diagram of the extended low-voltage network. DG units are connected to the red nodes.

TABLE IV
RATED POWER (KW) OF DG UNITS

Name	Node	Rated Power	Name	Node	Rated Power
DG 1	59	22	DG 4	54	50
DG 2	4	29	DG 5	27	15
DG 3	47	44	DG 6	6	49

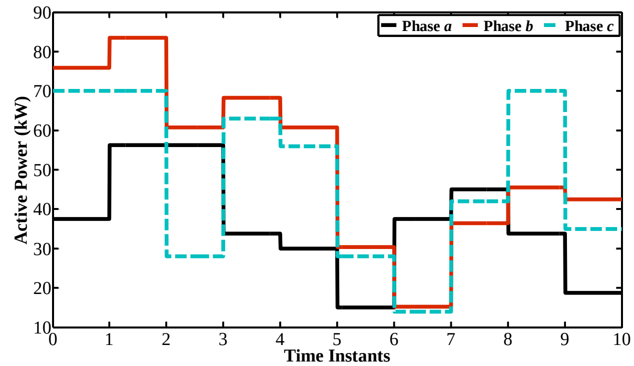

Figure 9. Aggregated load profile in each phase.

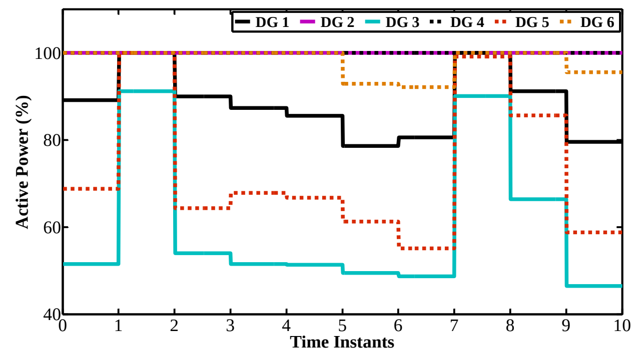

Figure 10. Injected active power of DG units.

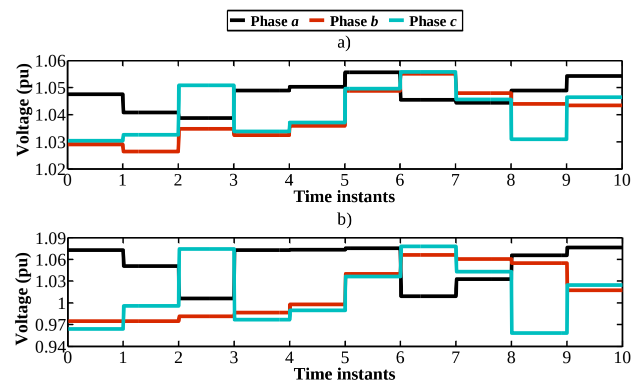

Figure 11. Voltage profile with respect to time instants. (a) Node 4 and (b) Node 27.

In Fig. 10, the injected active power of each DG unit as a percent of the corresponding rated power is depicted against time instants. The droop curve for each DG unit is implemented with respect to the maximum of the three phase voltages at the corresponding PCC. It is worth mentioning that DG units located further from the low-voltage side of the transformer suffer from larger active power curtailment due to the increased voltage profile along the feeder.

Furthermore, in Fig. 11 the voltage profile against time instants is presented for the nodes 4 and 27, where DG 2 and 5 are connected. Node 4 is placed closer to the transformer thus the voltage unbalance is less severe compared to node 27. Additionally, the maximum of the three phase voltages at node 27 is higher than that of node 4 which results in more active

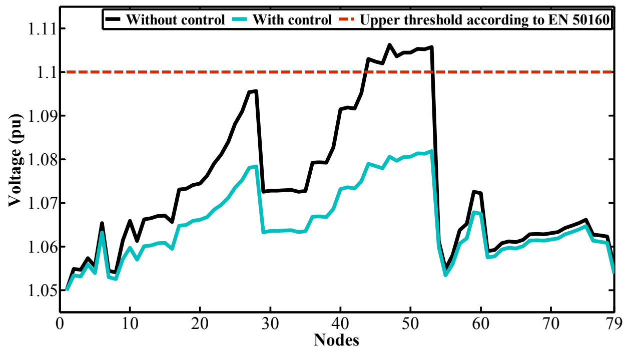

Figure 12. Voltage profile of phase *c* along the network for the 7-th time instant.

power curtailment of DG 5 compared to DG 2. Finally, in Fig. 12, the voltage profile of phase *c* for the 7-th time instant is depicted along the network. In case no control is activated and DG units inject their rated power, some nodes suffer from severe overvoltage, which is successfully mitigated with the activation of droop control.

V. Conclusions

In this paper, a flexible tool has been presented for the simulation of extended networks comprising DG units. Its distinct feature is the ability to integrate different control schemes of DG units, while presenting small execution times compared to time-domain software products.

The validity of the proposed tool is first shown in a simple low-voltage feeder, where the droop control of the active power with respect to the grid voltage is considered as the incorporated control scheme. Results are verified by comparison with the corresponding obtained by the time-domain simulation tool of MATLAB/SIMULINK, while a significant improvement in the execution time is observed.

The performance of the proposed tool is further demonstrated in an extended 79-node network with unbalanced loads, where the simulation with conventional time-domain software is prohibitive. Results show that the execution time is slightly affected by the size of the network, making the proposed software a powerful tool for the efficient simulation of extended distribution grids with controlled DG units.

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