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Fault tolerance enhancement in distribution power grids: a voltage set-point reconfiguration approach

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Abstract: In this paper we present a supervisory strategy for voltage regulation control problems in electrical power grids based on the Command Governor (CG) approach. The scheme consists of reconfiguring the nominal voltage set-point of the network in the presence of Distributed Generation (DG) units to avoid operative constraint violations in response to unexpected load changes and/or failures. Such a reconfiguration capability allows one to enhance the fault tolerability and to prevent undesirable phenomena from occurring in the electrical power grid. We focus on an electrical Medium Voltage (MV) distribution network subject to coordination constraints on maximum load voltages deviations and possible failures on the *on-load tap changers* (OLTC). Simulation results show that the CG unit ensures feasible evolutions of the overall network by reconfiguring the nominal voltage set-point, whenever critical events occur.

Keywords: Command Governor, Electrical power systems, distribution networks, power generation, Fault tolerance, Set-point control.

1. INTRODUCTION

In recent years major technological changes and power industry restructuring processes have begun to happen due to the deregulation and the power grids have evolved from a vertically organized and monopolized market to a liberalized open one, with various competing market players. The latter has created a fertile ground for a transition from a highly passive transmission grid towards a more active management of it, facilitating bidirectional flows of energy and the introduction of small-scale DG units, even located at the end-user sites.

This new scenario makes realistic research initiatives aimed at investigating innovative wide-area control and coordination strategies for ensuring safe and economical energy dispatch under the changed regulatory rules which has completely altered the normal practices (Blaabjerg et al. (2006)). As a consequence, researches on Distributed Generation have attracted an increasing interest and significant advances have been achieved in recent years (Iyer et al. (2005))-(Mogos and Guillaud (2004)).

Several aspects of DG have been identified and discussed in depth in recent literature. Among these, the overvoltage/undervoltage problem at different nodes due to the incorporation of DG in the distribution network is of special interest here and it is known to require special attention (Kojovic (2002)).

Distribution systems are generally designed to operate radially without any generation on the distribution lines or at the customer sites. The introduction of DG units can significantly affect the power flows and voltages at the customers and utility equipments. If significant DG power is introduced, this may deteriorate the effectiveness of standard voltage regulation systems in charge of handling load variations and adverse events in the transmission systems so that the customer supply voltages are kept within certain bounds.

In typical MV distribution networks, the voltage control is primarily carried out by *the on-load tap changers* (OLTCs). Normally there is not coordination amongst the OLTCs in the different branches of the network. Therefore, when DG units are connected to the power system, the subsequent change in the power factor may lead to incorrect operation if the embedded generator power is large compared to the customer load (Jenkins et al. (2000)). This is a crucial problem which needs to be assessed for proper operations of the power system.

Here the problem of *Voltage Regulation for Distributed Generation* will be rigourously addressed via constrained control theory. The goal is to determine a tap position in the OLTC unit under changed load conditions such that the MV bus voltages track as close as possible the nominal values compatibly with constraints on the MV customer bus voltages, which must be satisfied despite of any fluctuation in active and reactive powers.

A Command Governor (CG) approach based on the conceptual tools of predictive control methodologies will be used for solving the problem. The CG methodology consists of adding to a primal compensated system a nonlinear device whose action is based on the actual reference, current state and prescribed constraints. The aim of the CG is that of modifying, when necessary, the reference in such a way that the constraints are enforced and the primal compensated system maintains its linear behavior. Methodological studies along these lines have appeared in (Bemporad et al. (1997)), (Casavola et al. (2000)), while for CGs approached from different perspectives see (Gilbert and Kim (1995)).

Moreover, what is further investigated here is the CG capability to maintain constraints satisfaction also in presence of faults/failures and/or critical events which could seriously damage the normal operation modes of the power grid.

The paper is organized as follows. In Section 2, the power system network is described and the problem formulated. In Section 3, the CG scheme is discussed and its relevant properties summarized. Computer simulations are finally presented in Section 4 and some conclusions end the paper.

2. POWER SYSTEM MODELLING

Let us consider the radial power system network described in (Agustoni et al. (2002)) and obtained by suitably simplifying a typical part of the MV Italian distribution network. Such a network presents six MV loads (C_1, C_2, C_3, C_4, C_5, C_6) that are connected through two MV distribution lines (L_1, L_2) to the HV/MV transformer OLTC. Power generation phenomenon has been modelled by means of a single synchronous machine directly connected to the network. This represents the equivalent of one or more generators connected to the same node.
The HV/MV transformer tap position is computed at each control session with a time period of 15 minutes. By assuming loads balanced and symmetrical generation, one can derive the single-phase equivalent circuit of Fig. 1, which represents a static model of the network.

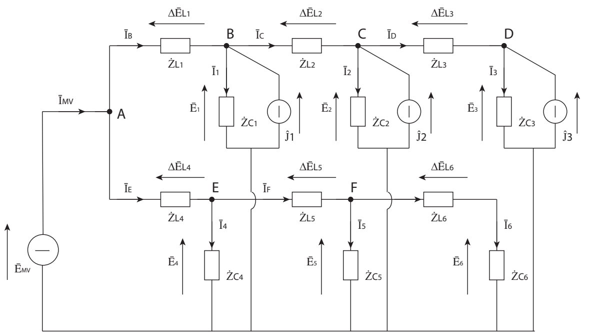

Fig. 1. Single-phase equivalent circuit

In this scheme, $\bar{E}_{MV}(t)$ denotes the transformer HV/MV buses secondary voltage, $\bar{I}_{MV}(t)$ the MV absorbed current, $\bar{E}_i(t)$, $i = 1, \ldots, 6$ the load voltages of C_i, $i = 1, \ldots, 6$, $\Delta\bar{E}_{L_i}$, $i = 1, \ldots, 6$, the MV line voltage drops $\bar{I}_i(t)$, $i = 1, \ldots, 6$, the absorbed current from the loads, $\dot{Z}_{C_i}$, $i = 1, \ldots, 6$, the load impedances and finally $\dot{Z}_{L_i}$, $i = 1, \ldots, 6$ the line impedances. It is worth to point out that the DG units has been represented as current generators, namely $\bar{J}_i$, $i = 1, 2, 3$.
Notice that, because the interest here is only to compute the theoretical voltage complying with the conditions specified in the sequel, we have represented the transformer HV/MV through the simple voltage generator $\bar{E}_{MV}(t)$. Moreover, it can be assumed w.l.o.g. that the power load is constant during each control session. It is obvious that such a hypothesis becomes realistic as the time interval between two subsequent control sessions is sufficiently small. By tacking into account the single-phase equivalent circuit of Fig. 1, via the Kirchhoff's laws and Thevenin's theorem, the following discrete time equations can be obtained

$$\begin{cases} \bar{E}_{MV}(t) + \dot{Z}_{L_1}(\bar{J}_1 + \bar{J}_2 + \bar{J}_3) - \bar{E}_1(t+1) \\ -\dot{Z}_{L_1}(\bar{I}_1(t+1) + \bar{I}_2(t) + \bar{I}_3(t)) = 0 \\[2ex] \bar{E}_{MV}(t) + \dot{Z}_{L_1}\bar{J}_1 + (\dot{Z}_{L_1} + \dot{Z}_{L_2})(\bar{J}_2 + \bar{J}_3) - \bar{E}_2(t+1) \\ -\dot{Z}_{L_1}\bar{I}_1(t+1) - (\dot{Z}_{L_1} + \dot{Z}_{L_2})(\bar{I}_2(t+1) + \bar{I}_3(t+1)) = 0 \\[2ex] \bar{E}_{MV}(t) + \dot{Z}_{L_1}\bar{J}_1 + (\dot{Z}_{L_1} + \dot{Z}_{L_2})\bar{J}_2 + (\dot{Z}_{L_1} + \dot{Z}_{L_2} + \dot{Z}_{L_3})\bar{J}_3 \\ -\bar{E}_3(t+1) - \dot{Z}_{L_1}\bar{I}_1(t+1) - (\dot{Z}_{L_1} + \dot{Z}_{L_2})\bar{I}_2(t+1) \\ -(\dot{Z}_{L_1} + \dot{Z}_{L_2} + \dot{Z}_{L_3})\bar{I}_3(t+1)) = 0 \\[2ex] \bar{E}_{MV}(t) - \bar{E}_4(t+1) - \dot{Z}_{L_4}(\bar{I}_4(t+1) + \bar{I}_5(t+1) + \bar{I}_6(t+1)) = 0 \\[2ex] \bar{E}_{MV}(t) - \bar{E}_5(t+1) - \dot{Z}_{L_4}\bar{I}4(t+1) \\ -(\dot{Z}_{L_4} + \dot{Z}_{L_5})(\bar{I}_5(t+1) + \bar{I}_6(t+1)) = 0 \\[2ex] \bar{E}_{MV}(t) - \bar{E}_6(t+1) - \dot{Z}_{L_4}\bar{I}4(t+1) - (\dot{Z}_{L_4} + \dot{Z}_{L_5})\bar{I}_5(t+1) \\ -(\dot{Z}_{L_4} + \dot{Z}_{L_5} + \dot{Z}_{L_6})\bar{I}6(t+1) = 0 \end{cases} \tag{1}$$

and the load characteristic equations lead to

$$-\bar{E}_i(t+1) + \bar{Z}_{C_i}\overline{I}_i(t+1) = 0, \; i = 1, \ldots, 6 \tag{2}$$

We shall assume hereafter that the disturbance affecting the system consists of load changes, which will be modelled as a variation on the nominal current absorbed by the loads. Specifically we have

- *Module of the absorbed current from a load* - The module of the current absorbed from a load can vary within 25% of the nominal value, i.e.

$$\delta_{I_i} = \pm 0.25 I_{n_i}, \;\; i = 1, \ldots, 6 \tag{3}$$

  where
  - δ_{I_i} represents the disturbance on the module of absorbed current of the i-th load;
  - I_{n_i} nominal current on the i-th load.
- *Load power factor* $\cos\phi_{C_i}$ - It has to belong to the following range:

$$0.8 \leq \cos\phi_{C_i} \leq 0.91, \;\; i = 1, \ldots, 6. \tag{4}$$

Therefore, from equations (1-2) and by recalling that

$$\begin{aligned} \dot{Z}_{L_i} &= R_{L_i} + j\, X_{L_i}, \;\; i = 1, \ldots, 6, \\ \dot{Z}_{C_i} &= R_{C_i} + j\, X_{C_i}, \;\; i = 1, \ldots, 6, \\ \bar{E}_i(t) &= E_{D_i}(t) + j\, E_{I_i}(t), \;\; i = 1, \ldots, 6, \\ \bar{I}_i(t) &= I_{D_i}(t) + j\, I_{I_i}(t), \;\; i = 1, \ldots, 6, \\ \bar{E}_{MV}(t) &= E_{MVD}(t), \end{aligned}$$

the following state space description can be derived

$$\begin{cases} x_p(t+1) = G\, u(t) + G_I\, \delta_I(t) + G_J\, J(t) \\ \quad\;\; y(t) = H\, x_p(t) \end{cases} \tag{5}$$

where

$$x_p(t) = \big[E_{D_1}(t)\, I_{D_1}(t)\, E_{D_2}(t)\, I_{D_2}(t)\, E_{D_3}(t)\, I_{D_3}(t)$$
$$E_{D_4}(t)\, I_{D_4}(t)\, E_{D_5}(t)\, I_{D_5}(t)\, E_{D_6}(t)\, I_{D_6}(t)\, E_{I_1}(t)$$
$$I_{I_1}(t)\, E_{I_2}(t)\, I_{I_2}(t)\, E_{I_3}(t)\, I_{I_3}(t)\, E_{I_4}(t)\, I_{I_4}(t)$$

$E_{I_5}(t)\, I_{I_5}(t)\, E_{I_6}(t)\, I_{I_6}(t)\big]^T$,

$u(t) = E_{MV}(t)$,

$\delta_I(t) = \big[\delta_{I_{D_1}}(t)\delta_{I_{I_1}}(t)\;\; \delta_{I_{D_2}}(t)\,\delta_{I_{I_2}}(t)\;\; \delta_{I_{D_3}}(t)\,\delta_{I_{I_3}}(t)\;\; \delta_{I_{D_4}}(t)\delta_{I_{I_4}}(t)$
$\delta_{I_{D_5}}(t)\,\delta_{I_{I_5}}(t)\;\; \delta_{I_{D_6}}(t)\,\delta_{I_{I_6}}(t)\big]^T$,

$J(t) = \big[J_{D_1}(t)\, J_{I_1}(t)\;\; J_{D_2}(t)\, J_{I_2}(t)\;\; J_{D_3}(t)\, J_{I_3}(t)\big]^T$,

and

$y(t) = \big[E_{D_1}(t)\, E_{D_2}(t)\, E_{D_3}(t)\, E_{D_4}(t)\, E_{D_5}(t)\, E_{D_6}(t)$
$E_{I_1}(t)\, E_{I_2}(t)\, E_{I_3}(t)\, E_{I_4}(t)\, E_{I_5}(t)\, E_{I_6}(t)\big]$.

The system matrices G, G_I, G_J and H can be straightforwardly derived. Notice that the resulting system (5) is static.
The idea, here exploited, is to consider the injected active and injected/absorbed reactive powers due to the presence of the DG units as further disturbances acting on the system. Therefore, the system model (5) will be rewritten according to the following extra notations
$d(t) = \begin{bmatrix} \delta_I(t) \\ J(t) \end{bmatrix}, \;\; G_d = [G_I\; G_J]$.

2.1 Constraints and control requirements

The model network (5) is subject to the following constraints:

1) The actuator, imposing the HV/MV transformer tap position, exhibits limitations due to its physical structure. In particular, the value of $\bar{E}_{MV}(t)$ can vary in percent with respect to the nominal voltage E_n, as follows
$$E_n \leq |\bar{E}_{MV}(t)| \leq (1+\beta)E_n, \;\forall t, \beta \in (0\; 0.1]; \quad (6)$$
2) Load voltages $\bar{E}_i(t),\; i = 1, 2, \ldots, 6$ cannot be imposed equal to the reference value E_n, because the voltage drops of the corresponding distribution lines are different each other. An admissible range of variation on the modules of $\bar{E}_i(t),\; i = 1, \ldots, 6$ with respect to E_n must be imposed:
$$\begin{array}{l}(1-\alpha)E_n^2 \leq |\bar{E}_i(t)|^2 \leq (1+\alpha)E_n^2, \\ i = 1, \ldots, 6,\; \forall t\end{array} \quad (7)$$
In (Ilic and Zabourszky (1997)), it is stated that deviations of $|\bar{E}_i(t)|\;\; i = 1, 2, \ldots, 6$ within $\pm 10\%$ tolerance from their nominal values E_n are reasonable.

Therefore the following problem can be stated:

DG Voltage Regulation Problem (DGVRP) - At each control session t, determine a control command such that:

- the load voltages $\bar{E}_i(t),\; i = 1, \ldots, 6$ fulfill the constraints (7);
- the HV/MV transformer secondary voltage $\bar{E}_{MV}(t)$ satisfies inequality (6).

The **DGVRP** will be recast as a constrained convex optimization problem and solved by means of a CG strategy (Bemporad et al. (1997)). In the next section, the main features of such an approach will be recalled.

3. COMMAND GOVERNOR APPROACH

A CG control scheme, with plant, primal controller and CG device, is depicted in Fig 2. Accordingly, let the primal-controlled system be described by the following linear, time-invariant representation
$$\begin{cases} x(t+1) = \Phi x(t) + Gg(t) + G_d d(t) \\ \quad\; y(t) = H_y x(t) \\ \quad\; c(t) = H_c x(t) + Lg(t) + L_d d(t) \end{cases} \quad (8)$$
where $x(t) \in \mathcal{R}^n$ is the state vector; $g(t) \in \mathcal{R}^m$ the manipulable command input, which if no constraints were present, would essentially coincide with the output reference $r(t) \in \mathcal{R}^p$; $d(t) \in \mathcal{R}^{n_d}$ an exogenous disturbance satisfying $d(t) \in \mathcal{D}$, $\forall t \in \mathcal{Z}_+$ with $\mathcal{D}$ a specified convex and compact set such that $0_{n_d} \in \mathcal{D}$; $y(t) \in \mathcal{R}^p$ the output, viz. a performance related signal which is required to track $r(t)$; $c(t) \in \mathcal{R}^{n_c}$ the constrained vector
$$c(t) \in \mathcal{C}, \;\; \forall t \in \mathcal{Z}_+ \quad (9)$$
which $\mathcal{C} \subset \mathcal{R}^{n_c}$ a prescribed constrained set. It is assumed that
$$(A1) \begin{cases} 1)\; \Phi \text{ is a stability matrix, i.e. all eigenvalues} \\ \quad\; \text{are in the open unit disk;} \\ 2)\; \text{System (8) is offset-free, i.e.} \\ \quad\; H(I_n - \Phi)^{-1}G = I_p \end{cases}$$
The CG design problem is that of generating the command input $g(t)$, at each time instant t, as a function of the current state $x(t)$ and reference $r(t)$
$$g(t) := \overline{g}(x(t), r(t)) \quad (10)$$
in such a way that, under suitable conditions, the constraints (9) are fulfilled for all possible disturbance sequences $d(t) \in \mathcal{D}$ and possibly $y(t) \approx r(t)$. Moreover, it is required that: 1) $g(t) \to \hat{r}$ whenever $r(t) \to r$, with $\hat{r}$ the best feasible approximation of r; and 2) the CG has a finite settling time, viz. $g(t) = \hat{r}$ for a possibly large but finite t whenever the reference stays constant after a finite time. By linearity, one is allowed to separate the effects of the initial conditions and input from those of disturbances, e.g. $x(t) = \overline{x}(t) + \tilde{x}(t)$, where $\overline{x}(t)$ is the disturbance-free component and $\tilde{x}(t)$ depends only on disturbances. Then, adopt the following notations for the disturbance-free solutions of (8) to a constant command $g(t) = w$
$$\begin{array}{rl} \overline{x}_w & := (I_n - \Phi)^{-1}Gw \\ \overline{y}_w & := H_y(I_n - \Phi)^{-1}Gw \\ \overline{c}_w & := H_c(I_n - \Phi)^{-1}Gw + Lw \end{array} \quad (11)$$
Consider next the following set recursions
$$\begin{array}{rl} \mathcal{C}_0 & := \mathcal{C} \sim L_d\mathcal{D} \\ \mathcal{C}_k & := \mathcal{C}_{k-1} \sim H_c\Phi^{k-1}G_d\mathcal{D} \\ & \vdots \\ \mathcal{C}_\infty & := \bigcap_{k=0}^{\infty} \mathcal{C}_k \end{array} \quad (12)$$
where $\mathcal{A} \sim \mathcal{E}$ is defined as $\{a \in \mathcal{A} : \; a + e \in \mathcal{A}, \forall e \in \mathcal{E}\}$. It can be shown that the sets $\mathcal{C}_k$ are nonconservative restrictions of $\mathcal{C}$ such that $\overline{c}(t) \in \mathcal{C}_\infty$, $\forall t \in \mathcal{Z}_+$, implies that $c(t) \in \mathcal{C}$, $\forall t \in \mathcal{Z}_+$. Thus, one can consider only disturbance-free evolutions of the system and adopt a "worst-case" approach. For reasons which will appear clear soon, it is convenient to introduce the following sets for a given $\delta > 0$

$$\mathcal{C}^\delta := \mathcal{C}_\infty \sim \mathcal{B}_\delta \quad (13)$$

$$\mathcal{W}_\delta := \{w \in \mathcal{R}^m : \bar{c}_w \in \mathcal{C}^\delta\} \quad (14)$$

where $\mathcal{B}_\delta$ is a ball of radius δ centered at the origin. We shall assume that there exists a possibly vanishing $\delta > 0$ such that $\mathcal{W}_\delta$ is non-empty. In particular, $\mathcal{W}_\delta$ is the set of all commands whose corresponding steady-state solutions satisfy the constraints with margin δ. From the foregoing definitions and assumptions, it follows that $\mathcal{W}_\delta$ is closed and convex.

The main idea is to choose at each time step a constant virtual command $v(\cdot) \equiv w$, with $w \in \mathcal{W}_\delta$ such that the corresponding virtual evolution fulfills the constraints over a semi-definite horizon and its distance from the constant reference value $r(t)$ is minimal. Such a command is applied, a new state is measured and the procedure is repeated. In this respect we define the set $\mathcal{V}(x)$ as

$$\mathcal{V}(x) = \{w \in \mathcal{W}_\delta : \bar{c}(k, x, w) \in \mathcal{W}_k, \forall k \in \mathcal{Z}_+\} \quad (15)$$

where

$$\bar{c}(k, x, w) = H_c\left(\Phi^k x(t) + \sum_{i=0}^{k-1} \Phi^{k-i-1} G w\right) + Lw \quad (16)$$

has to be understood as the disturbance-free virtual evolution at time k of c from the initial condition x at time zero under the constant command $v(\cdot) \equiv w$. As a consequence $\mathcal{V}(x) \subset \mathcal{W}_\delta$, and, if non-empty, it represents the set of all constant virtual sequences in $\mathcal{W}_\delta$ whose evolutions starting from x satisfies the constraints also during transients. Thus taking as a selection index, the CG output is chosen according to the solution of the following constrained optimization problem

$$g(t) = \arg\min_{w \in \mathcal{V}(x(t))} \|w - r(t)\|_\Psi \quad (17)$$

where $\Psi = \Psi^T > 0_p$ and $\|w\|_\Psi := x^T \Psi x$. In (Casavola et al. (2000)) the main properties for the above described CG have been discussed and proved.

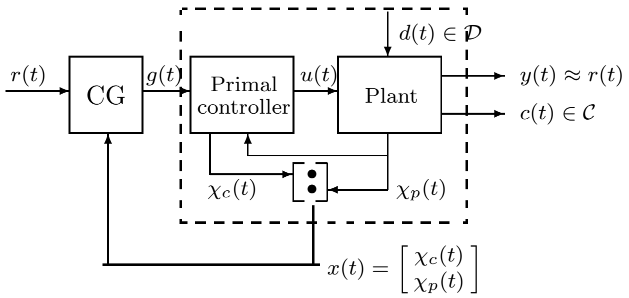

Fig. 2. Command Governor structure.

4. PRIMAL CONTROLLER DESIGN AND CG PRIMAL-CONTROLLED PLANT CONTROL SCHEME

The first step in a CG design consists in the synthesis of a primal controller in such a way that the *primal-controlled plant* is asymptotically stable and satisfies some desirable control specifications for small-signal regimes. To this end, let $\bar{e}_j(t) = \bar{E}_{r_i}(t) - \bar{E}_i(t)$, $i = 1, \ldots, 6$ be the phasor representing the tracking voltage error on the i-th load and define their real and imaginary parts as

$$\begin{cases} e_{D_i}(t) = E_{r_{D_i}}(t) - E_{D_i}(t), \\ e_{I_i}(t) = E_{r_{I_i}}(t) - E_{I_i}(t), \quad i = 1, \ldots, 6. \end{cases} \quad (18)$$

The primal controller will be designed with respect to the feedback control scheme of Fig. 3 where $\bar{E}_r(t) :=$

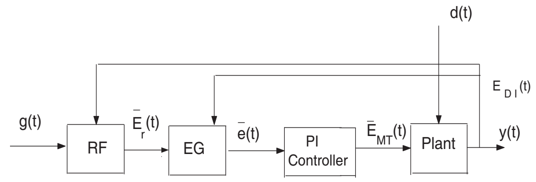

Fig. 3. Primal feedback control scheme

$[\bar{E}_{r_1}(t), \bar{E}_{r_2}(t), \bar{E}_{r_3}(t), \bar{E}_{r_4}(t), \bar{E}_{r_5}(t), \bar{E}_{r_6}(t)]$ is a vector of admissible reference values for the load voltage phasors whose module equals $g(t)$, and

$$\begin{aligned} \bar{E}_{DI}(t) := [&E_{D_1}(t), E_{I_1}(t), E_{D_2}(t), E_{I_2}(t), E_{D_3}(t), E_{I_3}(t), \\ &E_{D_4}(t), E_{I_4}(t), E_{D_5}(t), E_{I_5}(t), E_{D_6}(t), E_{I_6}(t)]. \end{aligned}$$

The latter is provided by the CG by suitably modifying the nominal voltage E_n in order to enforce all the prescribed constraints (see Fig. 4). Specifically, at each time instant, the **RF** module generates the couple of the reference phasors $\bar{E}_{r_i}(t)$, $i = 1, \ldots, 6$ with amplitude $g(t)$ and phase ϕ_i as follows

$$\bar{E}_{r_i}(t) = g(t)\, e^{j\,\phi_i(t)}, \quad i = 1, \ldots, 6, \quad (19)$$

where the phase displacements $\phi_i(t)$, $i = 1, \ldots, 6$ are those of the load voltages $\bar{E}_i(t)$, $i = 1, \ldots, 6$. This choice is arbitrary but justified in practice because the reference and actual voltage phasors are usually aligned under normal conditions. Finally, the **EG** error generator device computes the error

$$\begin{aligned} \bar{e}(t) := [&e_{D_1}(t)\, e_{I_1}(t)\, e_{D_2}(t)\, e_{I_2}(t) e_{D_3}(t) e_{I_3}(t) \\ &e_{D_4}(t)\, e_{I_4}(t) e_{D_5}(t)\, e_{I_5}(t)\, e_{D_6}(t)\, e_{I_6}(t)]^T \end{aligned}$$

as indicated in (18).

Because one of the requirements is to compensate the effect of constant disturbances, the following primal feedback PI control law has been considered

$$\bar{E}_{MV}(t) = \bar{E}_{MV}(t-1) + \sum_{i=1}^{6} [k_i\ k_i] \begin{bmatrix} e_{D_i}(t) \\ e_{I_i}(t) \end{bmatrix} \quad (20)$$

For the power network considered in the example of the next section, it results that parameters $k_1 \in [0,\ 0.5]$, $k_2 \in [0,\ 0.5]$ $k_3 = 0.01$, $k_4 = k_1$, $k_5 = k_2$ and $k_6 = k_3$ ensure that the compensated system is asymptotically stable and the tracking error specification (7) with $\alpha = 0.1$ is satisfied (see eq. (7)).

Finally, when a CG device is inserted in the previously described setup, the complete control scheme is depicted in Fig. 4.

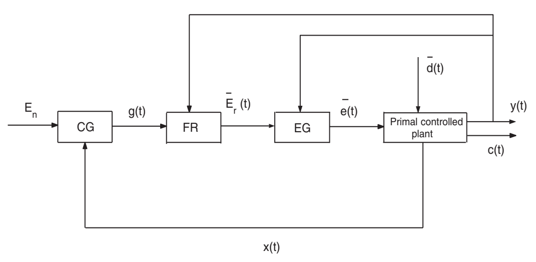

Fig. 4. CG primal-controlled plant control scheme

5. SIMULATIONS

The constrained strategy of Section 3 has been applied to the network model (5), whose data are

$$R_{C_i} = 14.4,\ R_{L_i} = 0.0678,\ i = 1, \ldots, 6$$
$$X_{C_i} = 7, \quad X_{L_i} = 0.1152,\ i = 1, \ldots, 6.$$

For the sake of simplicity, all variables have been considered in *pu* units.

In the simulations, the nominal operating set-point of the load voltage modules has been set to equal $E_n = 1$ and we have imposed $\beta = 0.04$ in (6). Moreover, at each time session the following constraint must be fulfilled

$$1 \leq |\bar{E}_{MV}(t)| \leq 1.04,\ \forall t. \tag{21}$$

Regarding the load voltage constraints (7) on $|\bar{E}_i(t)|$ (quadratic constraints), they have been (conservatively) replaced by constraints on the real parts E_{D_i} (linear constraints) $\bar{E}_i(t) \cong E_{D_i}(t)$, $i = 1, \ldots, 6$, $\forall t$, see (Ilic and Zabourszky (1997)) for details. As a consequence, the constraints (7) have been rephrased as

$$(1-\alpha)E_n \leq E_{D_i}(t) \leq (1+\alpha)E_n,\ \alpha \in (0\ 0.1],$$
$$i = 1, \ldots, 6,\ \forall t,$$

with $\alpha = 0.04$ the admissible variation in percent.

We have also supposed that the load power factors are held constant at each time instant to $\cos\phi_{C_i} = 0.9, i = 1, \ldots, 6$. The disturbance $\delta_I(t)$ on the loads C_i, $i = 1, \ldots, 6$ has been generated as an uniformly distributed sequence of random values satisfying the bounds defined in (3).

Moreover, it has been assumed that the GD units on the distribution line L_1 have the following properties:

- GD_1 injects active power: $P_{GD_1} = 0.1$;
- GD_2 injects active power: $P_{GD_2} = 0.1$;
- GD_3 injects active power: $P_{GD_3} = 0.15$ and absorbs reactive power: $Q_{GD_3} = 0.0726$,

at a constant power factor $\cos\phi_{GD_i} = 0.9,\ \ i = 1, 2, 3$.

Finally, the PI gains in (20), $k_1 = k_4 = 0.01$, $k_2 = k_5 = 0.305$ and $k_3 = k_6 = 0.01$, have been selected so as to obtain a satisfactory transient response.

The simulations are instrumental to show the capability the CG scheme to reconfigure the nominal voltage set-point E_n when its value is no longer compatible with the changed nominal conditions. To this end we consider the following control scenario:

- The load voltages $\bar{E}_i$, $i = 1, \ldots, 6$ deviate less than $\pm 4\%$ w.r.t. the nominal value E_n despite any possibly occurring disturbance sequence $d(t)$;
- The transformer HV/MV buses voltage $\bar{E}_{MV}(t)$ lies within the bounds defined in (21);

and the following critical event has been supposed:

the HV/MV transformer OLTC exhibits a 10% *reduction in its voltage generation due to a fault from* $t = 190$ *time units to* $t = 210$. *This implies that it supplies the network distribution lines with only* 90% *of voltage* (E_{MVD}) *w.r.t. the no faulty condition.*

Figs. 5-7 show the dynamics of the compensated linear system without the action of the CG unit. Under the proposed scenario, violations of the prescribed actuator and load voltage constraints result for both feeders. In fact, during the fault time interval starting at time $t = 190$, the unpredictable HV/MV transformer failure cannot ensure the satisfaction of the actuator constraint (6) and as a consequence this pulls down all the voltages on the feeders. On the contrary, on Figs. 8-10, where the responses of the system under the CG action are reported, no constraints violations are observed. This means that the viability of the pre-post fault transient is ensured despite of the presence of the three DG units on the feeder L_1 and the fault occurrence. This is achieved (see Fig. 11) by modifying the actuator set-point from its nominal and/or faulty value into its best feasible approximation $g(t)$. From simulations, the ability of CG to manage the fault occurrence or other adverse conditions is evident. It is worth commenting that the CG is not informed of the fault occurrence and its behaviour hinges on its intrinsic reconfiguration capability.

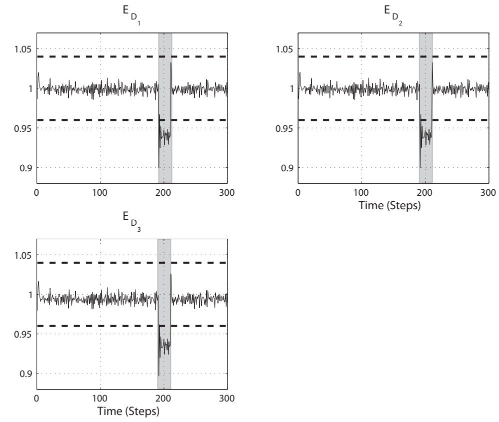

Fig. 5. Loads C_1, C_2, C_3 on the MV distribution line L_1 : without CG

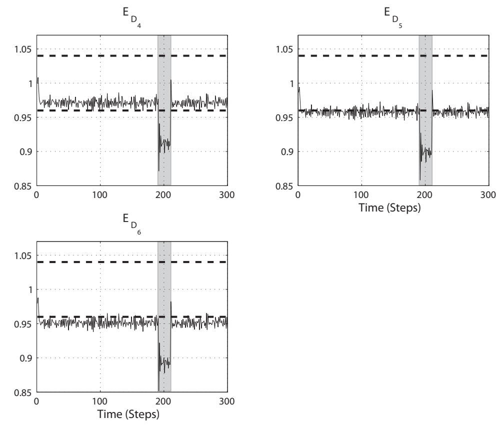

Fig. 6. Loads C_4, C_5, C_6 on the MV distribution line L_2 : without CG

6. CONCLUSIONS

The paper has addressed the voltage regulation problem in MV power networks when DG units are connected to the distribution grid. A discrete-time supervisory strategy has been proposed via the Command Governor approach. It has been shown that such the proposed approach seems to have an intrinsic reconfigurability capability which can be instrumental for ensuring viable solutions under unpredictable adverse conditions acting on the distribution power network.

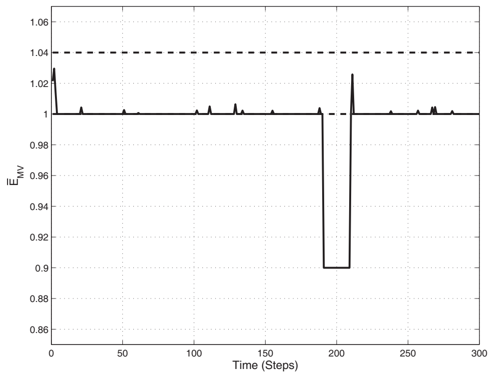

Fig. 7. MV Bus voltage: without CG

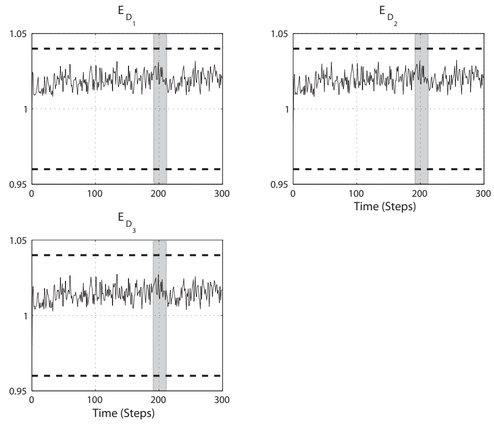

Fig. 8. Loads C_1, C_2, C_3 on the MV distribution line L_1 : with CG

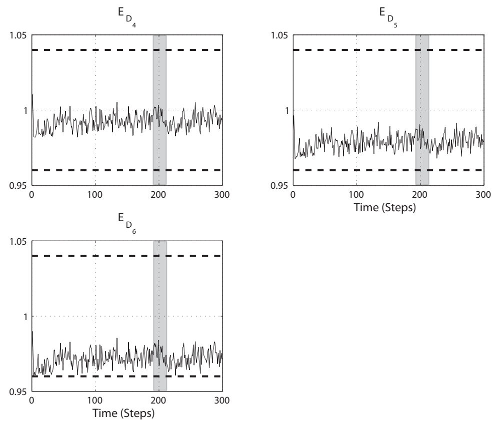

Fig. 9. Loads C_4, C_5, C_6 on the MV distribution line L_2 : with CG

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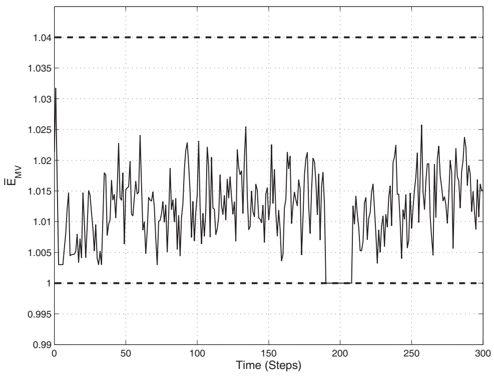

Fig. 10. MV Bus voltage: with CG

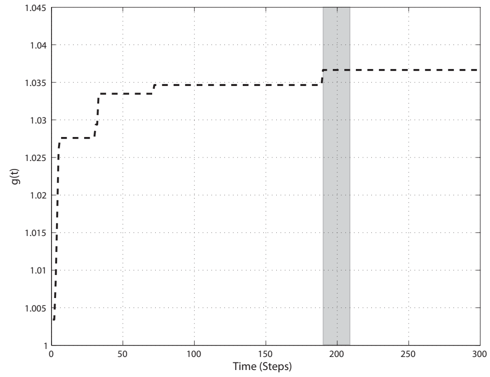

Fig. 11. Output of CG unit

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