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Maximising the utilisation of micro-generation using a multi-state optimal power flow

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Abstract

This article investigates the use of a multi-state optimal power flow algorithm that simultaneously optimises the capacity utilisation of micro-generators to produce electricity in combination with the provision of spinning/standing reserve. The optimisation will consider various market data including energy and reserve markets, operating cost and technical characteristics of micro-generators, network constraints to optimise the dispatch and allocation of reserves. Two operating states are considered: (a) one base case where the reserve contracts are allocated to micro-generators but have not been exercised and (b) another state where all scheduled reserve is utilised. The optimal power flow algorithm will ensure that in both states, the system can be operated securely and no network operating limits/constraints are violated. We demonstrate the feasibility of the proposed optimal power flow through a number of case studies on a low-voltage system. The studies demonstrate that micro-generators are capable to contribute to both local and system support services, particularly, in the forms of reserve and voltage control while simultaneously optimising the portfolio of energy production in order to maximise the benefits for the owners of micro-generators and improve the efficiency of the overall system.

Keywords

Distribution network, micro-generator, operating reserves, optimal power flow, smart grid

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Introduction

A radical shift from the business as usual ‘fit and forget’ approach to an active control and smart grid system will be a necessity, if we plan to have a significant portion of our future energy consumption supplied by domestic small-scale distributed generators or micro-generators (shortly, microgen). In this highly distributed energy environment, microgen and demand side have to take the responsibility for the delivery of system support services, taking over the role and displacing the capacity of central generation. This can be facilitated using the smart grid technologies to optimise the schedule and coordinate control actions from individual microgen. The objective is to maximise the value of microgen by enabling it to provide not only energy but also ancillary services (voltage support, frequency control and reserve) to both local networks and the high-voltage (HV) grids while respecting network security and operating constraints. This article explores the idea of using microgen as an alternative source for reserves.

Figure 1 shows different operating reserves commonly used nowadays. They are classified to three categories based on their operation time scales. The first category is ‘primary frequency control’ (according to the Union for the Coordination of Electricity Transmission terminology[1]), also called as ‘frequency response’ in the UK. The second category is ‘secondary frequency control’ and the third category is ‘tertiary frequency control’.

Traditionally, primary frequency control or frequency response services are mandatory services provided by central generators and managed by transmission system operator (TSO) to respond quickly to the rapid change in frequency due to outages in generation or rapid increase/decrease in system loads. TSO can also use demand to provide this service by tripping the demand when the system frequency drops below a certain threshold. Due to the intrinsic nature of the requirements, this service has to be available immediately after a disturbance event in

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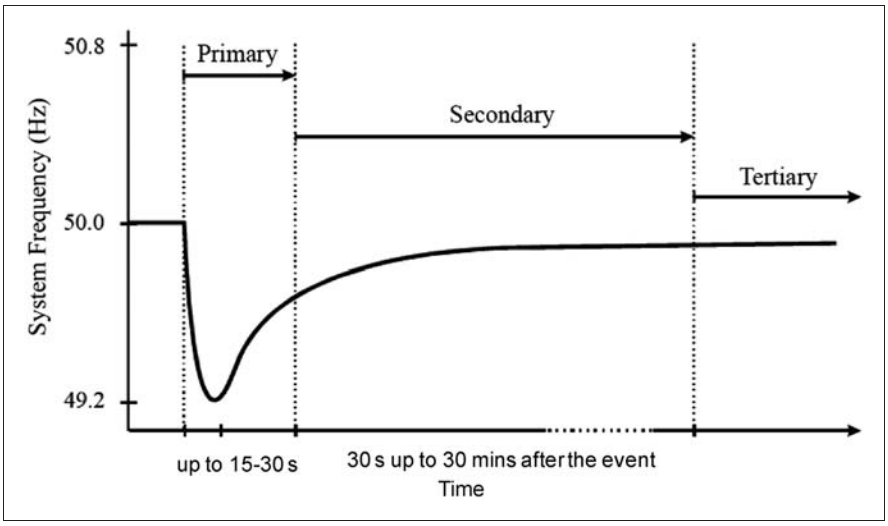

Figure 1. Time scale of various frequency control/reserve services.

the system and to be held (continuously available) for 15 s up to 30 s depending on system requirements.[2,3] Because of the time scale associated with this service, only synchronised generators running part-loaded can provide this service. Enhanced capability to provide this response services can be offered to TSO on a commercial basis.

Secondary frequency control is also centralised automatic control with a function to restore the balance between supply and demand and, by doing so, to restore the frequency back to its target value. After a disturbance event, this service should be available within 30 s and continuously available up to 30 min, if required. Considering the time scale, this service is provided only by synchronised generators running part-loaded.

Tertiary frequency control can be classified as 'slow reserve'. The TSO dispatches this service manually by increasing or decreasing central generation output to maintain the energy balance. This service can be provided by spinning or stand-by generators.

So far, the contribution of microgen on providing reserve services can be considered minimum. TSO treats microgen as negative loads and the balancing process occurring at distribution levels are treated the same as fluctuation in demand. Since the installed capacity of microgen at present is relatively low, this simple approach works well. However, for a system with high penetration of microgen, contribution of microgen should not be ignored, as discussed earlier.

As an alternative approach, controllable microgen technologies such as micro-turbines, fuel cells, can also provide various frequency control and reserve services.[4,5] This will bring benefits not only to the system by reducing primary and secondary control provided by central generators running part-loaded, but also to the owners of microgen by providing another stream of revenues to them.[6] The microgen controller (MC) can decide the optimal usage of its capacity. The MC also determines the amount of energy it should produce together with the ancillary services (reserves and reactive power support) that can be offered to the system. It is not in the scope of this article to discuss which microgen technologies can provide these system services.

Another important benefit derived from the use of microgen to provide secondary frequency control is the reduction of the number of generators running part-loaded. This is because small-scale microgen can be started and the output can ramp up quite quickly. For instance, according to studies carried out at the Lawrence Berkeley National Laboratory,[7] the fastest start-up of a 30 kW Capstone micro-turbine, including synchronisation time to the grid, can be less than 10 s. Such a micro-turbine would require only 120 s from start-up to maximum output if operated in a stand-alone mode. This means that this unit, even in a stand-by mode, can be used to provide secondary frequency control. This is in contrast to large-scale generators that need to be synchronised (spinning) to provide the secondary control service. This shows the feasibility of using small microgen in a stand-by mode to provide secondary frequency control services.

However, due to the scale of individual microgen, it is less efficient to offer their ancillary services on individual basis. The concept of virtual power plant can be applied to aggregate the volume of the ancillary services offered by microgen to TSO.[6,8,9] This will allow more efficient transaction costs, risk management and customer-related services.

Co-optimising dispatch of energy and ancillary services

In order to get the maximum value of the microgen, its utilisation has to be optimal. The capacity of the microgen should be committed to produce energy and

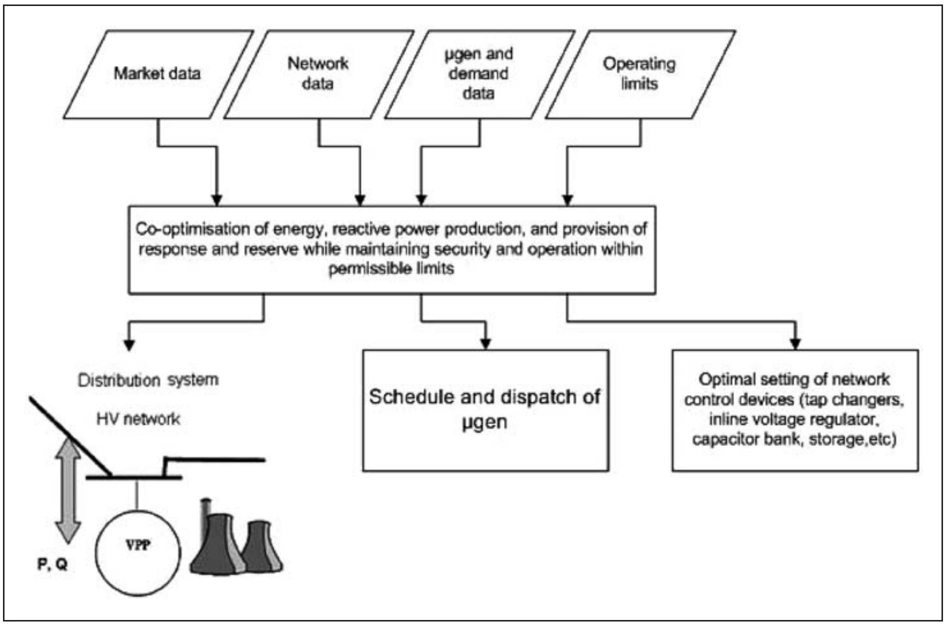

Figure 2. Process and information flows.

if profitable to support network operation by providing ancillary services including frequency control and reserves and voltage control services. Dispatch and commitment of microgen's capacity have to be optimised simultaneously across energy and ancillary services in order to maximise its value. This will also lead to more efficient energy and ancillary service market operation.[10]

Figure 2 shows the flowchart of a process carried out by a local smart-grid operator that optimises concurrently the energy production and ancillary services offered to the system. There are a number of input data required for this process. These include the following.

1. Market data that contain energy prices, prices of various ancillary services including prices for providing primary/secondary/tertiary frequency control, prices for reactive power supports, etc. The market data are normally time dependent and could be location specific too. The local controller may need to have forecasting capability to predict the market prices based on certain parameters and historical data.
2. Network data that contain network information including network topology and their electric parameters, network devices including tap changers, reactive compensators and their operating limits.
3. Microgen data include the minimum stable generation output, power rating, ability to provide response and reserve services (taking into account the start-up time and ramping up capability), operating cost data including fuel cost, no-load cost and start-up cost.
4. Demand data include nodal active and reactive loads.
5. Operating limits, in this case, include voltage and thermal limits.

A multi-state AC optimal power flow (OPF) algorithm (equations (1) to (11)) that maximises the efficiency of system operation and value of microgen can be applied by the local operator. The OPF will maximise the overall revenue from selling energy and ancillary services at the same time with minimising the overall operating costs. These include microgen fuel cost, no-load cost and start-up cost, and also the cost of importing electricity and reactive power from the grid. The OPF also simultaneously optimises operating decisions for the state where response and reserve services are executed to ensure that the system can still operate safely and within permissible operating limits while providing these services to the upstream grid. The decisions are based on the trade-off between the values of providing these services which are reflected by the market prices for these services and the value of electricity output from the microgen.

The OPF problem can be formulated as follows

$$Max = \sum_{i=1}^{NG}\left\{r_{rsp,i}(rsp_i, \pi_{rsp,i}) + r_{res,i}\ (res_i, \pi_{res,i})\right\} - \sum_{s=1}^{2}\rho^s \sum_{i=1}^{NG}\left\{c_{p,i}(P^s_{g,i}, \mu_i, \pi_{p,i}) + c_{q,i}(Q^s_{g,i}, \mu_i, \pi_{q,i})\right\} \quad (1)$$

Subject to (all constraints are applied to all states, i.e. base case and a state where response and reserve are

utilised) the following.
Nodal active power balance equation

$$P_g - P_d - \sum_{\substack{j=0 \\ j\neq 1}}^{MN} FP_{ij} = 0 \quad (2)$$

Nodal reactive power balance equation

$$Q_g - Q_d - \sum_{\substack{j=0 \\ j\neq i}}^{MN} FQ_{ij} = 0 \quad (3)$$

Voltage limit

$$V_{\min} \leqslant V \leqslant V_{\max} \quad (4)$$

Limits of active and reactive power generation

$$\mu P_g^{\min} \leqslant P_g \leqslant \mu P_g^{\max} \quad (5)$$

$$\mu Q_g^{\min} \leqslant Q_g \leqslant \mu Q_g^{\max} \quad (6)$$

Limits of network control devices (tap changers and shunts)

$$x_{\min} \leqslant x \leqslant x_{\max} \quad (7)$$

Limits of branch flows

$$S_{ij} \leqslant S_{ij\max} \quad (8)$$

$$S_{ji} \leqslant S_{ji\max} \quad (9)$$

The link between the output of generator i in state 2 where committed response and reserves are utilised and the output of generator i in the base case

$$P_{g,i}^2 = P_{g,i}^1 + rsp_i + res_i \quad (10)$$

Response limit: only a synchronised generator can provide frequency response

$$\mu^1 n P_g^{\min} \leqslant P_g^1 + rsp \leqslant \mu^1 n P_g^{\max} \quad (11)$$

where P_g, P_d are the vectors of active power generation and load (kW), respectively. Q_g, Q_d are the vectors of reactive power generation and load (kVAr), respectively. rsp, res are the vectors of generator capacity allocated to provide response and reserve, respectively. S_{ij}, S_{ji} are the power flows from node i to j and from j to i, respectively (kVA). π is a vector of generating operating cost for active and reactive power production (π_p, π_q) or market prices, i.e. reserve market (res), response market (rsp). μ is a vector of operating state of a generator. $\mu = 1$ for a synchronised generator and 0 when the generator is off. ρ^s is a probability of being in state s. For the base case ρ is always 1 while for state 2, ρ is the likelihood of committed response and reserve capacity to be exercised. This can be determined from historical data or guessed by the operator of generators. V is a vector of nodal voltages (V). X is a vector of control parameters for network control devices such as tap changers and shunts. FP_{ij}, FQ_{ij} are the active (kW) and reactive power (kVAr) flows from node i to node j, respectively, and as functions of demand, generation and network control. $c_{p,i}(P_{g,i}^s, \mu_i, \pi_{p,i})$, $c_{q,i}(Q_{g,i}^s, \mu_i, \pi_{q,i})$ are the cost function of active and reactive power production from a microgen, respectively. MN is the number of nodes in the system. NG is the number of generators in the system.

The first two components in equation (1) denote the revenue obtained from providing capacity for response and reserve services and the second two components denote the cost of procuring active and reactive power from the grid. The latter can be negative if the electricity production from the local microgen is greater than the local demand. In this formulation, two operating states are considered: (a) one base case where the reserve contracts are allocated to microgen but have not been exercised and (b) another state where all scheduled reserve is utilised. The OPF algorithm will ensure that in both states, the system can be operated securely and no network operating limits/constraints are violated.

Equations (2) to (9) are standard constraints in the AC OPF problem representing active and reactive power balance equations, voltage, generation, tap changer and flow limits. Equation (10) shows that the active power output of microgen i in the second state equals to its active power output in the first state plus the committed response and reserve power. Equation (11) is to ensure that response can only be provided by a microgen when it is synchronised to the system.

Simulation studies

A number of simulation studies have been developed to test and demonstrate the technical and commercial feasibility of the proposed solution for providing energy and ancillary services from microgen. A low-voltage (LV) test system, illustrated in Figure 3 was used for these studies.

The test system contains seven microgen (Table 1) with fuel costs varying from 3.05 to 4.25 c/kWh. The LV system has three feeders: (a) a residential feeder; (b) an industrial feeder with an industrial customer connected at the end of the feeder; and (c) a commercial feeder. Demand data for each type of customer have been developed carefully to reflect different pattern of electricity consumption from different customer types. The LV system is connected to a higher distribution network through a distribution

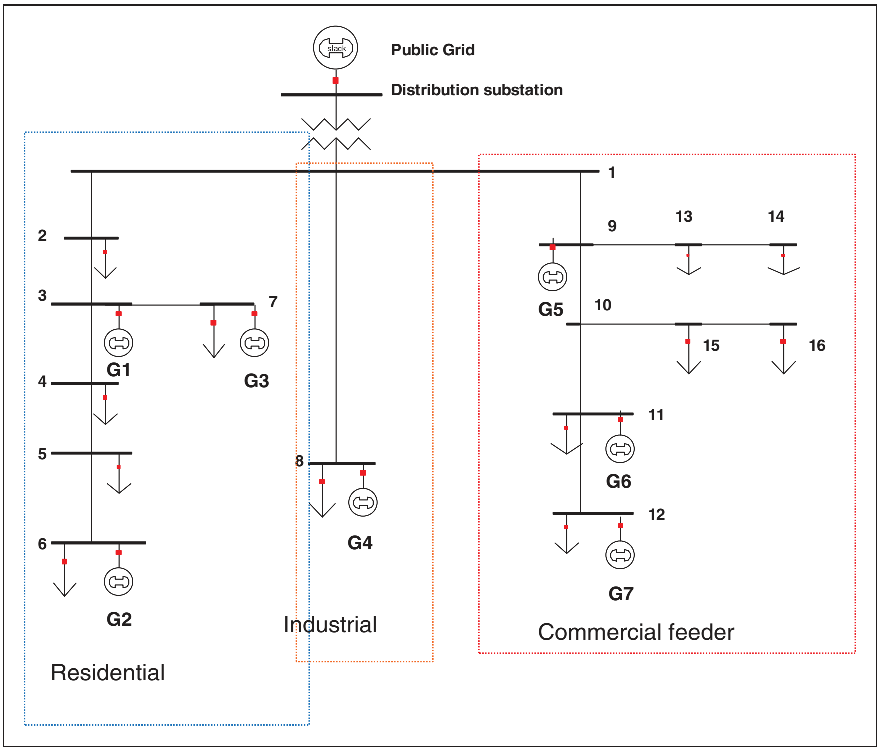

Figure 3. LV test system.

Table 1. Microgen data.

Bus	Type	P_{min} (kW)	P_{max} (kW)	Q_{min} (kVAr)	Q_{max} (kVAr)	Marginal fuel cost (c/kWh)
3	Micro-turbine	20.00	50.00	−24.22	24.22	4.25
6	Micro-turbine	10.00	25.00	−12.11	12.11	3.05
7	Micro-turbine	12.00	30.00	−14.53	14.53	3.10
8	Micro-turbine	12.00	30.00	−14.53	14.53	3.20
9	Micro-turbine	8.00	20.00	−9.69	9.69	3.50
11	Micro-turbine	4.00	10.00	−4.84	4.84	3.70
12	Micro-turbine	20.00	50.00	−24.22	24.22	4.00

transformer. In this case study, we simulated a 24 h period with changes in demand (Figure 4) and market prices (Figure 5). The monetary unit used in this study is Euro (€).

Market prices shown in Figure 5 were developed only for illustration purposes but the hourly profile of energy prices resembles a variation in the spot market prices for electricity from APX Power UK. The market price data also contain prices for providing ancillary services including the price for frequency response, reserve and reactive power. They tend to be much smaller compared to the energy price at present; however, if these sources from central generators become less available in the future, the prices will tend to go up. Nevertheless, it still provides additional revenue streams for the microgen owners.

The scheduling of microgen and the committed reserve services produced by the OPF algorithm are summarised in Figures 6 to 8. PG *i* denotes the active power output from the microgen unit *i*. Rsp *i* and Rsv *i* denote the frequency response and reserve capacity committed by the microgen unit *i*, respectively. Rsp *i* relates to the provision of primary frequency control as discussed previously in 'Introduction' and it can only be provided by part loading the synchronised microgen. Rsv *i* relates to the provision of secondary and tertiary frequency control. In contrast to Rsp *i*, a microgen can provide reserve even it operates in a stand-by mode (see discussion in 'Introduction').

It is interesting to observe that during off-peak demand periods, microgen can be dedicated to provide reserves as it is not economical to generate energy

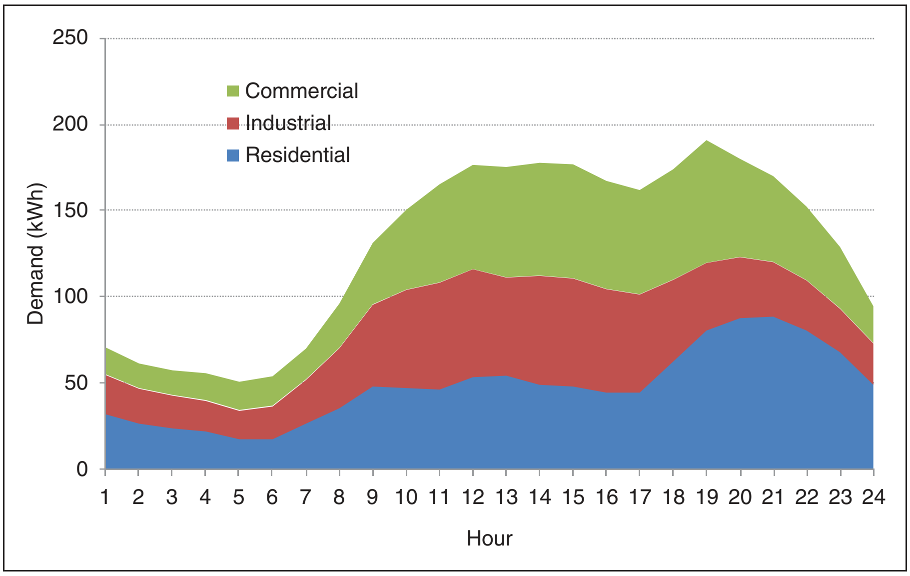

Figure 4. Load profile.

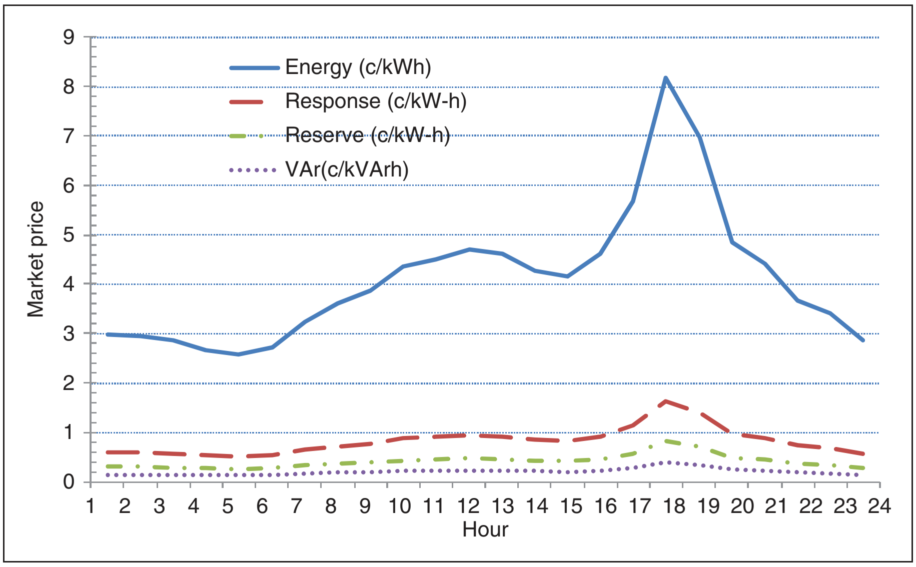

Figure 5. Market prices.

since it is cheaper to import energy from the grid. On the other hand, during peak demand periods, it is more economical (in this example) to generate electricity from cheaper local sources. In this context, selling services during peak electricity prices become less attractive. As one can expect that the dispatch and the capacity allocation of various services from microgen will be sensitive to market prices, sensitivity analysis can be carried out using this methodology.

Figure 9 shows the cumulative microgen's capacities that have been committed to provide energy and ancillary services. Total available capacity is 215 kW. It shows that during the off-peak demand (hour 1–hour 7), the use of the microgen capacities has been constrained while in other hours, the capacity can be used fully.

The additional revenues from offering frequency response and reserve services in this case are €7.97/day and €6.71/day respectively. In total, the additional revenue is €14.68/day. This constitutes 17.7% of the value of electricity output from microgen (€82.71/day). It is important to note that it is likely that the demand for ancillary services in the future will increase along with the increased penetration of renewable energy. This is likely to increase the market prices for these services and, therefore, it can provide reasonable additional revenue for the owners of microgen.

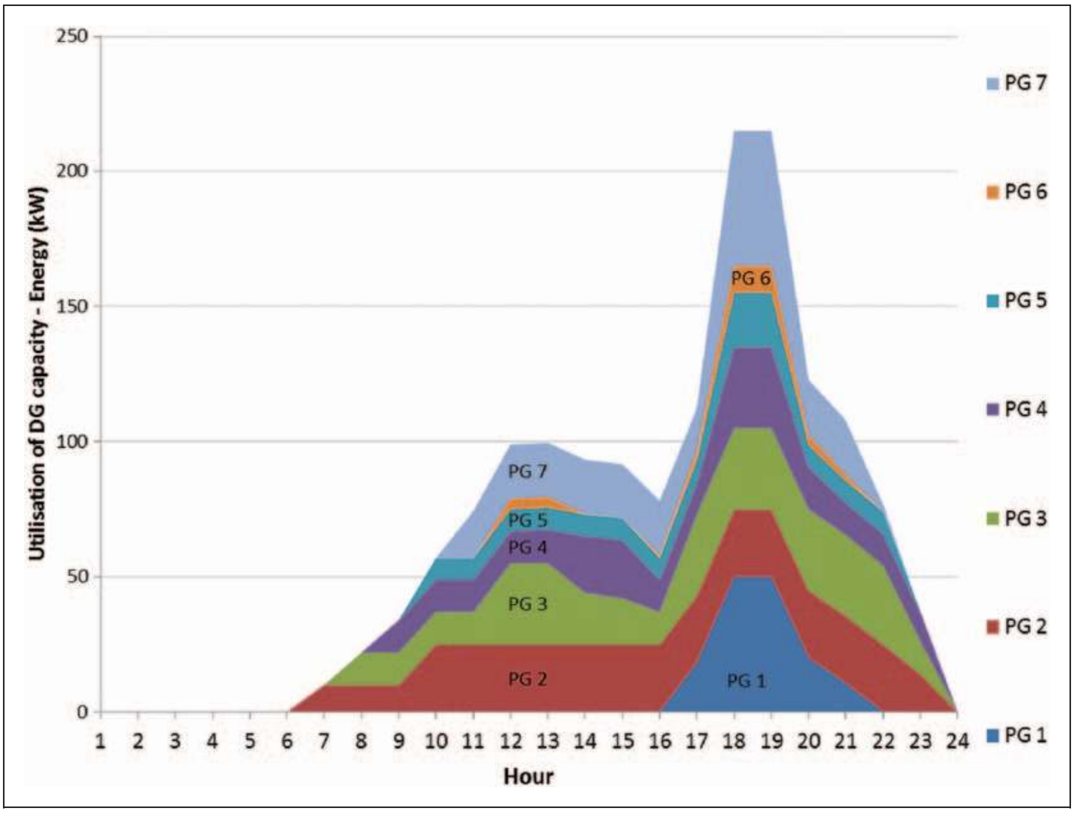

Figure 6. Energy dispatch.

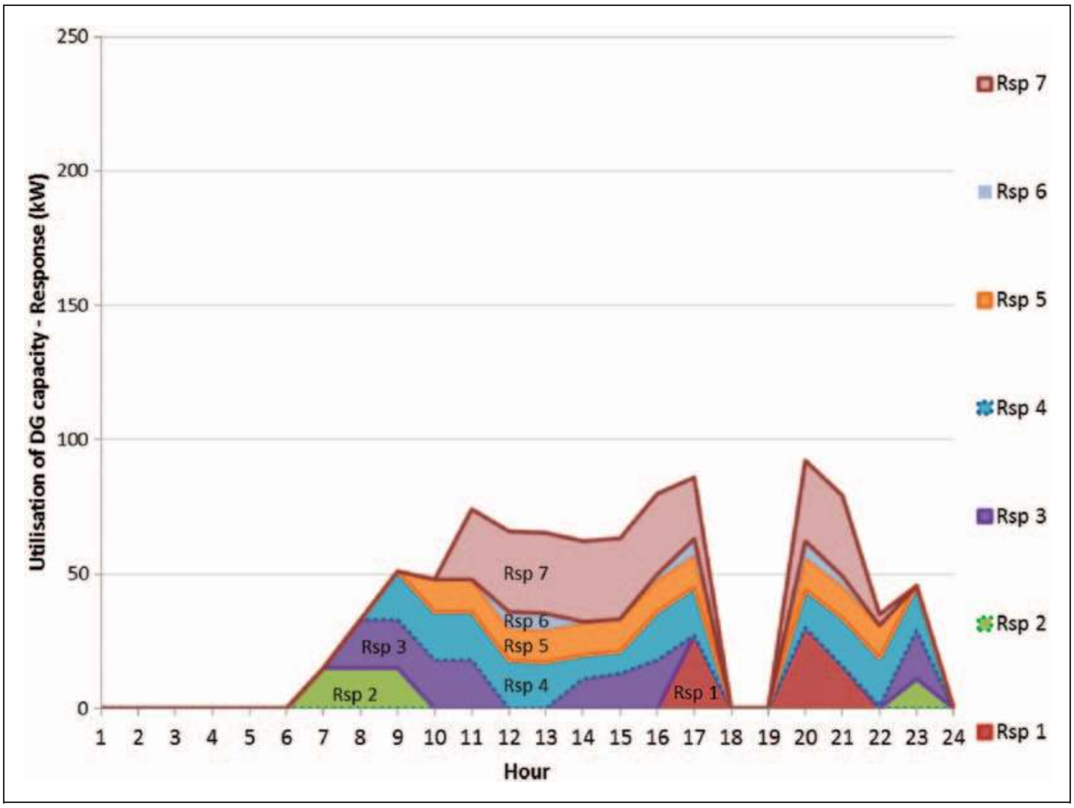

Figure 7. Response commitment.

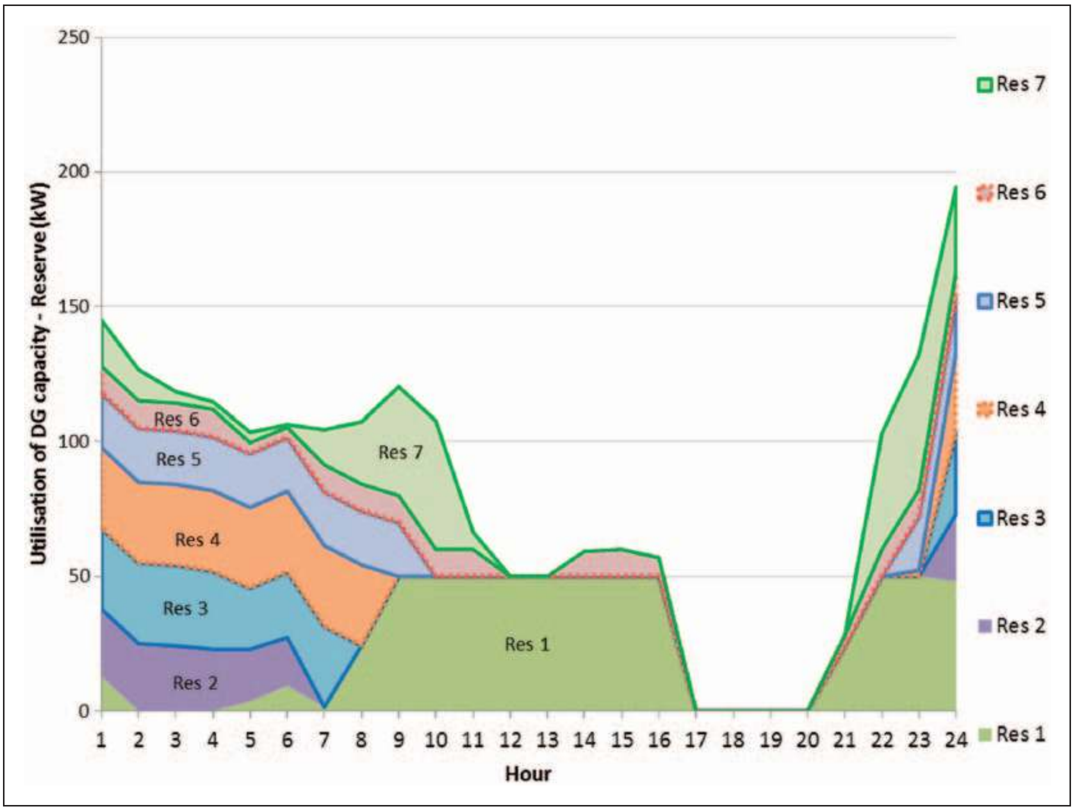

Figure 8. Reserve commitment.

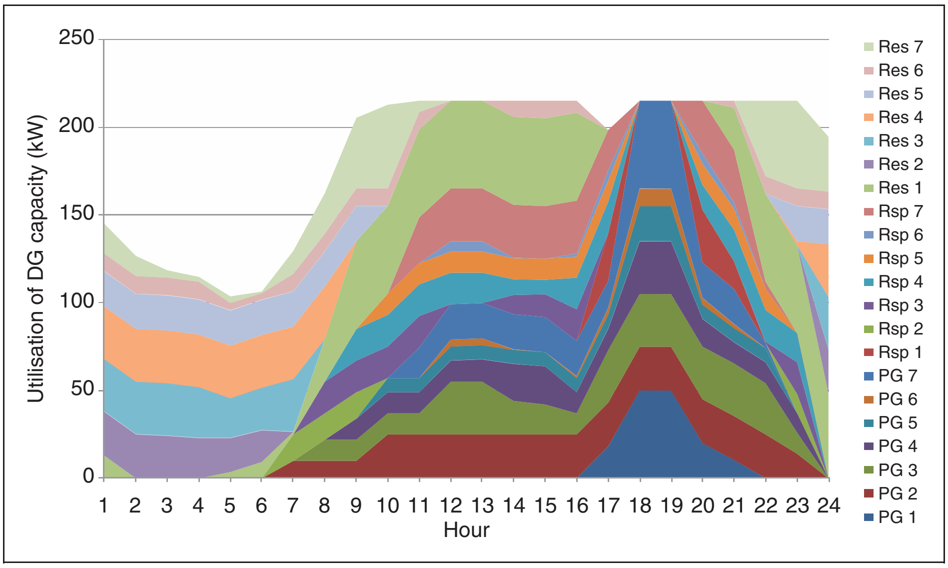

Figure 9. Capacity utilisation.

Figure 9 indicates that the use of the microgen capacity has been constrained by the maximum voltage limits. It is intentional to set the maximum voltage limit to be 3% above the nominal voltage in order to show this constraint effect. Ranges of voltage variations across the LV system are shown in Figure 10.

During off-peak demand, voltage rise problems may occur especially when microgen produce significant power, e.g. when reserve contract is exercised. In this example, the voltage rise problem occurs in bus 6 at the end of the first feeder. Bus 17 is the HV side of the LV substation.

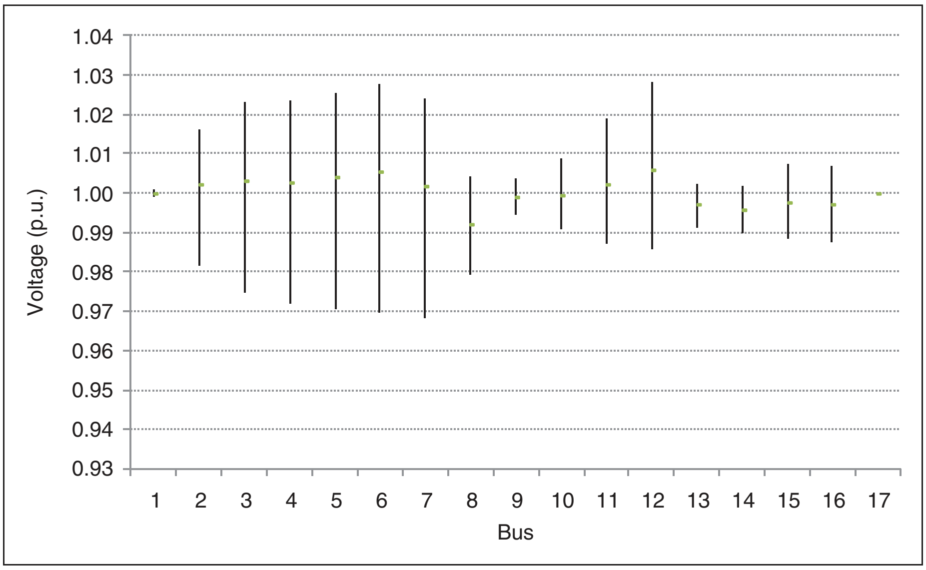

Figure 10. Voltage variations.

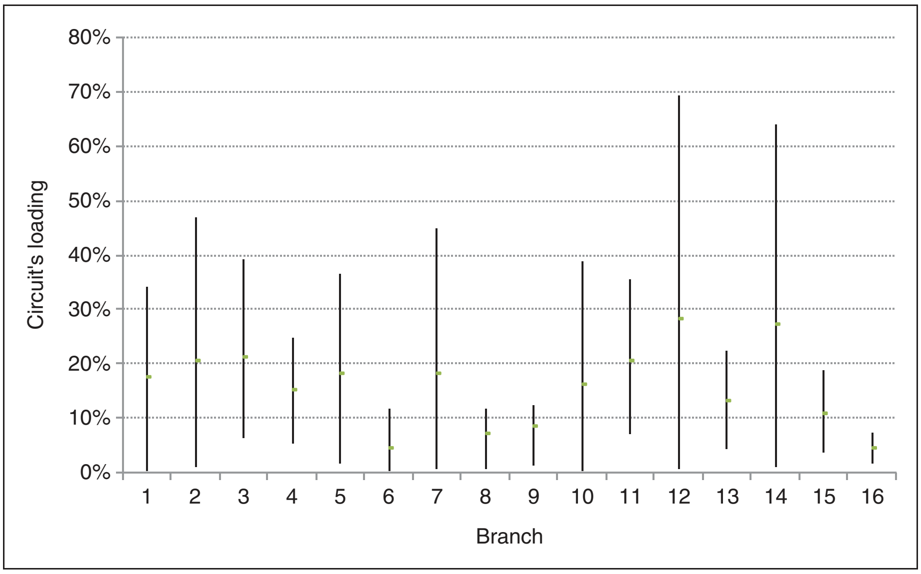

Figure 11. Circuit loading variations.

In addition to voltage constraints, the solution has to respect the capacity of network circuits and should not cause overloading. In this example, there is no overload, as shown in Figure 11. Branches 1–16 are described in the network data in the Appendix.

We have also studied the use of an on-load tap changer (OLTC) in the distribution substation to control network voltages and to enable higher utilisation of microgen's capacity, especially if it has been constrained by voltage limits during off-peak demand conditions, as illustrated in the previous examples. By optimising the setting of the tap-changing transformer, the results in Figure 12 show that the capacity of microgen can be utilised fully.

Conclusion

In a highly distributed energy system where there is a significant installed capacity of microgen, the responsibility for delivery of system support services has to be shared between central and microgen in order to reduce system capacity requirements and to improve overall system operation efficiency. In this context, a multi-state OPF-based algorithm has been developed for a smart-grid to simultaneously optimise energy and reserve provision from microgen in order to minimise the cost of system operation while maximising the utilisation of the microgen capacity. Two operating states including the state where the committed

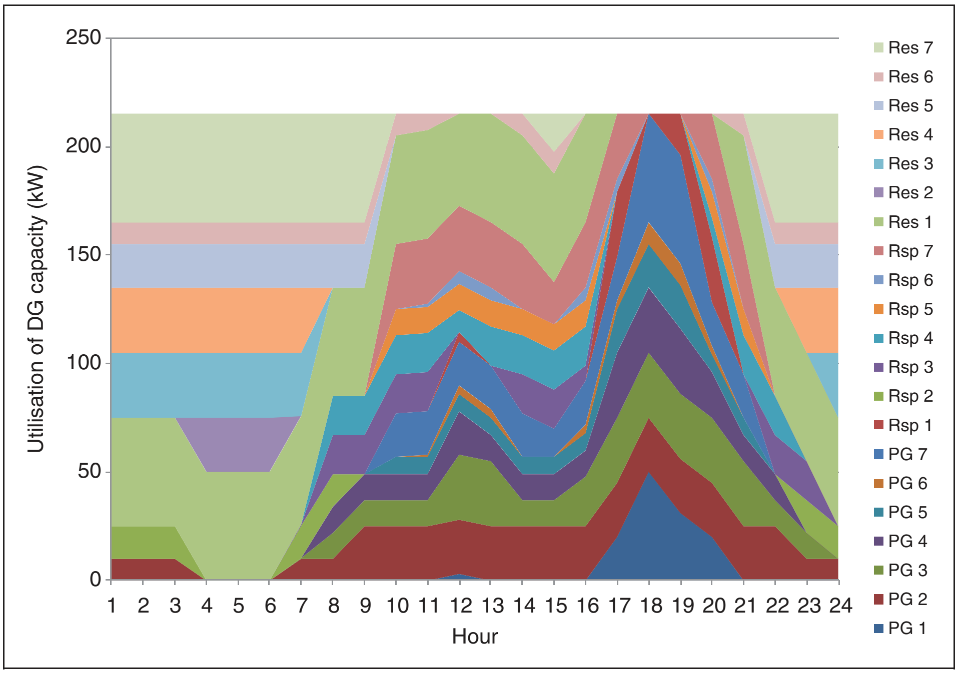

Figure 12. Capacity utilisation after implementing OLTC distribution transformer.

response and reserve capacities are utilised are modelled in the OPF to ensure that operating constraints are met.

The technical feasibility of this concept has been demonstrated through a number of numerical studies conducted on a LV system. The studies demonstrate the use of microgen to support system ancillary services particularly in the forms of frequency response and reserve while simultaneously optimising the portfolio of energy production in order to maximise the capacity utilisation of microgen. The studies also show that an active network control can improve the capacity utilisation of microgen by removing voltage constraints.

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Appendix

Network data

Table 2. Capacitor bank: 150 kVAr at node 1.

Sending end bus name	Receiving end bus name	*R* (p.u.)	*X* (p.u.)	Rating (kVA)
1	2	0.030010	0.008010	170.0
1	8	0.033125	0.008750	110.0
1	9	0.007500	0.005000	110.0
17 (LV substation)	1	0.001150	0.003830	400.0
2	3	0.012500	0.003750	170.0
3	4	0.012500	0.003750	170.0
3	7	0.021870	0.004380	60.0
4	5	0.012500	0.003750	170.0
5	6	0.012500	0.003750	170.0
9	10	0.015000	0.010630	110.0
9	13	0.010630	0.005630	70.0
10	11	0.021250	0.005630	70.0
10	15	0.023130	0.006250	50.0
11	12	0.021250	0.005630	70.0
13	14	0.010630	0.005630	70.0
15	16	0.023130	0.006250	50.0

LV: low voltage.