

Fuel Consumption Minimization of a Microgrid

Carlos A. Hernandez-Aramburo, *Member, IEEE*, Tim C. Green, *Member, IEEE*, and Nicolas Mugniot

Abstract—A cost optimization scheme for a microgrid is presented. Prior to the optimization of the microgrid itself, several schemes for sharing power between two generators are compared. The minimization of fuel use in a microgrid with a variety of power sources is then discussed. The optimization of a small power system has important differences from the case of a large system and its traditional economic dispatch problem. Among the most important differences is the presence of a local heat demand which adds another dimension to the optimization problem. The microgrid considered in this paper consists of two reciprocating gas engines, a combined heat and power plant, a photovoltaic array and a wind generator. The optimization is aimed at reducing the fuel consumption rate of the system while constraining it to fulfil the local energy demand (both electrical and thermal) and provide a certain minimum reserve power. A penalty is applied for any heat produced in excess of demand. The solution of the optimization problem strongly supports the idea of having a communication infrastructure operating between the power sources.

Index Terms—Distributed generation, microgrids, power sharing, small power systems, unit commitment.

I. INTRODUCTION

POWER generation has seen an increased penetration of distributed generation in recent times. This penetration has mainly been driven by social pressures (mostly brought about by environmental awareness), regional strategic changes intended to diversify the nature of energy sources [1], and actions toward improving the reliability, power quality [2], and economics of a system [2], [3].

A distributed generation scheme should seek to achieve the following goals [4]:

- cost reduction for consumer and utilities;
- integration and promotion of renewable resources;
- improvement of the reliability of the present system;
- reduction of the environmental impact due to load growth.

Pursuit of these goals promoted the creation of “microgrids” [5]–[7]. It is generally accepted that “microgrids” are small power systems with enough local power generation to supply entirely a local load demand (or at least a significant portion of it) and have the ability to work in grid-connected or islanded modes of operation. The microgrid is often taken to imply a high penetration of power electronic devices acting as an

interface between the power generation and the distribution network.

The connection point between a microgrid and the main grid may not necessarily be “active” at all times. It could be the case that the connection does exist but is normally open and only closes in a particular event such as an internal outage or simply because it is financially convenient to establish an energy trade with the main grid. Microgrids may have many different sizes and forms; two examples are the power networks of the Greek island of Lemnos and that of the English borough of Woking. The island of Lemnos bases its power production (with a capacity of 14.84 MW) on diesel generators, wind turbines and, to a lesser degree, on solar panels [8]. The borough of Woking has a power production of less than 2 MW predominantly relying on combined heat and power (CHP) plants and fuel cells [9].

To obtain maximum benefits from the resources available in a power system, an appropriate unit commitment strategy (power sharing scheme) must be established. For large power systems, unit commitment is a well established topic within the topic of economic dispatch. For microgrids, there is an important difference with respect to large power systems that needs to be made clear. Committing a unit in a large power system usually means bringing into production a large power plant (such as a hydro generator) of several hundreds if not thousands of megawatts. In the context of a microgrid, committing a unit usually means bringing online a generator of several tens of kilowatts to few megawatts. The difference is not only related to the size but also to the complexity of the logistics behind each action. The (inherent) simplicity of switching on and off smaller generators, opens up the possibility of increasing the frequency at which a particular plant is re-called for operation.

The subject of power sharing usually includes the question of whether power sharing should be coordinated by a dedicated communication link or not. It is expected that communicated and noncommunicated schemes will have a variety of relative advantages and disadvantages. The discussion of this topic is far from being over and it will become even more important as both communication networks and power networks continue their rapid development.

This paper uses several scenarios to explore the benefits of having a unit commitment strategy supported by a communication link. The exploration is based on the minimization of running costs and is extended to cover a heat demand scenario in the microgrid.

II. UNIT COMMITMENT STRATEGIES

Four power-sharing schemes are presented in this paper: linear, nonlinear, dynamic, and optimized. Although the optimized scheme falls into the “nonlinear” category, it is treated in a different section.

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C. A. Hernandez-Aramburo and T. C. Green are with Imperial College London, London, SW7 2AZ, U.K. (e-mail: c.a.hernandez@imperial.ac.uk; t.green@ic.ac.uk).

N. Mugniot is with the Laboratoire d'Electrotechnique de Grenoble, ENSIEG, F-38402 Saint Martin d'Hères Cedex, France.

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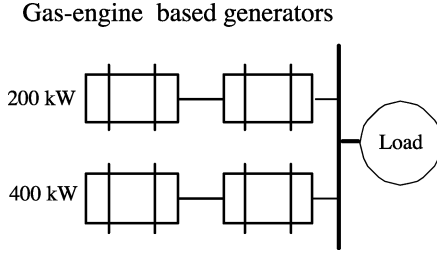


Fig. 1. Two parallel-connected gas-engine generators.

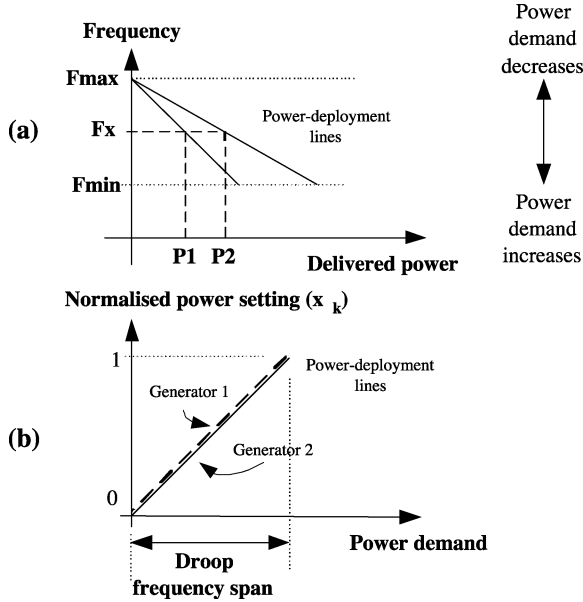


Fig. 2. Linear power sharing by frequency droop.

To illustrate some of the features of the chosen power sharing strategies, a simple example of only two gas-engine generators is considered first. These generators are connected to a common power bus serving a load, as shown schematically in Fig. 1. Assume that the two generators are 200 and 400 kW reciprocating gas-engine generators. This particular kind and size of generator seems to be economically realistic for microgrid applications [10].

A. Linear Power Sharing

It is possible to establish a linear unit commitment strategy in this system based on a **frequency droop** scheme. The basics of this scheme can be found in textbooks [11]. In broad terms, this scheme uses a (small) change in the power bus frequency to determine the amount of power that each generator should put into the power bus. This strategy is depicted in Fig. 2(a). As the power demand increases, the frequency droops to a certain value (say F_x) and the projection of this value over the generators' power-deployment curves indicates how much power each generator should put into the bus. As expressed in (1) to (3), the droop characteristics are defined by their slopes kp_1 and kp_2 and by their y -intercept frequencies F_{o1} and F_{o2}

$$Fx = F_{o1} - kp_1 \cdot P_1 \quad (1)$$

$$Fx = F_{o2} - kp_2 \cdot P_2 \quad (2)$$

$$F_{o1} = F_{o2} = F_{\max} \quad (3)$$

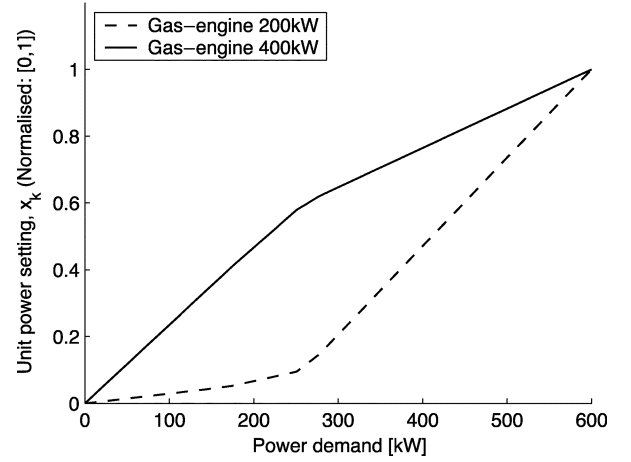


Fig. 3. Piecewise-linear power sharing scheme.

The power deployment curves can also be drawn as shown in Fig. 2(b). This figure is the result of mapping the frequency droop span into the power demand axis and normalizing the power settings of each generator (i.e., the power settings (x_k) are bounded between 0 and 1 [dimensionless] and the power requested of each generator is $x_k P_{\text{rated},k}$ [watts]). For the linear power sharing strategy the power deployment curves are straight lines. Additionally, if the power generators are deployed from 0% to 100% of their capacity as the total demand increases from 0 to the total installed power, the power deployment lines have a slope equal to 1, as depicted in Fig. 2(b).

This power-sharing scheme is (within reason) fault tolerant with respect to the failure of one of the generators. If one of the generators fails, the power bus frequency will further droop and more power will be requested from the remaining generator. This holds true, of course, as long as the remaining generator can cover the demand. The main advantages of this scheme its simplicity, effectiveness, and robustness.

B. Nonlinear Power Sharing

A nonlinear power-sharing scheme may be created by defining a set of nonlinear power-deployment curves such as the one depicted in Fig. 3. In principle, these curves may be highly nonlinear; however, for illustration purposes only, the curves shown are piecewise linear with two sections each.

The characteristics of each of these linear sections may be defined according to a higher level regulating policy. For example, the policy could be to improve the efficiency of the system or to improve the dynamic response or to allow a particular reserve power within an operating range. The power deployment lines in Fig. 3 were defined to reduce the fuel consumption of the system in comparison to the linear power sharing scheme. This will become evident in Section III.

C. Dynamic Power Sharing

In the strategy described in Section II-A, the y -intercept frequencies F_{o1} and F_{o2} were fixed and equal to F_{\max} and were static. The dynamic power sharing scheme considered in this section offers the possibility of moving, independently, the y -intercept frequency of each droop to modify the amount of power each source contributes to the overall demand.

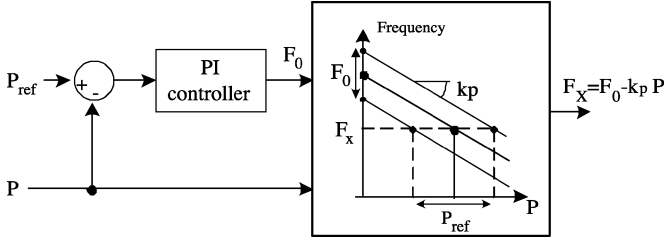


Fig. 4. Dynamic-frequency droop architecture.

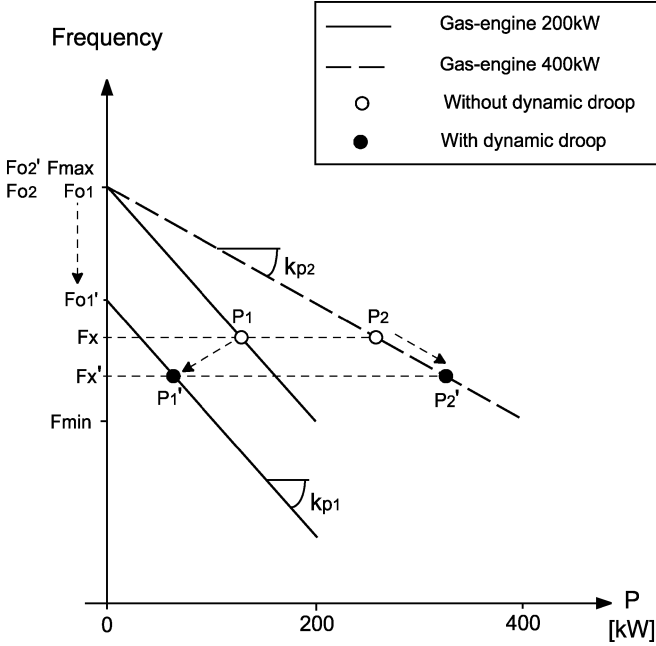


Fig. 5. Active power sharing with one dynamic droop characteristic.

As depicted in Fig. 4, a proportional–integral (PI) controller can be used to set the y -intercept frequency of the droop to a particular power setting. The slope k_p remains constant but the y -intercept frequency F_o is variable. Having a variable slope is also possible but this is not covered in this paper.

To illustrate how this dynamic power sharing works, consider that the frequency droop of the 400-kW generator is kept static by setting F_{o2} to F_{\max} but the y -intercept for the 200-kW generator is allowed to vary. As Fig. 5 shows, if the contribution of the 200-kW generator is to be decreased from P_1 to P'_1 , the intercept point F_{o1} must be decreased to F'_{o1} . As a consequence of this action, the 400 kW generator is forced to increase its contribution from P_2 to P'_2 so that the combined power delivered by both generators remains constant. There is a consequent reduction in the operating frequency from F_X to F'_X .

Dynamic droop characteristics can be very useful when reconnecting an islanded microgrid to the main grid. Indeed, a smooth reconnection requires equality in voltage magnitude and phase angle between the two systems that are to be connected together. If this is not the case, high circulating currents may flow and these could cause serious damage to either of the systems but especially to the microgrid. Smooth reconnection can be assured by an arbitration system between the microgrid and

the main grid. As shown in Fig. 6, when reconnection is decided upon, the reconnection control system sends a signal the microgrid sources to start a re-synchronization process.

For this example, assume that the microgrid is operating in island mode with $F_{\mu\text{grid}} < F_{\text{main-grid}}$ [see Fig. 7(a)]. Assume also that the load remains constant during the reconnection process. When the synchronization order is received, the frequency intercepts F_{o1} and F_{o2} are increased until the operating frequency of the microgrid is higher than the frequency of the main grid [Fig. 7(b)]. The frequency difference will, in time, cause the difference in phase between the two grids to decrease and when it is equal to zero the circuit breaker can be closed. At this point the reference frequency for the microgrid must be changed to match that of the main grid [Fig. 7(c)] and the power sharing scheme must then be adjusted to work in grid-connected mode.

Note that if the y -intercept frequencies F_{o1} and F_{o2} are moved simultaneously and by the same value, the power sharing ratio between the generators is not affected. Observe also that, under certain circumstances, only one droop characteristic may need to be adjusted to achieve re-synchronization with the grid.

The voltage magnitude of the microgrid can be regulated with a similar dynamic droop method imposed on the reactive power contributed by the generators.

D. Optimal Power Sharing

For certain applications, it may be desirable to establish a highly nonlinear power sharing scheme which may be optimized for a specific purpose. Among other considerations, an optimized power sharing strategy may take into account the running costs of the generating plants. If this is the case, the problem requires a constrained optimization formulation to minimize the running costs while providing the required power to the load [12].

The model of the system to be optimized is shown in Fig. 8. The inputs of the model are the normalized power settings (x_k) for each generator. The outputs are the total delivered power and the total running cost of the system. The optimization problem is then to find the power settings $0 \leq x_k \leq 1$ such that the cost is minimum.

The **cost function** (the fuel consumption rate) may be defined as in (4)

$$\text{Cost func} = \sum_{k=1}^2 (x_k P_{\text{rating}_k}) \times (\text{Fuel cons. rate per unit of power}). \quad (4)$$

Maintenance and management costs are outside of the scope of this paper.

The **constraint** for the optimization problem is that the power produced by the two generators must be equal to the power demand. A security reserve is not considered for this particular problem but it is taken into account in Section IV.

The optimization problem described above was implemented in Matlab and a discussion of the results follows.

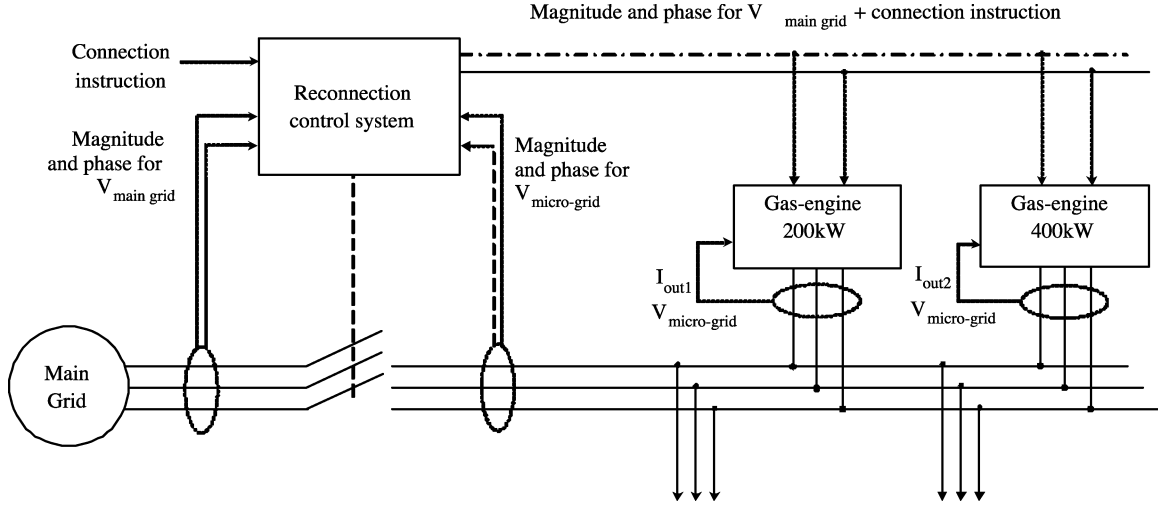


Fig. 6. Reconnection system architecture.

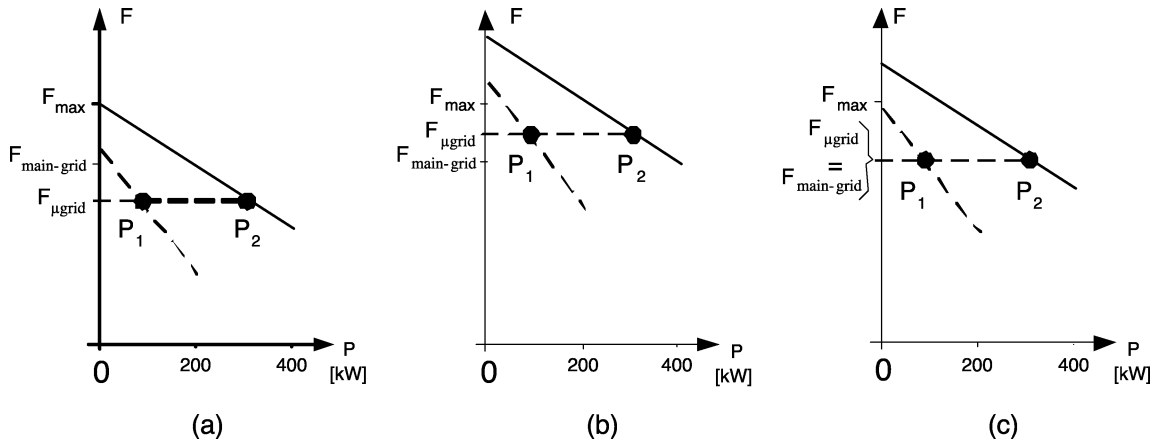


Fig. 7. Dynamic-frequency droop during a reconnection process.

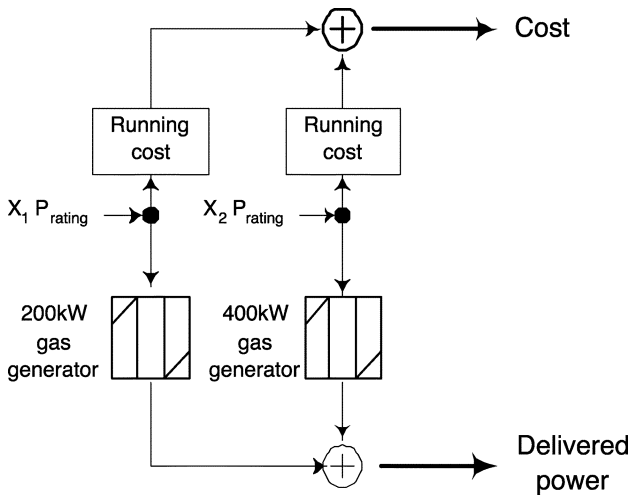


Fig. 8. Model of two parallel-connected gas-engine generators.

Fig. 9 shows the cost-optimized power settings (or power-deployment curves) for the two gas-engine generators shown in Fig. 1. These settings are different to those shown in Figs. (2b) and 3. In the linear and piecewise-linear cases both generators are on-line at all times, as opposed to the optimal case where

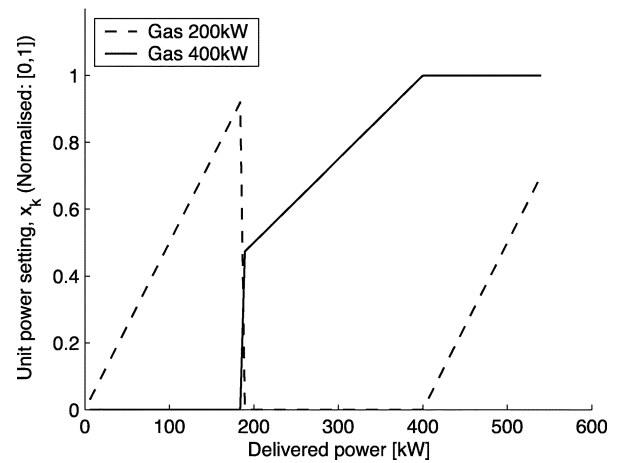


Fig. 9. Optimal operation of two gas-engine generators.

only one generator is online in certain operating regions, Fig. 9. When the load is relatively small it can be entirely covered by the 200-kW generator and, therefore, the 400-kW generator is simply switched off. When the power demand exceeds the rating of the small generator, a handover procedure takes place and the large generator is brought online and committed before the

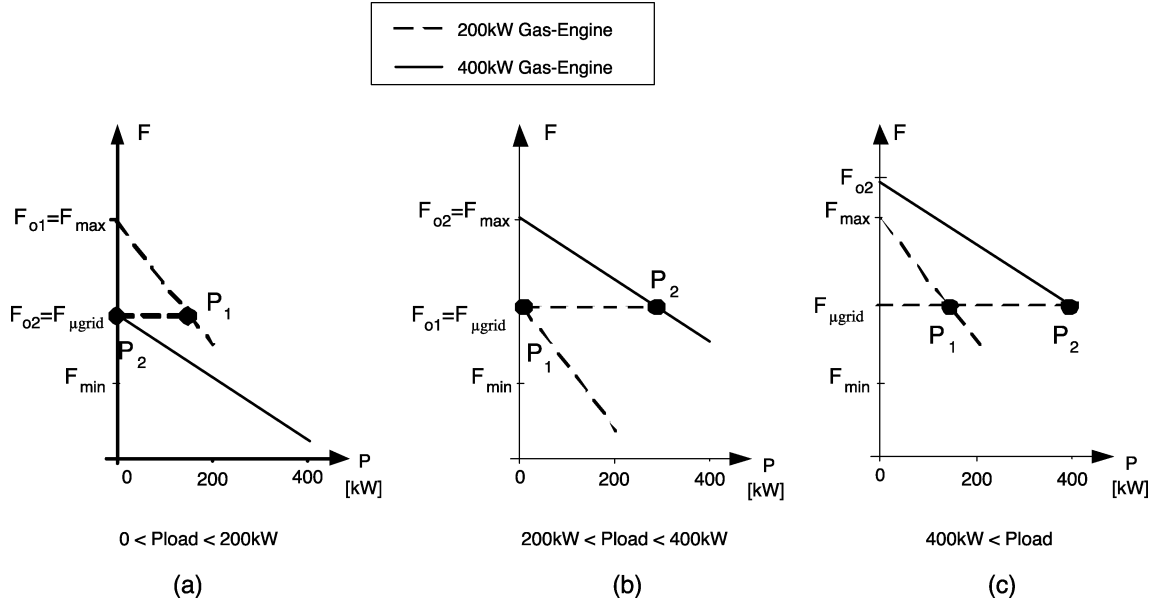


Fig. 10. Dynamic droop scheme for optimal power sharing.

small one is brought offline. When the power demand exceeds the capability of the large generator (or is close to doing so), the small one is brought online to supplement the power.

The dynamic scheme explained in Section II-C could be used to implement this optimal power sharing scheme, including the handover procedure. As Fig. 10(a) depicts, if the load can be entirely covered by the 200-kW generator, the frequency droop of this generator may be static (F_{o1} fixed at F_{max}) and the frequency droop of the 400-kW generator may be dynamic so that this generator contributes with no power to the system (F_{o2} is set equal to $F_{\mu grid}$).

When the handover procedure occurs, at around 200 kW (see Figs. 9 and 10(b)), the frequency droop of the 400-kW generator becomes dynamic and F_{o2} is increased until it reaches F_{max} and is then clipped to this value. At the same time, F_{o1} is decreased to $F_{\mu grid}$ so that the 200-kW generator provides no power.

Finally, when the power demand exceeds the capability of the large generator (at about 400 kW in Fig. 9), F_{o1} is fixed to F_{max} and F_{o2} is increased as much as necessary to ensure that the 400-kW generator provides its maximum power at the operating frequency of the microgrid. This is in accordance with the optimal power sharing scheme depicted in Fig. 9.

III. FUEL CONSUMPTION COMPARISON

A fuel consumption comparison was carried out in order to illustrate the impact of the various power sharing strategies presented in earlier sections. According to data from a manufacturer [13], typical fuel consumption characteristics for reciprocating gas-engine generators are of the form given in Fig. 11 (for 200- and 400-kW examples). The data have been curve fitted and interpolated by a fourth-order polynomial between 25%–100% of the rated power, and extrapolated between 0%–25%. It is assumed that a small fuel consumption occurs even with the generator delivering zero power.

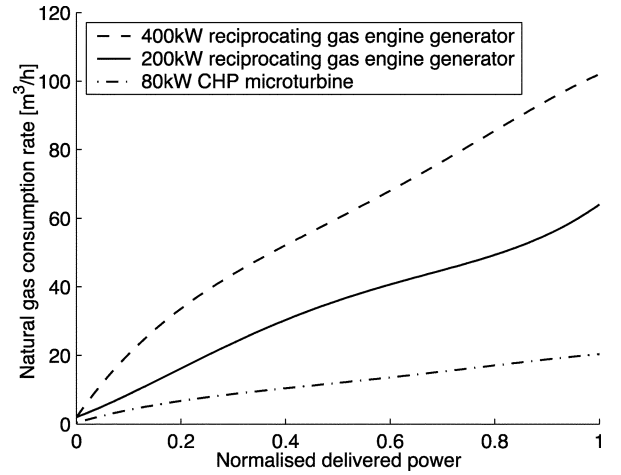


Fig. 11. Fuel consumption rate for two reciprocating gas engines and a CHP microturbine.

For these fuel consumption rates, the total fuel consumption was calculated across the range up to the total installed power for all of the power sharing strategies depicted in Figs. 2(b), 3 and 9 (linear, piecewise-linear, and optimized strategies, respectively). The results obtained are plotted in Fig. 12.

From this figure it can be observed that the piecewise-linear power sharing brings an important fuel saving with respect to the linear scheme when the power demand is between 15%–60% of the total installed power (600 kW). The maximum saving is about 15% with a load of 35%. This saving appears even more important if one considers the relatively small change made to the original power-deployment curves.

The unit commitment strategy obtained by the optimization process brought an additional reduction in fuel consumption over a wide power demand range. The fuel savings are about 20% when the power demand is between 30%–60% of the total installed power.

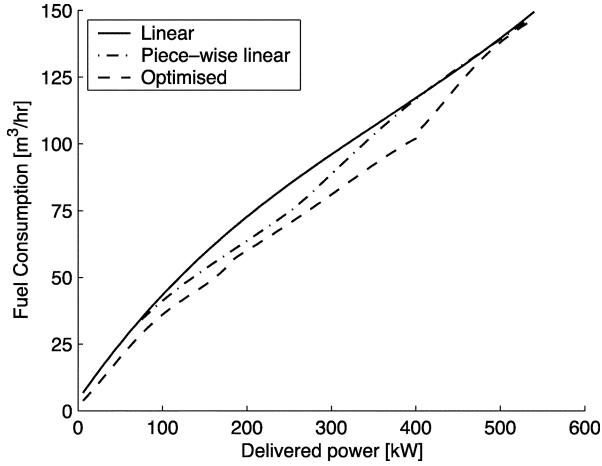


Fig. 12. Fuel consumption comparison.

The case of a microgrid consisting of only two generators is somewhat limited and it was presented for illustrative purposes only. It is expected that a microgrid will have a variety of power sources such as CHP plants, photovoltaics (PVs), and wind generators. It is important to consider also the heat demand of a system because co-generation may play an important role in distributed generation schemes [4].

The optimal power settings for a microgrid that contains a combination of plants of different kinds are presented in the next section.

IV. A MICROGRID WITH A VARIETY OF POWER SOURCES

Fig. 13 shows how the optimization problem for a microgrid with a variety of power sources may be arranged. The diagram shown in this figure is similar to that of Fig. 8 but it has some additional features. In Fig. 13, an additional input variable A_k has been included to account for the availability of the k th generator. This variable (bounded between 0–1 inclusive) models the condition in which a particular generator is completely unavailable for maintenance or the condition in which a particular resource is not fully available (such as the case of low solar irradiance).

The optimization problem represented in Fig. 13 also takes into consideration a case in which a heat demand exists. This introduces a new dimension to the problem because the heat demand could be covered by the CHP plant and/or by an electric heater or by a combination of them. These two elements (CHPs and heaters) are also implemented in the optimization formulation. The heat to electricity ratio of the 80-kW CHP microturbine introduced in the system under study was taken from the manufacturer's datasheets [13] as 1 : 1.75. However, the fuel consumption rate was not available from these datasheets and it was, therefore, assumed to be similar to that of the 200-kW gas engine but scaled linearly according to the power rating. The resulting fuel consumption characteristic for the microturbine is shown in Fig. 11.

Penalty functions may be added to the cost function if necessary. For the case under study, it was considered that any heat in excess of that required could be safely released to the environment but that a penalty should be paid for this.

The penalty function for the current problem was added to the cost function and was defined as the square of the difference between the required heat and the delivered heat (in kW_{th}) divided by an arbitrary scaling factor (equal to 50 for this particular example).

A **security margin** should be considered to enable the microgrid to respond to unexpected and sudden increases in the local power demand or to make power readily available to another microgrid. In the terms used to describe automatic generation control, a reserve should be available to another control area through any tie-line [14].

Choosing a security margin for a microgrid is not a straightforward procedure because the best choice might depend heavily on the load the microgrid is serving, and the type of connection to the main grid. Some options to define a security margin may be as follows:

- to cover for the largest load still to be connected to the microgrid at any instant;
- to cover for the failure of the largest generator presently connected;
- to provide a certain amount of power for up to a certain duration (in other words, a reserve energy).

For this study, the power reserve was arbitrarily defined as 5% of the available power in the microgrid.

The reserve power available from each online gas-engine generator is calculated as the difference between the rated power and the delivered power. Offline generators do not contribute to the security margin for this system. For the PV and wind generators the power in reserve is defined as the difference between the maximum power that could be delivered under the prevailing conditions and the power that is actually delivered. This assumes that the PV and wind systems might be operating at less than their current maximum power and that there is a means to estimate that maximum power.

Analysis of the stability of the control area was not included in the scope of this study.

The **penalty and constraint functions** for the optimization problem described in this section may be summarized as follows.

- 1) The power produced must be equal to the power demand

$$P_{\text{delivered}}^e = P_{\text{demand}}^e.$$

- 2) The power in reserve must be equal to or larger than a user-defined value

$$P_{\text{reserve}}^e \geq P_{\text{min. reserve}}^e.$$

- 3) The amount of generated heat must be equal or larger than the heat demand

$$P_{\text{delivered th}} \geq P_{\text{demand th}}.$$

- 4) The penalty function added to the cost is defined as

$$\text{Penalty} = \left(\frac{P_{\text{delivered}}^h - P_{\text{demand}}^e}{50} \right)^2.$$

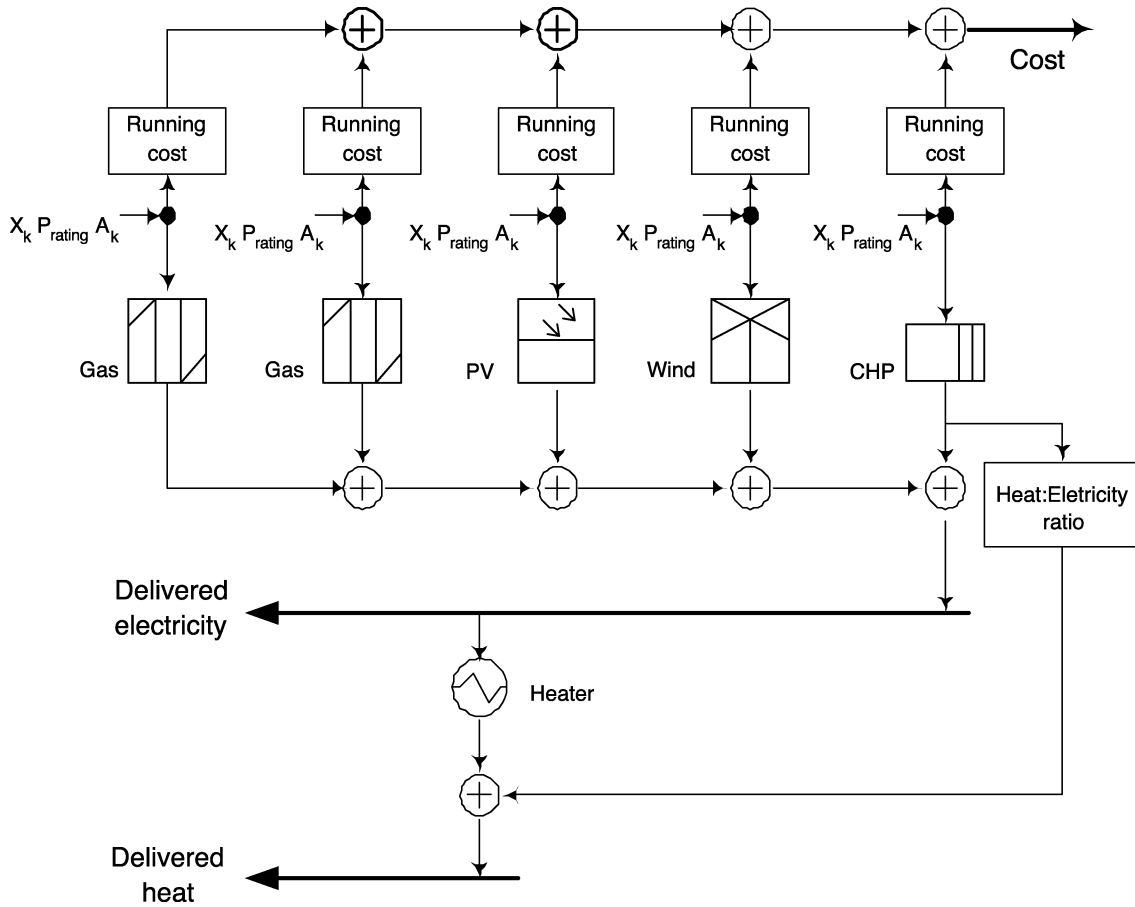


Fig. 13. Model of a microgrid with a variety of energy sources.

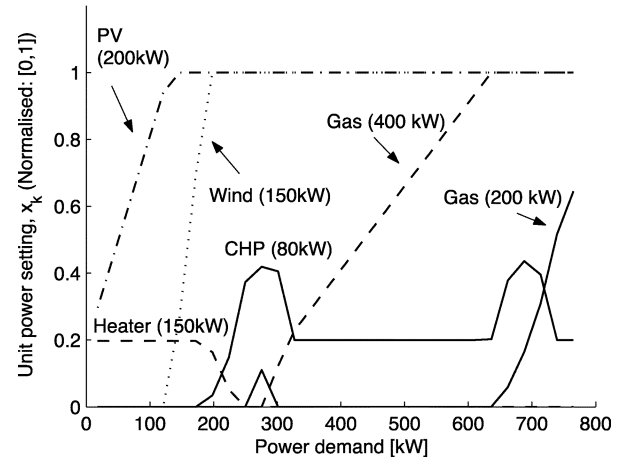
V. RESULTS

The optimization model described in the previous section is applied to a range of operating conditions. The electricity demand varies between 2%–85% of the total available electrical power and the heat demand varies between 0%–80% of the available thermal power. The available power from the PV and the wind generators were set to 80% and 40% of their rated power, respectively.

The set of power-deployment curves found by the optimization algorithm is shown in Fig. 14. These curves are plotted against the delivered electrical power and they correspond to a heat demand of 28 kW_{th}.

It may be observed from this figure that when the electricity and heat demands are both low, the best choice, in terms of cost, is to provide the heat demand with the electric heater and supply the electricity demand (including the heater) with the fuel-cost-free energy sources. This confirms that the optimizer has made reasonable selections. The selections for the rest of the electricity demand span are not so straightforward. The 200-kW gas-engine generator is the least preferred plant and it is fired only at about 275 kW to provide (to provide reserve power) and above 625 kW when there are no other generation options available. There are some conditions (those around 275 and 650 kW) where the CHP plant is forced to waste useful heat despite the inclusion of the penalty in the cost function.

The power settings for all generators and for the whole test range of heat and electricity demand are difficult to present

Fig. 14. Optimal operation for the microgrid at 28 kW_{th}.

in one single figure. This is because the settings are surfaces in three dimensions with the delivered heat and electricity in the x and y axes, respectively. One of these surfaces, for the CHP plant, is shown in Fig. 15. It can be seen that the optimal power-setting surface for this plant is not of a simple geometry. Further, it corresponds to only a single set of reserve power, solar irradiation, and wind speed conditions. In reality, the shape of the curve presented in this figure may vary significantly over time and according to the availability of the system resources and the required reserve power.

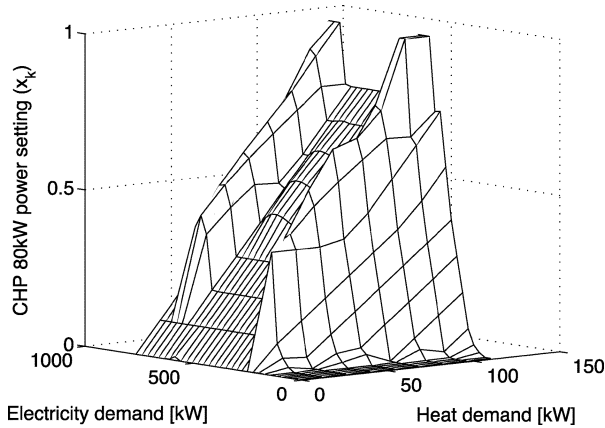


Fig. 15. Optimal operation for the CHP plant with a PV and wind generation availability of 80% and 40%, respectively.

VI. DISCUSSION

In the previous section, it was found that the optimal power-deployment curves for a particular element in a microgrid may substantially change in response to several variables including weather conditions, maintenance actions and, of course, the actual power demand. This indicates that it may not be useful to pre-program optimal governor settings for a particular plant (such as the CHP microturbine). Further, whereas the electrical power demand may be “mapped” into a modified form of frequency droop characteristic, the combination of several variables (heat and electricity demands, reserve power and generator availability) may not. These two arguments suggest that it might be very difficult to obtain optimal performance of a microgrid without a communication infrastructure over which to update governor settings.

A **communication infrastructure** in a microgrid may be used not only to minimize the running costs of the system but also to allow the coordination of power plants whose availability is usually predictable (on a short-term basis at least) such as wind turbines and PV arrays.

By adding a communication link, the cost of the system increases and its reliability is subject to one more failure risk. However, the power sharing strategy may now be more flexible because the power dispatch controller sets explicitly and individually the amount of power each generator must export to the common bus according to the current state of the system.

A possible scheme of a microgrid with a communication infrastructure is shown in Fig. 16. Each power generator is governed by a *local power dispatch controller*, which also receives data on the power demand and on the availability of the various plants. It might also include the current trading prices for power exchange with the main grid.

It is likely that a particular microgrid may tighten or relax certain constraints. For example, a microgrid with a slowly changing heat demand may simplify the optimization problem and relax the computing requirements of the power dispatch controller. An upper level control strategy in the dispatch controller may also use the thermal time constant of the system to divert the electrical power away from the electric heaters to cover a sharp increase in the power demand. Another particular

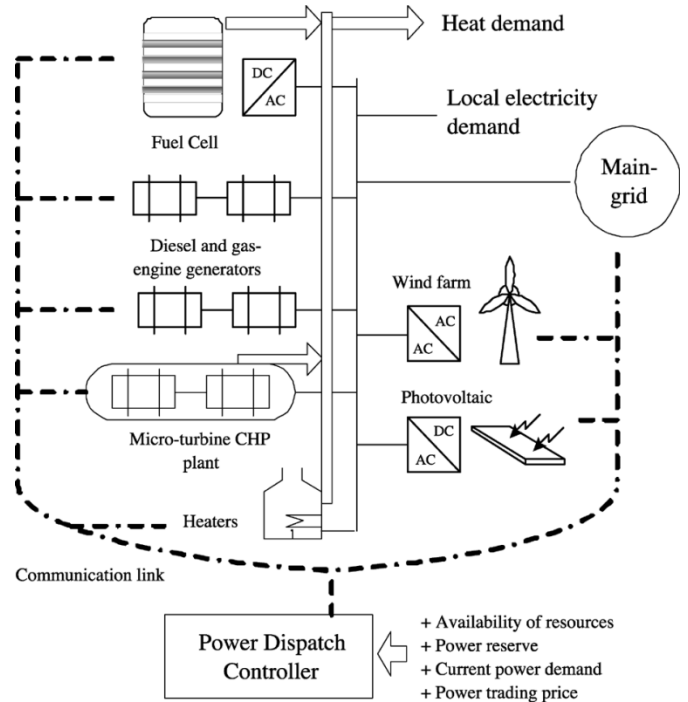


Fig. 16. Schematics of a microgrid with a communication infrastructure.

case is that in which both the electrical and thermal demands change slowly. In this case, the optimal power settings for each generator may be uploaded to the local plant controllers at a relatively slow rate, reducing then the bandwidth requirement for the communication link. These are all, however, very particular scenarios.

VII. CONCLUSION

There is a considerable amount of experience, accrued over many years, behind the cost optimization procedures of traditional power systems. However, microgrids present different conditions to those found in the traditional problem and which is focused on large generators within a large system. To illustrate some of the characteristics of the emerging microgrid scenarios, a cost optimization for a microgrid has been presented.

The optimization problem includes a variety of energy sources that are likely to be found in a microgrid: gas fired reciprocating engines, a combined heat and power microturbine, PV arrays, and wind generators. Heat demand is an important part of the scenario because combined heat and power will play an important role in a distributed generation scheme. Penalty and constraint functions added to the optimization problem to reflect some of the additional consideration often found in a small-scale generation system: a penalty is imposed for any heat generated in excess of demand and a power reserve to cover sudden changes is required.

The cost, constraint, penalty, and availability functions make the optimal power setting for each plant a complex surface. This leads to the conclusion that a power-sharing scheme aimed at maximizing the financial benefits in a microgrid is likely to rely on a communication infrastructure.

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Carlos A. Hernandez-Aramburo (M'03) received the B.Sc. and M.Sc. degrees from the Universidad de las Americas, Puebla, Mexico, in 1994 and 1998, respectively, and the Ph.D. degree from Imperial College London, London, U.K., in 2003.

He is currently a Lecturer in the Control and Power Research Group, Imperial College London. His professional interests lie in the application of power electronics in power systems and the integration of distributed energy resources into the grid.



Tim C. Green (M'89–SM'03) received the B.Sc. (Eng.) (first class honors) degree from Imperial College London, London, U.K., in 1986, and the Ph.D. degree from Heriot-Watt University, Edinburgh, U.K., in 1990, both in electrical engineering.

He was with Heriot-Watt University until 1994 and is currently a Reader at Imperial College London and a Member of the Control and Power Research Group. He has research interests in power engineering, covering distributed generation, microgrids, power quality, active power filters, FACTS technology, control of power systems using FACTS devices, and active distribution networks.

Dr. Green is a Chartered Engineer in the U.K. and a Member of the Institution of Electrical Engineers, U.K.



Nicolas Mugniot received the B.Sc. and M.Sc. degrees in electrical engineering from the Institut National Polytechnique de Grenoble, Grenoble, France, in 2003 and 2004, respectively.

As part of his studies, he joined the Control and Power Research Group at Imperial College London to study distributed generation related issues, with particular emphasis on control of inverters in islanded mode. He is currently with the Laboratoire d'Electrotechnique de Grenoble, ENSIEG, Saint Martin d'Hères, France, where his focus is on combined heat and power schemes for EDF Energy.