A Market Model for Clustered Microgrids Optimisation including Distribution Network Operations

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Abstract–This paper proposes a market model for the purpose of optimisation of clustered but sparse microgrids (MGs). The MGs are connected with the market by distribution networks in for the sake of energy balance, and to overcome emergency situations i.e. overloading or over-generations within the cluster. The developed market structure enables the integration of virtual power plants (VPPs) in energy requirement of MGs. The MGs, internal service providers (ISPs), VPPs and distribution network operator (DNO) are present as distinct entities with individual objective of minimum operational cost. Each MG is assumed to be composed of dispatchable and non-dispatchable distributed energy resources (DERs) with a commitment to service its own loads prior to export. Thus an optimisation problem is formulated with the core objective of minimum cost of operation, reduced network loss and least DNO charges. A novel optimal control strategy is proposed for coordinated operation of MGs. The formulated problem is solved by using heuristic optimization technique of Genetic Algorithm. Case studies are carried out on a distribution system with multiple MGs, ISP and VPPs which illustrates the effectiveness of the proposed market optimisation strategy. The key objective of the proposed market model is to coordinate the operation of MGs with the requirements of the market with the help of the DNO, without decreasing the economic efficiency for the MGs nor the distribution network.

***Index Terms*– Distributed generation, Distribution network operator (DNO), Grid integration, Microgrid (MG), Optimization, Virtual power plant.**

Nomenclature

BSS	Battery storage system
DDER	Dispatchable distributed energy resource
DER	Distributed energy resource
DG	Diesel generator
DNO	Distribution network operator
GST	General sales tax
ISS	Interconnecting static switch
ISP	Internal service providers
MG	Microgrid
MMA	Multi-microgrid area
NDDER	Non-dispatchable distributed energy resource
OF	Objective function
SP	Service provider
SSP	Shared service provider
SMBP	Smart bidding prices
SOC	State of charge
TMG	Troubled microgrid
VPP	Virtual power plant

1. Introduction

1.1. Motivation

Remote area microgrids (MGs) are clusters of distributed energy resources (DERs), loads and battery energy storage systems (BSSs). An MG is considered as intelligent power network with two modes of operation: (a) autonomous mode for fulfilling the local load demand self-sufficiently, and (b) grid-connected mode with the ability to import/export power from/to the utility feeder [1-2]. An MG can be composed of dispatchable DERs (DDERs), like diesel generators (DGs), BSS and non-dispatchable DERs (NDERs), like photovoltaic and wind energy resources.

A modern distribution system may consist of multiple neighbouring MGs and a distribution network operator (DNO) in which each MG and the DNO will act as autonomous entities. In this context, [3] and [4] have highlighted the challenges of the system operation due to variable DERs generation coordination amongst different MGs, and the DNO and MGs, as well as the difficulty in optimal and integrated energy management of both entities.

1.2. Literature Review

It has been suggested in the literature that the coordinated control for energy management in MG clusters and DNO can be considered as a three-level hierarchical system that includes: (a) the primary local area droop-based control of DERs in MGs [5-6], (b) the secondary controller for each MG [7-9], and (c) a tertiary controller for optimal power flow management across the multi-MG remote area system [10-11]. In this hierarchical system, the third level (the main focus of this research) is important from the economic aspect of MG operation.

To realise the above hierarchical control, a communication system is essential to ensure the transfer of data from MGs to DNO, from DNO to market and also the tertiary controller for necessary actions. Ref. [12] and [13] have highlighted the essential features of the required communications system for the implementation of a hierarchical control in MGs. By utilising the communication protocols, it is possible to develop an MG which can operate co-ordinately with a DNO and market participants. For example, Ref. [14] has proposed a multi-agent based optimal energy management of clustered MGs with the integration of different market entities. The coordinated operation of DNO and clustered MGs is achieved by using a hierarchal deterministic optimisation algorithm and without the involvement of the market [15]. In [16], a decentralised Markov decision process is used to solve the optimal control problem of clustered MGs. The main aim was to minimise the cost of operation of all clustered MGs. On the other hand, the technique proposed in [17] allows customers to participate in the demand response within the clustered MG and optimisation was achieved by a multi-agent-based power management control. Similarly, another approach is proposed by [18] to minimise the operation cost of clustered MGs by using a cooperative power dispatching algorithm. The above studies have highlighted the optimal control of clustered MGs by not using all factors at a time. Hence, the solution to the problem of optimal power flow is achieved in the above studies by either of the DNO, market or power-sharing mechanism of neighbouring MGs. This paper is focused on the coordinated management of power in MGs while integrating and coordinating DNO and the market participants. Hence the control is based on achieving the minimum cost of operation by optimising jointly and effectively all options from the MGs, the neighbouring MGs, DNO and market participants.

Many optimisation strategies are used in the literature for coordinating the power exchange amongst MGs, control of the power of conventional generators and load curtailment. For instance, [19] has considered DGs fuel consumption and emission cost, along with power exchange with DNO, in the formulated objective function (OF). On the other hand, [20] discusses the effect of load curtailment in MGs by considering the probabilistic uncertainties of loads, NDERs and sensitivities in nodal power injection. To this end, the cost of load curtailment, as well as the expense/revenue of exchanging power between the MG and DNO, is focused. In these studies, the main objectives are maximising the footprint of renewable energies in supplying the demand and minimising the contribution of conventional generators. However, curtailment of renewable energy resources is not considered which is essential in case of overgeneration that often happens at low demand periods. The voltage rise problem in MGs because of renewable energy-based DERs is solved in [21] by curtailing their output power using droop control. On the other hand, [22] employs an optimisation technique to maximise the lifetime characteristics of BSSs in MGs when compensating the variabilities of loads and renewable sources while minimising the power generation cost of DGs. Alternatively, a bargaining technique is used in [23] to facilitate proactive energy trading and fair benefit sharing among remote area clustered MGs in which the main criterion is minimising the total operational cost. Similarly, [18] applies demand management in remote area MGs using a cooperative power dispatching algorithm for the minimisation of MG's operational cost while satisfying the load demand. Ref. [24] and [25] have formulated an economic dispatch problem, which aims at minimising the power loss on top of the costs of fuel consumption, external power sharing and BSSs.

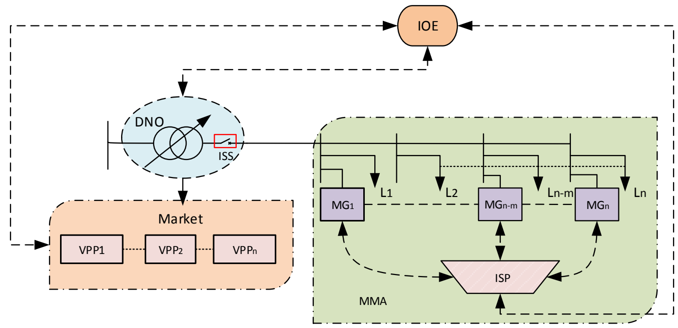


Fig. 1. *Considered large remote MMA.*

In this work, an OF is formulated with the core focus of minimisation of operation cost related to MGs (same as the above-mentioned studies) but with a key difference of considering DNO and market participants in parallel with that. This is the key novelty of the proposed technique in this paper. As such, the proposed technique aims at optimal control of clustered MGs with defined operational and economic objectives in a distribution system, while providing the required basis for MGs to coordinate with market with the help of DNO and without decreasing the economic efficiency for both MGs and distribution network. The formulated optimisation problem is based on a stochastic analysis while the control is modelled as a bi-level optimisation problem. As such, the synergies between the MGs and DNO are directly correlated to resolve the possible power imbalance-initiated emergencies within the remote area MGs.

1.3. Contribution

The main contributions of this study to the research field can be summarised as below:

- Developing a new technique for optimal power flow control of clustered MGs,
- Formulating an OF focusing on minimisation of the operation costs of MGs while considering DNO and market participants in parallel,
- Coordinating the operation of MGs with the requirements of the market with the help of the DNO, without decreasing the economic efficiency for the MGs nor the distribution network
- Directly correlating the synergies between the MGs and DNO in addressing the power imbalance-initiated emergencies within the remote area MGs.

1.4. Paper Organisation

The remainder of the paper is organised as follows: Section 2 presents the main concept of the proposed market optimisation while the mathematical formulation of the problem is introduced in Section 3. This Section also introduces all the considered technical constraints. The performance evaluation of the proposed technique is evaluated through numerical analyses in Section 4. Section 5 summarises and highlights the key findings of this research.

2. Main Concept

Consider a large remote multi-MG area (MMA) consisting of several MGs (see Fig. 1). Every MG is assumed to be composed of multiple DERs (including both DDERs and NDERs), BSSs and loads that are connected through a network of lines. The NDERs are renewable based energy sources (e.g., photovoltaic or wind turbine) with intermittent nature and no power smoothening BSS. They will harvest and inject maximum possible power in market-unavailability mode while their output power is assumed to be curtailable, depending on the command signal received from the MG's secondary controller. On the other hand, each DDER is assumed to have its own local droop-based primary controller, and thus, will be operating in the grid-forming mode when MMA is detached from the market. The market is assumed to be composed of the market operator, termed as virtual power plant (VPP), which will take consent from the MGs to support MMA in power imbalance-initiated emergency situations. The communication between MMA and VPP will take place through the DNO. All MGs are assumed to be coupled through proper interconnecting lines and interconnecting static switches (ISSes) to facilitate exchanging power amongst the neighbouring MGs, termed as shared service providers (SSP), and the VPPs.

Let us define a troubled MG (TMG) as an MG in which an emergency overloading or excessive generation is observed because of an unpredicted power generation-demand imbalance. The secondary controller of the TMG, termed as the internal service provider (ISP) will then take the necessary actions to retain the normal operation of the TMG by sending/receiving power to/from SSP(s). If the ISP is successful in handling the TMG's emergency situation, the tertiary controller will not take any action. However, if the ISP fails to overcome the emergency situation, then the tertiary controller will take action and will negotiate an open access charge with the DNO. The tertiary controller is assumed as the internet of energy (IOE) with the ability to transfer the data over the DNO network. Therefore the proposed optimisation technique at the tertiary control aims to resolve the problem at the lowest cost. The basic purpose is to consider the market to attain the maximum benefit. To this end, an optimisation problem is formulated and solved, as described in the following Section. The proposed optimisation technique will proceed in the sequence of steps as:

- Droop control or/and BSS control will be applied with the help of MG's local primary controllers,
- Coupling among neighbouring MGs will take place,
- Power transaction with VPP(s) will take place,
- Load-shedding or NDERs curtailment will take place in TMG(s), as a last resort.

Hence, if the emergency situation is not resolved by the first step, then the proposed optimisation technique will go to the next step, and so on. But the cost will increase proportionally with each step. Thus, the focus is to look for the most optimal

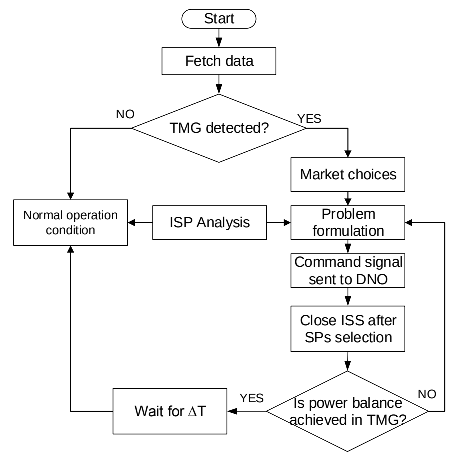
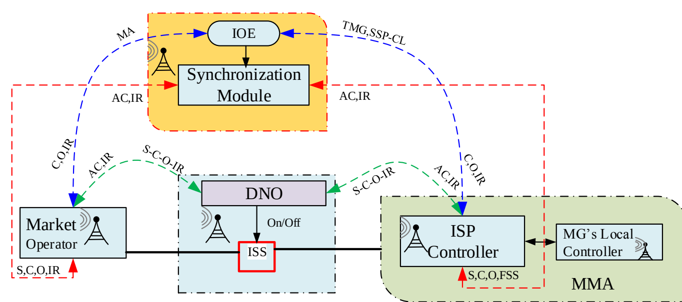


Fig. 2. *Flowchart of the proposed technique.*



S-Synchronize, C-Close, O-Open, AC- Action Complete, IR-Information received , CL-Contribution level, MA-Market availability, FSS- Feasible solution sent

Fig. 3. *Communication enabling functions for the proposed market model.*

solution by considering all the possibilities. Once a TMG is detected and found within the MMA, the tertiary controller will look for the most optimal combination of service providers (SPs) using the formulate market optimisation problem. Therefore, the corresponding DNO will respond and send a command to close the ISS between the determined neighbouring MGs, based on the command received from the tertiary controller. In this way, the power imbalance issue of the TMG will be addressed. If not, then the optimisation algorithm will again formulate market optimisation problem until a feasible solution is achieved. Fig. 2 demonstrates the flowchart for the proposed technique.

The assumed communication protocols needed for the transmission of information among all controllers is also depicted in Fig. 3.

3. Problem Formulation

The IOE optimisation is formulated as

$$OF = \min \Bigg[k_1 \sum_{MG_1}^{MG_N} OF_{ISP} + k_2 \sum_{ESP_1}^{ESP_N} OF_{VPP} + k_3 \sum_{IOEP_1}^{IOEP_N} \sum_{SSP_1}^{SSP_N} \sum_{State=1}^{n} OF_{DNO} \Bigg] \times \Delta T \quad (1)$$

and shows that the main objective for optimal choice selection from IOE depends on three factors of (a) the operational cost of ISP (OF_{ISP}), (b) the cost of support to/from VPP (OF_{VPP}), and

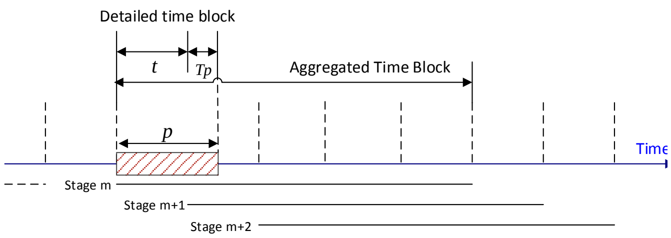


Fig. 4. *Pictorial representation of rolling-horizon approach for ISP.*

(c) the operational cost of the DNO (OF_{DNO}). k_1, k_2 and k_3 in (1) are the weightings assigned to each OF such that $\sum_{i=1}^{3} K_i = 1$, and ΔT is the period within which the IOE will re-evaluate the MMA condition. These OFs are discussed in details below.

3.1. ISP Operation

A. *ISP Operation*

For ISP OF formulation, rolling horizon optimization approach [27] is used (see Fig .4.).Therefore (t+T_p) is the total time considered for optimization window of ISP where T_p is the time taken by ISP to implement necessary changes according to IOE optimization decision. Scenarios *i* and *p* are related to rolling horizon time *t* and T_p respectively. The operation of ISP is assumed as a

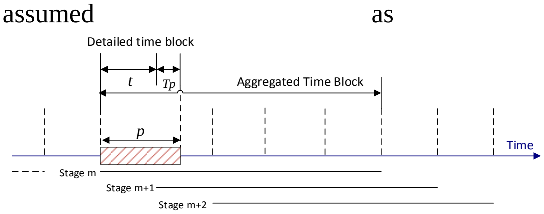


Fig .4. Pictorial representation of rolling-horizon approach for ISP

bi-level stochastic process [28] so decision variables are divided into two groups. At first, actual realization of supply and demand is done using power flow analysis based on modified guass-siedel iterative technique [29]. Once the uncertain scenarios have unfolded, further operational adjustments can made according to IOE decision. Hence, the OF for ISP is the combination of sum of operational costs of TMG both in emergency *(i)* and adjustment of emergency *(p)* scenarios as under:

$$OF_{ISP} = min \sum_{TMG=1}^{N} \left(\sum_i Cost_t^{S1} + \sum_p Cost_{T_p}^{S2} \right) \quad (2)$$

$$\forall \text{ ISP} \in \text{MMA}$$

where

$$\sum_i Cost_t^{S1} = \sum_t \Bigg(\sum_i C^{DG} P_{i,t,n}^{DG} + \sum_i C^{emi} \partial_i P_{i,t,n}^{DG} + C_{inturruption}^{NDERs,load} P_{i,t,n}^{load,NDERs} + C_{lifeloss}^{BSS} P_{i,t,n}^{BSS} + \left(C_{SSP}^{imp} \alpha_{j,t}^{imp} - C_{SSP}^{expo} \beta_{j,t}^{expo} \right) \Bigg) \quad (2a)$$

$$\sum_p Cost_{T_p}^{S2} = \sum_{T_p} \Bigg(\Bigg(\gamma_{p,DG,n} \sum_p (C_{i,p,T_p,}^{adj} + \Delta\partial_i C_{emi,p,T_p}^{adj}) \Delta P_{i,p,T_p,n}^{DG} \Bigg) + \gamma_{p,BSS} C^{BSS} \Delta P_{i,t,T_p,n}^{BSS} + \gamma_{\gamma_{p,load/NDERs}}^{curtailment} + \gamma_{p,IOEP} \left(C_{IEOP}^{imp} \alpha_{j,T_p}^{imp} - C_{IEOP}^{expo} \beta_{j,T_p}^{expo} \right) \Bigg) \quad (2b)$$

s.t.

$$P_{SSP} = \alpha_{j,t}^{SSP} - \beta_{j,t}^{SSP} \quad , \quad \alpha, \beta = \begin{cases} 0 \\ 1 \end{cases} \, , \forall i \in t \quad (3)$$

$$SOC_{k,i,min} \leq SOC_{k,i} \leq SOC_{k,i,max}, \forall \, k, i \in t \quad (4)$$

$$SOC_{k,i,t} = SOC + \int \frac{P_{BSS,rate} P_{BSS\,i,t}}{V_{dc} I_{dc,rate} C_{BSS,rate}} dt, \forall \, k, i \in t \quad (5)$$

$$-P_{BSS,k,i}^{Ch,max} \gamma_{k,i,t} \leq P_{BSS,k,i} \leq P_{BSS,k,i}^{dch,max} \lambda_{k,i,t}, \forall \, k, i \in t \quad (6)$$

$$\gamma_{k,i,t} + \lambda_{k,i,t} \leq 1 \, , \qquad \forall \, i, k \in t \quad (7)$$

$$P_{i,t} = \sum_{i=1}^{N} |V_I| \, |V_l| (G_{Il} Cos\emptyset_{Il} + B_{Il} Sin\emptyset_{Il}) \, , \forall I, l \in t \quad (8)$$

$$Q_{i,t} = \sum_{i=1}^{N} |V_I| \, |V_l| (G_{Il} Cos\emptyset_{Il} + B_{Il} Sin\emptyset_{Il}) \, , \forall I, l \in t \quad (9)$$

$$\emptyset_{Il} = \delta_I - \delta_l \quad (10)$$

$$1 - \varepsilon \leq V_{i,t} \leq 1 + \varepsilon \, , \forall i \in t \quad (11)$$

$$P_{i,t}^{exp.out} \leq P_{i,t}^{DG} + \sigma_{k,t} P_{k,t}^{BSS} - P_{i,t}^{loss} + \sum_{i,n,t} P_{i,t}^{NDERs} \, , \forall i \in t \quad (12)$$

$$Q_{i,t}^{exp.out} \leq Q_{i,t}^{DG} + \sum_{i,n,t} Q_{i,t}^{NDERs} \, , \forall i \in t \quad (13)$$

$$P_{i,t}^{DG} + P_{k,t}^{BSS} + \sum_{i,n,t} P_{i,t}^{NDERs} \leq \sum_{i,t} P_{i,t}^{load} \, , \forall i \in t \quad (14)$$

$$P_{i,l,t}^{loss,min} mp_{i,l,t} \leq \sum_{i=1}^{N} P_{i,l,t}^{loss} \leq P_{i,l,t}^{loss,max}, mp_{i,l,t} \geq 0, \forall i \in t \quad (15)$$

$$C_{p,T_p}^{\gamma_p} \geq (C^{DG} + C^{emi} + C^{imp} + C^{exp}), \forall i \in t, p \in T_p \quad (16)$$

$$\Delta P_{IOEP} = \Delta\alpha_{j,T_p}^{IOEP} - \Delta\beta_{j,T_p}^{IOEP} \quad , \quad \Delta\alpha \geq 0, \Delta\beta = 0, \forall p \in T_p \tag{17}$$

$$SOC_{k,p,min} \leq SOC_{k,i} + \Delta SOC_{k,T_p} \leq SOC_{k,p,max}, \forall\, k,p \in T_p \tag{18}$$

$$SOC_{k,p,T_p} = SOC + \Delta SOC_{k,p,T_p} + \int \frac{P_{BSS,rate}\Delta P_{BSS_{i,p}}}{V_{dc}I_{dc,rate}C_{BSS,rate}}dt, \quad \forall\, k,p \in T_p \tag{19}$$

$$-P_{BSS,k,p}^{ch,max}\gamma_{k,p,T_p} \leq P_{BSS,k,p,T_p} + \Delta P_{BSS,k,p,T_p} \leq P_{BSS,k,i}^{dch,max}\lambda_{k,p,T_p} \quad \forall\, k,p \in T_p \tag{20}$$

$$\gamma_{k,p,T_p}^{adj} + \lambda_{k,p,T_p}^{adj} \leq 1, \quad \forall\, k,p \in T_p \tag{21}$$

$$\Delta P_{i,p,T_p} = \sum_{i=1}^{N} |\Delta V_I|\,|\Delta V_l| G_{Il}\mathrm{Cos}(\emptyset_{Il} + \Delta\emptyset_{Il}) + B_{Il}Sin(\emptyset_{Il} + \Delta\emptyset_{Il}), \forall I,l \in T_p \tag{22}$$

$$\Delta Q_{i,p,T_p} = \sum_{i=1}^{N} |\Delta V_I|\,|\Delta V_l| G_{Il}\mathrm{Cos}(\emptyset_{Il} + \Delta\emptyset_{Il}) + B_{Il}Sin(\emptyset_{Il} + \Delta\emptyset_{Il}), \forall I,l \in T_p \tag{23}$$

$$\Delta\emptyset_{Il} = \Delta\delta_I - \Delta\delta_l \tag{24}$$

$$1 - \varepsilon \leq V_{i,t} + \Delta V_{p,T_p} \leq 1 + \varepsilon, \forall i \in T_p \tag{25}$$

$$\Delta P_{i,p,T_p}^{exp.out} = \Delta P_{i,p,T_p}^{DG} + \sigma_{k,T_p}\Delta P_{k,p,T_p}^{BSS} - P_{i,p,T_p}^{loss} + \sum_{i,n,T_p} P_{i,t}^{NDERs}, \forall i,p \in T_p \tag{26}$$

$$\Delta Q_{i,p,T_p}^{exp.out} = \Delta Q_{i,p,T_p}^{DG} + \sum_{i,n,T_p} Q_{i,t}^{NDERs} \quad , \forall i,p \in T_p \tag{27}$$

$$\Delta P_{i,p,T_p}^{DG} + \Delta P_{k,T_p}^{BSS} + \sum_{i,n,T_p} \Delta P_{i,p,T_p}^{NDERs} < \sum_{i,T_p} \Delta P_{i,p,T_p}^{load}, \forall i,p \in T_p \tag{28}$$

$$P_{i,l,T_p}^{loss,min} mp_{i,l,T_p} \leq \sum_{i=1}^{N} P_{i,l,T_p}^{loss} \leq P_{i,l,T_p}^{loss,max}, mp_{i,l,T_p} \geq 0, \forall i \in T_p \tag{29}$$

Equation (2) is the desired OF for ISP operation and it consists of two parts: first is related with cost analysis of TMGs during emergency condition, while second part describes the adjustments of operational costs proposed from IOE optimal solution. For scenario i, VPPs cannot be included in the optimization horizon. It typically relates with the demand/supply analysis of TMG(s). Eq (2a) is associated with level one of bi-level stochastic programming in which ISP will describe the demand supply situation of TMGs and possible SSP(s) contributions to overcome power deficiency situation. ISP will make demand/supply analysis at this stage and cost analysis will show existing economics of TMGs. Part two i.e. Eq (2b) is related with second level of bi level stochastic program. Part two describes the adjustments of operation cost to overcome the emergency situation after IOE optimal analysis which is described in the coming section of this paper. Cost of import/export power from VPPs is also included in the predictive horizon. This decision directly effects on the connect/disconnect condition of ISS. The first item in (2a) represents generation cost of all DGs present in the TMGs. Second item is the estimated cost of diesel generator emissions. NDERs (WT, PV) and BSS have zero fuel cost but cost due to unpredictable changes in the output of NDERs and load is included here. Fourth and fifth item represents BSS life loss cost, and import/export energy cost among SSPs respectively. After IOE optimization solution, adjustment of costs described in (2a) is needed. These adjustment costs not only play role in demand management but also give idea that V/f controls are achieved or not. For example if demand management is not possible by SSPs adjustment as shown in (2a) then request will be sent to ISP. The proposed control action between ISP and MMA-MGs is based on master-slave control strategy. DG or BSS inside TMGs, which are adopting constant V/f control can serve as the master control unit [30]. All other DGs will adopts P/Q control for certain active and reactive power output. They provide reference voltage locally in MGs. It is obvious that frequency adjustment is not needed if MMA is working in connection with VPPs. Moreover for connect/disconnect purpose of ISS it is assumed that only low bandwidth communications are needed to control the MG power flow and synchronization with ESPs (see Fig .2.). There are two possibilities in this situation: 1) importing energy from SPs or 2) exporting energy to the SPs. Hence fourth item of objective function represents adjustment cost for import/export power between VPPs and ISP with the intermediate connection of IOE.

Constraint (3) represents power exchange between SSPs. As it is assumed that during level one of bi level stochastic programming, VPPs cannot participate in the planning horizon because of V/f control so parameters (α, β) are set equal to 0 or 1. It means TMG can or cannot import/export power from/to a certain SSP. Constraint (4) represents state of charge (SOC) limits for BSS. Constraint (5) is related to SOC value available in existing in time t. Constraint (6) represents charge/discharge limit for BSS. Constraint (7) shows that charging and discharging of BSS cannot take place at the same time, means either γ or λ will be equal to zero during operation of the network. Constraint (8-9) are power flow equations of network. Constraint (10) is the difference in voltage angle between two nodes of distribution system. Constraint (11) represents that voltage deviation at each bus of system will have voltage deviation within permissible limits. ε is a constant applied to guarantee the voltage deviation. Its value can be set between 0.05 to 0.08. Constraint (12-13) are expected active/reactive power output from TMG following first level of stochastic programming. Active power losses which is substantial issue in distribution system are also included in equation (14). Constraint (15) shows that at first stage load can or cannot be equal to generation from DGs. Constraint (16) shows the permissible limit of system losses so that power factor cannot drop to minimum range. Constraint (17) assumes that cost of adjustment for second level can be equal or greater than first level cost of operation.

Constraints (17-29) represents the adjustment scenarios applied for overcoming emergency situation. p is chosen as the probability and T_p is the time in which adjustment take place. It is to be noted over here that i is also included in some constraints because total time of optimization window is $(t{+}T_p)$, therefore some constraints can be effected by stage one variables also.

Constraint (18) represents adjustment of power needed from upstream network following P/Q control. Due to power emergency in TMG(s), power transaction will be carried out. Therefore import/export parameters are set as $\Delta\alpha \geq 0, \Delta\beta \geq 0$. Constraint (19-22) represents adjustments of BSS second stage variables i.e. $\Delta SOC, \Delta P_{BSS}$. Constraint (23-24) are power flow equations representation for scenario p with adjustment variables $\Delta P_{i,p,T_p}, \Delta Q_{i,p,T_p}$ and $\Delta\emptyset_{Il}$ respectively. Constraint (25) guarantee that voltage at each bus of the network will not deviate from its permissible limits when supply adjustment take place. Variable $\Delta V_{p,T_p}$ is the voltage adjustment variable. Constraint (26-27) are expected active/reactive power output after second stage of stochastic programming.$\Delta P^{DG}_{i,p,T_p}/\Delta Q^{DG}_{i,p,T_p}, \Delta P^{BSS}_{k,p,T_p}$ are adjustments in active/reactive powers of MCU operators. Constraint (28) guarantees that DGs generation is still less than load demand as V/f control was failed at first level so ESP power import is needed. Constraint (29) shows the permissible limit of system losses after adjustments for power factor correction.

3.2. Market Model

The main idea of restructuring the electricity market is to gain maximum benefit for the buyers by making an environment of competition. In the proposed strategy it is assumed that more than one energy import choices are available in the form of VPPs. Three entities mainly participates in the market model. These are 1) ISP on behalf of MMA as buyer 2) VPPs as sellers 3) DNO as the choice provider for most economical solution. Static monopsony exploitation model exists in case of one buyer and many sellers, so arguably buyer can exploit the sellers by setting low prices for gaining profit. Two main types of contracts are available in such situation i.e. the day-ahead market and hour-ahead mechanism [30]. So in both methods the availability of generation mix, trades and bids are determined on per day or per hour basis respectively. Each VPP will compete to sell electricity to MMA and in the result, price will typically decreases as every service provider tries to underbid each other. It is also assumed that one or multiple VPP(s) can be chosen as qualifier bidders if one seller could not meet the necessary requirement. Hence the overall objective function for VPP can be defined as

$$OF_{VPP} = OF_{Trans.Access} + OF_{EEL} \qquad (30)$$

in which the first part of (30) relates to the minimisation of VPP pricing for providing transmission access to DNO in emergency situation and defined as

$$OF_{Trans.Access} = P^{imp/expo} \times time \times NAI \times Cost^{energy} \qquad (31)$$

where $P^{imp/expo}$ is the required power transaction for TMG, $time$ describes how long the transaction will take place, NAI is the network availability index and it is defined as

$$NAI = capacity^{line} \times load\ factor \qquad (32)$$

Now if $load\ factor > 1$ then cost will remain as base charge/kW but if $load\ factor < 1$ then DNO will charge the highest pricing cost. The last part of (31) relates to cost of energy transfer in $/kWh.

For the second part of (30), let us assume that P is the VPPs bidding price and B is the economic benefit of ISP by using monopoly price, R is the total revenue which increases with increase in *B*. The main objective is to choose B such that profit Pr would be maximised and given by

$$Pr(L) = R(B) - P(B).B \qquad (33)$$

Suppose at the maximum profit $Pr'(B) = 0$, so for the purpose of maximisation

$$0 = R'(B) - P'(B).B - P(B) \qquad (34)$$

where $\omega'(B)$ is the derivative of the function $P(B)$, rearranging (40) gives

$$R'(B) = P'(B).B + P(B) \qquad (35)$$

Now left hand side of (35) is the marginal revenue (MR) produced for MMA in case of extra P generated due to increased *B*, and right hand side is the marginal cost of electricity from VPPs due to extra cost requested from ISP in case of emergency situation. So the marginal cost will be higher than the supplied bidding cost from ESPs. The economic cost curves for market model is shown in Fig. 5. The grey triangle describes competitive social surplus i.e. benefit for both consumer and supplier [31] and triangle ACM highlighted in yellow color is the deadweight loss (DWL) or allocative inefficiency i.e. it is the loss of economic efficiency and described as

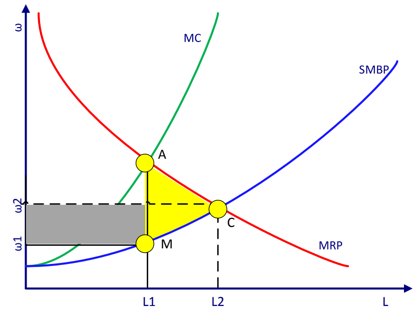


Fig. 5. *Overview of economic cost curves for market model.*

$$DWL = DWL^{VPP} + DWL^{ISP} \qquad (36)$$

where

$$DWL^{VPP} = Cost^{ISP}_{monopoly} \qquad (37)$$

$$DWL^{ISP} = Cost^{SMBP} + Cost^{GST} + Cost^{supply} \qquad (38)$$

DWL composed of two parts: The first part (34) describes that due to monopsony ISP can take advantage of monopoly pricing and this causes economic efficiency loss for VPPs. The second part (35) relates to the environment of competition in which each provider tries to be a qualifier bidder which causes DWL on VPPs side but on the other hand this will result in overall increase of $R(L)$ for MMA. Hence, the cost of electricity bidding prices provided by VPPs are assumed to be smart bidding prices (SMBP) but of course due to monopsony it will be bounded by the conditions of *R(L)*. The main aim of SMBP is to encourage the MMA customers to shift their usage of electricity to off-peak hours by offering reasonably low prices as compared to peak load hours. Second and third costs in (38) are general sales tax (GST) cost on overall consumption and electricity supply cost (both are the costs applied irrespective of the usage of electricity and taken as the excess burden and should be paid by ISP on the total import power from ESPs). Idea of timing of the days and corresponding estimated costs for SMBP is taken from Synergy

Western Australia [32] and are shown in Appendix. To this end, OF for economic efficiency loss can be formulated as

$$OF_{EEL} = P^{VPP} DWL^{VPP} + P^{ISP} DWL^{ISP} \quad (39)$$

s.t.

$$\sum_{ESPs} MC > \sum_{ESPs} SC \quad (40)$$

$$SMBP = \begin{cases} P_{min}, & if\ P_{min} \geq P(B) \\ P(B), & if\ P_{min} \leq P(B) \end{cases} \quad (41)$$

$$e = \frac{R'(P) - P}{P} \quad (42)$$

$$EBP \leq (\omega_{VPP} + \omega_{sup.cost}) \times \%\ GST \quad (43)$$

Constraint (40) is for economic cost curves of SPs and (41) is the relationship between SMBP and MMA monopoly pricing to maximise (B). Now as all VPPs are under state of competition therefore rate of exploitation will be equal to zero i.e. $e = 0$ in (42). Total electricity bidding price will be the combination of VPPs bidding price, supply charges and tax on total cost as described in (43).

3.3. DNO Operation

The third part of (1) is related with the operation of DNO to connect the selected TMG(s) with SPs by using ISS

$$OF_{DNO} = P^{line\ loss} \times Cost^{switchable\ lines} \quad (44)$$

s.t.

$$\sum_{state=1}^{n} ISS_{operation} \leq T_x \quad (45)$$

$$\forall\ \text{ISS} = 1,2, \dots, \text{n}\ \&\ \ T_x = T_{x_1} + T_{x_2} + T_{x_3}$$

The basic operation of DNO is to determine the available SPs and their respective distance from TMG(s) to calculate line losses along with cost of switching between SPs transmission lines as shown in (41). In (45), the main function of ISS is to automatically shift between SPs connected and intentional islanding operation modes. The cost of ISS can be based on the opening, closing and re-closing states. For this purpose a multi-agent based control method is assumed for ISS operation [33] as shown in Fig. 2. Thus, the operational stages of ISS can be divided into three states i.e. 1) closing ISS after getting signal from IOE 2) energy transaction duration 3) ISS opening after power/supply balance achieved in TMGs. So the total operational time for ISS will be the addition of three states such that if $T_{x_1} = x$ seconds, then $T_{x_2} = x \times 60\ minutes$, and $T_{x_3} = 2x$ seconds respectively.

4. Performance Evaluation

The performance of the proposed market model is evaluated by applying it on both small scale and large scale MG based system. The formulated market optimization problem is assessed by performing exhaustive simulations in Matlab. As an example of small scale, a network consisting of three MGs and two VPPs is assumed as shown in Fig .6. The assumed data for the transmission lines in the considered network and the respective distance of each MG and VPP from DNO is explained in Fig .6. It is to be noted over here that communication lines are not shown in the shown network but the protocols are same as previously describes in Fig .2. The MGs assumed to have same topology within themselves. Although in reality it is not possible but this assumption is made for the sake of complexity reduction and simplicity. Impedance data for MGs internal structure is taken from [29]. The nominal capacities of DERs existing inside MGs are shown in Table A of Appendix B while all costs data used in simulations is shown in Table 1. The maximum and minimum ranges of technical impacts of voltage and frequency of each MG in islanded mode are depicted in Fig .7a and 7b respectively. Genetic Algorithm is the solver utilised here for finding the best feasible solution for the market optimisation of the assumed network. The analysis is done for total 150 iterations. In each iteration, first a population is initialised with multiple chromosomes which includes the droop set points of DDERs and NDERs in MGs, BSS state of operation, power exchange with SSPs, the power export/import to/from VPPs and transmission lines power loss.

Secondly OF in (1) is calculated for optimal solution along with constraints application as previously shown in Section III of this paper to realise the evaluation criteria. Once the parent solution pool is formed by the selection procedure, then the off springs are created by the recombination process. The top scaling, heuristic cross-over and adaptive feasible mutation are used as Genetic Algorithm operators. Finally the developed market optimisation technique will continues until the minimum desired cost is achieved for the considered MGs cluster to overcome the emergency situation. The Pseudo code of optimisation algorithm is shown here.

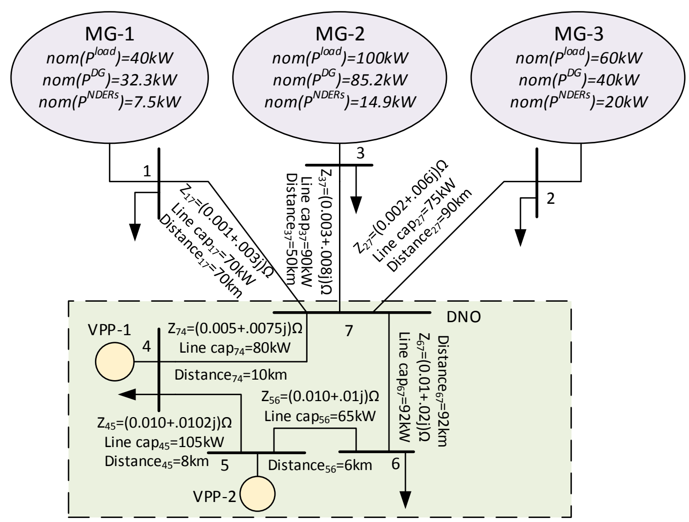
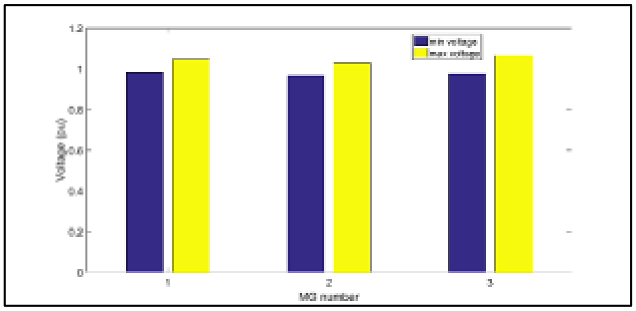
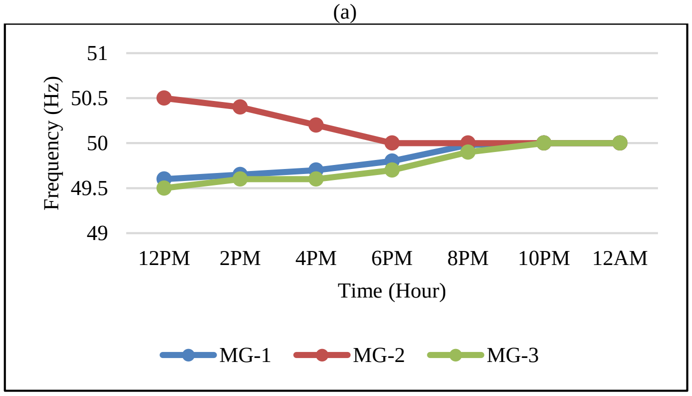


Fig. 6. *Considered network topology along with line impedances and respective distance of each line from central position of DNO for small scale study.*



(a)



(b)

Fig. 7. *(a) Highest and lowest voltage levels of each MG in MMA (b) Sample of frequency for each MG.*

Table 1 Assumed cost data for numerical analysis.

Cost data for DERs of MGs used in ISP operation			
C^{DG}	0.1$/kWh	C_{DG}^{adj}	0.15$/kWh
C^{emi}	0.02$/kg	C_{emi}^{adj}	0.025$/kg
$C_{inturruption}^{NDERs,load}$	0.3$/kWh	∂	0.003kg/kWh
$C_{lifeloss}^{BSS}$	10$/kWh	$C_{inturruption}^{adj}$	0.35$/kWh
Cost data for market model analysis			
Electricity price offered by MGs in MMA network			
MG-1 = 0.52$/kWh , MG-2 = 0.49$/kWh , MG-3 = 0.45$/KWh			
$Cost^{energy}$= 0.75$/kWh			
SMBP offered by VPPs			
VPP-1		VPP-2	
$\omega_{VPP1.sup}$	0.3$/h	$\omega_{VPP2.sup}$	0.32$/h
$\omega_{VPP1.AMGs}$	0.15$/h	$\omega_{VPP2.AMGs}$	0.17$/h
ω_{x11}	0.52$/kWh	ω_{x21}	0.37$/kWh
ω_{x12}	0.26$/kWh	ω_{x22}	0.15$/kWh
ω_{x13}	0.21$/kWh	ω_{x23}	0.18$/kWh
ω_{x14}	0.13$/kWh	ω_{x24}	0.1$/kWh
Technical permissible limits			
$f^{nom} = 50$ Hz; $f^{min} = 49.5$ Hz; $f^{max} = 50.5$ Hz			
$V^{nom} = 1$pu; $V^{min} = 0.975$ pu; $V^{max} = 1.075$ pu			
Cost data for DNO operation			
$Cost^{switchable\ lines}$= 2$			

ISS operational states with respective costs				
State	Closing	Operation	Opening	Re-closing
Time (includes DNO request)	$T_{x_1} = 2 - 3sec$	T_{x_2}= 40-60 min	$T_{x_3} = 4 - 6\ sec$	If needed then 3-7 sec after DNO request
$Cost^{SL}$	0.1$	0.8$ for 1 hr and 0.5$ for every extra hour requested	0.1 $	0.3$

Algorithm: The Genetic Algorithm Solver for market optimization technique.

1. *for* MG-1 to MG-N
2. Define the output of secondary controller based on DERs set-points ;
3. Declare the MG(s) as a TMG;
4. Define the minimum and maximum bounds for NDERs/loads curtailment, DGs, BSSs and power transaction for each MG in MMA;
5. end
6. Initialize Genetic algorithm parameters (initial population, individual fitness evaluation, selection and recombination)
7. Generate initial population with all selected control variables and constraints along with crossover and mutation probabilities;
8. Define optimization stopping criteria;
9. *while* iterations <= Iteration ^{maximum}
10. *for* function tolerance =< 1e-6 and ΔT <= t (sec)
11. Define number of SPs and the MG(s) which are not participating as SSP;
12. Recognize the MG(s) isolated from cluster as due to emergency condition ;
13. Call modified Gauss–Seidel-based power flow analysis function [29] ;
14. Identify the DDERs, BSS and NDERs outputs, load demand, SoC of BSSs, frequency and voltage deviation for MG(s) in MMA and TMG(s);
15. Calculate cost of DG, cost of emissions, BSSs life loss cost, curtailment of load/NDERs cost (if any) ,DWL ,power loss in transmission lines cost;
16. Calculate the cost of power transaction (import/export) for each TMG(s) in MMA;
17. Evaluate the equality, inequality and bound constraints;
18. If the feasible solution is not converged "OR" constraints are not met then repeat lines (13 to 17) by applying small increase in integer variables tolerance;
19. Calculate OF_{ISP}, OF_{VPP} **and** OF_{DNO} along with their weightings using (2), (30) and (44) ;
20. Calculate OF using equation (1) for each individual population;
21. end
22. Define the most feasible population of current iteration and identify the best chromosomes with high rank fitness;
23. Update the values of chromosomes in selected population and limit them with bound constraints and tolerance;
24. end

4.1. Small Scale Case Study

Let us consider case study-I (numerically described in Table 2) in which MG-2 is declared as a TMG with nominal frequency of 50.6Hz and voltage maximum limit is on 1.095pu (both are above permissible limits as defined in Table 1). The major reason is due to DG is operating at 62kW while its nominal capacity is 65kW, load is 77kW and NDERs contribution is 12 kW while BSS is present with standby mode of operation. As the data has been collected on day ahead basis so the time slot for this study is noted as weekend shoulder. Without developed optimisation strategy the best solution is to do NDERs curtailment of 9kW so that both frequency and voltage will be within permissible limits. A sample operation profile of MG-2 is shown in Fig 8.

The developed strategy proposes to export power of 10 kW to SSP and VPP. Therefore DNO will recommend power export to MG-3 and VPP-2 as the best feasible solution. In this way, MG-

Table 2: Numerical values observed for case study-I in order to overcome the emergency situation of over generation in single TMG present inside MMA							
Initially observed data							
Observed TMG	TMG status	f^{nom} (Hz)	V^{max} (pu)	P^{DG} (kW)	P^{load} (kW)	P^{NDERs} (kW)	Time slot
MG-2	Over generated	50.6	1.095	62	77	12	Weekend

Market optimization solution									
P_{Total}^{expo} (kW)	Available SSP	Selected VPP	P_{SSP}^{load} (kW)	P_{SSP}^{DG} (kW)	P_{SSP}^{NDER} (kW)	P_{SSP}^{BSS} (kW)	P_{SSP}^{expo} (kW)	P_{VPP}^{expo} (kW)	$P^{line\ loss}$ (kW)
10	MG-3	VPP-2	36	25	9	2 (discharge)	2.2	7.8	0.9
OF ($) = 13.41$									

OF_{ISP}($)	4.81	OF_{VPP}($)	6.62	OF_{DNO}($)	1.98

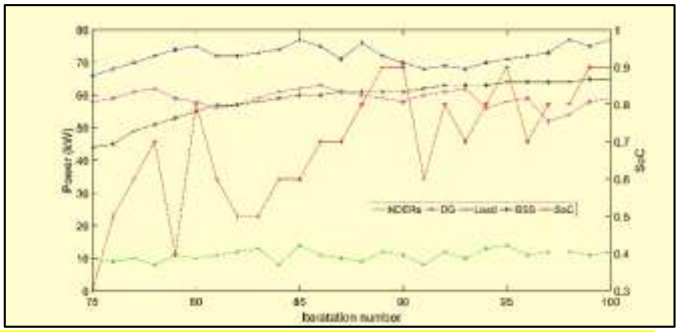


Fig. 8. *Sample operation profiles for 25 iterations out of total 150 iterations in case study-I when MG-2 is under emergency situation of over generation*

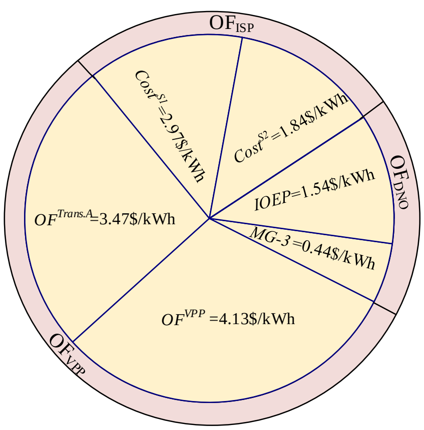
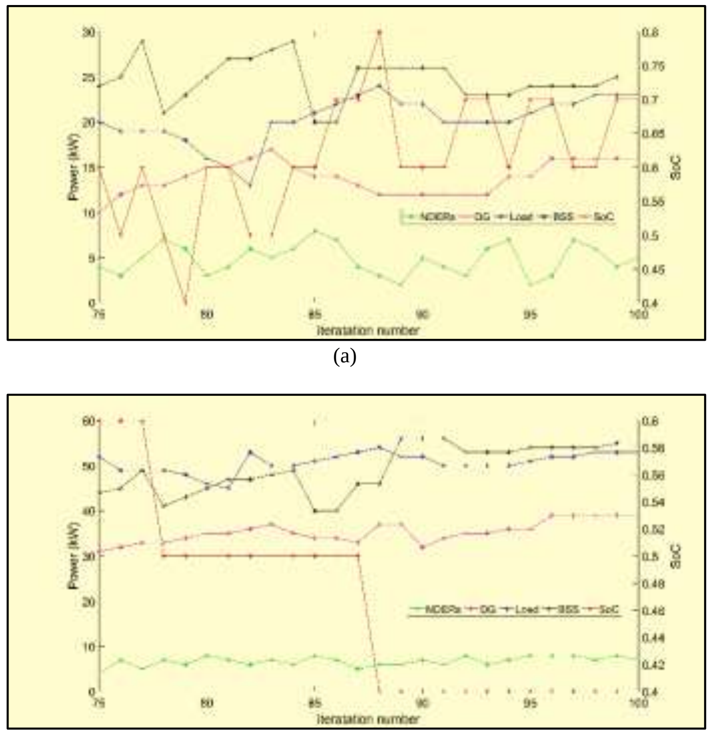


Fig. 9. *Contribution of each OF in reaching optimal solution to accommodate the emergency situation of over generation of case study-I.*



(a)

(b)

Fig. 10. *Sample operation profiles for 25 iterations out of total 150 iterations in case study-II when MG-1 (a) and MG-3 (B) are under emergency situation of over loading.*

Table 3: Numerical values observed for case study-II in order to overcome the emergency situation of over loading in multiple TMG(s) present inside MMA								
Initially observed data								
Observed TMG	TMG status	f^{nom} (Hz)	V^{max} (pu)	P^{DG} (kW)	P^{load} (kW)	P^{NDERs} (kW)	P^{BSS} (kW)	Time slot
MG-1	Overloaded	49.41	1.037	16	23	6	1	Peak
MG-3		49.38	0.098	39	54	8	7	

Market optimization solution					
P_{Total}^{imp} (kW)	Available SSP	Selected VPP	P_{VPP}^{expo} (kW)	Distance from DNO (km)	$P^{line\ loss}$ (kW)
12	-	VPP-1	11	10	2.3
		VPP-2	4	5	0.7
OF ($) = 23.64$					

OF_{ISP}($)	7.2	OF_{VPP}($)	12.3	OF_{DNO}($)	4.14

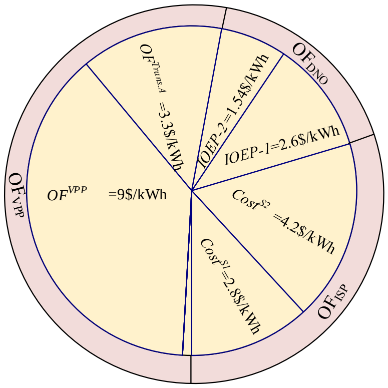


Fig. 11. *Contribution of each OF in reaching optimal solution to accommodate the emergency situation of overloading and over generation of MMA's TMG(s).*

3 couple with MG-2 and form a power sharing environment between two neighbors. MG-3 will work as SSP (load is 36kW, DG is operating at 25kW, NDERs contribution is 9kW, BSS has discharged for 2kW to accommodate the load). Now MG-2 export 2.2kW to MG-3 with transmission line loss of 0.2kW, while 7.8kW is transmitted to VPP-2 out of which 0.7 kW is wasted as power loss due to the distance of 8km from common central node of DNO. The minimum cost of operation for this solution is calculated as 13.41$ (out of which OF_{ISP} is 4.81$, OF_{IOEP} is 6.62$ and OF_{DNO} is 1.98$ respectively). The related costs with each OF are shown in Fig. 9.

It is clear from pictorial representation that maximum cost is to be paid by VPP-2 (i.e. 4.13$/kWh) and it matches to the idea that extra burden of supply cost and GST is also included. But an interesting fact revealed over here that as this emergency situation happened on weekend shoulder time, therefore SMBP is relatively low as 0.21 $/kWh. Similarly the minimum cost has been emerged for SSP (i.e. MG-3 in this case) due to the reason that it is available on minimum distance from DNO (i.e. at 5km as shown in Table 3), therefore corresponding transmission line loss is relatively low. Similarly due to the application of proposed optimisation technique the technical aspects of TMG (i.e. MG-2 in this study) has been settled down i.e. maximum voltage reaches to 1.044 pu and frequency is exactly 50Hz due to interconnection with VPP-2.

Now let us consider another case study-II (numerically described in Table 3) in which MG-3(with nominal frequency of 49.38Hz and voltage maximum limit is on 0.0986pu i.e. both are below permissible limits as defined in Table 1) and MG-1(with nominal frequency of 49.41Hz and voltage maximum limit is on 1.037 pu i.e. frequency is below permissible limit while voltage is in normal range) are declared as TMGs.In MG-3 (load is 54kW, DG is operating at 39kW with 8kW coming from NDERs and 7kW is the power support from BSS) and MG-1 (load is 23kW, DG is operating at 16kW with 6kW coming from NDERs and only 1kW is the power support from BSS). As the data has beencollected on day ahead basis so the time slot for this study is noted as peak hours. Sample operation profiles for both TMG(s) is shown in Fig 10. Without developed optimisation strategy the best solution is to do load curtailment of total 12kW so that both frequency and voltage will be within permissible limits.

The developed strategy proposes to import power of 12 kW from both VPPs while no SSP will be observed to overcome emergency situation. Therefore DNO will recommend power import from -1 and VPP-2 as the best feasible solution. In this way, 11kW is transmitted from VPP-1 out of which 2.3 kW is wasted as power loss due to the distance of 10km from common central node of DNO, while 4kW is imported from VPP-2 out of which 0.7kW is being wasted as transmission line power loss. The minimum cost of operation for this solution is calculated as 23.64$ (out of which OF_{ISP} is 7.2$, OF_{IOEP} is 12.3$ and OF_{DNO} is 4.14$ respectively). The related costs with each OF are shown in Fig. 11. It is clear from pictorial representation that maximum cost is to be paid by VPP-1 (i.e. 9$/kWh) and it matches to the idea that extra burden of supply cost and GST is also included. But an interesting fact revealed over here that as this emergency situation happened on peak weekday time, therefore SMBP is relatively high for VPP-1 as 0.52 $/kWh, while VPP-1 is importing power of 3.3kW at the relative low cost of 0.37$/kWh. Similarly VPP-1 is at more distance of 10km from DNO as compared to VPP-1, therefore the transmission line losses for VPP-1 is 2.6kW while VPP-1 is present with lower loss of 1.54kW. Similarly due to the application of proposed optimisation technique the technical aspects of TMGs (i.e. MG-3 and MG-1 in this study) has been settled down i.e. MG-3 maximum voltage reaches to 1.035 pu and MG-1 voltage is steady at 1.038pu, while both MGs are working within permissible limit of frequency as well.

4.2. Large Scale Case Study

The formulated optimization problem is assessed using large scale network consists of 6 MGs and 6VPPs as shown in Fig 12. Exhaustive simulations are carried out in Matlab for the verification of the developed market model. Six MGs are considered here in connected mode with each other. It is assumed that all MGs have the same topology. In reality it is not possible but this assumption is made here for the purpose of simplification and complexity reduction.

Lots of scenarios are generated and computational effort is reduced by using simulation backward reduction method. Firstly, identification of TMG is made based on ISP analysis. Once the status of participating MG is known then DNO will take necessary action for power transaction. Developed GA algorithm will choose one or more out of six MGs at a time as TMG. After this DNO identifies the available cluster MG, then bidding VPP from market, curtailment of non-essential loads or generation output of NDERs and change in power transaction is being calculated. Based on these calculations and given cost data (Table 1) objective function is being calculated to find out the cost of operation for each possible scenerio. Once OF is calculated then single VPP or group of VPPs is selected based on minimum cost to give maximum benefit to TMG.

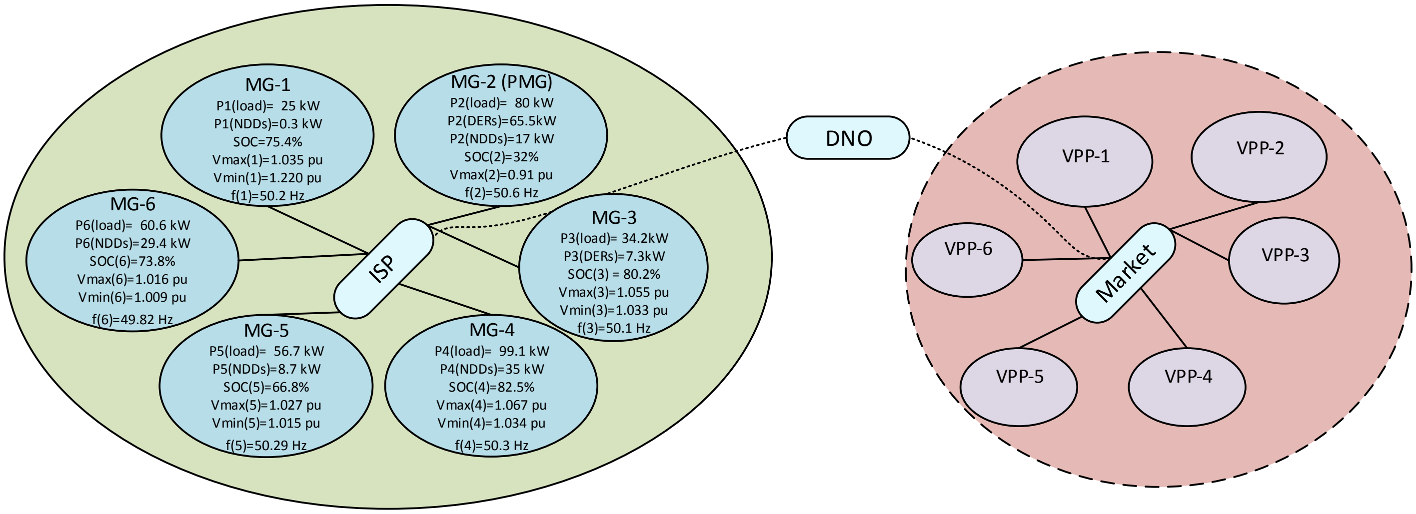


Fig. 12. ***Considered network topology along with MMA and market for large scale study.***

Table 4: Sample results of the DNO analysis with identification of TMGs which can be selected for coupling with determined VPP based on OF formulation

DNO determined TMG	Observed VPP(s)	$\sum \Delta P_{NDERs}$ (kW)	$\sum \Delta P_{Load}$ (kW)	OF_{ISP}		OF_{DNO}	OF_{VPP}		ΔP^{trans} (kW)	OF_{value} ($)
				Cost S1	Cost S2	IOEP	OF^{TRANS}	OF^{VPP}		
$\mathbf{MG_3}$	VPP_1	6.25	0	1.6	4.2	-10	10	67	10.54	9.3015
$\mathbf{MG_5}$	VPP_3, VPP_4	2.6,0	0,0.41	1.2,2.6	1.5,2.7	-15, -13	15, 13	90,85	5.39,9.8	15.3426
$\mathbf{MG_1}$	VPP_2, VPP_3, VPP_5	10.40,15.23, 13.06	0.52,0,0	1.6, 1.2,0.9	2.1,1.8, 1.4	-31,-21, - 11	31,21,11	40,65,55	11.9,7.5,6.8	36.6584
$\mathbf{MG_6}$	VPP_4	0	0.89	6.4	4.3	-13	13	75	-27.54	25.8312
$\mathbf{MG_6}$	VPP_2, VPP_3	11.40,5.89	1.08,0	1.6,2.8	1.8,3.1	-23	23	80	18.68,21.56	39.47
$\mathbf{MG_2}$	VPP_4	1.46	0	1.2	2.5	-18	18	40	29.76	27.6538

The $Time$ factor is set to approximately 10 minutes (i.e. 1/6 hour) for overcoming the emergency condition in considered MMA network.

Sample results generated for DNO are shown in table 4. As an example let us consider that MG_3 is determined as TMG and DNO identifies VPP_1 as the only available market participant. Then curtailment in NDERs generation is 6.25 kW, while no need to shed any load. In the same way change in DG output limits for diesel are 1.6kW and 4.2 kW respectively. BESS state of charge limit is 67%. Now the DNO will calculates change in transaction power which is 10.54 kW in this case and corresponding objective function calculated for this case is 9.3015$. This value is being transferred to ISP of TMG to overcome the emergency situation.

The prescribed algorithm is checked on the same system with 150 repetitions. As the inputs of DGs, NDDs and loads are created in stochastic environment therefore every time selected TMG will be different from the previous time. One sample of the OF value is shown for selected (45-67) repetition interval is depicted in Fig .3. It is also possible that for one TMG, more than one or group of VPPs selected by DNO for making the overall objective function value as minimum as possible. In result overall cost paid by TMG will be minimum giving benefit to the respective MG. As an example from table 4 suppose MG_1 is declared as PMG with severe shortfall or inadequate generation then DNO identifies group of VPPs i.e. VPP_2, VPP_3, VPP_5 to overcome emergency condition. No load shedding is noted in participating CMGs i.e. MG_3 and MG_5 but 0.52 kW load unnecessary load is being shed inMG_2. DG outputs are also within limits for example SOC for storage system is not violated. So the required exported power is being shared by the group of three selected VPPs giving overall value of objective function as 36.6584$ respectively. Now if power export from TMG to VPP is considered then from table 4, MG_6 is declared PMG with excess power due to for example fault condition. Now DNO will look for such MG which is working in such situation such that it can accept power import for supporting its future expected over loadings. These over loadings are for example are calculated on day ahead or hour ahead mechanism. Then MG_4 is selected as such supporting MG and it can be seen from SOC of BESS of MG_4 that it is going to be near minimum value so it will be a good idea to import power from MG_6 then to increase operational limits of diesel. It can cause power saving and will be economical as well. So 27.54 kW will be imported from MG_6 to VPP_4 as represented by negative sign. Corresponding OF value is calculated as 20.8312$. Now this cost is lower as compared to exporting cases because MG is on buyer end and VPP has to sell its unnecessary power to overcome emergency condition, thus acting on seller end.

5. Conclusion

This paper proposes a market model for the purpose of optimisation of clustered but sparse microgrids (MGs). The MGs are connected with the market by distribution networks in for the sake of energy balance, and to overcome emergency situations i.e. overloading or over-generations within the cluster. The developed market structure enables the integration of virtual power plants (VPPs) in energy requirement of MGs.This paper provides a strategy for market optimisation of remote area MGs by utilising the interaction among MGs and VPPs with the help of DNO. The DNO and each MGs have their own objectives for minimising the overall cost of operation. The optimal control of the entire network is achieved by using heuristic optimisation approach of Genetic Algorithm. Case studies are done on an example network of two VPPs and three MGs. The simulation results show that stochastic decisions ends out at optimal value of operation cost, permissible limits of voltage level and minimum efficiency loss. The results also highlights the signicance of utilising SMBP costs which gives substantial benefit to MG customers. Compared to previous efforts made in literature about MGs market optimisation, this work gives liberty to VPPs for providing consent to export or import power in certain emergency situation of MMA. The interaction among DNO and MGs for integration of VPPs are also taken in account to ensure safe operation of the network. Through a Monte Carlo analysis in MATLAB®, the successful operation of the proposed technique is validated for a wide range of emergencies in an assumed large remote area, consisting of multiple MGs.

This research only considered the direct connection of neighboring MGs to each other (i.e., via three-phase ac lines). However, they can also connect through a dc line with voltage source converters at two sides of the line. This will help the neighboring MGs to form a CMG and exchange power with each other, while each MG will operate at a separate frequency. Modifying and developing the proposed technique to cater such connection topologies can be an avenue of future research in this area.

7. References

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6. Appendix I

Table A1 lists the SMBP offered by VPPs with corresponding timings while Table A2 lists the assumed DERs nominal capacities for MGs in the considered MMA.

Table A: Time slots and SMBP for VPPs [33]

VPPs		
GST = 10% of (Supply charge & Consumption)		
Supply Charge = $\boldsymbol{\omega_{VPP1.sup}}$ \$/day Supply charge for additional MGs = $\boldsymbol{\omega_{VPP1.AMGs}}$ \$/day		
Time Slot	Timings	$\boldsymbol{\omega_{VPP}}$ (\$/kWh)
Peak	[3]Weekdays : 11am to 5pm (Summer) Weekdays : 7am to 11am (Winter) Weekdays : 5pm to 9pm (Winter)	ω_{x1}
*Weekday Shoulder	Weekdays : 11am to 5pm (Summer) Weekdays : 7am to 11am (Winter) Weekdays : 5pm to 9pm (Winter)	ω_{x2}
Weekend Shoulder	7am to 9pm	ω_{x3}
*Off-Peak	Everyday 9pm to 7am	ω_{x4}
*Shoulder and off-peak mean the more consumption shifted to these times the more will be the saving for electricity cost.		

Table B: Nominal capacities of DERs of MGs in MMA

Photovoltaic		Diesel Generator	
P_{PV}^{cap}	10 kW	P_{DG}^{min}	13 kW
Wind		P_{DG}^{max}	80 kW
P_{wind}^{cap}	15 kW	Storage System	
Load		Capacity	70 kW
P_{load}^{cap}	100 kW	SOC_{LIMIT}	20% - 90%
$P_{BSS}^{CH,MAX}$	14 kW	$P_{BSS}^{DCH,MIN}$	65 kW

Appendix II

The considered structure for chromosome of GA is shown in Fig. B1.

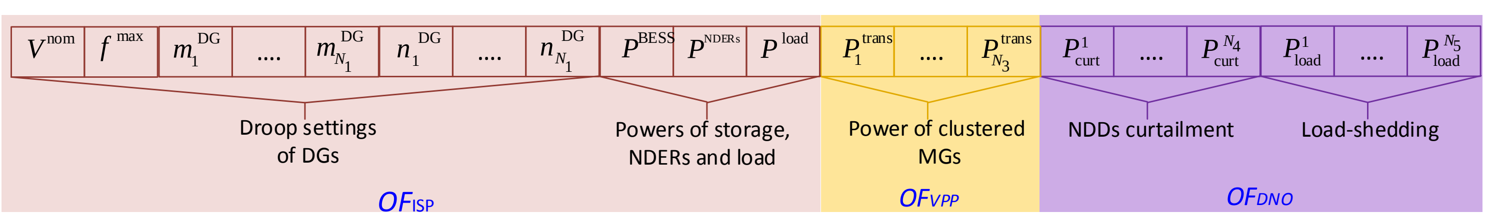

Fig. B1. Considered structure of the chromosome in GA