ACTAS

DE LAS

XXXVIII Jornadas de Automática

Gijón · Palacio de Congresos · 6, 7 y 8 de Septiembre de 2017

CEA 50 ANIVERSARIO

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Actas de

XXXVIII
Jornadas de Automática

Servicio de Publicaciones de la Universidad de Oviedo
Campus de Humanidades. Edificio de Servicios. 33011 Oviedo (Asturias)
Tel. 985 10 95 03 Fax 985 10 95 07
http: www.uniovi.es/publicaciones
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DL AS 2749-2017

ISBN: 978-84-16664-74-0

Prefacio

Las *Jornadas de Automática* se celebran desde hace **40 años** en una universidad nacional facilitando el encuentro entre expertos en esta área en un foro que permite la puesta en común de las nuevas ideas y proyectos en desarrollo. Al mismo tiempo, propician la siempre necesaria colaboración entre investigadores del ámbito de la Ingeniería de Control y Automática, así como de campos afines, a la hora de abordar complejos proyectos de investigación multidisciplinares.

En esta ocasión, las Jornadas estarán organizadas por la Universidad de Oviedo y se han celebrado del 6 al 8 de septiembre de 2017 en el Palacio de Congresos de Gijón, colaborando tanto la Escuela Politécnica de Ingeniería de Gijón (EPI) como el Departamento de Ingeniería Eléctrica, Electrónica de Computadores y de Sistemas del que depende el Área de Ingeniería de Sistemas y Automática.

Además de las habituales actividades científicas y culturales, esta edición es muy especial al celebrarse el **50 aniversario de la creación de CEA**, Comité Español de Automática. Igualmente este año se conmemora el 60 aniversario de la Federación Internacional del Control Automático de la que depende CEA. Así se ha llevado a cabo la presentación del libro que se ha realizado bajo la coordinación de D. Sebastián Dormido, sobre la historia de la Automática en España en una sesión en la que han participado todos los ex-presidentes de CEA conjuntamente con el actual, D. Joseba Quevedo.

Igualmente hemos contado con la presencia de conferenciantes de prestigio para las sesiones plenarias, comunicaciones y ponencias orales en las reuniones de los 9 grupos temáticos, contribuciones en formato póster. Se ha celebrado también el concurso de CEABOT, así como una nueva Competición de Drones, con el ánimo de involucrar a más estudiantes de últimos cursos de Grado/Máster.

En el marco de las actividades culturales programadas se ha podido efectuar un recorrido en el casco antiguo situado en torno al Cerro de Santa Catalina y visitar la Laboral.

Gijn, septiembre de 2017

Hilario López
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Visión por Computador

Robust PI controller for disturbance attenuation and its application for voltage regulation in islanded microgrid

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Resumen

This work faces the problem of frequency deviation in microgrid systems. The considered microgrid includes renewable energy sources such as wind and solar photovoltaic. As long as these sources provide an irregular power supply or there is a sudden change in the system load, the power system frequency deviates. In order to compensate such deviations, alternative, conventional energy sources should be commanded in order to provide the corresponding power deficit. In this paper a very simple and of common industrial practice control approach such as the Direct synthesis based on first order plus time delay models is proposed to tune a PI controller. Time domain simulations show the effectiveness of the approach as compared with other more sophisticated controllers (Fractional order PID) already proposed in the literature.

Palabras clave: PI Control, Disturbance attenuation, Microgird,

1 Introduction

A MicroGrid (MG) is a small scale grid that can integrate distributed renewable energy sources, conventional generators, energy storage systems and consumers. It can be operated in either grid-connected or islanded mode in case of grid faults or planned islanding. [1,2]. The MG embodies the concept of a single organized power subsystem comprising a number of distributed generation systems, both renewable (such as photovoltaic, wind power, hydro and fuel-cell devices) and/or conventional generation (such as internal combustion engines, micro-turbines and diesel generators) and a cluster of loads [1]. Some of the benefits of MG, including enhanced local reliability, reduced feeder loss, better local voltage support, increased efficiency, voltage sag correction or uninterruptible power supply function are also reviewed in [2, 3].

In recent years, emphasis has been placed on renewable energy based MG systems. In order to improve the efficiency of MGs and to reduce fossil fuel usage and pollution, renewable energy sources may be integrated with traditional MGs. Renewable energy sources include photovoltaic power, hydro power and wind power. These are clean and abundantly available energy sources. However as the power generation of such units is highly dependent of external environmental factors, the generated powers are subject to variations that can impact the MG supplied frequency and therefore the quality of the MG as a generation system. In order to facilitate to operate in islanded mode for extended periods with renewable energy sources involved, it is critical to maintain the frequency deviations within a small range in order to satisfy operating requirements.

Therefore, a reliable and stable operation of isolated hybrid renewable energy system is more complex, unlike those that are grid connected. The fluctuations in both wind speed and solar radiation lead to mismatch between the power generation and load demand resulting into deviation in system frequency and voltage from the nominal value. These undue disturbances if allowed to exceed beyond the tolerance limit may lead to undesired performance and result into damage of the connected devices/equipments.

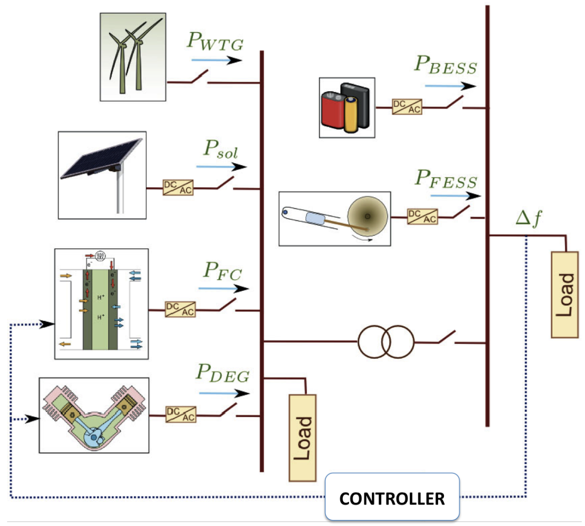
As a result of the reported problem, different control methods have been proposed in the literature to tackle frequency deviations. Proportional-Integral-Derivative (PID) control has been well studied by a number of researchers [4], [5], [6]. H_{inf} control is considered in [7] and [8]. Recently, there has been some interest in the application of intelligent approaches such as those based on Fuzzy Logic control, as in [9], or evolutive optimization algorithms such as genetic algorithm based PID controllers [10], robust PSO-based H_{inf} [7], robust H_∞ and μ-synthesis approaches [11]. The application of such advanced optimization methods has also been focused in the tuning of fractional order PID (FOPID) controllers. As an example, the kriging based surrogate modeling method in [12] is used to design a FOPID controller, whereas in [13] a chaotic PSO based fractional order fuzzy PID controller is faced. In addition, [14] utilised a chaotic NSGA-II algorithm to design a FOPID.

The main focus of the mentioned approaches is to regulate for frequency deviations. However, it is also important to account for control input usage. As the main task of the controller will be to push for conventional generation when power delivered by the renewable sources does not satisfy demand, this control signal will determine the requirement for extra fuel in the generation units. This need for more efficient control from the input usage, while maintaining frequency deviation within the required limits, is the main motivation for the application of simple control strategies that while achieving average frequency deviation within the desired levels, its tuning allows for an easy tradeoff between accuracy and control input usage. This input usage will directly translate from smooth to high frequency power demand generation.

The controller that is proposed pin this paper is a simple PI controller tuned on the basis of the Internal Model ControlOne of the attractive features of the PI based IMC. This is a very straightforward approach, also well known from industrial practice. The controller design complexity is kept at a minimum. There will be no need for going through complex optimization approaches and, in addition, the process information will be as simple as a first order plus dead time model. As these models are usually employed in industry, jointly with IMC formulations, it is the authors opinion that this fact will definitively help system operators to gain confidence in the control scheme.

2 Micro Grid system description and modelling

A typical setup of a MG with storage system is shown in Figure 1. The energy sources include both conventional and renewable generation systems. This system can be easily extended to more complex MGs, with additional generators. However the main idea is to increase the usage of renewable energy, and so reduce the fossil fuel consumption, while at the same time maintaining system stability. Here system stability is reflected by incurring only limited system frequency deviations, despite the presence of significant transients. The MG system used in this work is based on the study presented in [15] and used in [12] to derive a FOPID controller. The system includes various power generating units like the wind turbine, photovoltaic cell, fuel cells, and diesel energy generator. There is also a battery and a flywheel energy storage system. The dynamical models in



Figuea 1: Layout for the microgrid system considered in this work. [12]

Figure 1. are represented here as small signal linearized transfer functions which captures the dynamic characteristics at a specific operating point [15],[10]. Even with such simplifications, these models still capture the essential power/frequency tradeoffs present in a MG system. Since is caused by the imbalance between the power generated and the power consumed by the load, signals in the model are first normalized to per-unit (pu), and then shifted to deviations around 0 (corresponding to deviations from nominal 60 Hz [16]). The characterization of the renewable energy sources power as well as the load power demand follows the patterns presented in [10]. The established deterministic drifts are complemented here with stochastic power fluctuations. A general template that gives rise to a time-series with small stochastic fluctuations about the mean generated or demand power is used. The general template is chosen as:

$$P = \frac{\phi\nu\sqrt{\beta}(1 - G(s)) + \beta}{\beta}\Gamma = \chi\Gamma \qquad (1)$$

where, P represents the power output of the solar, wind or the load model, ϕ is the stochastic component of the power, β contributes to the mean value of the power, $G(s)$ is a low pass filter, ν is a constant in order to normalize the generated or demand power (χ) to match the per unit (pu) level, Γ is a time dependent switching signal with a gain which dictates the sudden fluctuation in mean value for the stochastic power output. Being $U(-1,1)$ a random uniform distribution between -1 and 1, and $h(t)$ the unitary Heaviside step function, the parameters in (1) for each one of the three generators are given by:

Wind Power generation:

$$\phi \equiv U(-1,1), \nu = 0.8, \beta = 10, G(s) = 1/(10^4 s{+}1)$$

$$\Gamma = 0.24h(t) - 0.04h(t-140)$$

Solar Power generation:

$$\phi \equiv U(-1,1), \nu = 0.1, \beta = 10, G(s) = 1/(10^4 s{+}1)$$

$$\Gamma = 0.05h(t) + 0.02h(t-180).$$

Load Power demand:

$$\phi \equiv U(-1,1), \nu = 0.9, \beta = 10$$

$$G(s) = 300/(300s+1) + 1/(1800s+1)$$

$$\begin{aligned}\Gamma = 0.02h(t) + (1/\chi)(0.9h(t) + 0.03h(t-110) \\ + 0.03h(t-130) + 0.03h(t-150) \\ - 0.15h(t-170) + 0.1h(t-190))\end{aligned}$$

For what matters to the small signal models for each one of the MG system components, they are given as in [15] and [12] by the following transfer functions and model parameters:

Wind turbine generator (WTG)

$K_W = 1$, $T_W = 1.5sec$ and

$$G_{WTG}(s) = \frac{\Delta P_{WTG}}{\Delta P_W} = \frac{K_W}{T_W s + 1}$$

Solar photovoltaic (PV) system

$T_{IN} = 0.04sec$, $T_{IC} = 0.004sec$ and

$$G_{PV}(s) = \frac{\Delta P_{PV}}{\Delta P_{sol}} = \frac{1}{(T_{IN}s+1)(T_{IC}s+1)}$$

Diesel engine generator (DEG)

$T_G = 0.08sec$, $T_T = 0.4sec$ and

$$G_{DEG}(s) = \frac{\Delta P_{DEG}}{\Delta u} = \frac{1}{(T_G s+1)(T_T s+1)}$$

Fuel cell (FC)

$K_{FC} = 1$, $T_{FC} = 0.26sec$ and

$$G_{FC}(s) = \frac{\Delta P_{FC}}{\Delta u} = \frac{K_{FC}}{(T_{FC}s+1)(T_{IN}s+1)(T_{IC}s+1)}$$

Battery energy storage system (BESS)

$K_{BESS} = 1$, $T_{BESS} = 0.1sec$ and

$$G_{BESS}(s) = \frac{\Delta P_{BESS}}{\Delta f} = \frac{K_{BESS}}{T_{BESS}s+1}$$

Flywheel energy storage system (FESS)

$K_{FESS} = 1$, $T_{FESS} = 0.1sec$ and

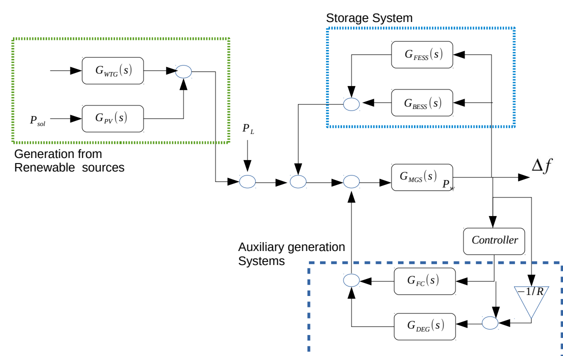
$$G_{FESS}(s) = \frac{\Delta P_{FESS}}{\Delta f} = \frac{K_{FESS}}{T_{FESS}s+1}$$

Microgrid system

$D = 0.015pu/Hz$, $H = 1/12pu.sec$, $R = 3Hz/pu$ and

$$G_{MGS}(s) = \frac{\Delta f}{\Delta P_e} = \frac{1}{2Hs+D}$$

For a more detailed description of the different units the interested reader is referred to [15] and [12]. Figure (2) provides the corresponding block diagram identifying the constitutive blocks of the MG system.



Figuea 2: Block diagram for the considered microgrid.

3 Direct synthesis design (DS-d)

he Internal Model Control (IMC) approach for controller design as presented in [17] and further developed in [18] is based on the very basic principle of *close the loop when necessary.*

One of the drawbacks of the IMC design is its poor response for load disturbance attenuation, specially when the system has slow time constants. Main reason for this is the fact that the plant dynamics appear in the disturbance to output response. In order to improve the regulation capabilities, some proposals have appeared in the literature. Widely referred works that concentrate

on tuning for improved disturbance rejection are, for example, [19, 20]. the direct synthesis (DS-d) method presented in [19] is perhaps the most generic one (it applies to a wide selection of process dynamics) for tuning of PI/PID controllers for input load disturbance attenuation.
The direct synthesis method is based on the specification of a desired y/d relation, denoted as $(y/d)_d$, and impose this relation for the regulatory closed-loop transfer function as:

$$C_y(s) = \frac{P_d(s)}{\left(\frac{y}{d}\right)_d P_u(s)} - \frac{1}{P_u(s)} \qquad (2)$$

that simplifies to

$$C_y(s) = \frac{1}{\left(\frac{y}{d}\right)_d} - \frac{1}{P_u(s)} \qquad (3)$$

when $P_d(s) = P_u(s)$. It is under this assumption and for a set of concrete dynamics for the process model transfer function $P_u(s)$, that in [19] tunings for the PI/PID controller parameters are suggested.

PI tuning relations

In fact, The DS-d method is presented as the disturbance counterpart to the more extended IMC that is based on specifying a tracking specification. For these two methods, the tuning relations that are provided for a PI controller applied to a first order plus time delay model are:

- *Process model:*

$$P_m(s) = \frac{K_m e^{-L_m s}}{T_m s + 1}$$

- *PI-IMC Tuning:*

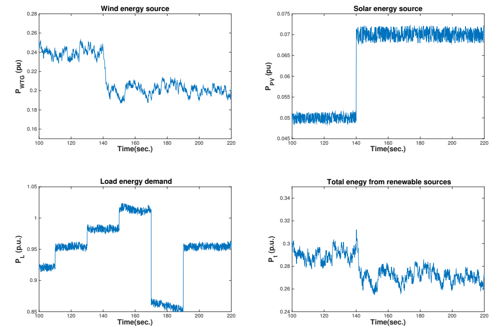
$$K_p = \frac{T_m}{K_m(\lambda + L_m)} \qquad T_i = T_m$$

- *PI-Load (DS-d) Tuning:*

$$K_p = \frac{2T_m - \lambda}{K_m \lambda} \qquad T_i = \frac{(2T_m - \lambda)\lambda}{T_m}$$

4 Control problem definition

In this section the control goals that will be used to evaluate and to compare the different control approaches will be defined first. Second, we present the different controllers that will be applied to the MG scenario presented above. Two of the selected approaches are taken from recent literature results that are based on the same micro grid layout as the one presented here. Therefore more well suited for a fair comparison.



Figuea 3: Sotochastic realization for the wind and solar energy generation and power load demand

4.1 Control problem definition

As detailed when presenting the MG model, the power generation for the wind turbine generator, solar photovoltaic and the load are based on random functions. Figure 3 shows a single realization of the corresponding stochastic processes. As per the framework defined in [10] and [12], in the present work, it is considered that the MG was operating at 1 p.u. load during $0 < t < 100$ sec and the control system performance has been evaluated then for a finite time horizon of $100 < t < 220$ sec considering the changes in both the demand load and renewable generations shown in Figure 3. The primary goal of the control system is to maintain frequency fluctuation Δf at a minimum hence better power quality. Regarding the frequency deviation, as commented in [8], in general, for MGs, should be limited to within 1%, and the recovery time limited to couple of seconds. Otherwise most conventional breakers will trip, with the subsequent possibility of cascade effects. On that basis, we will take here a band of ± 0.005 that corresponds to a deviation of 0.5%. As a statistical measures will compute its mean $\mu(\Delta f)$ and standard deviation $\sigma(\Delta f)$.
In order to provide good quality of supply frequency can be maintained at the desired level by maintaining the active power balance between generation and demand. For such purpose, there is the need of a control system that compensates for the high fluctuations in renewable energy generators such as those based on wind and solar units. For such purpose the controller should provide the needed additional power. This is accomplished by sending the control signal to the fuel cell (FC) and the diesel energy generator (DEG) on the basis of the frequency deviation in the MG. The control signal, basically determines the supply for extra fuel on these units i.e., like the hydro-

gen flow rate in the FC and mass flow rate of oil in DEG. Regarding the flywheel and battery units, as in [9] their inputs are directly directly taken from the grid frequency oscillation signal without the intervention of the controller as these devices does not need sophisticated control.
Even the small signal models are transfer function based, saturation and rate limit constraints are used in order to constraint the extraction/storage of power. The output saturations (in pu) and rate constraints for the different energy storage and generation units are [12]:

$$|P_{FESS}| < 0.11, |P_{BESS}| < 0.11$$

$$0 < P_{FC} < 0.48, 0 < P_{DEG} < 0.45$$
$$|\dot{P}_{FESS}| < 0.05, |\dot{P}_{BESS}| < 0.05$$
$$|\dot{P}_{FC}| < 1, |\dot{P}_{DEG}| < 0.5$$

4.2 (FOPID) Fractional PID

In [12] the use of a fractional order PID (FOPID) controller for a MG is investigated. The transfer function representation for the considered FOPID controller is given by

$$C(s) = K_p + \frac{K_i}{s^\lambda} + K_i s^\nu \qquad (4)$$

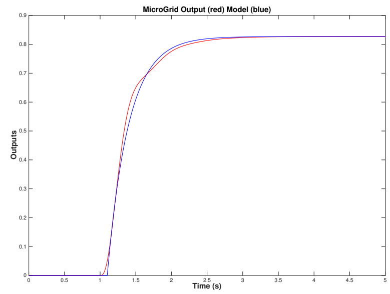
In [12], a global optimization approach is employed to obtain the five parameters of the FOPID controller. A kriging assisted surrogate modelling methodology is embedded within a global optimization framework for the design of the FOPID. As the models for the load and renewable energy sources are defined statistically, the evaluation of the cost function is stochastic. Therefore the function is evaluated multiple times and the expected value of the objective function is considered for optimization. The chosen cost function is a combined quadratic cost function that tradeoffs the frequency deviation and control usage:

$$J = \int_{t_{in}=100}^{t_{fi}=220} \left[\omega(\Delta f)^2 + \frac{(1-\omega)}{K_n}(\Delta u)^2 \right] dt \qquad (5)$$

where, ω determines the relative importance of the two conflicting objectives and K_n is a normalizing constant. The values used in [12] are $\omega = 0.7$, $K_n = 10^4$. The resulting optimal values for the FOPID are

$$K_p = 0.950 \; K_i = 4.350 \; K_d = 1.250 \; \lambda = 0.66 \; \nu = 0.7 \qquad (6)$$

In the same work, [12], it is shown that the FOPID provides superior performance over the integer order ideal controller. However, It has to be said



Figuea 4: FOPTD model approximation for the MG system to the relation $\Delta f/\Delta u$

that both controllers, fractional and integer, are formulated as ideal controllers. Therefore, no derivative filters are mentioned. This may be a serious practical problem when using derivative action as any noise in the measurements will be transferred into the control signal. Another important point regarding the obtention of 6 is that the optimsation is carried out by considering the overall MG model. This does includes the stochastic power generation from the renewable sources.

4.3 PI controller

The design of an IMC controller entails no secrets. The first element we need in order to face the IMC design is a model of the system. As usual industrial practice and in order to show the simplicity of the approach, a first order model will be approximated on the basis of a step-response test. Assuming the production of energy and load requirements are balanced, therefore there is no disturbance in the system, a step change is applied at the control input and the generated effect in the Δf recorded. As a result, it can be seen in figure 4 that a first order plus time delay (FOPTD) model

$$P_m(s) = \frac{K_m e^{-L_m s}}{T_m s + 1} = \frac{0.496 e^{-0.1s}}{0.35s + 1} \qquad (7)$$

suffices to provide a reasonable approximation of the MG dynamics. Notice that the disturbance generators (variations in the power generation and/or power load demand) are not modelled here. With this model approximation, the PI controller can be tuned by using either the IMC or the DS-d approach. The only thing that is left to choose is the λ parameter. In order to select the appropriate value for λ, a tradeoff analysis between the frequency deviation and input usage has been conducted. Input usage has been measured in terms of the total variation (TV) of the control signal.

$$TV(u) = \sum_{k=1}^{N} |u(t_k) - u(t_{k-1}|$$

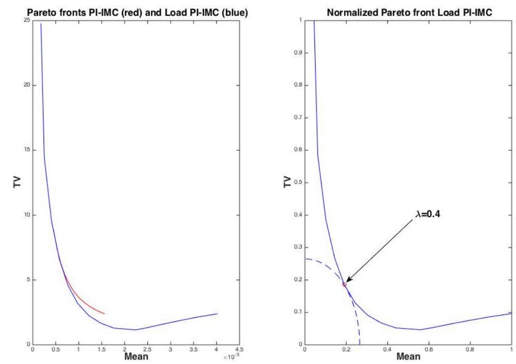
This way, in figure (5) the influence of λ on performance and control usage has been determined. For both approaches λ has been ranged between 0.1 and 1 and a sufficiently smooth approximation to the respective Pareto fronts has been determined. Due to the fact that the renewable energies are defined by stochastic processes, in order to get a well defined Pareto front, a Montecarlo experiment should be ran. In order to compare the tradeoff offered by both approaches, the objective functions have been normalised (each one of them according to its respective worst values). As it can be seen in figure (5) the solutions corresponding to the DS-d design dominates the IMC ones. It can be seen that if high accuracy (low mean) is expected, both approaches provide the same tradeoff. However, it is in the middle region and for lower levels of input usage that the load disturbance approach provides better tradeoff. In some sense this was to be expected, but the Pareto fronts confrontation provides a clear qualitative measure of the superiority of the regulatory designs. The figure also shows the points corresponding to the minimum distance to the origin. The corresponding point in the Pareto front provides the tradeoff solution that minimises (the normalised version of)

$$J = \sqrt{(\Delta_f)^2 + TV^2}$$

Whereas for the DS-d design the best tradeoff is $J = 0.26$, for the IMC PI, the best tradeoff provides $J = 0.73$. In the next section, time domain simulations of the fractional PID controller will be compared with this tradeoff DS-d solution. Note this is a slightly different version of the cost (5) where there is no need for an *a priori* selection of any weight.

5 Simulation results

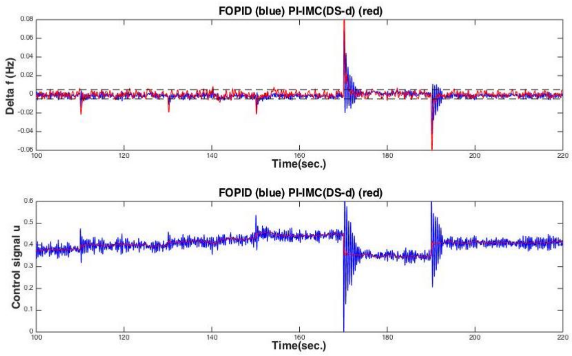
This section shows time domain simulations of the MG system affected by the stochastic variations determined by the changing power generation and load demand. It is considered that the MG was operating at 1 p.u. load during $0 < t < 100$ sec and the control system performance has been evaluated then for a finite time horizon of $100 < t < 220$ sec considering changes in both the demand load and renewable generations according to Figure 3.



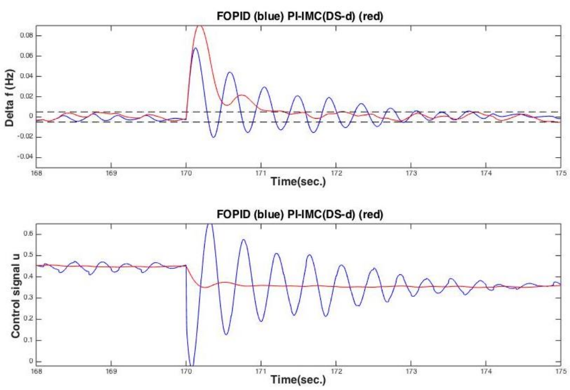
Figuea 5: Tradeoff analysis between the mean of the frequency deviation ($\mu(\Delta f)$ and the required input usage, $TV(u)$. Comparison of Pareto fronts for the IMC and DS-d PI

Figure 6, shows the frequency deviation from its nominal value for all the evaluation period. As it can be seen, both controllers are able to keep the frequency deviation is maintained within a ± 0.005 interval almost all the time. Even this global appreciation, the dynamics of the fractional order controlled system can be appreciated to be highly oscillating. Even during normal operation (no sudden load changes) the frequency deviation oscillation is kept within the allowed interval, the needed control signal is of considerable larger magnitude. The immediate repercussion of this manipulated variable high activity is the power demand that will be asked to the storage system, that will be continuously going up and down. This is reflected on the TV value for the Fractional PID, $TV_{FOPID} = 76.31$, whereas for the PI-IMC this value goes down to $TV_{PI-IMC} = 4.59$. In fact, the PI control signal is dramatically smoother than that of the Fractional order PID. This high control signal activity is directly translated to the system's output.

Regarding the overall performance of both control systems, table (1) shows the mean and standard deviations. For both metrics, the PI controller improves perforamnce within one order of magnitude. It should be noted that the computed standard deviation also includes the deviation generated by the large disturbances incurred because of the sudden changes in the load demand. Apart from the general, aggregated, regulation properties of the controller it is important to recover from a sudden change in the power deficit (either because of lower power generation from the renewable sources or increment of the load power demand) as fast as possible. On that respect, figure 7 shows a more detailed view of the signals corresponding to the 7sec. interval where the



Figuea 6: Regulated power system frequancy deviation for the Fractional order PID and the IMC Pi designed for load disturbance



Figuea 7: Comparison of recovery from a large change in the load demand

large load demand occurs. It is seen that the PI-IMC controller, recovers to the ± 0.005 band in almost 1sec, whereas the FOPID; because of the large gains incurred, takes almost 3 sec. Regarding the control signal activity, it is rather easy to take it into account because of the λ parameter in the IMC approach. This is quantitatively reflected in the tradeoff curve presented in the previous section. However it is clear the effect of increasing λ in case we need to smooth the control signal even more in order not to damage the pumps, motors, etc for the fuel supplies. As an example, if we use an IMC controller tuned with $\lambda = 0.6$, we loose some degree of performance as me move to $\mu(\Delta f) = 1.810^{-3}$ with a standard deviation of $\sigma(\Delta_f) = 2.410^{-2}$. On the other hand, control signal usage has been decreased to 1.29 and the associated IAE also decreased $IAE_u^{PI-IMC} = 0.0085$.

Table 1: Performance comparison

Controller	$\lvert\mu(\Delta f)\rvert$	$\sigma(\Delta f)$	TV(u)
Fract. PID	$2.87\ 10^{-3}$	$2.84\ 10^{-2}$	76.31
IMC-load (DS-d)	$0.76\ 10^{-3}$	$1.75\ 10^{-3}$	4.59

6 Conclusions

In this paper a Proportional-Integral controller tuning based on Internal Model Control has been proposed and applied to the frequency deviation problem in isolated microgrid systems. The considered microgrid is based on the use of renewable energy generation units such as those based on wind and solar. The major problem that these kind of systems has to encompass is the regulation compensation for sudden generated power deficits. It has been shown that the PI controller is able to command the conventional generators in a very smooth way. The major benefit of this approach is the drastic reduction in control activity and energy generated from the conventional generation units such has diesel and fuel cells.

It has to be highlighted that the tuning of the controller is very intuitive as it is based on the selection of just one parameter with a clear interpretation regarding the closed-loop control system bandwidth and, correspondingly, control signal activity.

The main proposal of the work was to keep the control algorithm complexity at a minimum. Both in its formulation and in its design. As a continuation work, other control approaches that could be recast within the IMC framework. Specially robust control approaches will be foreseen as one aspect not examined in this work is the effect of parameter variations in the system components. This robustness issue is very important as the design of the controller is based on very simple models originated from a small signal analysis.

Acknowledgements

This work was partially supported by the grant MINECO/FEDER DPI2016-77271-R. The support received from the University of Costa Rica is also greatly appreciated.

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