



HAL
open science

Fault-Tolerant Energy Management in Renewable Microgrids using LPV MPC

Marcelo Menezes Morato, J J Marquez, A Zafra-Cabeza, C Bordons, J E
Normey-Rico

► **To cite this version:**

Marcelo Menezes Morato, J J Marquez, A Zafra-Cabeza, C Bordons, J E Normey-Rico. Fault-Tolerant Energy Management in Renewable Microgrids using LPV MPC. 2022. hal-03714311

HAL Id: hal-03714311

<https://hal.science/hal-03714311>

Preprint submitted on 5 Jul 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Fault-Tolerant Energy Management in Renewable Microgrids using LPV MPC[★]

M. M. Morato^{*,***} J. J. Marquez^{**} A. Zafra-Cabeza^{**}
C. Bordons^{**} J. E. Normey-Rico^{*}

^{*} *Dept. de Automação e Sis., Univ. Fed. de Santa Catarina, Brazil.*

^{**} *Dep. de Ing. de Sis. y Autom., Universidad de Sevilla, Spain.*

^{***} *Univ. Grenoble Alpes, CNRS, Grenoble INP[†], GIPSA-lab, 38000 Grenoble, France. [†]Institute of Engineering Univ. Grenoble Alpes. (marcelomnzm@gmail.com)*

Abstract: In this brief paper, we formalise a fault-tolerant control and mitigation strategy for the energy management of renewable microgrids. The scheme is composed by a Model Predictive Control (MPC) algorithm based on a Linear Parameter Varying (LPV) model for the microgrid energy dispatch. The MPC uses fault diagnosis information to correctly schedule the microgrid model, while adapting the process constraints in consonance with the level and location of faults. We show how closed-loop stability is ensured with simple quadratic terminal ingredients, provided through LMI-solvable remedies. Nonlinear simulation results for a real microgrid benchmark are included in order to demonstrate the effectiveness of the approach.

Keywords: Microgrids, Model Predictive Control, Linear Parameter Varying Systems, Reconfiguration, Fault-Tolerant Control.

1. INTRODUCTION

The search for a healthier future for nature and ecology has been topic of many international treaties and conventions over the last decades. More recently, the so-called "2030 agenda" has presented concrete Sustainable Development Goals (SDGs) to act on (Sachs, 2012). For the establishment of SDG 7 ("affordable and clean energy"), we stress that the transition to renewable energy sources, together with distributed generation paradigms, are essential.

Accordingly, the study of smart-grid/microgrid (MG) technologies has received considerable attention over the last years, e.g. (Parisio et al., 2014; Hu et al., 2021). MGs allow to efficiently benefit from renewable energy sources by "shifting" load demands to periods of greater availability (Morato et al., 2018), enabled by intermediate storage units (exceeding energy is stored at a given moment in order to compensate, later on, for lacking generation).

Model Predictive Control (MPC) has been shown as a key approach to manage energy generation in such renewable MGs (Prodan and Zio, 2014; Morato et al., 2021). Adequate control synthesis in this context is, nowadays, admittedly established, e.g. (Bordons et al., 2020). Nevertheless, recent works have raised attention to faulty behaviours of such systems; the study of faults in MGs is indeed a serious topic, since renewable generation is usually inconsistent, with many unpredictability-related issues. Some few works have addressed the topic of fault mitigation and fault-tolerant energy management of renewable MGs, i.e. (Morato et al., 2020a; Bernardi et al., 2021; Marquez et al., 2021), but concrete assessments with stability and

performance guarantees are still lacking. Accordingly, we note that recent theoretical advances on the design of MPC algorithms for systems with Linear Parameter Varying (LPV) models have provided a well-suited set of tools to render such properties (Morato et al., 2020b).

Benefiting from the LPV paradigm to model faulty renewable MGs, our contributions to the discussed topics are:

- We provide an unified methodology to represent renewable MGs subject to additive faults within an LPV representation, with corresponding faulty process constraints (Sec. 2).
- Then, we synthesise an LPV MPC algorithm for the fault-tolerant energy management of these systems. This fault-tolerant control (FTC) scheme is able to directly encompass different multi-objective performance goals and process constraints (Sec. 3).
- Corresponding stability and recursive feasibility guarantees are enabled through quadratic terminal ingredients, generated by through sufficient Linear Matrix Inequality (LMI) constraints (Sec. 4).
- Finally, a high-fidelity nonlinear microgrid benchmark simulator is used to demonstrate the effectiveness of the proposed method (Sec. 6).

Notation. The index set $\mathbb{N}_{[a,b]}$ represents $\{i \in \mathbb{N} | a \leq i \leq b\}$, with $0 \leq a \leq b$. The identity matrix of size j is denoted as I_j ; $I_{j,\{i\}}$ denotes the i -th row of I_j . The predicted value of a given variable $v(k)$ at time instant $k+i$, computed based on the information available at instant k , is denoted as $v(k+i|k)$. For a vector of n variables v , v_j denotes the j -th variable, while $\text{diag}\{v\} = \text{diag}\{v_1, \dots, v_n\}$ gives the diagonal matrix generated with this vector. \mathcal{K} refers to the class of positive

[★] This work has been supported by *CNPq* (304032/2019 – 0) AND BY ...?

and strictly increasing scalar functions that pass through the origin. $\|\cdot\|$ denotes the 2-norm. (\star) denotes the corresponding symmetrical transpose within an LMI.

2. SETUP: RENEWABLE MICROGRID MODEL

2.1 Original Model

In this paper, we follow the "energy hubs" modelling approach to renewable microgrids (e.g. (Geidl et al., 2007)). Additionally, we complement it with the original additive fault framework description, as given in (Marquez et al., 2021). Thus, consider the following microgrid description:

$$x(k+1) = Ax(k) + B(u(k) + f(k)) + B_w w(k), \quad (1)$$

where $x \in \mathbb{R}^{n_x}$ are the microgrid states (level of charge in energy storage units), $u \in \mathbb{R}^{n_u}$ are the corresponding control inputs, $w \in \mathbb{R}^{n_w}$ are the renewable disturbances (such as solar irradiance, wind speed etc), and $f \in \mathbb{R}^{n_u}$ are the additive faults. In short notation, $x := \mathcal{G}(u, f, w)$ denotes the transfer function form of Eq. (1).

We stress that this model considers slow, tertiary-level dynamics; the discrete-time behaviour is in the order to hours. Therefore, it is implied that the control inputs u are, in fact, set-points to lower-level controllers, which ensure tracking within one sample (in less time than each sampling period T_s). Accordingly, each input $u_j, \forall j \in \mathbb{N}_{[1, n_u]}$ corresponds to a set-point value for the j -th subsystem of the renewable MG. Moreover, each fault term $f_j, \forall j \in \mathbb{N}_{[1, n_u]}$ is related to possible faults that occurs upon the corresponding j -th subsystem.

2.2 Fault Detection and Diagnosis

Throughout the sequel, we assume that there exists an operational Fault Detection and Diagnosis (FDD) scheme, similar to the one proposed in (Freire et al., 2020). Fig. 1 illustrate the overall setup, where the FDD provides online information regarding the occurrence of faults in the controlled microgrid. In this figure, $u := \kappa(x)$ denotes the proposed FTC scheme, detailed in Sec. 3.

There are many possible ways to formulate FDD schemes able to provide accurate fault information in the case of renewable microgrids. This topic has been addressed, for instance, with geometric residual-based approaches, as in (Marquez et al., 2021), and with observer-based techniques (Morato et al., 2019). We stress that the synthesis and design of modular FDD schemes for renewable microgrid deserve attention by their own, and thus are out of the scope of this paper.

Thus, for simplicity, we assume henceforth that the additive fault variable $f(k)$ is known for all sampling instants $k \geq 0$. Moreover, we consider that there are known bounds imposed over each fault term, that is $f_j(k) \in [f_j^-, f_j^+], \forall j \in \mathbb{N}_{[1, n_u]}$. These bounds relate to the distinct situations that may happen in the microgrid subsystems. For instance, an Li-ion battery bank may fail due to electrical issues in its inverters, just as a hydrogen compressor may exhibit faults due to partial leakages of the gas.

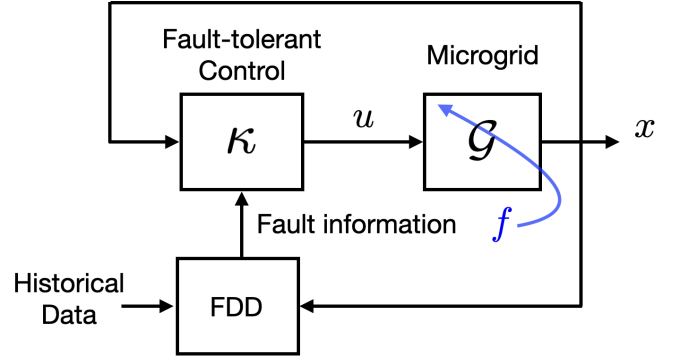


Fig. 1. Microgrid, FDD scheme, and FTC strategy.

2.3 LPV Representation

In order to apply the proposed fault-tolerant energy management strategy with stability and performance guarantees, we first adapt the model from Eq. (1) to a suitable LPV coordinates.

For such, we re-write each fault and control input entry sum as follows: $u_j + f_j = \rho_j u_j, \forall j \in \mathbb{N}_{[1, n_u]}$. This implies that each introduced (scheduling) variable ρ_j satisfies the constraint: $\rho_j = \left(1 + \frac{f_j}{u_j}\right) \in [\underline{\rho}_j, 1], \forall j \in \mathbb{N}_{[1, n_u]}$. By using such multiplicative representation, we obtain the following model, where $B(\rho) = B \text{diag}\{\rho_1, \dots, \rho_{n_u}\}$:

$$x(k+1) = Ax(k) + B(\rho(k))u(k) + B_w w(k). \quad (2)$$

In Sec. 3, we detail how this model is used for fault-tolerant energy management control synthesis using MPC. We note, for now, that the fault-related scheduling variables $\rho_j(k)$ are known for each sampling instant k , while unknown for any future sample. Moreover, we stress that each ρ_j indicates the *loss of effectiveness* related to the j -th subsystem of the controlled microgrid. For instance, $\rho_1 = 0.6$ indicates that the first subsystem exhibits a 40% default on its behaviour.

2.4 Faulty Process Constraints

In order to correctly mitigate the effect of faults and maintain an adequate performance of the controlled microgrid, we consider operational constraints that are also subject to the effect of faults.

Under nominal, faultless conditions, we assume that the states and inputs should be bounded to nominal admissibility sets. Nonetheless, when faults occur, the input space should be further constrained. This is quite natural in practice: for instance, if a given system shows an energy conversion deficiency, it is reasonable to expect that its correlated control input space is smaller. If the input space is not further constrained when faults happen, the fault-tolerant controller could simply generate an input that compensates the loss of effectiveness by respectively magnifying the input, which is not coherent. A suitable FTC scheme would re-distribute inputs in order to maintain performances if a given subsystem fails, and not simply further exploit the faulty input.

Taking into account this discussion, we use the following fault-related constraints: $x(k) \in \mathcal{X}$ and $u(k) \in \mathcal{U}_{\rho(k)}, \forall k \geq 0$, as gives Eq. (3). We note that $\mathcal{U}_{\rho(k)}$ is a time-varying set, whose bounds vary according to the level of faults measured through $\rho(k)$.

$$\begin{aligned} \mathcal{X} &:= \{x \in \mathbb{R}^{n_x} : |x_j| \leq \bar{x}_j, \forall j \in \mathbb{N}_{[1, n_x]}\}, \\ \mathcal{U}_{\rho(k)} &:= \{u \in \mathbb{R}^{n_u} : |\rho_j(k)u_j| \leq \bar{u}_j, \forall j \in \mathbb{N}_{[1, n_u]}\}. \end{aligned} \quad (3)$$

3. THE FAULT-TOLERANT LPV MPC APPROACH

Bearing in mind the considered setting of a renewable microgrid subject to faults, we now present the proposed LPV MPC that works as a fault-tolerant energy management scheme.

Denote $e_x(k+j|k) = x(k+j|k) - x_r(k+j)$ and $e_u(k+j|k) = u(k+j|k) - u_r(k+j)$ as error variables, being x_r and u_r are known state and input reference signals, respectively, which are assumed to be known. Thus, we firstly consider the following multi-objective cost function $J := \sum_{j=0}^{N_p-1} \ell(e_x(k+j|k), e_u(k+j|k)) + V(e_x(k+N_p|k))$, where the stage cost $\ell(e_x, e_u) := \|e_x\|_Q + \|e_u\|_R$ has positive weights Q and R used to imply the envisioned trade-off between control effort and state regulation; $V(e_x)$ is a terminal cost.

Then, the proposed MPC scheme is based on the faulty LPV model from Eq. (2), using $\rho(k+j|k) = \rho(k), \forall j \in \mathbb{N}_{[0, N_p-1]}$ (assuming fault levels will remain constant), and on the fault-related set constraints from Eq. (3). Its solution is retrieved by solving the following optimisation problem at each instant k :

$$\begin{aligned} \min_{U_k} \quad & \sum_{j=0}^{N_p-1} \ell(e_x(k+j|k), e_u(k+j|k)) + V(e_x(k+N_p|k)), \\ \text{s.t. :} \quad & x(k+j+1|k) = Ax(k+j|k) \\ & + B(\rho(k))u(k+j|k) + B_w w(k+j), \\ & u(k+j|k) \in \mathcal{U}_{\rho(k)}, \\ & x(k+j|k) \in \mathcal{X}, \\ & e_x(k+N_p|k) \in \mathbf{X}_f, \end{aligned} \quad (4)$$

where \mathbf{X}_f is a terminal invariant set. Assume that $J^*(x(k), \rho(k), x_r, u_r)$ is the optimal solution of this problem, for which U_k^* is the minimiser. Then, the control input is retrieved by applying the first entry of the solution to the microgrid, i.e. $u^*(k|k)$. Note that Eq. (4) is a simple quadratic program at each sampling instant, since $\mathcal{U}_{\rho(k)}$ is constant and the prediction model becomes LTI. In the literature, this approach is widely referred to as frozen or gain-scheduled LPV MPC (Morato et al., 2020b).

4. STABILITY AND PERFORMANCE

In this Section, we discuss how the proposed MPC is able to guarantee performance and input-to-state stability, despite the presence of faults. For such, we give a simple remedy to compute the terminal ingredients of the corresponding optimisation ($V(\cdot)$ and \mathbf{X}_f). These ingredients also ensure that the MPC optimisation is continuously

recursively feasible, even though the process model and constraints vary along iterations.

Theorem 1. Stability and Recursive Feasibility

Suppose there exists a terminal control law $u = \kappa_t x$. Consider that the LPV system in Eq. (2) is controlled by the proposed state-feedback MPC, as rendered through Eq. (4). Then, asymptotic input-to-state stability is ensured if the following conditions hold $\forall \rho \in \mathcal{P}$:

- (C1) The origin $x = 0$ lies in the interior of \mathbf{X}_f ;
- (C2) \mathbf{X}_f is positively invariant under the terminal feedback controller $\kappa_t x$;
- (C3) The discrete Lyapunov equation is verified within this invariant set, this is, $\forall x \in \mathbf{X}_f$ and $\forall \rho \in \mathcal{P}$: $V((A + B(\rho)\kappa_t)x) - V(x) \leq -\ell(x, \kappa_t x)$;
- (C4) The image of the terminal control is admissible, i.e. $\kappa_t x \in \mathcal{U}_{\rho}, \forall \rho \in \mathcal{P}$;
- (C5) The terminal set \mathbf{X}_f is a subset of \mathcal{X} .

Assuming that the initial solution of the MPC problem U_k^* is feasible, then, the MPC is recursively feasible, steering $x(k)$ to the origin.

Proof 1. This proof is standard; refer to further details in (Mayne et al., 2000; Morato et al., 2020b). Note that x_r, u_r and w are considered null, for demonstration simplicity.

In order to satisfy the conditions required by Theorem 1, we use simple quadratic terminal ingredients, this is: $V(x) = x^T P x$, where $P = P^T \geq 0$ is a positive definite weight. The terminal set \mathbf{X}_f is taken as a corresponding sub-level set to $V(x)$, i.e. $\mathbf{X}_f := \{x \in \mathbb{R}^{n_x} \mid x^T P x \leq 1\}$. By definition, \mathbf{X}_f is an ellipsoid, which should be positively invariant for the terminal feedback $\kappa_t x$ in order to satisfy the baseline conditions from Theorem 2. Accordingly, we give a numerically solvable sufficient solution that can be used to generate these terminal ingredients:

Theorem 2. Terminal Ingredients

Conditions (C1)-(C5) from Theorem 1 are satisfied if there exist a symmetric positive definite matrix $P \in \mathbb{R}^{n_x \times n_x}$ and a rectangular matrix $W \in \mathbb{R}^{n_u \times n_x}$ such that $Y = T^{-1} > 0$, $W = \kappa_t Y$ and that LMIs (5)-(7) hold under the minimisation of $\log \det\{Y\}$ for all $\rho \in \mathcal{P}$. Then, the terminal feedback is $u = \kappa_t x$.

$$\begin{bmatrix} Y & \star \\ (AY + B(\rho)W) & Y \\ Y & 0 \\ W & 0 \end{bmatrix} \begin{array}{c} \star \\ \star \\ Q^{-1} \\ 0 \end{array} \begin{array}{c} \star \\ \star \\ \star \\ R^{-1} \end{array} \geq 0, \quad (5)$$

$$\begin{bmatrix} \rho_i \bar{u}_i^2 & | & I_{\{i\}} W \\ \star & | & Y \end{bmatrix} \geq 0, \quad i \in \mathbb{N}_{[1, n_u]}, \quad (6)$$

$$\begin{bmatrix} \bar{x}_j^2 & | & I_{\{j\}} Y \\ I_{\{j\}} Y' & | & Y \end{bmatrix} \geq 0, \quad j \in \mathbb{N}_{[1, n_x]}. \quad (7)$$

Proof 2. Apply two consecutive Schur complements to LMI (5), thus obtaining (C3), which suffices for (C1) and (C2) due to the ellipsoid form of the terminal set. (C4) and (C5) are obtained by Schur complements over LMIs (6) and (7), respectively. Note that LMI (6) implies a time-varying constraint over each control input, i.e. $\|u_j\|_2 \leq \rho_j \bar{u}_j, \forall j \in \mathbb{N}_{[1, n_u]}$. This concludes this brief proof. \square

Theo. 2 provides infinite-dimensional LMIs ((5) and (6)), which should hold for all $\rho \in \mathcal{P}$. Yet, since herein we consider LPV scheduling variables which stand for

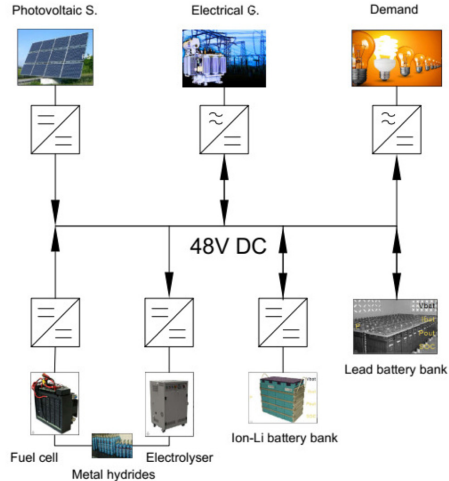
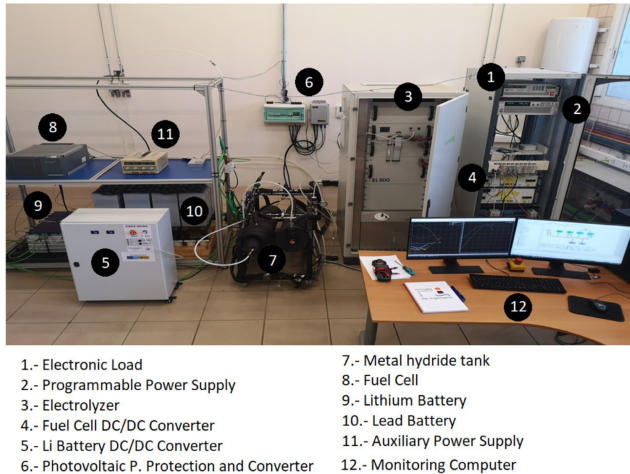


Fig. 2. Hylab Microgrid Setup.

multiplicative fault terms such that $\rho_j \in [\rho_j, 1], \forall j \in \mathbb{N}_{[1, n_u]}$, these LMIs can be simplified. In practice, their solution can be generated by enforcing these inequalities over a sufficiently dense grid of points over $\mathcal{P} := [\rho_1, 1] \times [\rho_2, 1] \times \dots \times [\rho_{n_u}, 1]$. Then, they should be verified for a denser grid. Note that the worst-case complete breakdown condition of a given subsystem (implying that $\rho_j = 0$) imposes a null terminal feedback, which is inherently infeasible. Thus, we use henceforth $\rho_j > 0, \forall j \in \mathbb{N}_{[1, n_u]}$.

5. RESULTS: NUMERIC BENCHMARK

Now, we test the proposed fault-tolerant energy management scheme for a realistic simulation environment of the Hylab microgrid from the University of Seville, via Matlab and SimuLink. This MG, illustrated in Fig. 2 is composed of a lead-acid battery bank, a Li-ion battery bank, a photovoltaic field, an electrolyser, a fuel cell, a programmable energy source (which is used to mimic a solar photovoltaic (PV) system), an electronic load, DC/DC converters and metal hydride tanks; parameters and specifications are given in (Marquez et al., 2021, Table 2). The model which describes this MG is in the likes of Eq. (2), where $x \in \mathbb{R}^3$ collects the state of charge of the lead-acid and Li-ion batteries, and the level of charge of the hydride tanks; the control inputs $u \in \mathbb{R}^4$ are the power outlet set-points of the electrolyser, of the fuel cell, of the Li-ion battery, of the lead-acid battery, and the total power that is consummated from the external grid (in order to comply with demands, when there occur shortages). The system disturbance w is the solar irradiance input, which generates PV energy.

Accordingly, we consider the same MPC costs and weights as in (Marquez et al., 2021), which is herein complemented with the terminal ingredients detailed in Sec. 4. The cost J is used to enforce that the total generated power follows a given demand profile (assumed to be known for all sampling instants). Moreover, the multi-objective cost J also weights the variation of the MG states x (level of charge in batteries and H_2 tank) to the target of 50%, in order to avoid excessive fluctuation in these energy storage units. Note that all state and input variables are subject

to hard box-type constraints (in the form of those given in Eq. (3)). We stress that the state-related constraints are quite direct: $x_j \in [0, 100] \%, \forall j \in \mathbb{N}_{[1, n_x]}$, since each state is related to a level of stored energy. The supervisory, energy management MPC operates each $T_s = 30$ s; the lower-level controllers, corresponding to each subsystem, are functional and well-posed.

In the sequel, we evaluate the effectiveness of the proposed FTC under nominal (faultless) and faulty conditions. W.r.t. the latter, we consider the following situation: the Li-ion battery bank exhibits a sudden breakdown of 60% in its effectiveness, i.e. $\rho_4(k) = 0.4, \forall k \geq k_{\text{fault}}$, being k_{fault} the sampling instant when the event occurs. In order to evaluate the mitigation actions of the proposed LPV MPC scheme, we compare the faulty situation under the action of the proposed scheme, but also under the action of a nominal MPC, which does not take into account the presence of faults (i.e. using the model and constraints in Eqs. (2) and (3) with $\rho_j(k) = 1, \forall k \geq 0, j \in \mathbb{N}_{[1, n_u]}$).

First, we show how the system operates in closed-loop when there are no faults. Accordingly, in Fig. 3, we present the power outlets of the Hylab microgrid, coordinated by the action of the LPV MPC. The most important aspect is that the MPC is able to successfully coordinate all subsystems in order to obtain the envisioned goal: the total produced power is equal to the load demand requirements (null power balance). Moreover, the control system intelligently acts to benefit as best as possible from the PV generation, while maintaining the levels of charge (states) near the 50% target, as shows Fig. 4.

Next, we assess the performances obtained in the faulty situation, with and without fault mitigation (that is, with an MPC based on fixed model and constraints, and with an MPC with the LPV time-varying model and constraints, as well as the stability-related terminal ingredients). Regarding this context, we first show that the demand compliance goal is continuously guaranteed with the proposed FTC, as illustrates Fig. 5. This is, the MPC is able to coordinate the MG in such a way that the dispatched energy meets the demand requirements (null power balance between the produced energy and load demand requirements).

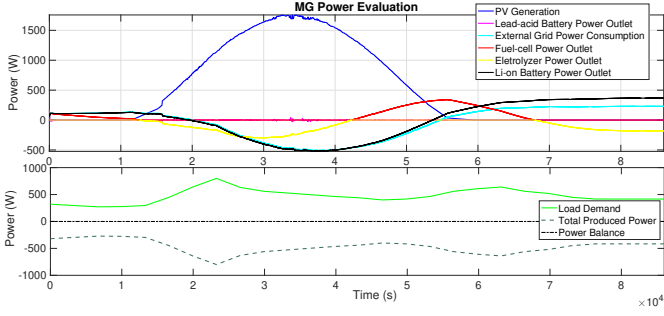


Fig. 3. Faultless scenario: MG Power Evaluation.

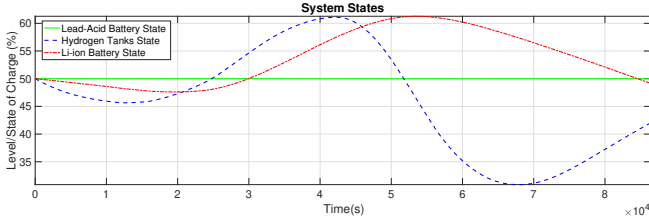


Fig. 4. Faultless scenario: MG States.

Nevertheless, we note that the fixed-model MPC, which has no inherent fault mitigation (named "no FTC"), is not able to ensure this goal. Thereby, a while after the occurrence of the Li-ion battery fault, the MG is not able to deliver sufficient energy and, thus, the corresponding MPC optimisation becomes infeasible. This nominal scheme ensured demand satisfaction whenever there were no faults, but, from the moment the fault occurs onward, it takes incorrect actions which soon lead the system to be unable to comply with demands (we demonstrate the incorrect coordination in the sequel). Anyhow, we stress that the proposed scheme has guaranteed stability and recursive feasibility, despite faults, due to the parameter ingredients detailed in Sec. 4. In a real-life condition, a total breakdown/stop of the MG, as happens with the "no FTC" approach, would be troublesome and certainly lead to economic losses.

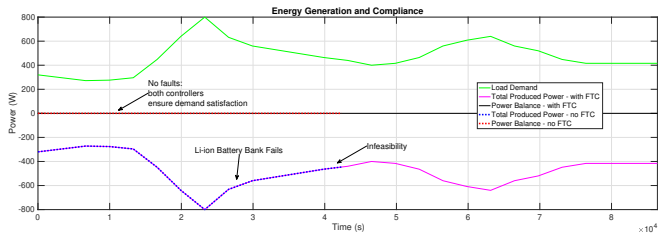


Fig. 5. Faulty case: MG Power Generation and Demand Compliance.

In Fig. 6, we show in more details how the sudden fault affects the Li-ion battery subsystem. Specifically, this figure gives the corresponding control input, u_4 (set-point), together with the corresponding real actuation of the subsystem upon the MG, $\rho_4 u_4$. Evidently, the fault plays a significant role in decreasing the amount of power that is made available from these batteries to the MG, as well as in its capacity of absorb excessive energy and compensate fluctuations.

Complementary, Fig. 7 further illustrates how the proposed FTC scheme is able to mitigate faults, by compensating the lack of energy at one subsystem by the use of others. In this figure, we show the level of charge of the energy storage units of the MG (states), where we can see how the FTC approach tends to make a heavier use of the Lead-acid battery in order to handle the deficiencies of the Li-on battery under the faulty conditions. We stress that, when the fault occurs, the mitigation comes at the cost of a transient behaviour with some oscillations. Since the LPV model has parametric variations, the corresponding MPC issues slightly oscillatory inputs in order to overcome infeasibility (the "no FTC" approach tends to use the Lead-Acid battery in opposite fashion (issuing energy to the MG and not storing it), which causes the infeasibility issue. Anyhow, we recall that stability is ensured by design, and that these oscillations can be smoothed by the use of stronger slew-rate type constraints. We have not show other tuning results due to lack of space, but we note that an interesting option is to further constraint the slew-rate of the systems that did not fail, in order to avoid abrupt usage, i.e. if $\rho_1(k) \neq 1, \forall k \geq k_{\text{fault}}$, for instance, we can take $|u_j(k+1) - u_j(k)| \leq \rho_1 \delta u_j, \forall j \in \mathbb{N}_{[2, n_u]}, \forall k \geq k_{\text{fault}}$.

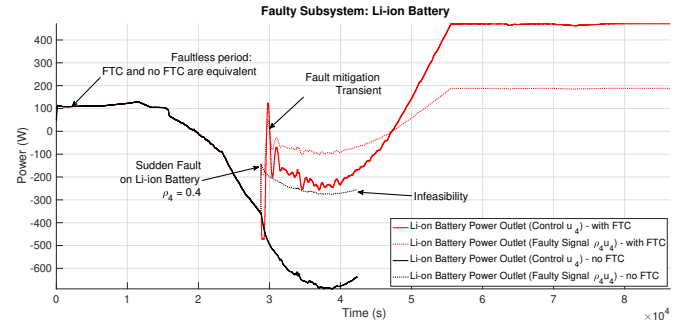


Fig. 6. Faulty case: Control Input and Fault.

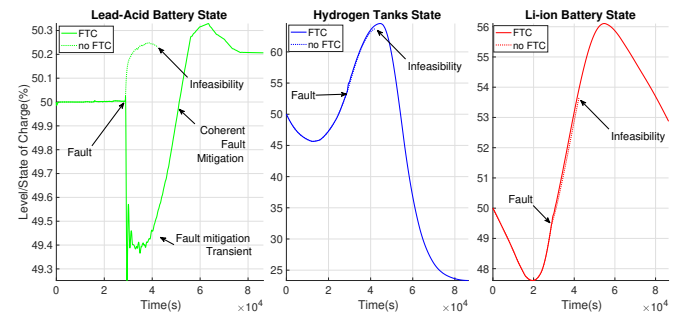


Fig. 7. Faulty case: MG States.

Last, but not least, we show, in Fig. 8, the total power coordination of the considered MG, under the presence of faults in the Li-ion battery bank, with and without the fault-tolerant design. In this figure, it becomes clear how the FTC coordinates the remaining subsystem in order to ensure energy dispatch, with a transient behaviour related to fault mitigation. This intelligent coordination is not enabled by the nominal MPC, which fails to operate the system correctly.

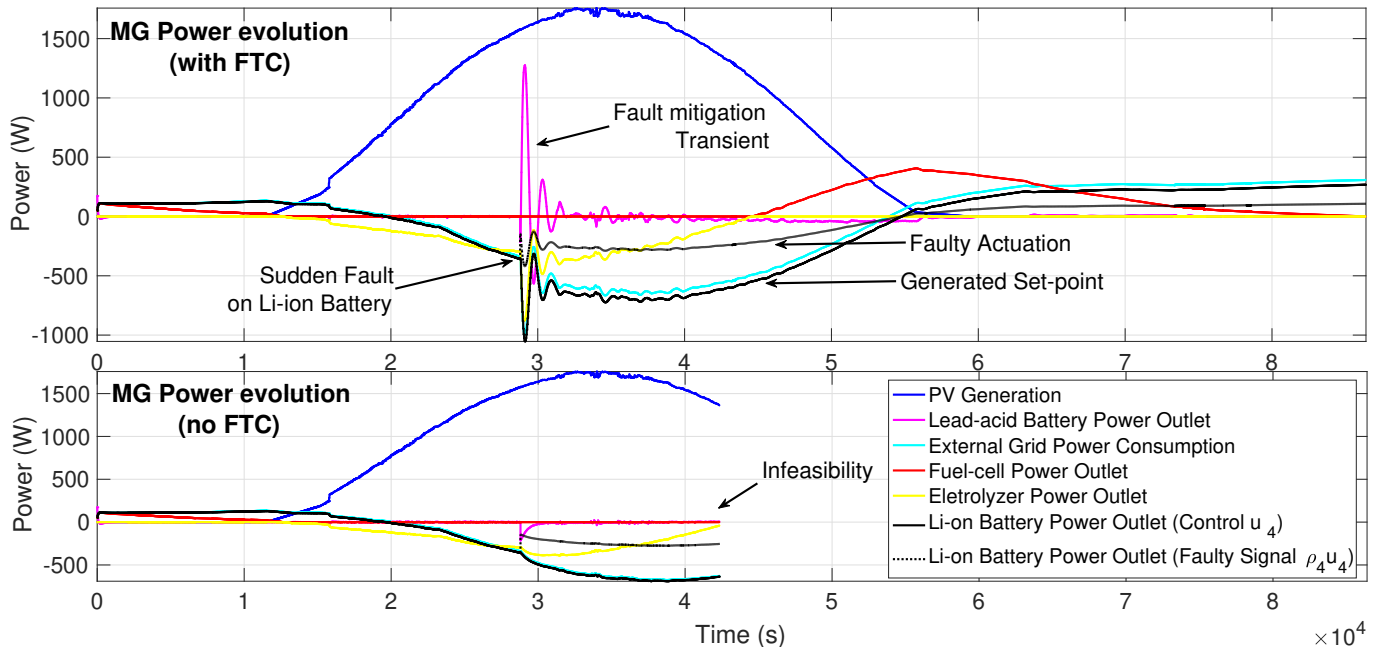


Fig. 8. Faulty case: MG Power Evaluation with no Mitigation.

6. CONCLUSIONS

In this paper, we studied how fault-tolerant energy management schemes for renewable microgrids can be synthesised using LPV MPC formulations. Accordingly, we provided a synthesis based on a fault-related LPV model, together with LPV constraints. The method is able to ensure input-to-state stability of the closed-loop, as well as recursive feasibility of the optimisation, enabled through standard LMI synthesis. A realistic high-fidelity benchmark system is used to illustrate the features of the proposed method, which is compared against a nominal energy management MPC which has no fault-tolerant features, exhibiting enhanced performances. We recall the main features of our method:

- (1) It does not require any ad-hoc re-tuning of the MPC parameters and weights, thus maintaining the same optimisation under both faultless and faulty environments.
- (2) The LPV prediction model is able to automatically schedule the controller action according to the level of faults.
- (3) It ensures performance satisfaction and guarantees, even when abrupt faults happen.

For future works, we aim at experimentally validation our method, as well as comparing it with other FTC approaches.

REFERENCES

- Bernardi, E., Morato, M.M., Mendes, P.R., Normey-Rico, J.E., and Adam, E.J. (2021). Fault-tolerant energy management for an industrial microgrid: A compact optimization method. *International Journal of Electrical Power & Energy Systems*, 124, 106342.
- Bordons, C., Garcia-Torres, F., and Ridao, M.A. (2020). *Model predictive control of microgrids*, volume 358. Springer.
- Freire, V.A., Márquez, J.J., Bordons, C., Zafra-Cabeza, A., and de Arruda, L.V.R. (2020). Energy management system for microgrid considering operational faults in power supply. In *2020 International Conference on Smart Energy Systems and Technologies (SEST)*, 1–6. IEEE.
- Geidl, M., Koeppl, G., Favre-Perrod, P., Klockl, B., Andersson, G., and Frohlich, K. (2007). Energy hubs for the future. *IEEE Power and Energy magazine*, 5(1), 24–30.
- Hu, J., Shan, Y., Guerrero, J.M., Ioinovici, A., Chan, K.W., and Rodriguez, J. (2021). Model predictive control of microgrids—an overview. *Renewable and Sustainable Energy Reviews*, 136, 110422.
- Marquez, J., Zafra-Cabeza, A., Bordons, C., and Ridao, M.A. (2021). A fault detection and reconfiguration approach for mpc-based energy management in an experimental microgrid. *Control Engineering Practice*, 107, 104695.
- Mayne, D.Q., Rawlings, J.B., Rao, C.V., and Sokaert, P.O. (2000). Constrained model predictive control: Stability and optimality. *Automatica*, 36(6), 789–814.
- Morato, M.M., Mendes, P.R., Normey-Rico, J.E., and Bordons, C. (2020a). LPV-MPC fault-tolerant energy management strategy for renewable microgrids. *International Journal of Electrical Power & Energy Systems*, 117, 105644.
- Morato, M.M., Normey-Rico, J.E., and Sename, O. (2020b). Model predictive control design for linear parameter varying systems: A survey. *Annual Reviews in Control*, 49, 64–80.
- Morato, M.M., Regner, D.J., Mendes, P.R., Normey-Rico, J.E., and Bordons, C. (2019). Fault analysis, detection and estimation for a microgrid via h_2/h_∞ lpv observers. *International Journal of Electrical Power & Energy Systems*, 105, 823–845.
- Morato, M.M., Vergara-Dietrich, J., Esparcia Jr, E.A., Ocon, J.D., and Normey-Rico, J.E. (2021). Assessing

- demand compliance and reliability in the philippine off-grid islands with model predictive control microgrid coordination. *Renewable Energy*, 179, 1271–1290.
- Morato, M.M., da Costa Mendes, P.R., Cani, A.A., Normey-Rico, J.E., and Bordons, C. (2018). Future hybrid local energy generation paradigm for the brazilian sugarcane industry scenario. *International Journal of Electrical Power & Energy Systems*, 101, 139–150.
- Parisio, A., Rikos, E., and Glielmo, L. (2014). A model predictive control approach to microgrid operation optimization. *IEEE Transactions on Control Systems Technology*, 22(5), 1813–1827.
- Prodan, I. and Zio, E. (2014). A model predictive control framework for reliable microgrid energy management. *International Journal of Electrical Power & Energy Systems*, 61, 399–409.
- Sachs, J.D. (2012). From millennium development goals to sustainable development goals. *The lancet*, 379(9832), 2206–2211.