Impact of intentional islanding of distributed generation on electricity market prices

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Abstract: The battle for electricity customers in an increasingly competitive and deregulated market environment is one of the challenges facing the electric power utilities of today. Customers expect a reliable and efficient supply of power from their utilities. One of the advantages that a distributed generator (DG) can provide to the electric utility and to customers is the possibility of improving the continuity of supply by implementing safe intentional islands in the event of upstream utility supply outage. Implementing intentional islanding of DG in a deregulated era will have an impact on electricity market prices. This problem is considered in this paper by solving the optimal power flow problem while accounting for islanded operation.

1 Introduction

A large number of business failures in numerous industries has been attributed to the inability to recognise customer needs. In the competitive electricity market environment, power utilities are now realising that customer preferences and their purchase decisions are greatly affected by power supply reliability. Consequently, one of the main challenges is to provide enhanced levels of services to the customers while maintaining acceptable reliability standards. The other aim is to lower the cost of operation and maintenance to provide lower rates to customers [1].

The electricity distribution system is a vital part of the total electric power supply system, since it is the link between the bulk transmission system and the customers. It has been estimated that 80% of the supply interruptions faced by customers are because of failures that occur in the distribution network. Automation in communication and control has been introduced to distribution systems in many countries in recent years to improve the overall system reliability and hence service to electricity customers [2]. In the UK, the Office of Gas and Electricity Markets (OFGEM) has set up standards that specify that an interruption should not last more than 24 hours, otherwise the utility will have to pay customers an amount of money as compensation.

It is envisaged that within the coming decade there will be significant changes in distribution system configuration and this will include a large growth in DG capacity [3]. A study by Electric Power Research Institute (EPRI) indicates that by the year 2010, DGs will account for up to 25% of all new generation capacity in the US [4]. Another study by the National Gas Foundation estimates that this figure could be as high as 30% [5].

The current practice in distribution system protection is either to disconnect all DGs once a fault occurs or to implement an islanding detection algorithm that detects an islanding situation and initiates DG disconnection [6]. However, with increasing competition to secure more customers, the energy supply companies are now increasingly under pressure to maintain a high degree of uninterrupted power supply quality and reliability. Therefore the practice of disconnecting all DGs once a fault occurs is not a practical solution in a deregulated electricity market environment since it relies on power outage (brownout, if not a blackout) to manage the system protection.

It can be expected that in the near future there will be modifications to the operating policies with regard to DG disconnection after a disturbance. Operation of safe intentional islands would be a viable solution in distribution system protection. In fact, the new IEEE Standard 1547-2003 [7] emphasises the implementation of intentional islands in cases of power outages in the system as one of its tasks for future consideration.

If intentional islanding is eventually approved and allowed by the system operator and other appropriate authorities, the DG can supply some customers within the distribution network in the event of an outage in the main feed line of the distribution system or in the primary substation. Obviously the voltage and frequency in the islanded portion of the distribution network have to be controlled because they might deviate from the required standard levels [8]. Besides that, creation of islands in the system could possibly impact the electricity market prices. In some cases the total generation capacity from DGs within the island could be less than the total islanded region demand. As a result, some of the loads would need to be curtailed. Certain rules should be set by the system operator to produce a safe island and prevent market price spikes in case of intentional islanding.

This paper examines the effect of implementing safe intentional islanding of DGs and how such islanding action affects the close-to-real-time electricity market prices. The market clearing price is determined by formulating an optimal power flow problem but with the addition of a new constraint responsible for simulating the effect of intentional islanding. The effect of the cost of unserved energy on market clearing prices within the island is also examined.

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2 DG islanding

Distributed generator islanding is a condition in which a portion of the electric utility system that contains both load and DG resources (which the utility has no control over) remains energised while isolated from the remainder of the utility system [9]. Distributed generators can increase reliability of electricity supply if the units are configured to provide backup islands during upstream utility source outages. Figure 1 shows a scheme where an upstream automatic switch is used to island a section of a distribution feeder.

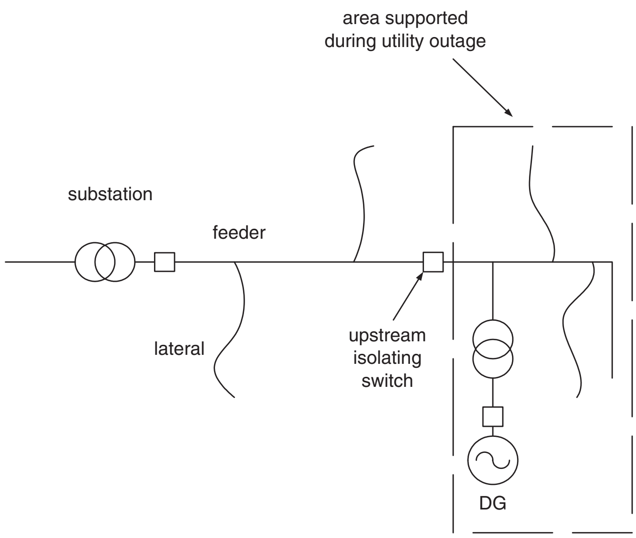

Fig. 1 *Distributed generation islanding*

One of the important aspects in classical distribution system protection is the prevention of islanding. The IEEE Standard 929-2000 [4] necessitates the prevention of islanding due to the following reasons:

- The utility has no control over the voltage and frequency in the island, and hence, there is a possibility of damage to customer equipment.
- Islanding may interfere with restoration of normal services by the utility.
- Islanding can lead to potential risk of life for utility line workers if a line remains energised, while it could be assumed to be disconnected from all energy sources.

However, with a multitude of DG resources now being connected to the grid it is becoming absolutely essential for line workers to strictly adhere to the established rules for line maintenance and repairs. This includes elaborate testing procedures for islanding detection [6]. Therefore line workers operating in such strict operating regimes are not expected to be at any increased risk due to DG intentional islanding.

In [8] some control techniques that enable safe islanding operation of DGs were proposed that addressed some of the previously mentioned problems associated with islanding. In [10, 11] the authors state that a new approach to system operation, protection and planning is required to produce safe islanding. The authors in [12] proposed an islanding scheme to avert a blackout in real time after a fault occurs.

Moreover, for the first time, the new standard IEEE Standard 1547-2003 [7] addresses the topic of intentional islanding and proposes to consider this topic in its future revisions. Collapsing part of the system could result in loss of revenue for the utility because they cannot sell energy to the disconnected part. Customers can lose confidence and choose alternative sources of energy that are more reliable. Due to the aforementioned reasons, there is a demanding need to produce safe intentional islands to serve some of the critical loads [13].

3 Problem formulation

In this work we consider a single-auction market where the generators bid for supplying the power while the market operator has a forecast of the demand in very close to real time [14]. The single auction market was popularised by the erstwhile British power pool, and has been adopted in Australia. In Ontario, although theoretically it is a double-sided auction, the demand-side participation is very low (about 5%), and thus can be considered a single auction market for practical purposes. The work presented here is, however, generic enough and can be extended to the double-auction model without difficulty. The structure and design of various market models and auction mechanisms have been discussed in detail in [14]. The market prices are determined every five minutes, and this is similar to the Ontario electricity market price settlements [15]. We formulate the single-auction market settlement model in an optimal power flow framework where the generation bid prices are available with the market operator and the nodal prices are obtained every five minutes by maximising the social welfare.

Within the same market simulation framework we subsequently introduce scenarios of system operation considering islanding of a part of the system following a disturbance to analyse how the market prices are affected. Since there is a possibility that the island demand is greater than the generation, the cost of unserved energy shall be included in the 'social welfare' objective function and the unserved power in the associated power-flow equations.

3.1 Market simulation model in normal operation

The standard objective for single-auction market settlement is the maximisation of social welfare, which is the total revenue less the total generation costs [16]. Thus to maximise the social welfare implicitly relates to minimising the total generation cost, which has been considered as objective (1) in this market solution

$$J = \sum_{i=1}^{NG} C_i(P_i) \tag{1}$$

where $C(P_i) = aP_i^2 + bP_i + c$, J is the total generation cost, $C_i(P_i)$ is the generator's bid (cost) function submitted to the market operator under the assumption of a perfect market, P is the generator power output, while NG is the number of generators. The function is minimised subject to the following constraints:

(i) *Power flow equations*

$$P_i - PD_i = \sum_j |V_i||V_j|Y_{i,j}\cos(\theta_{i,j} + \delta_j - \delta_i) \tag{2}$$

$$Q_i - QD_i = -\sum_j |V_i||V_j|Y_{i,j}\sin(\theta_{i,j} + \delta_j - \delta_i) \tag{3}$$

where V is the bus voltage, δ is the angle associated with the voltage, $Y_{i,j}$ is the element of the bus admittance matrix, θ is the angle associated with $Y_{i,j}$, P and Q are real and reactive power generation, respectively, PD and QD are real and reactive power demand, respectively.

(ii) *Generator limits*

$$P_i^{Min} \le P_i \le P_i^{Max} \tag{4}$$

$$Q_i^{Min} \le Q_i \le Q_i^{Max} \tag{5}$$

P^{Min}, P^{Max}, Q^{Min} and Q^{Max} are the limits on real and reactive power, respectively.

(iii) *Voltage limits*

$$V_i^{Min} \le V_i \le V_i^{Max} \quad \forall i \in 1, \ldots, NL$$

$$|V_i| = \text{constant} \quad \forall i \in 1, \ldots, NG \tag{6}$$

V^{Min} and V^{Max} are the limits on bus voltage, NL is the number of load buses and NG is the number of generator buses.

(iv) *Uniform market price formulation*

The uniform market price is the highest value of the bus incremental cost obtained by solving the foregoing model. Thus

$$\rho \ge \lambda_i \quad \forall i \in 1, \ldots, N \tag{7}$$

where ρ represents the electricity market price, λ is the incremental cost at a bus and N is the number of buses in the system.

3.2 Market simulated model in islanded operation

The system under intentional islanding has certain issues that are similar to the case of a transmission-line congestion problem. A system is said to be congested when the generators and customers are producing and consuming in amounts that would cause the transmission system to operate beyond its transfer limits. The challenge of congestion management is to set rules that will assure the secure and reliable operation of the power system in both the short and long term while maximising market efficiency. In the price area congestion management scheme, when congestion occurs the market operator or a similar entity declares splitting of the system into price areas. Spot-market participants must submit separate bids for each price area in which they have generation or load. The area with excess generation will have lower prices while the areas with excess load will have higher prices [17].

Similarly, when an intentional island is formed the system is split into two separate price areas. In cases where there is a possibility of excess load on the islanded part, the cost of unserved energy is taken into consideration in the mathematical model for market settlement, described as follows.

The objective function is appropriately modified to include the unserved power P_{un} along with a cost of unserved energy C_{un}.

$$J = \sum_{i=1}^{NG} C_i(P_i) + \sum_{i=1}^{N} C_{un} P_{un}(i) \tag{8}$$

(i) *Intentional islanding constraint*

$$P_{i,j} = 0 \quad \forall i, j \text{ specified buses} \tag{9}$$

This constraint ensures that the power flow on a specified line connecting the transmission system to the distribution system is zero. The island operation of the distribution system is thereby simulated.

(ii) *Uniform market price formulation*

During intentional islanding condition, the system is electrically split into two areas. Consequently the electricity market is also split and we arrive at two different market prices for the two areas, in this situation

$$\rho_{MAIN} \ge \lambda_{MAIN,i} \quad \forall\, i \in NM \tag{10}$$

$$\rho_{ISLAND} \ge \lambda_{ISLAND,i} \quad \forall\, i \in NI \tag{11}$$

where ρ_{MAIN} is the market price on the main system network while ρ_{ISLAND} is the market price on the islanded part of the system, λ_{MAIN} is the incremental cost at buses within the transmission system while λ_{ISLAND} is the incremental cost at buses within the island, NM are the buses on the main system while NI are the buses on the islanded system.

(iii) *Other constraints*

Constraints (2)–(6) are also included in the aforementioned model.

4 Scenarios

The system under study, shown in Fig. 2, consists of a six-bus transmission system with two generating units G_1 and G_2 with capacity of 500 and 250 MVA, respectively. The transmission system is connected to a three-bus distribution system, with two interconnected DG units each of capacity of 30 MVA, through a 100 MVA transformer.

To examine intentional islanding of DG resources and hence its impact on electricity market prices, four scenarios

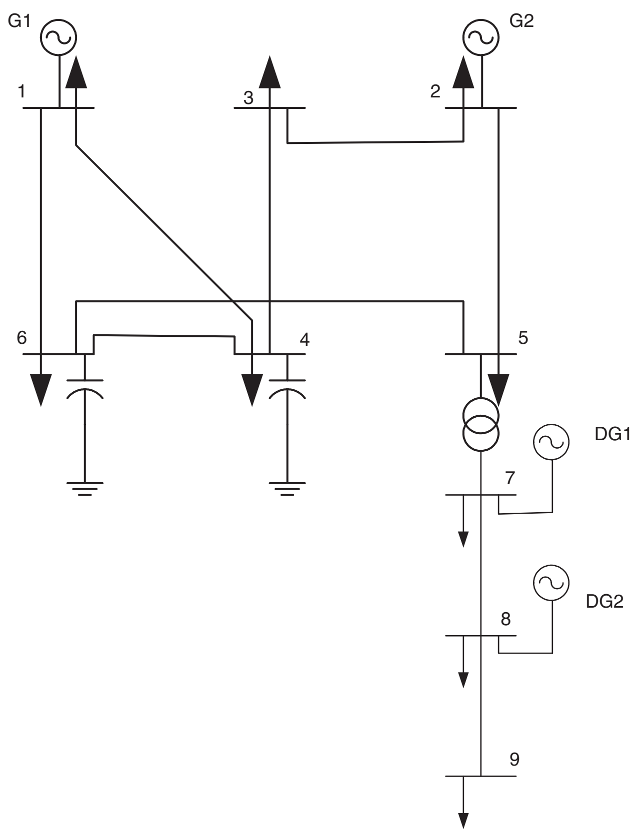

Fig. 2 *System network configuration*

are constructed that represent possible outcomes encountered in an electricity market with DG islanding. Since the current practice is to prevent islanding, one of the scenarios constructed illustrates the effect of islanding prevention on market prices.

4.1 Scenario 1: normal operation

This scenario is the base case where the system is operating normally, without any disturbance or faults occurring. To take into account the variations in power of the loads a load scaling factor was used as shown in Fig. 3. The active power at each bus given in Table 1 in the Appendix (Section 8) is multiplied by the scaling factor at the different time intervals. Since no disturbances were considered, the market simulation model described in Section 3.1 is used (Table 2).

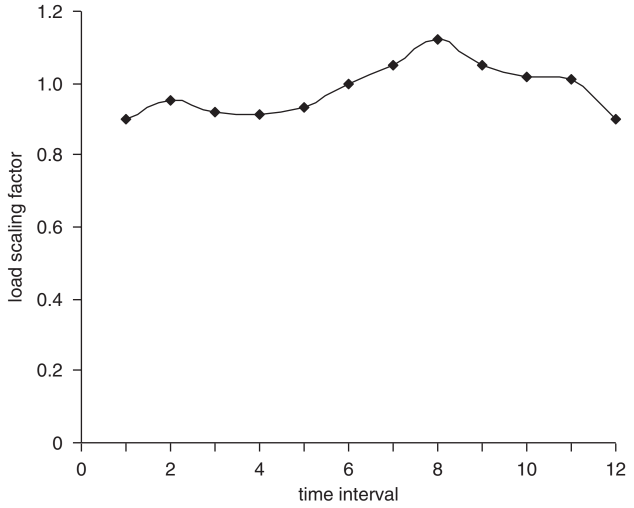

Fig. 3 *Load per unit variation with time*

4.2 Scenario 2: current practice following disturbances

In this scenario a fault occurs between bus-5 and bus-7 in the system (Fig. 2), which leads to a complete blackout of the distribution system. At the instant the fault occurs, all DGs were disconnected, as per the current practice, and the circuit-breaker on the secondary side of the transformer opens, thus preventing the occurrence of islanding.

4.3 Scenario 3: intentional islanding with deficit capacity in islanded system

In this scenario a fault occurs between bus-5 and bus-7 (Fig. 2), thereby splitting the system into two separate parts. The distribution system (with DGs) is intentionally islanded to provide power to customers in the islanded region. However, the total demand in the islanded system is greater than the DG capacity available in the island. To simulate the effect of intentional islanding the market simulation model described in Section 3.2 is used.

4.4 Scenario 4: intentional islanding with surplus capacity in islanded system

This scenario is similar to scenario 3 except that the total DG capacities in the distribution system is greater than the demand. Load curtailment is not required since there is no unserved energy in the islanded system after the fault occurrence, and the island demand is fully supplied by the DGs.

5 Simulation results

This Section presents the simulation results for the problem formulated in Section 3 and the scenarios constructed in Section 4. The market simulation models are nonlinear programming models and are solved using MINOS5.1 in GAMS (general algebraic modelling system) environment [18]. A one-hour time frame, divided into 12 five-minute intervals is used for the simulations. The market prices are obtained every five minutes and this is similar to the Ontario electricity market. The uniform market prices are determined by calculating the incremental cost at each bus and setting the highest bus incremental cost as the market price.

5.1 Scenario 1: normal operation

Figure 4 shows the market-clearing price for normal market operation. It can be observed that the market clearing price varies over time due to its dependence on system demand condition at different time intervals. Figure 5 shows the optimal power generation schedule of the generating units and the DGs. Both DGs are working at a full capacity of 30 MW, the rest of the demand on the distribution system is

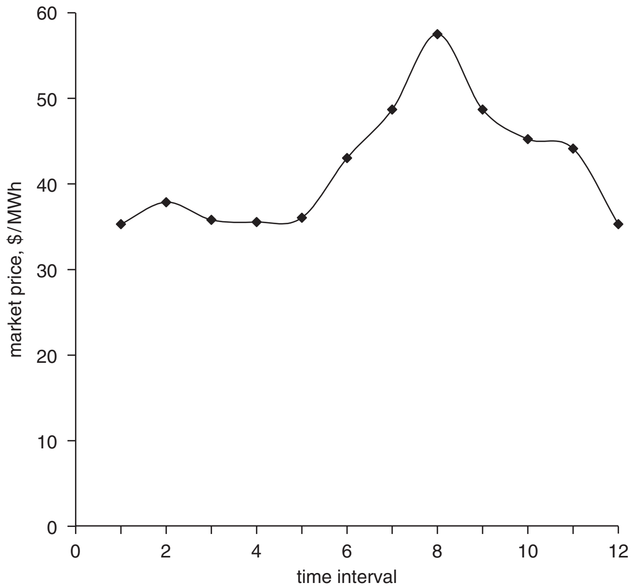

Fig. 4 *Market clearing price for normal market operation*

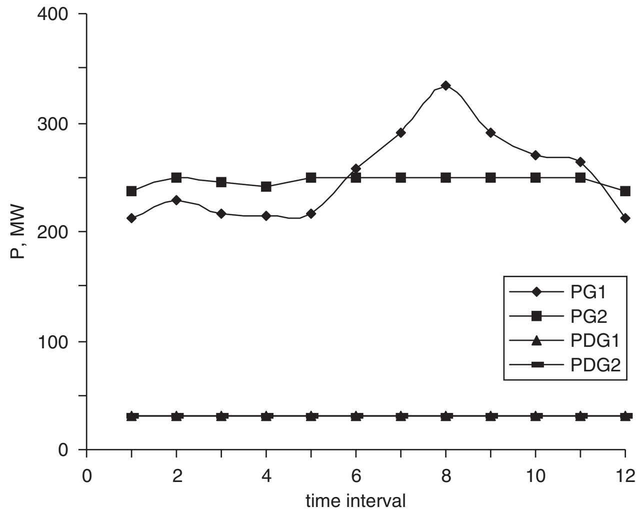

Fig. 5 *Power generation of each generator*
Power generated by both DGs is same (30 MW or 0.3 p.u.) hence PDG1 and PDG2 coincide

being supplied by generators G_1 and G_2. Consequently there is power flowing from the transmission system to the distribution system through the transformer connecting buses 5–7 (Fig. 2).

5.2 Scenario 2: current practice following disturbances

In this case at interval-8 the distribution system and its DGs were disconnected after a fault, thus replicating the current system protection practice that involves prevention of islanding after a disturbance. Figures 6 and 7 show the market clearing prices and the power generated by each generator.

From Fig. 6 we observe that the moment a fault occurs on the system at interval-8, the market price decreases. This is due to the decrease in the demand as a result of disconnection of the distribution system.

Figure 7 shows the generation schedules over the market operation time-frame. The two generators located in the main system G_1 and G_2 continue to operate, though the output level of G_1 is reduced after interval-8 to match the demand. Both DG_1 and DG_2 are shut down at the eighth interval coinciding with the occurrence of the fault.

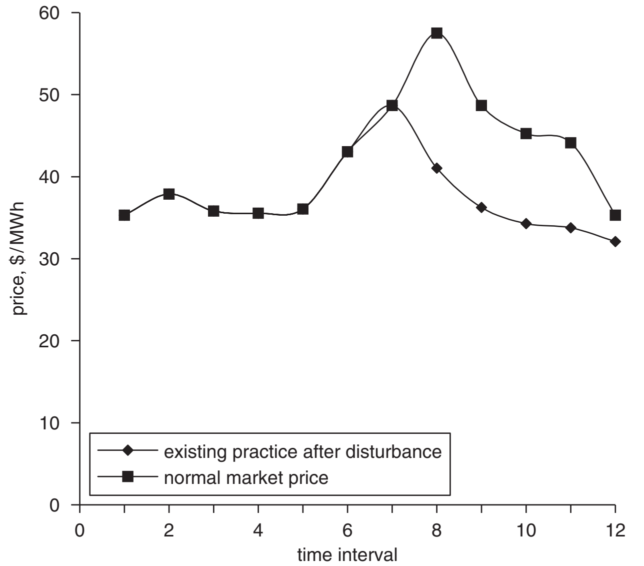

Fig. 6 *Market clearing price without intentional islanding operation compared with normal market price*

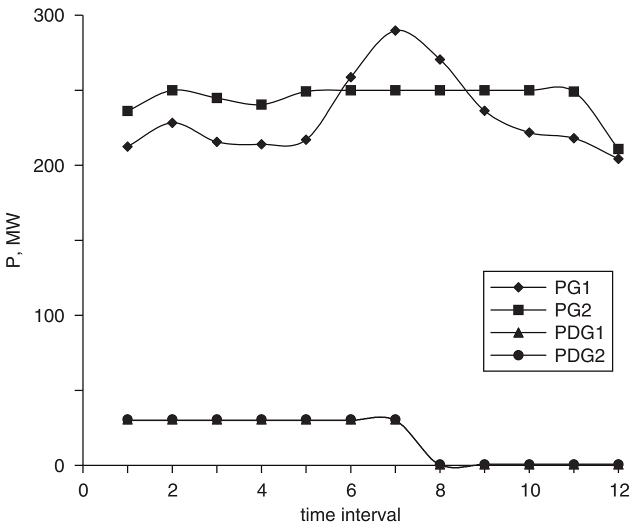

Fig. 7 *Power generation of each generator*

Although this could lead to customers on the transmission side being satisfied as a result of the decrease in market prices during the interruption period, the distribution company could be paying its customers the cost of the unserved power during this interruption period, which can be very high. A solution to this is to implement safe intentional islands during an outage occurrence, which is discussed in the following Section.

5.3 Scenario 3: intentional islanding with deficit capacity in islanded system

So far we examined the market prices for the case of normal operation (scenario-1) and the case when the distribution system was on outage following a disturbance (scenario-2). In the present scenario and in the following, we examine the effect of intentional islanding of the DGs. As previously mentioned, the system is now split into two separate areas, one comprising the main transmission system and generators G_1 and G_2 (referred to as 'main') while the second area comprises the distribution system with the DGs DG_1 and DG_2 (referred to as 'island'). A disturbance has occurred at time interval-8 and the distribution system is isolated from rest of the system due to a fault, but it continues to supply its customers in islanded condition from the DGs. However, since the total DG capacity is 60 MW, there would remain some unserved demand in the island.

We consider the cost of unserved energy as \$16/MWh initially. This is the cost at which the DGs are forced to operate at their maximum capacities. Subsequently we use a significantly higher cost of \$50/MWh to examine the effect of cost of unserved energy on the islanded system market price.

Figures 8 and 9 show the market prices in the two areas over the one-hour market operation time frame, for the two values of the cost of unserved energy, respectively. We observe the following

- The main system price is reduced significantly after interval-8 when the islanding is in effect, as compared with the normal market operation price (scenario-1).
- However, the main system price is the same as obtained in secenario-2 which depicts the current practice after a disturbance. This implies that the main-system price is unaffected by the state of the distribution system after a

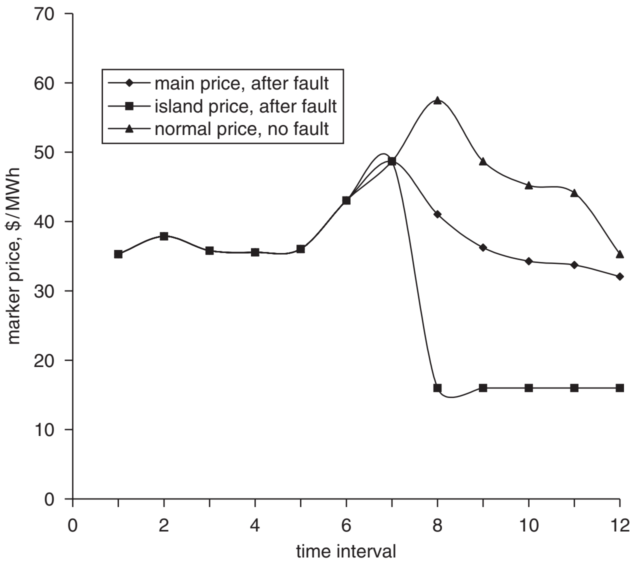

Fig. 8 *Market clearing price with intentional islanding operation and cost of unserved energy of 16 \$/MWh*

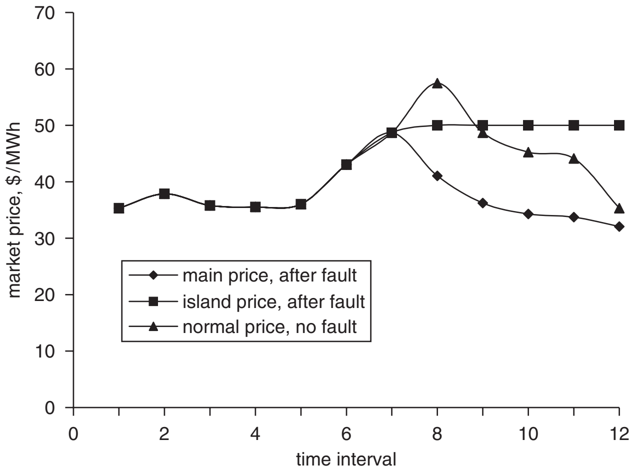

Fig. 9 *Market clearing price with intentional islanding operation and cost of unserved energy of 50 $/MWh*

disturbance, i.e. whether the distribution system is disconnected with DGs shut down, or is operating in island mode with DGs supplying power.

- The main-system price is also unaffected by the cost of unserved energy, as observed in the two cases considering cost of unserved energy to be 16 and \$50/MWh, respectively.
- The island-system price is equal to the cost of unserved energy once the DGs are operating at their full capacities and there is still energy unserved in the island.
- The island-system price is also directly affected by the state of the system after a disturbance. If it is disconnected, all the power is unserved and the distribution company has to pay for the loss of supply. If it is in island operation, with capacity deficit in the island, the island price is equal to the cost of unserved energy considered.

Hence, as we observe from Figs. 8 and 9, the distribution system operator has to judiciously determine the cost of unserved energy. For example, a high valuation of this cost would result in a high market price in the island in case of intentional islanding. On the other hand, an under-valued cost of unserved energy would lead to under-utilisation of the DG capacity.

Assigning a true figure to the cost of unserved energy is an extremely complex problem. It would depend on several factors such as the level of societal development, economy of the region, etc., and on more specific factors such as the interruption duration or system condition.

Figure 10 shows that the two DGs are operating at their maximum capacities and continue supplying a part of the total system demand after the outage. Figure 11 shows the amount of power not served at the three distribution buses (bus 7, 8 and 9) after an outage at interval-8. If the loads on the distribution system were to submit their *willingness-to-pay* bids for uninterruptible service, then the amount of bus-wise unserved power will depend on the offered bids.

To reiterate, DG owners could take advantage of the situation, knowing that there is excess demand in the distribution system, and increase their offer prices. For this reason, choice of the cost of unserved energy is critical for market efficiency. Additionally, firm rules should be set by the utility to prevent market inefficiency.

An effective approach to safe intentional islanding management should encourage demand elasticity. By lowering the consumption of electricity when islanding occurs,

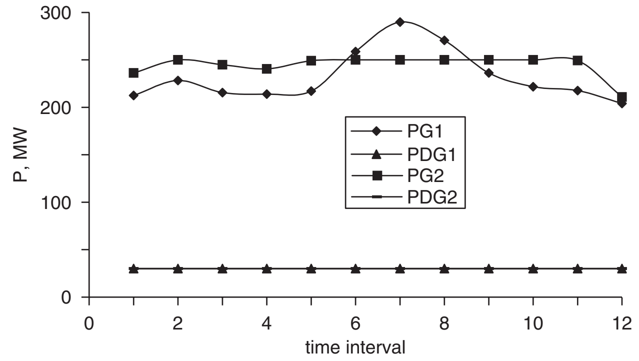

Fig. 10 *Power generation of each generator*

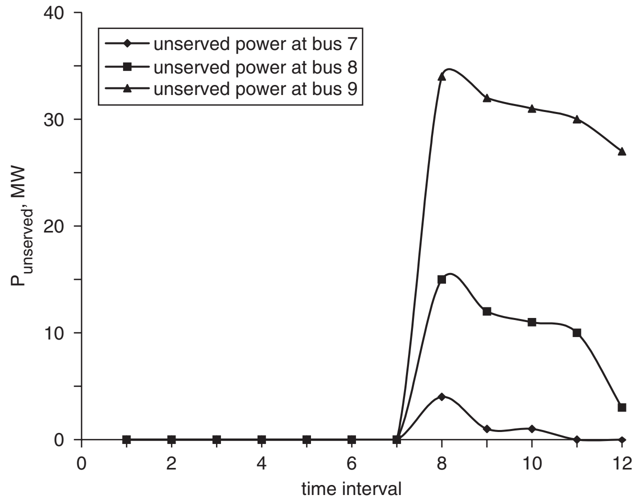

Fig. 11 *Unserved power on each bus in distribution system*

a reduction in market price could be achieved [19]. An elastic load means that a variation in the price causes a variation in the demand. The actions of price responsive loads may be represented in terms of willingness to pay. When a load is elastic, the demand is no longer fixed. Each customer expresses his willingness to pay to a given level of demand and continuity of supply through a bid [20]. As soon as an outage occurs, some of the loads are curtailed depending on the willingness to pay as offered by each load.

The challenge in intentional islanding management is to set rules that will assure the secure and reliable operation of the power system in both the short term and long term while maximising market efficiency. These rules must be robust enough so as to prevent aggressive entities seeking advantage of an islanding situation to create market power and enlarge profits [17]. For example, if a market has only few participants the bid curves could be manipulated to gain additional profits at the expense of society. Such noncompetitive situations can occur when intentional islanding is implemented and power cannot flow into the area, thus participants in this area are isolated from the other competitors [21]. In this case, market power is a real concern.

5.4 Scenario 4: intentional islanding with surplus capacity in islanded system

This case is similar to scenario-3 but now we consider the DGs to have higher capacities, i.e. each of 60 MW. If an outage of the transformer between bus-5 and bus-7 occurs (Fig. 2), the DGs will be capable of supplying the entire distribution system demand when in islanded operating state, and thereby preventing any load curtailment.

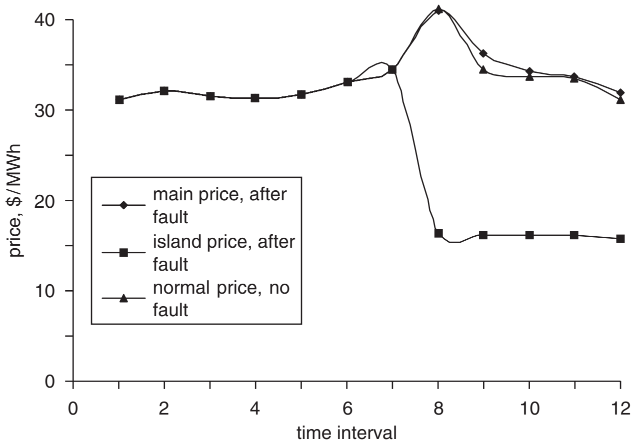

Fig. 12 *Market price with intentional islanding operation and excess generation on island*

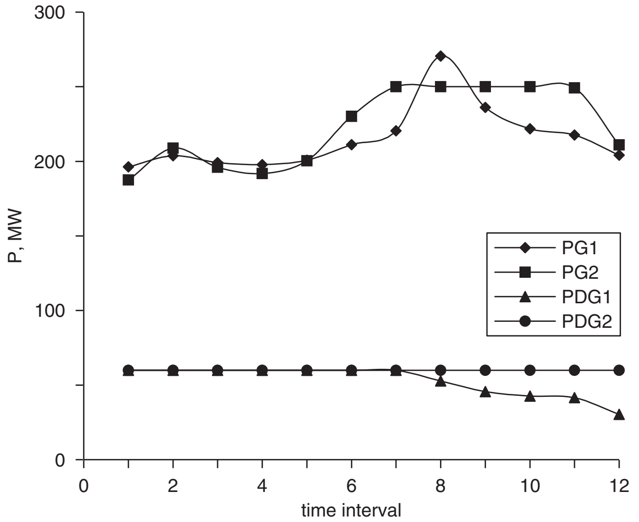

Fig. 13 *Power generated by each generator*

Figures 12 and 13 show the market clearing prices and power generated by each generator.

We observe that once an island occurs each area will have its own market price. Customers on the transmission side experience a slight rise of prices. Customers on the islanded part are satisfied because of the continuity in the supply despite the outage. As previously explained, the only problem is the noncompetitive situation that might occur due to the islanding situation.

6 Conclusions

The paper analyses and examines the effect of implementing intentional islands on electricity market prices. Some of the issues that should be taken into consideration prior to producing intentional islands have been highlighted. Before islanding is considered, certain rules should be set by the system operator so as to ensure the safe operation of the system while maintaining market efficiency. During islanding the system is split and each island will have its own market price. Customers within an island could experience price spikes due to a noncompetitive situation, created because of a monopoly. DG owners could become the sole controllers of the market prices within the island, thus possessing market power. However, since faults are relatively rare in well-operated systems and mostly short-duration events, such price spikes may not arise frequently in the context of a full year's time cycle.

In cases where the generation is less than the load within the island, some of the loads should be curtailed depending on the customer's willingness to pay for the continuity of supply. The system operator should set rules to control the market operation and prevent any participant from possessing market power. With such rules in place, in the event of the occurrence of an intentional island, distribution utilities owning DGs could accomplish more revenue while customers can continue to receive their power supply, even during system faults, at acceptable market prices, thus increasing power system reliability and maximising market efficiency. This function of the DG can also be considered within the purview of system ancillary services where the DG provides reserve generation, reactive power control and frequency regulation services.

The analysis presented is for a typical system and operating conditions and the general findings and conclusions remain valid even for changes to these parameters. Nevertheless, it needs to be stated that in an islanded condition, the island market prices depend on the loading condition and DG capacity available within the area and the "worth" attached to the unserved energy variable.

As markets mature and retail competition penetrates further, the issue of intentional islanding will gain increased attention among system operators, market operators, distribution utilities and the policy makers. As outlined, DG islanding has significant benefits but some issues still need to be addressed such as control and communication protocols particularly with regard to monitoring fault conditions, advance notification of system conditions and market prices *vis-à-vis* DG operation.

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8 Appendix

Table 1: Generation and bus data

Bus	a	b	C	P_{max}	P_{min}	P_d	Q_d	Q_{max}	Q_{min}
1	0.05	8.5	5	5	1	0.73	0.19	3	−0.2
2	0.01	25.5	9	2.5	0.5	0.92	0.29	1.5	−0.2
3	0	0	0	0	0	0.78	0.39	0	0
4	0	0	0	0	0	1.12	0.31	1	0
5	0	0	0	0	0	0.26	0.12	0	0
6	0	0	0	0	0	0.67	0.24	1	0
7	0.005	15	11	0.3	0.1	0.30	0.06	0.3	−0.1
8	0.004	12	5	0.3	0.1	0.40	0.10	0.3	−0.1
9	0	0	0	0	0	0.30	0.06	0	0

Table 2: Transmission line data

From bus to bus	Resistance (p.u)	Reactance (p.u)	Line charging (y/2)(p.u)
1–4	0.0662	0.1804	0.003
1–6	0.0945	0.2987	0.005
2–3	0.021	0.1097	0.004
2–5	0.0824	0.2732	0.004
3–4	0.107	0.3185	0.005
4–6	0.0639	0.1792	0.001
5–6	0.034	0.098	0.004
5–7	0	0.1	0
7–8	0.054	0.082	0
8–9	0.054	0.082	0