Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

Load/Frequency Control in the presence of Renewable Energy Systems: a Reference-Offset Governor approach.

Francesco Tedesco and Alessandro Casavola

Dipartimento di Ingegneria Informatica, Modellistica, Elettronica e Sistemistica, Università degli Studi della Calabria, Via Pietro Bucci, Cubo 42-c, Rende (CS), 87036, Italy,
{ftedesco,casavola}@dimes.unical.it

Abstract: In this paper a supervisory strategy for load/frequency control problems in networked multi-area electrical micro-grids in the presence of Renewable Energy Systems (RES) is presented. The proposed strategy exploits a recently developed constrained supervision methodology known in the literature as the Reference-Offset Governor (ROG) approach. Here, the ROG approach is extended to operate in the presence of rate-bounded disturbances acting as non-manipulable inputs on the plant. The main aim is at adequately orchestrating, during the on-line operations, the switching among different ROG configurations, suitably calibrated on the intensity of the disturbances, to efficiently satisfy the prescribed constraints. It is shown that the use of a bank of ROGs, instead of a single one, can remarkably reduce the conservativeness of the solution and improve the overall performance if the disturbance intensity changes. The effectiveness of the proposed approach is demonstrated on a two-area power system subject to coordination constraints on maximum frequency deviations, exchanged and generated powers and injected power from local RESs.

Keywords: Reference Governors, Multi-area power Microgrids, Load frequency control, Renewable Energy Systems, Bounded Rate Disturbance

1. INTRODUCTION

In the last two decades many works (Outhred *et al.* [2007], Pecas *et al.* [2007]) focused on the integration of Renewable Energy Systems (RESs) into power system grids. Their impact presents both negative and positive aspects that involve power quality, optimum power flow, voltage and frequency control, load dispatch and system economics. In particular, as far as the the nature of RESs power variation is concerned, the effect on the load frequency control (LFC) issue has attracted increasing research interest (Bevrani and Gerard [2010], Dreidy *et al.* [2017]). The LFC problem basically relies upon the global matching between power generation and load demand that need to be balanced regardless of sudden small load perturbations that continuously affect the normal operations of a power system. Severe frequency deviations from nominal may lead to disconnection of some loads and generation units with consequent cascading failure and system collapse.

High RES penetration in power systems may increase uncertainties during abnormal operations and opens important questions, as to whether the traditional LFC control approaches are still adequate to these more challenging contexts. A possible expedient to mitigate the uncertainties arising from the RES integration in traditional grids is the use of storage units (batteries) between the power system and the intermittent energy sources. In this way, a smart coordination among the energy storages and the power generator can be adopted to avoid abnormal power dispatching during the peak hours of the RES production. In fact, fast energy storage actions can be provided to help the LFC control to attenuate the system oscillations after load perturbations occurring during peak load periods.

Inspired by the above described scenario, in this paper a predictive control scheme is proposed and shown to be suitable to act as a tertiary LFC supervisory level for managing generation units connected by distribution lines to remotely distributed loads in microgrids.

The core of the proposed strategy relies on the existing supervision scheme referred as *Reference-Offset Governor* (ROG) Casavola *et al.* [2009]. The ROG unit is a nonlinear device feeding a closed-loop system by modifying, whenever necessary, the nominal references into their feasible versions and generating an offset signal to be added to the plant input terminal. Its main aim relies on the enforcement of pointwise-in-time constraints in spite of possible unknown exogenous inputs acting as disturbances that are usually assumed to be confined into a bounded set. In this way the ROG computes its control action by considering in the predictions the worst-case scenario where the impact on the plant evolution produced by the disturbances is as severe as possible. In most applications such an approach is quite conservative being exogenous inputs characterized by a bounded rate.

Moving from these considerations in this paper we will assume that disturbances acting on the plant present a limited rate, and show that in a such a case a less conservative ROG scheme can be designed for enlarging admissible solution sets at a price of getting a slight more complicated design. The idea is to decompose the bounding region where the disturbance is confined into several inner nested sub-sets and to design a dedicated ROG unit for each sub-set. Then, a suitable switching logic unit is built up in charge of safely orchestrating the transitions among ROG units on the basis of the disturbance subset membership, estimable on-line from related measurable system variables.

Finally, an illustrative example involving a two-area interconnected power system is presented. Simulations show clearly the advantages of the multi-ROG approach with respect to the traditional ROG scheme in managing the uncertainty arising from the presence of RESs.

PRELIMINARIES AND NOTATIONS

$\mathbb{R}$, $\mathbb{R}_+$ and $\mathbb{Z}_+$ denote respectively the real, non-negative real and non-negative integer numbers. The Euclidean norm of a vector $x \in \mathbb{R}^n$ is denoted by $\|x\| = \sqrt{x_1^2 + ... + x_n^2}$ whereas $\|x\|_\Psi^2, \Psi = \Psi^T > 0$, denotes the quadratic form $x^T \Psi x$. A generic ball in an Euclidean n-space $\mathbb{R}^n$ is defined as $\mathcal{B}_\delta := \{x \in \mathbb{R}^n : \|x\| \leq \delta\}$. The boundary of a a compact set $\mathcal{A}$ is defined as $\partial(\mathcal{A})$

Definition 1.1. Given the sets $\mathcal{A}, \mathcal{E} \subset \mathbb{R}^n$, $\mathcal{A} \oplus \mathcal{E} := \{a + e : a \in \mathcal{A}, e \in \mathcal{E}\}$ is *Minkowski Set Sum.*

Definition 1.2. Given the sets $\mathcal{A}, \mathcal{E} \subset \mathbb{R}^n$, $\mathcal{A} \sim \mathcal{E} := \{a : a + e \in \mathcal{A}, \forall e \in \mathcal{E}\}$ is *the Pontryagin-Minkowski set difference.*

2. PROBLEM FORMULATION

Let us consider the following pre-compensated plant model

$$\begin{cases} x(t+1) = \Phi x(t) + G w(t) + d(t) \\ y(t) = H_y x(t) \\ c(t) = H_c x(t) + L w(t) \end{cases} \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state of the closed loop plant, $w(t) = [g^T(t), \theta^T(t)]^T$ the ROG action where $g(t)$ is a suitably modified version of the reference signal $r(t) \in \mathbb{R}^m$, while $\theta(t) \in \mathbb{R}^p$ is an adjustable offset on the nominal control input which we assume to be selected from a given convex and compact set Θ, with $0_m \in \mathit{int}\,\Theta$. Moreover $y(t) \in \mathbb{R}^m$ is the plant output which is required to track $r(t)$ and $c(t) \in \mathbb{R}^{n_c}$ the constrained output vector

$$c(t) \in \mathcal{C}, \quad \forall t \in \mathbb{Z}_+ \tag{2}$$

with $\mathcal{C}$ a specified convex and compact set. Finally $d(t) \in \mathcal{D} \subset \mathbb{R}^d$, $\forall t \in \mathbb{Z}_+$ with $\mathcal{D}$ a compact set with $0_d \in \mathcal{D}$ is an unknown exogenous rate-bounded sequence, i.e.

$$\|d(t+1) - d(t)\| \leq \bar{\Delta}_d \tag{3}$$

In the sequel, the following assumptions are made:

Assumption 1 :

A1. *Φ is a Schur matrix*

A2. *The system (1) is offset-free, i.e. $H_y(I_n - \Phi)^{-1} G = I_m$.*

The ROG design problem can be stated in the following way:

Problem *1. Determine, at each time instant t a suitable reference sequence $w(t)$ which is the best feasible approximation of $[r^T(t), 0_m^T]^T$ such that its application never produces constraint violations, i.e. $c(t) \in \mathcal{C}, \forall t \in \mathbb{Z}_+$*

2.1 Reference Offeset Governor basic design

The traditional solution Casavola *et al.* [2009] for the above stated problem does not take into account the rate-boundedness on the signal $d(t)$. For this reason the resulting scheme is based on a worst case approach where $d(t)$ can take all possible values within the set $\mathcal{D}$. To this end the following Minkowski difference recursions on the constrained set $\mathcal{C}$ are considered

$$\mathcal{C}^0 := \mathcal{C}, \ \mathcal{C}^k := \mathcal{C}^{k-1} \sim H_c \Phi^{k-1} \mathcal{D}, \ \mathcal{C}^\infty := \bigcap_{k=0}^{k=\infty} \mathcal{C}^k \tag{4}$$

Moreover, it is convenient to define the disturbance-free steady state solution of (1) under a constant command $w(t) \equiv w \, \forall t$,

$$\begin{aligned} \bar{x}_w &:= (I_n - \Phi)^{-1} G w, \\ \bar{y}_w &:= H_y (I_n - \Phi)^{-1} G w, \\ \bar{c}_w &:= H_c (I_n - \Phi)^{-1} G z + L w \end{aligned}$$

Now we have all the ingredients for introducing the output admissible set for the system (1)

$$\mathcal{Z} := \left\{ \begin{bmatrix} x \\ w \end{bmatrix} \in \mathbb{R}^{n+m+p} \,\middle|\, \begin{array}{l} c_g \in \mathcal{C}^\delta := \mathcal{C}^\infty \sim \mathcal{B}_\delta, \\ \bar{c}(k, x, w) \in \mathcal{C}^k, \, \forall k \in \mathbb{Z}_+ \end{array} \right\} \tag{5}$$

where $\bar{c}(k, x, w) := H_c \bar{x}(k, x, w) + L w$, with $\bar{x}(k, x, w) := \left(\Phi^k x + \sum_{i=0}^{k-1} \Phi^{k-i-1} G w \right)$ and are the disturbance-free c-variable and state predictions under the constant input sequence w from a generic initial state x. Moreover, let

$$\mathcal{X} := \left\{ x \in \mathbb{R}^n : [\![x^T, w^T]^T \in \mathcal{Z} \text{ for at least one } w \in \mathbb{R}^{m+p} \right\} \tag{6}$$

be the set of all initial states x that can be steered to feasible equilibrium points without constraints violation.

Then the standard ROG device (Casavola *et al.* [2009]) for a plant in form of (1) is designed in order to compute at each time instant the action $w(\cdot)$ according to the following convex optimization

$$w(t) = \arg \min_{w \in \mathcal{V}(x(t))} ||g - r(t)||_{\Psi_g}^2 + ||\theta||_{\Psi_\theta}^2, \tag{7}$$

where $\Psi_g = \Psi_g^T > 0$, $\Psi_\theta = \Psi_\theta^T > 0$ and

$$\mathcal{V}(x) = \left\{ w \in \mathbb{R}^{m+p} : [x^T, w^T]^T \in \mathcal{Z} \right\} \tag{8}$$

is the set of all constant virtual commands whose state evolution starting from x satisfies all the constraints (2) also during the transients.

3. SUPERVISORY ROG ARCHITECTURE

Problem 1 is here solved by exploiting the predictive ideas of the ROG approach of Section 2.1 which is properly adapted in order to comply with rate bounded disturbances. To this end it is assumed that the set $\mathcal{D}$ has been decomposed into L inner sets $\{\mathcal{D}_i\}_{i=0}^{L-1}$ such that $\mathcal{D}_0 := \mathcal{D}$ and $\mathcal{D}_{i+1} \subset \mathcal{D}_i$. In this respect it is convenient to define the minimum time, say it the *minimum disturbance transition time* MDTT τ_d^i, needed to the sequance $d(t) \in \partial(\mathcal{D}_i)$ to transit outside the set $\mathcal{D}_{i-1}$, i.e.

$$\tau_d^i := \inf_{d \in \partial(\mathcal{D}_i)} \{\tau : d \oplus \tau \mathcal{B}_{\bar{\Delta}_d} \nsubseteq \mathcal{D}_{i-1}\} \tag{9}$$

The idea is to design a dedicated ROG unit for each subset $\mathcal{D}_i$, $i \in \mathcal{I} := \{0, ..., L-1\}$ and a Switching Logic unit capable to safely orchestrate the transitions among the ROG units.

A sketch of the ROG-based supervisory architecture is reported in Fig. 1. There a **Bank** of L ROG units say it $\{ROG_0, ROG_1..., ROG_{L-1}\}$, where each ROG unit is off-line designed by considering the $i-th$ disturbance configuration $\mathcal{D}_i$, is ruled by the **Switching Logic** unit that selects the proper ROG_i guaranteeing best tracking performance and constraints fulfillment.

More in details each ROG_i is designed on the basis of the procedure presented in Section 2.1 with recursions (4) computed on the particular set $\mathcal{D}_i$ so that the action of the ROG_i device for the $i-th$ disturbance configuration can be simply determined as follows

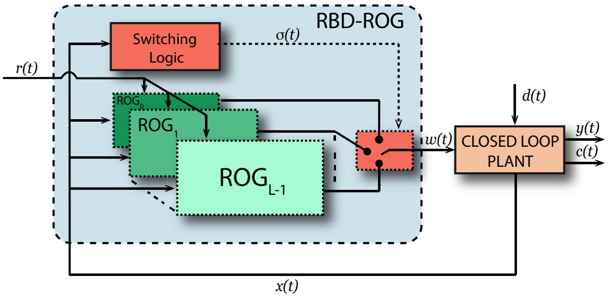

Fig. 1. Supervisory ROG architecture for rate-bounded disturbance

$$w(t) = \arg \min_{w \in \mathcal{V}_i(x(t))} ||g - r(t)||^2_{\Psi_g} + ||\theta||^2_{\Psi_\theta} \qquad (10)$$

where

$$\mathcal{V}_i(x) := \{w \in \mathbb{R}^{m+p} : [x, w] \in \mathcal{Z}_i\} \qquad (11)$$

with the set $\mathcal{Z}_i$ computed on the basis of $\mathcal{C}_i^k$ and $\mathcal{C}_i^\delta := \mathcal{C}_i^\infty \sim \mathcal{B}_\delta$.

The **Switching Logic** unit is in charge to safely activate a transition between two adjacent ROG devices on the basis of set-membership $d(t)$ with respect to $\{\mathcal{D}_i\}_{i=0}^{L-1}$. Its output is represented by the signal $\sigma : \mathbb{Z}^+ \to \mathcal{I} := \{0, \dots, L-1\}$ being a piecewise constant sequence that orchestrates the switchings between ROG devices.

In view of this the first aspect to be clarified is related to the identification of disturbance signal set-membership. Although the signal $d(t)$ cannot be measured, it is possible from (1) to derive the value of $d(t-1)$ in the following way

$$d(t-1) = x(t) - \Phi x(t-1) + G w(t) \qquad (12)$$

For this reason, at each time instant the **Switching Logic** seeks for the smallest set $\mathcal{D}_{i^\star}$ among the family $\{\mathcal{D}_i\}_{i=0}^{L-1}$, such that $d(t-1) \in \mathcal{D}_{i^\star}$, and the signal $\sigma(t)$ is determined in order to guarantee that, under formal conditions, the ROG switching complies with the prescribed constraints.

To this end a second key aspect deserving a proper investigation concerns the derivation of switching conditions ensuring constraints fulfilment.

3.1 *Reference offset governor switching conditions*

The conditions, under which a switching between any two ROG configurations is admissible, are given in the sequel. The main result in this respect is represented by the following Theorem

Theorem 1. Let $\{\mathcal{X}_i\}_{i=0}^{L-1}$ be a family of sets determined according to definition (6) by taking account $\mathcal{D}_i$ for each $i \in \mathcal{I}$, then

$$\mathcal{X}_{i+1} \supset \mathcal{X}_i, \forall i \in \mathcal{I} \qquad (13)$$

Proof - Omitted for space reasons

In view of these achievements, if at a certain time instant $\hat{t}$ during the online operations, the following condition holds true

$$d(\hat{t}) \in \mathcal{D}_{i-1} \qquad (14)$$

any switch of kind $ROG_{i-2} \to ROG_{i-1}$ can be immediately enabled, while kind of switches $ROG_i \to ROG_{i-1}$ can be allowed only if the following condition holds true

$$x(\hat{t}) \in \mathcal{X}_{i-1} \qquad (15)$$

In fact, in the latter case it is required to steer the state trajectory $x(\cdot)$ into $\mathcal{X}_{i-1}$ before the switching event can take place. To this end, a guard time interval must be imposed. This reasoning leads to the dwell-time concept Liberzon *et al.* [1999] that will be discussed and adapted to the proposed framework.

Here, the aim is to define and compute the maximal among the needed time intervals existing between any switch between ROG_i and ROG_{i-1} that are necessary in order to ensure the satisfaction of the above safe switching condition (15) whatever is the starting state condition $x(t) \in \mathcal{X}_i$.

To this end, we will make use of the concept of transition dwell time specialized to comply with the RBD-ROG structure. More precisely, let $\mathcal{X}_i$ and $\mathcal{X}_{i-1}$ be the operating compact regions pertaining to ROG_i and ROG_{i-1}. Then, system (1) is safe under the switching $ROG_i \to ROG_{i-1}$ if there exists for each possible initial condition $x(0) \in \mathcal{X}_i$ a transition dwell time τ_i such that

$$x(t) \in \mathcal{X}_{i-1}, \ t \geq \tau_i \qquad (16)$$

Due to reasons that will be clear soon, we are interested to define the upper-bound among all possible τ_i satisfying the above stated prescriptions. Such a quantity, here denoted as *maximal transition dwell-time* (MTDT), can be formally defined as follows:

$$\tau_i^\star := \sup_{x \in \mathcal{X}_i} \inf_{w \in \mathcal{V}_i(x)} \{\tau : \bar{x}(k, x, w) \in \mathcal{X}_{i-1}, \ \forall k \geq \tau\} \qquad (17)$$

Please notice that the latter quantity needs to be compatible with the MDTT of (9) in order to satisfy both conditions (14)-(15) at switching time $\hat{t}$. Then it is required that

$$\tau_i^* \leq \tau_d^i \qquad (18)$$

and

$$d(t') \in \mathcal{D}_j, j \geq i+1 \qquad (19)$$

3.2 *ROG for rate bounded disturbance*

Given system (1), we will assume that the L ROG units, each one complying with the corresponding disturbance set $\mathcal{D}_i$, have been off-line designed by following the procedure given in the previous Section 3.

Then, the scheme consists of the following Algorithm 1, where admissible switching events amongst the L ROG configurations take place in order to satisfy Problem 1 requirements.

Algorithm 1: Rate Bounded Disturbance Reference Offset Governor (***RBD-ROG***) algorithm

INPUT: $x(t)$, $r(t)$
OUTPUT: $w(t)$

determine $d(t-1)$ via (12)
find
$$i^\star := \arg\max_{i\in\mathcal{I}} i \quad s.t. \quad d(t-1)\in\mathcal{D}_i$$
if $\sigma(t-1) < i^\star$ and $x(t)\notin\mathcal{X}_{i^\star}$ then
  Solve
$$\begin{aligned} w(t) &= \arg\min \|g - r(t)\|^2_{\Psi_g} + \|\theta\|^2_{\Psi_\theta} \\ s.t. \quad & w = [g^T, \theta^T]^T \in \mathcal{V}_{\sigma(t-1)}(x(t)) \\ & \bar{x}(\tau_d^i, x(t), w) \in \mathcal{X}_{\sigma(t-1)-1} \end{aligned} \tag{20}$$
else
  $\sigma(t) \leftarrow \max\{0, i^\star - 1\}$
  Solve
$$w(t) = \arg\min_{w\in\mathcal{V}_{\sigma(t)}(x(t))} \|g - r(t)\|^2_{\Psi_g} + \|\theta\|^2_{\Psi_\theta} \tag{21}$$
end if
apply $w(t)$;
$t \leftarrow t+1$.

The main properties of the **RDB-ROG** strategy are summarized in the next Theorem 2.

Theorem 2. Let the constrained system (1)-(2) be given. Then, if at time $t = 0$, $x(0)\in\mathcal{X}_i$ and $d(0)\in\mathcal{D}_{i+1}$ then the **RDB-ROG** scheme satisfies Problem 1 prescriptions for all $t\in\mathbb{Z}_+$ regardless of any disturbance realization complying with (3).

Proof - Omitted for space reasons.

4. POWER SYSTEM APPLICATION

In this section a case study involving a Medium Voltage (MV) microgrid is presented. The goal is to design a tertiary Load Frequency Controller based on the presented RDB-ROG aimed at supervising some generation units connected by distribution lines to remotely distributed loads in microgrids. The power grid of interest consists of the two-area microgrid depicted in Figure 2 where Area 1 only is depicted in details as both areas present the same structure. There, for each area, f_{iref} is the frequency set-point and θc_i an additional offset added to the nominal control input. The constant term $\frac{f_{iref}}{K_{P_i}}$ accounts for the representation of the LTI model of the power system in terms of absolute variables (unlike the incremental models more often used in the literature). Moreover, $P_{T_i}(t)$ is the active power produced by the generator unit, $P_{D_i}(t)$ the local load demand, $P_{v_i}(t)$ the change in the valve position of the turbine and $P_{c_i}(t)$ the control action.

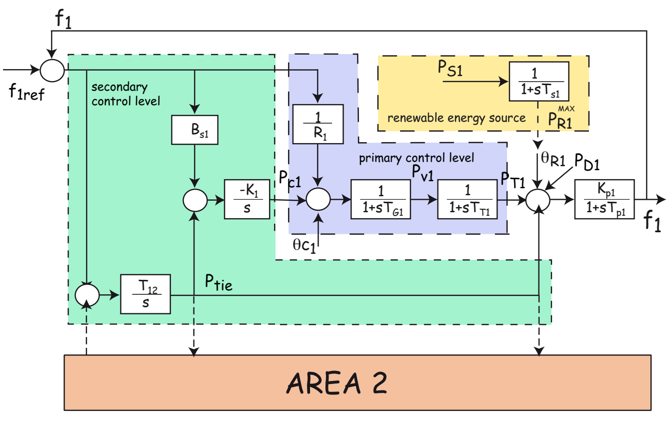

Fig. 2. A two-area power system

For each area the presence of a Renewable Energy System (RES) is considered whose produced power $P^{max}_{R_i}(t)$, depending on an external renewable and intermittent energy source $P_{S_i}(t)$, can be exploited through the further manipulable offset $\theta_{R_i}(t)$ jointly with $P_{T_i}(t)$ to balance the load demand $P_{D_i}(t)$. All other parameters are standard and their values can be found in Casavola *et al.* [2009]. Please notice that with respect to the plant used in this latter work, we added in both areas the renewable energy source blocks with parameters $T_{s_i} = 0.08$, $i = 1, 2$. Such blocks are inspired to Bevrani and Gerard [2010] and model in a very simple way a RES with a storage facility.

The following constraints are imposed and define the normal operations of the grid (expressed in Hz and MW)

$$58.5 \le f_i(t) \le 61.5, \tag{22}$$
$$|P_{tie\,i}(t)| \le 0.5, \tag{23}$$
$$2.2 \le P_{T_i}(t) \le 3.8, i = 1, \ldots 2. \tag{24}$$
$$-1 \le \theta_{R_i}(t) \le P^{max}_{R_i}(t), i = 1, \ldots 2. \tag{25}$$

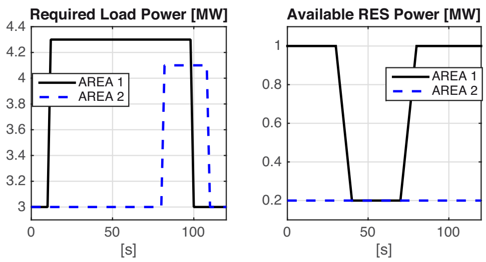

Fig. 3. Load demands (left) and achievable local renewable energy sources power (right)

The aim of this example is at analyzing the behavior of a supervised networked power system and verifying the capabilities of the proposed RDB-ROG scheme, with a standard ALFC control acting as primal controller, to reconfigure the frequency set-points and control offsets during large load deviations from nominal conditions in order to satisfy the constraints. Comparisons with the traditional ROG solution (Casavola *et al.* [2009]) will be also presented.

In the simulation we have assumed that the nominal frequency of each area is $f_{iref}(t) = 60\,Hz$, $i = 1, 2$, $\forall t$, Andersson [2004]. The power demand has the following form $P_{D_i}(t) = \bar{P}_{D_i} + \tilde{P}_{D_i}(t)$, $i = 1, 2$, where the same nominal constant load $\bar{P}_{D_i} = 3$ [MW], has been considered for each area. On the contrary, $\tilde{P}_{D_i}(t)$ is allowed to be time-varying with a rate bounded as $|\tilde{P}_{D_i}(t+1) - \tilde{P}_{D_i}(t)| \le 0.04$ [MW], $i = 1, 2$ and is used to model different and specific load variations on each area. It has also been assumed that the power demands could vary up to $\pm 40\%$ with respect to $\bar{P}_{D_i}$, $i = 1, 2$.

Moreover, even the exogenous signal $P_S(t)$ is rate bounded as $|P_{S_i}(t+1) - P_{S_i}(t)| \leq 0.02$ [MW], $i = 1,2$ and each component can vary from 0.2 to 1 [MW]. Please notice that this signal is a further degree of freedom in balancing the load demand. In particular, in view of the enforcement of the constraints (25), an increment of the magnitude of $P_S(t)$ represents a constraint "relaxation", as it produces a direct increment of the signal P_{RES}^{max}. However, in the ROG design, it is convenient to consider the complementary signal $\breve{P}_{S_i}(t) := 1 - P_{S_i}(t), i = 1,2$ that, in this form, actually represents a disturbance with components ranging from 0 to 0.8 [MW].

In order to exactly characterize the set of admissible load changes of interest, characterized by $\tilde{P}_D$ (in MW), the following convex and compact regions

$$\mathcal{D}_{\mathcal{P}_D} := \left\{ \tilde{P}_D \in \mathbb{R}^2 \,:\, U_D \tilde{P}_D \leq h_D \right\}, \qquad (26)$$

is considered, with $U_D = \begin{bmatrix} 1 & 0 & -1 & 0 & 1 & -1 \\ 0 & 1 & 0 & -1 & 1 & -1 \end{bmatrix}^T$ and $h_D = [\,1.4\;1.4\;1.4\;1.4\;2\;2\,]^T\;[MW]$.

A similar reasoning holds for the signal $\breve{P}_S(t)$ that is confined into the following compact and convex set

$$\mathcal{D}_{\mathcal{P}_S} := \left\{ \breve{P}_S \in \mathbb{R}^2 \,:\, U_S \tilde{P}_S \leq h_S \right\}, \qquad (27)$$

where $U_S = \begin{bmatrix} I_2 \\ -I_2 \end{bmatrix}$ and $h_S = [\,0.8\;0.8\;0\;0\,]^T\;[MW]$.

In order to comply with the problem statement, a bank of 23 ROG devices has been designed by means of the procedure sketched in Algorithm 2 taking as input $L_{max} = 100$, $\mathcal{D} := \mathcal{D}_{\mathcal{P}_D} \times \mathcal{D}_{\mathcal{P}_S}$ and $\mathcal{Z}$ and $\mathcal{X}$ computed on the basis of equations (5)-(6).

Please observe also that the traditional ROG solution (Casavola *et al.* [2009]) corresponds to the first unit of the designed bank, viz.ROG_0, designed for the worst case scenario where the magnitude $P_{S_i}(t) = 0.2[MW]$, $P_{D_i}(t) = 1[MW]$, $i = 1,2$.

We assume for the microgrid the load variation scenario depicted in Figure 3(left). In the same Figure (down) the power variation related to renewable source are reported.

It is worth pointing out that each area of the power system of Figure 2 has the capability to autonomously balance its own nominal load if the current variations are contained within the generable power limits (23). However, in the presented scenario the requested load demand exceeds the local areas capabilities. Then, the ROG-based supervisory level needs to compute proper set-points in order to safely manage the power-flow between the two areas in order to balance the load demand.

Then, in order to show the effectiveness of the proposed ROG strategy, we first restrict our attention to the time range $[10-30]s$ when the first load request overcomes the maximal power production of Area 1 (see constraints (23)). The corresponding system evolutions are reported in Figs. 4-8. Because Area 1's generator is not capable to produce the maximal power request of $4.3\,MW$, as shown in Fig. 7, a new equilibrium has to be determined.

Specifically, in the traditional ROG case (please refer to the black dashed lines in the simulation figures) Area 1

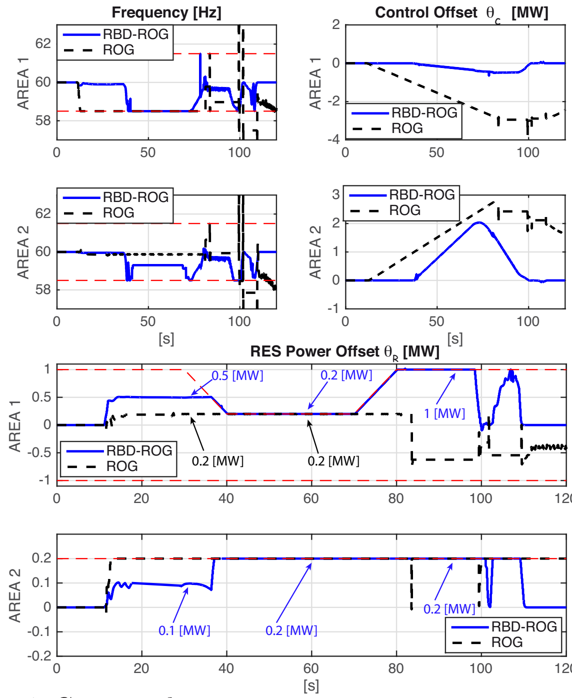

Fig. 4. Computed set-points.

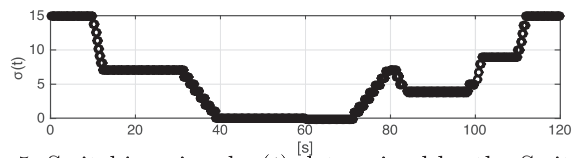

Fig. 5. Switching signal $\sigma(t)$ determined by the Switching Logic.

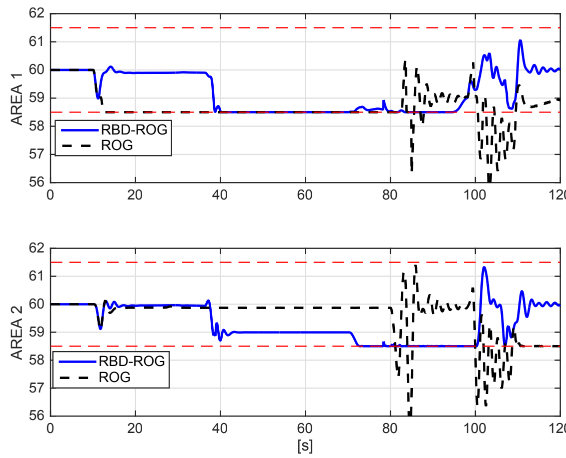

Fig. 6. Frequencies.

autonomously produces $3.7\,MW$ and the power fraction required to accomplish the request is furnished via tie-line $P_{tie\,1} = 0.4\,MW$. and local RES facility with $P_{RES}(t) = 0.2[MW]$ (Fig. 4). In fact, Area 2 produces more power than its local needs, as it is evident from Figure 7.

On the other hand, in the RDB-ROG case, the supervisory level can directly take advantage of the higher available power $P_{RES}^{max}(t) = 1$, Therefore, although Area 1 autonomously produces $3.8\,MW$, the residual required power is provided by the local RES facility $P_{RES}(t) = 0.5[MW]$ and no power flows through the tie-line. This translates

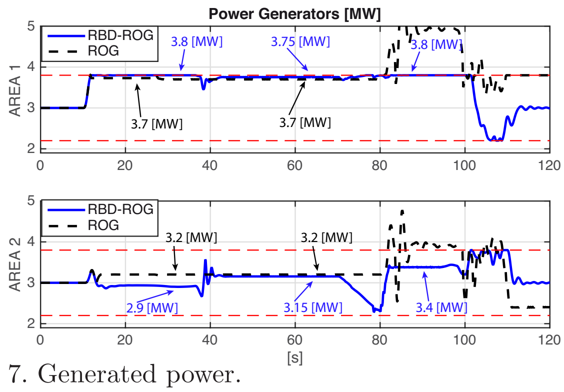

Fig. 7. Generated power.

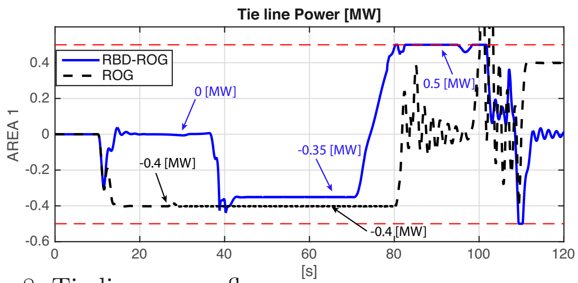

Fig. 8. Tie-line power flow.

into an almost negligible frequency variation as depicted in Fig. 6. Such a behavior significantly changes in the time-range $[30-70]s$ as the available power $P_{RES}^{max}(t)$ slight decreases to $0.2\,[MW]$. In order to satisfy the prescribed constraints the Switching-Logic unit starts to reduce the signal $\sigma(t)$ up to 0 (Fig. 5).

In this situation the RDB-ROG presents a behavior similar to that of the traditional ROG scheme. In fact, the load demand needs to be satisfied via power exchange from the tie-line, that provides extra $0.35\,MW$. As a consequence, frequency variations on both areas are observed. Subsequently, at time $t = 70s$, a new increment of the signal $P_{RES}^{max}(t)$ leads to the selection of a less conservative ROG device, via the signal $\sigma(t)$ that settles down to 7 a time $t = 77s$.

A further interesting situation occurs in the time-range $[80 - 110]s$, when a load request of $4.1MW$ appears on Area 2 while in Area 1 a $4.3MW$ load demand still persists. Please notice that in this case the signal $P_D(t)$ does not belong to $\mathcal{D}_{P_D}$ for all $t \in [80 - 110]s$. For this reason the traditional ROG tertiary level is not able to deal with such a critical event as the underlying optimization problem results unfeasible. As a consequence, the produced power and frequency responses (Figs. 7,6) overcome their prescribed limits. On the contrary, the RDB-ROG scheme shows a significant level of performance. In fact, it is able to satisfy the load requests of both areas by exploiting all the available RES power (Fig. 4). In this way the entire amount of available power increases up to 50% with respect to traditional ROG. In particular, on Area 1 the produced power is $3.8MW$. Then, the extra power of $0.5MW$ further necessary to balance the load is provided by the local RES whose production ($1MW$) exceeds the local needs. As a consequence, the power in excess ($0.5MW$) is conveyed via tie-line (Fig. 8) to the Area 2 that in this way is able to balance its local load request thanks to the power coming from the turbine ($3.4MW$ Fig. 7) and from the local RES ($0.2MW$ Fig. 4).

5. CONCLUSIONS

In this paper, a particular ROG scheme has been developed for dynamically interconnected linear systems subject to local and global constraints in presence of rate-bounded disturbances and used for solving Load/Frequency supervision problems in networked multi-area power systems equipped with RES facilities.

The proposed strategy extended the traditional ROG scheme of Casavola *et al.* [2009] to operate in presence of rate-bounded disturbances acting as non-manipulable inputs on the plant.

The effectiveness of the proposed method has been demonstrated in the final example. Due to its intrinsic capability to reconfigure its action on the basis of disturbance intensity, the proposed scheme can face load requests that are 50% higher than those its traditional version is able to deal with.

REFERENCES

Andersson G., Modelling and analysis of eletrical power systems, *Lecture227-0528-00*, EEH-Power Systems Laboratory, 2004, ETH Zürich.

"Nonlinear Control of Constrained Linear Systems via predictive Reference", *IEEE Transactions on Automatic Control*, Vol. 42, pp. 340–349, 1997.

H.A.G. Bevrani, and L. Gerard, "Renewable energy sources and frequency regulation: survey and new perspectives". *IET Renewable Power Generation*, vol.4(5), pp. 438-457, 2010.

A. Casavola, D. Famularo, G. Franzè, E. Garone, "Set-points reconfiguration in networked multi-area electrical power systems", *International journal of adaptive control and signal processing*, Vol. 23(8), pp. 808–832, 2009.

M. Dreidy, H. Mokhlis, M. Saad, "Inertia response and frequency control techniques for renewable energy sources: A review." *Renewable and sustainable energy reviews*, vol. 69, pp. 144-155, 2017.

"Discrete-time Reference Governors and the Nonlinear Control of Systems with State and Control constraint", *International Journal on Robust and Nonlinear Control*, Vol. 5, pp. 487–504, 1995.

D. Liberzon, J. P. Hespanha, and A. S. Morse, "Stability of switched linear systems: A Lie-algebraic condition", *Sys. & Contr.l Lett.*, Vol. 37, No. 3, pp. 117–122, 1999.

H. Outhred, S.R. Bull, S. Kelly, "Meeting the challenges of integrating renewable energy into competitive electricity industries". *Renewable Energy Integr. Law Proj.*, 2007.

J.A. Pecas Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, P., N. Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities". *Electric power systems research*, vol. 77(9), pp. 1189–1203, 2007.