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Real Time Optimal Scheduling of Generation and Storage Sources in Intermittent Microgrid to Reduce Grid Dependency

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Abstract

Objectives: Algorithms used for realtime scheduling need be simle, fast and require lesser communications with remote units. This paper introduces a two-stage algorithm for realtime scheduling in microgrids with intermittant sources. **Methods/Statistical Analysis:** The proposed two stage algorithm prioritizes the intemittant sources available in the microgrid based on their cost of generation in the first stage. First stage is an offline process. The second stage schedules generation among the sources in realtime using a Modified Increase-Decrease algorithm. Two modifications are proposed to the already reported Increase-Decrease algorithm to enhance optimization under two different cases of microgrid operation/ownership. **Findings:** The proposed algorithm is validated by using it to optimize the cost of generation in a microgrid with intermittant renewable sources in grid connected mode. The algorithm is tested under two different types of operation/ownership of the microgrid. It is found to be promising in reducing the cost of generation to a sizeable extent in both the cases of operation/ownership when compared to the already existing Increase-Decrease algorithm. After having validated its performance, the same is employed to reduce grid dependency of a microgrid with intermittant sources using a battery storage. The algorithm is found to arrive at a very optimal mix of generators and storage scheduling, ensuring lesser power drawal from the grid. **Application/Improvements:** Although the algorithm is used for optimization of cost of generation in this paper, it can be extended to any real time application with suitable modifications.

Keywords: Energy Storage, Grid Dependency, Intermittent Sources, Microgrid, Optimization of Generation

1. Introduction

The usage of Renewable Energy Sources (RES) has gained its importance due to many reasons like increased sanctions against emissions, substantial improvement in the efficiencies of PV units and wind turbines, increased subsidised policies by the governments to reduce their ex-chequer on coal and petroleum imports, reduced costs due to advanced technologies in the production of PV units, substantial increase in the capacity of Wind generators from kW to MW, innovations of multi-fuel CHPs to replace conventional CHPs, enhanced capacity and efficiencies of storage facilities etc[1]. These on-going developments in utilisation of RESs lead to competitive system of power generation and distribution by private parties at distribution level, termed as Distributed Generation, which in the near future is sure to replace at least partially the traditional centralized systems, which in large are state run. For example the European Union countries aim to reach 20% of their demand from ESs by 2020[2]. The future power systems need to integrate the fast emerging Distributed Generation (DG) technologies and increasingly utilised ESs and hence the grids have to grow smart[3].

Though the increased penetration of Distributed Generation is much appreciated and most welcome development, the intermittent nature of the power availability from the ESs is posing control problems in balancing and stabilizing the power systems and increases the complexity in optimization. For example, the wind and solar energy availability forecasts will have a lot of variations in real time when the climate changes. Due to

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these uncertainties, increased penetration level of RESs and DGs into a grid increases the operational difficulties. The intermittency and variabiliity of power availability from the non-conventional sources like solar and wind along with spatiotemporal uncertainty in loads further complicate the operation of a microgrid[4]. The intermittent nature of the renewable energy impacts the dynamics and stability of the micro grid[5]. However, the advantage of the microgrid is that the excess power generated after meeting the local load demand, can either be exported to the utility grid or can be stored[6]. The main difference in generation scheduling of a traditional grid and a microgrid is the uncertainty in power availability and this is a major hurdle in real time generation scheduling in a microgrid. It requires a continuous bidirectional communication between the central Energy Management System (EMS) and the remote units. The EMS not only receives the current status of each component but also can send control signals to each component to maintain balance and stability. To facilitate a faster decision making and implementation, the EMS requires an optimization algorithm, which is simple, fast computing, requiring fewer computational requirements and minimum communications with the remote units. One such algorithm is Additive Increase Multiplicative Decrease (AIMD) algorithm. The original AIMD algorithm, which is explained in detail in Section 2.1, is well adopted in communication networks to avoid network congestion[7–11] in real time. As distribution network resembles a communication network in many aspects. The AIMD algorithm could be used for generation scheduling in a microgrid. Its suitability for real time generation scheduling in a microgrid environment is established by researchers in[12]. A few drawbacks are identified in the AIMD algorithm as applied to optimization of a microgrid in[12] and required modifications are proposed in this paper to enhance the optimization.

The objective of this paper is to formulate a two stage algorithm for economic scheduling of generation among the available RESs in real time. In the first stage, the ESs are prioritized based on their cost of generation. The hierarchy of choice of RESs among the available types is made on this priority basis. The first stage is carried out in off line as the EMS will have a record of cost of generation of each generator in the microgrid. The second stage uses an Additive Increase and Multiplicative Decrease algorithm with a few modifications proposed in this paper (hereafter termed as Modified Additive Increase and Multiplicative Decrease (MAIMD) algorithm) for economic generation scheduling in real time. Thus this paper contributes methodology for 1. Selection of a RES among the available types based on a priority basis and 2. Optimization of generation scheduling among the selected ESs using MAIMD in real time.

The rest of the paper is structured as follows. Section 2 deals with the AIMD algorithm, its drawbacks, modifications proposed in the present article to overcome the drawbacks and the proposed two stage algorithm for real time scheduling of sources. The actual problem of economic scheduling and reducing grid dependability in a microgrid is formulated in Section 3. Numerical results and discussions are presented in Section 4. Conclusions are drawn in Section 5.

In AIMD algorithm[12], as adapted to a microgrid, an agent, say one generator among many connected in the microgrid, gently increases its generation in steps during the Additive Increase phase, until it receives a signal from the network indicating that the total generation has exceeded the demand. Let us call this signal excess generation signal. This signal indicates a state where the sum of generation of all the units is more than the demand. On receiving this excess generation signal, the agents decrease their generation rate in a multiplicative manner. This is called Multiplicative Decrease phase. The agents continue this Multiplicative Decrease phase until they stop receiving excess generation signal. The communication required here is only one way. The increment phase is by a constant amount (additive) and the decrement phase is by a constant factor (multiplicative). The value of multiplying factor should lie between '0' and '1'. Preferably its value should be closer to '1' for faster convergence. The readers are directed to refer[7] for convergence conditions.

The advantage of AIMD algorithm lies in its simplicity and the fact that it can be implemented with only one way communication between the EMS and the RESs in a network[12]. The EMS needs to send only one bit information which may be called excess generation signal to the ESs at the moment when total power generation exceeds the demand. The RESs are assumed to be receiving this notification, understand it and stop further increment of generation. At times they may be required to reduce their generation in the decrement phase. The information that a particular RES is decreasing its generation need not necessarily be communicated to the EMS because the

EMS continuously compares the total generation with the demand after every time interval. Moreover the ESs also need not communicate their maximum power availability to the EMS. The algorithm so provides that when one particular class of ESs have reached their maximum generation levels, ESs with next immediate higher cost functions is brought into generation. Neither the ESs are required to communicate among themselves[12].

Apart from its advantages, AIMD algorithm suffers from several serious disadvantages when used in optimization problems. The original algorithm considers same additive parameter *A* in increment phase for all the Energy Sources (ESs) in the system and it is used simultaneously for all the generators, which has several drawbacks. The main drawback is that when the additive parameter is same, all the generators will be scheduled equal amount of power (limited by maximum power availability) at the end of given number of iterations. This is not fair in view of widely varying cost of generation among the different classes of Energy Sources (ESs). For example, the wind and solar PV resources will have a wide difference in cost of generation , which should not be neglected. The second drawback is that it implements additive phase simultaneously for all the generators. This does not allow the priority based generation scheduling as may be required in some cases as explained in the coming sections. The ESs with lower cost of generation should be utilized first and then the next costlier one for better economy. The third drawback is that the AIMD algorithm will be forced to consider the generator with least generation ramp for fixing the value of Additive parameter and apply the same for all the generators. When the additive parameter is fixed smaller, it requires more iterations to balance the load with generation, which means more number of communications between the EMS and the generator control system. This may lead to stability issues if the gap to be bridged is large. As a remedy to this shortcoming of the algorithm, we propose that the additive parameter of each generator shall be in inverse proportion to its cost of generation.

The original algorithm considers decrement phase for each of the ESs used, in case where the total generation allocation is more than the demand, which results in decrementing the generation share of cheaper sources on par with costlier sources. For economy, the generation from the costliest resource alone should be decremented. To overcome this drawback, we propose that at the end of incremental phase, if the total generation is more than the demand, the decrement phase shall be implemented in the reverse order of priority index '*n*', i.e., the costliest source will be decremented first and then next cheaper source. This ensures that, during decrement phase, the generation share of costliest source is decreased while the share of cheaper sources is not affected.

2. Modified AIMD Algorithm (MAIMD) and Proposed Two Stage Algorithm

Modification 1: The additive parameter for each generator is different and it is in inverse proportion to its cost of generation.

$$\mathbf{A_1 : A_2 : \ldots . . A_n = C_n : C_{n-1} : \ldots . . C_1} \quad (1)$$

Modification 2: The decrement phase should be implemented in reverse order of priority index 'n'.

The above two modifications ensure that the cheaper sources are exploited best when there is a choice for selection, i.e., when the microgrid is with excess generation. [$\boldsymbol{\Sigma}_{\downarrow}(i = 1)^{\uparrow} n \, [pg]_{\downarrow} imax > d(t)$].

Modified AIMD algorithm

Initialize the generations ($pg_i(t)$), loads ($d(t)$), Cost of generation (C_i) and time (t)

Evaluate Additive parameter

$$A_1 : A_2 : \ldots . . A_n = C_n : C_{n-1} : \ldots . . C_1$$

Repeat

$t = t + 1$ **If**

$$\sum_{i=1}^{n} pg_i(t) < d(t)$$

$$pg_i(t+1) = \min[pg_i(t) + A_i, \quad pg_{imax}(t)], \forall_i = 1, \ldots \ldots, n \quad \textbf{(AI)}$$

(Note that *i* is in priority order, 1 to *n*)

Else

$$pg_i(t+1) = \max[B * p_i(t), pg_{imin}(t)], \forall_i = n, \ldots \ldots \ldots 1 \quad \textbf{(MD)}$$

(Note that i is in reverse order, n to 1)

Evaluate error

$$error(t) = \sum_{i=1}^{n} pg_i(t) - d(t)$$

If
error(t) is less than allowable
end

Method of calculating Additive parameter: At each step, the costs of generations are compared, the cheapest source (highest priority source) is selected and it is assigned with the highest Additive parameter equal to its ramp rate. The additive parameters of other generators are calculated in proportion to their cost of generation using Equation (1).

2.1 Proposed Two Stage Algorithm

The proposed algorithm is carried out in two stages. In the first stage, the ESs are prioritized according to the cost function. Accordingly a priority index 'n' is given to each ESs. The highest value of priority index equals the number ESs in the microgrid. In the second stage, the power generation is shared among the ESs using the modified AIMD algorithm.

2.1.1 Stage 1

This stage is used to prioritize the ESs based on their cost of generation on unit basis. This is an off-line process and the EMS is assumed to have a record of the various energy sources available and their cost of generation.

2.1.2 Stage II (MAIMD Algorithm)

This stage is used to implement MAIMD algorithm for generation scheduling. This is a real time process and the EMS uses communication system between itself and the remote generators for balancing the generation and load.

Modification 1 takes two different forms in the following two different types of operation/ownership of microgrids. In Model-1, when there is no mandate that all the sources shall be used simultaneously. Such a condition prevails in the microgrids where the generating ESs are owned by the microgrid operator. As the generators are at his disposal, he is at his will to use any or all of them for generation simultaneously at any time. In such case the additive phase should be carried out in forward order of priority, i.e., first the cheapest source should be exploited completely before using the next costlier resource. The additive parameter $\mathbf{A_i}$ can be same for all the ESs and it is limited by the ramp of generation allowed. However if $\mathbf{A_i}$ is maintained same, it has to be equal to the lowest ramp of all the generators. But fixing a lower value for $\mathbf{A_i}$ results in more iterations and hence more communication between EMS and the generator control units. Hence we propose Equation (1) for calculation of additive parameters. In Model 2, when there is a mandate that all the sources shall be used simultaneously: This condition prevails in microgrids where the ISO purchases power in the open market from different ESs owners and sells it to the customers. Under such ownership, the microgrid operator will be required to meet the contractual commitments in terms of minimum power to be drawn from each generator. In such case, additive phase should be carried out as outlined in the original AIMD algorithm but with additive parameters of the respective ESs in inverse proportion to their cost of generation according to Equation (1). This proposal ensures that for the given number of iterations, the cheaper source will have more share of generation, as its additive parameter is larger. The additive parameter $\mathbf{A_i}$ is different for each ESs and it is limited by the ramp of generation allowed.

2.1.3 *Implementation Steps*

- Read and initialise parameters.
- Generate priority indices n for sources based on the cost of generation.
- Initialise additive increment phase.
- Generate additive parameters for generators by choosing any of the two cases explained in Section 2.2.2.
- Increment the generation by additive parameter in priority order (1 to n).
- Check if the total generation is more than the load.
- If total generation is less than the load, go to Step 5.
- If the total generation is more than the load, initialise decrement phase.
- Decrement the generation in reverse priority (n to 1).
- Check if error is within limits. If not, go to Step 9.
- Print the generation schedule.

Figure 1 shows flow chart for the proposed MAIMD algorithm. It is assumed that the EMS has a record of priority indices and understands it. It is also assumed that the excess generation signal sent by the EMS is either received by only that RES which is indexed as '*n*' or it is received by all the ESs but only that RES indexed as '*n*' responds to it and decrements its generation in the decrement phase.

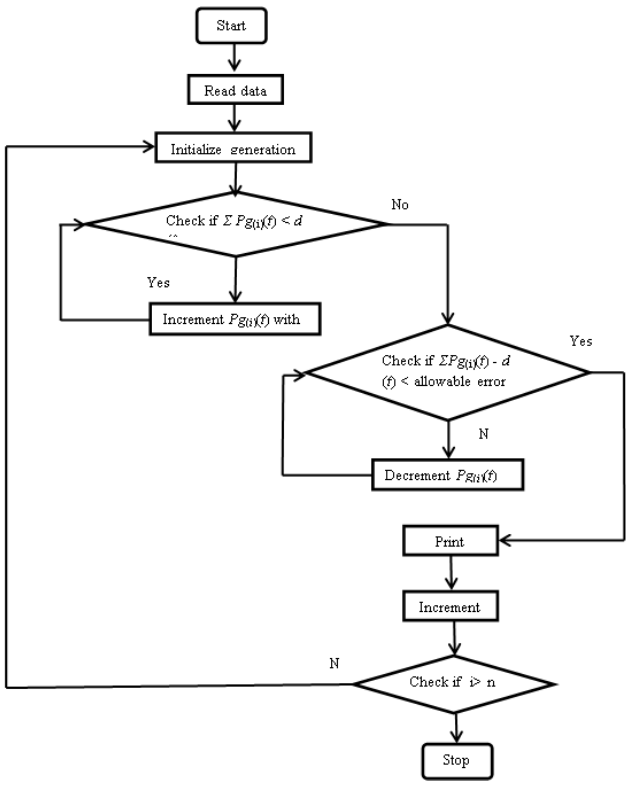

Figure 1. Flow chart of MAIMD algorithm.

The proposed algorithm is quite robust and has the inherent capability to handle the intermittency of power availability with the ESs. In fact it is the advantage of the algorithm which enables it for real time scheduling application. It is already explained Section 2.1 that the generators need not communicate their maximum power availability to the EMS. Neither the generators need to communicate among themselves. At any time 't' when the EMS receives a deficit generation signal from the network, it signals the generators to increment their generation by one additive parameter. If the incremented generation is not sufficient to balance the load, it continues to receive the deficit generation signal from the network and in turn it signals the generators to increment their generation. The sequence continues until it stops receiving deficit generation signal. If for any ESs, its remaining power availability is less than its additive parameter value, it stops responding to the generation increment signal because it cannot increment its generation. But because there is still deficit generation, the EMS continues to receive the generation signal and hence it continues to send generation increment signal to the generators. The other generators respond to it and continue to increment their generation until they stop receiving the signal from the EMS. The algorithm so provides that it continues the increment in generation until a power balance is attained. If the correction is so minor that it is lesser than the additive parameter, it increments the generation by one additive parameter. However the EMS receives an excess generation signal from the network and hence it signals the generator to decrement its generation by a multiplicative parameter and decrement phase continues until the balance is reached. Thus the algorithm works equally well for both major and minor corrections. Similar correction measures are taken when the microgrid is under excess generation also. Thus the performance of algorithm is independent of the maximum power availability of the generators, which is an indicator that the algorithm is quite robust.

3. Problem Formation

The utility optimization function considered in this paper is the cost of generation. The cost function can be stated by

$$f\,(pg_i(t)) = \sum_{i=1}^{n} [\{[V_i](t) pg_i(t) C_i(t) + C_{OMi}] + C_{\frac{up}{down_i}} + p_{grid}(t)\, C_{grid}(t)\} \qquad (2)$$

Where V_i is the state vector showing the ON/OFF of the i^{th} generator, pg_i is the power generated by i^{th} generator at time interval (t) , C_i is the cost of generation per unit of energy, $C_{\frac{up}{down_i}}$ is the start up/Shut down costs of the i^{th} generator, p_{grid} is the power drawn from or pumped into the utility grid and C_{grid} is the cost of the grid power[12–14].

The optimization problem can be stated as

$$min \sum_{i=1}^{n} f(pg_i(t)) \qquad (3)$$

subject to conditions,

$$\sum_{i=1}^{n} pg_i(t) = d_i(t), \text{ (Power balance)} \qquad (4)$$

$pg_{imin}(t) \leq pg_i(t) \leq pg_{imax}(t)$ (generator limits) (5)

$A_i \leq generation\ ramp\ allowed,$ (limits of additive parameter) (6)

$S_{OC\,min} \leq S_{OC}(t) \leq S_{OC\,max}$, (State of charge of battery limits) (7)

$P_{bat} \leq P_{bat\,max}$ (Charging/discharging power limits of battery) (8)

4. Numerical Results

To validate effectiveness of the proposals made, the microgrid scenario presented in[13] is investigated for optimization of generation cost, under two types of operation/ownership as explained in model-1 and model-2. The microgrid consists of a micro turbine (30 kW), a wind turbine (20 kW), a fuel cell (30 kW) and a PV module (15 kW) capacity in grid connected mode. The hourly demand, maximum power availability of wind and PV generators are as tabulated in Table 1. The hourly cost of energy of the different sources considered is as given in Table 2. The grid power is drawn only under deficit condition, irrespective of its cost. The minimum power generation for all the sources are taken as zero kW. A ramp rate of 3 kW is assumed for all the sources, at approximately 10% of micro turbine. Along with the MAIMD-Model and Model 2, the original AIMD algorithm is also implemented for comparison and validation sake.

Table 1. Hourly demand and the max power availabilities of DGs (kW)

Hour	Demand	WT	PV	Hour	Demand	WT	PV
1	52	16.01	0	13	72	11.67	10.7
2	50	16.08	0	14	72	10.15	9.7
3	50	16.16	0	15	76	14.75	8.12
4	51	16.17	0	16	80	16.21	4.95
5	56	17.68	0	17	85	16.14	1.1
6	63	16.17	0	18	88	19.13	0.1
7	70	14.73	0	19	90	17.53	0
8	75	14.56	0.1	20	87	18.95	0
9	76	14.65	0.59	21	78	19.04	0
10	80	13.16	1.98	22	71	19.11	0
11	78	11.67	7.75	23	65	19.93	0
12	74	10.15	9.8	24	56	19.15	0

Figure 2 shows the results for AIMD algorithm. Irrespective of the cost of generation, the AIMD algorithm allocates equal share of generation (Pmt and Pfc are same as evident from Table 3 and they are overlapping in Figure 2) except for the maximum power availability limitations. The allocation to wind and PV generators are restricted by their Maximum Power availabilities (Pmax). The total cost of generation over a day sums up to 176.56 Euros when AIMD is implemented. The additive parameter is taken as 3 kW, considering 10% generation ramp for micro turbine generator. Figure 3 shows the results for MAIMD Model-1 algorithm. When there is no mandate that all the sources should be used simultaneously, the sources are prioritized based on their

Table 2. Hourly biddings of energy generation of DGs in Euros per kWh

Hour	MT	FC	PV	WT	P_{grid}	Hour	MT	FC	PV	WT	P_{grid}
1	0.0823	0.1277	0	0.021	0.033	13	0.0885	0.1308	0.0662	0.138	0.215
2	0.0823	0.1277	0	0.017	0.027	14	0.0885	0.1308	0.0654	0.135	0.572
3	0.0831	0.1285	0	0.0125	0.02	15	0.0885	0.138	0.0646	0.132	0.286
4	0.0831	0.129	0	0.011	0.017	16	0.09	0.1315	0.0638	0.114	0.279
5	0.0838	0.1285	0	0.051	0.017	17	0.0908	0.1331	0.0638	0.11	0.086
6	0.0838	0.1292	0	0.085	0.029	18	0.0915	0.1331	0.0662	0.0925	0.059
7	0.0846	0.1292	0	0.091	0.033	19	0.0908	0.1338	0	0.091	0.05
8	0.0854	0.13	0.0646	0.11	0.054	20	0.0885	0.1331	0	0.083	0.061
9	0.0862	0.1308	0.0654	0.14	0.215	21	0.0862	0.1315	0	0.033	0.181
10	0.0862	0.1315	0.0662	0.143	0.572	22	0.0846	0.1308	0	0.025	0.077
11	0.0892	0.1323	0.0669	0.15	0.572	23	0.0838	0.13	0	0.021	0.043
12	0.09	0.1315	0.0677	0.155	0.572	24	0.0831	0.1285	0	0.017	0.037

Table 3. Hourly generation scheduling of DGs (kW)and the cost (Euros) of generation by implementing AIMD

Hour	Pmt	Pfc	Pw	Ppv	Pgrid	Ptotal	Cost
1	17.9964	17.9964	16.0068	0	0	51.9996	4.1154
2	16.9728	16.9728	16.0543	0	0	49.9999	3.8372
3	16.9456	16.9456	16.1083	0	0	49.9995	3.787
4	17.4405	17.4405	16.115	0	0	50.996	3.8764
5	19.1712	19.1712	17.6535	0	0	55.9959	4.9704
6	23.4366	23.4366	16.1263	0	0	62.9994	6.3627
7	27.6474	27.6474	14.702	0	0	69.9968	7.2489
8	30	30	14.56	0.1	0.34	75	8.0884
9	30	30	14.65	0.59	0.76	76	8.763
10	30	30	13.16	1.98	4.86	80	11.3239
11	29.2912	29.2912	11.6665	7.7477	0	77.9966	8.7563
12	27.0431	27.0431	10.1287	9.7794	0	73.9943	8.2221
13	24.8577	24.8577	11.6502	10.6319	0	71.9974	7.7628
14	26.0817	26.0817	10.1429	9.6932	0	71.9996	7.723
15	26.5734	26.5734	14.7353	8.1119	0	75.9939	8.488
16	29.441	29.441	16.1776	4.9401	0	79.9997	8.6806
17	30	30	16.14	1.1	7.76	85	9.2299
18	30	30	19.13	0.1	8.77	88	9.0316
19	30	30	17.53	0	12.47	90	8.9567
20	30	30	18.95	0	8.05	87	8.7119
21	29.4853	29.4853	19.0305	0	0	78.001	7.0469
22	25.9584	25.9584	19.0794	0	0	70.9962	6.0684
23	22.5548	22.5548	19.8901	0	0	64.9997	5.2399
24	18.6663	18.6663	18.6663	0	0	55.999	4.2671
						Total Cost	**176.56**

cost of generation at each hour and the cheaper sources are completely exploited prior to the costlier sources. The cheapest source MT at every hour, is completely used as evident from Figure 3 and Table 4. The remaining sources are used in the priority order of their cost of generation at each hour. The total cost of generation per day as calculated by implementing MAIMD- Model-1 is 165.26 Euros, with a net savings of 3.2% compared to AIMD algorithm. The additive parameter for each of the ESs is taken as same (3kW) considering 10% generation ramp for micro turbine. Figure 4 summarises the results for MAIMD- Model-2, when there is a mandate that all the sources shall be used all the time. The MAIMD- Model-2 is implemented with different additive parameters for the ESs in inverse proportions to their cost of generation according to Equation (1). The maximum value of A_i is limited by the generation ramp allowed (3kW) i.e., the cheapest source is incremented with an additive parameter of 3 kW and the additive parameters for the other sources are adjusted in the ratio of their cost of generation according to Equation (1). This ensures that the cheapest source gets the highest share of generation and the other sources get a share in inverse proportion to their cost of generation, at end of given number of iterations. At each hour, all the sources are utilized subject to their power availability. The MAIMD -Model-2 puts the total cost of generation over a day as 168.2 Euros, with a net savings of 1.4% compared to AIMD algorithm. Table 5 consolidates the results of scheduling for MAIMD-Model 2. All the three cases are giving same result when there is no choice of generators allowed, i.e., under the deficit condition, $[\sum_{i=1}^{n} pg_{i\,max} < d(t)]$, between hours 9-11 and 16-21. Under deficit, all the three cases are utilizing all the sources completely and the balance power required to meet the demand is drawn from the grid. The cost of generation under such condition is same for all the three cases. Figure 5 shows the costs of generation obtained by implementing all the three cases and a comparison endorses the validity of the proposed algorithm with MAIMD. The multiplicative parameter *B* is taken very close to 1[10] for faster convergence.

Table 4. Hourly generation scheduling of DGs(kW) and the cost (Euros)of generation by implementing MAIMD Model-1

Hour	Pmt	Pfc	Pw	Ppv	Pgrid	Ptotal	Cost
1	30	5.9928	16.01	0	0	52.0028	3.5705
2	30	3.9227	16.08	0	0	50.0027	3.2433
3	30	3.8424	16.16	0	0	50.0024	3.1887
4	30	4.8328	16.17	0	0	51.0028	3.2943
5	30	8.3225	17.68	0	0	56.0025	4.4851
6	30	16.83	16.17	0	0	63	6.0629
7	30	25.2694	14.73	0	0	69.9994	7.1432
8	30	30	14.56	0.1	0.34	75	8.0884
9	30	30	14.65	0.59	0.76	76	8.763
10	30	30	13.16	1.98	4.86	80	11.3239
11	30	30	10.2513	7.75	0	78.0013	8.7012
12	30	30	4.2022	9.8	0	74.0022	7.9598
13	30	30	1.3528	10.65	0	72.0028	7.4707
14	30	30	2.303	9.7	0	72.003	7.5243
15	30	30	7.8809	8.12	0	76.0009	8.3598
16	30	28.835	16.21	4.95	0	79.995	8.6556
17	30	30	16.14	1.1	7.76	85	9.2299
18	30	30	19.13	0.1	8.77	88	9.0316
19	30	30	17.53	0	12.47	90	8.9567
20999	30	30	18.95	0	8.05	87	8.7119
21	30	28.9564	19.04	0	0	77.9964	7.0221
22	30	21.8881	19.11	0	0	70.9981	5.8787
23	30	15.0726	19.93	0	0	65.0026	4.892
24	30	6.8525	19.15	0	0	56.0025	3.6991
						Total cost	**165.26**

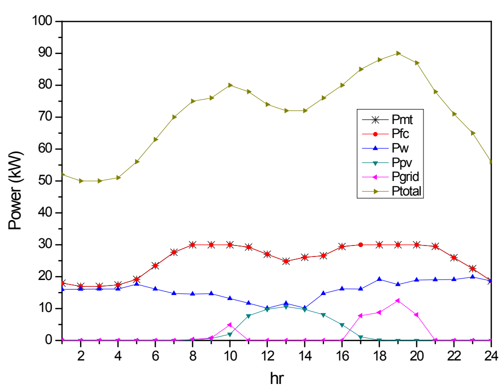

Figure 2. Generation scheduling results obtained using AIMD algorithm.

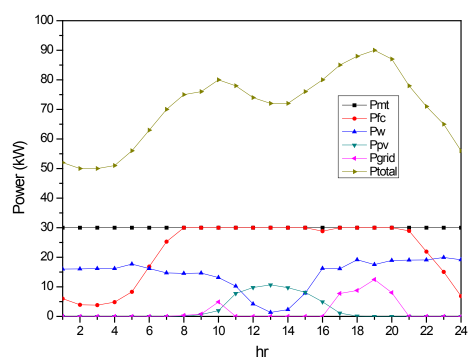

Figure 3. Generation scheduling results obtained MAIMD-Model1 algorithm.

Table 5. Hourly generation scheduling of DGs (kW) and the cost (Euros) of generation by implementing MAIMD Model-2

hour	Pmt	Pfc	Pw	Ppv	Pgrid	Ptotal	Cost
1	21.9806	14.166	15.8523	0	0	51.9989	3.9509
2	20.7659	13.3832	15.8485	0	0	49.9977	3.6875
3	20.6154	13.3318	16.0489	0	0	49.9961	3.6269
4	21.2647	13.6984	16.0347	0	0	50.9978	3.7106
5	23.3607	15.2344	17.4011	0	0	55.9962	4.8027
6	28.7977	18.6784	15.522	0	0	62.998	6.1459
7	29.8862	25.4403	14.6741	0	0	70.0006	7.1506
8	30	30.0000	14.56	0.1	0.34	75	8.0884
9	30	30	14.65	0.59	0.76	76	8.763
10	30	30	13.16	1.98	4.86	80	11.3239
11	29.9071	28.7339	11.6339	7.726	0	78.0009	8.7312
12	29.7342	24.4928	10.0601	9.7132	0	74.0002	8.1138
13	29.356	20.8006	11.4195	10.4214	0	71.9974	7.5845
14	29.8534	22.39	10.1004	9.6526	0	71.9963	7.5655
15	29.7074	23.6411	14.6061	8.0408	0	75.9955	8.339
16	29.8982	29.0115	16.155	4.9332	0	79.9978	8.6622
17	30	30	16.14	1.1	7.76	85	9.2299
18	30	30	19.13	0.1	8.77	88	9.0316
19	30	30	17.53	0	12.47	90	8.9567
20	30	30	18.95	0	8.05	87	8.7119
21	29.8444	29.2089	18.9412	0	0	77.9946	7.0386
22	29.7997	22.2131	18.9824	0	0	70.9951	5.9011
23	27.5284	17.7452	19.7238	0	0	64.9975	5.028
24	22.4884	14.5431	18.9651	0	0	55.9966	4.06
						Total Cost	168.20

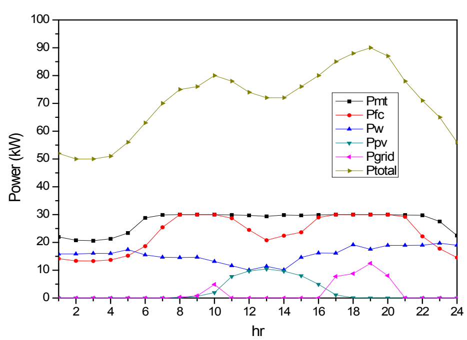

Figure 4. Generation scheduling results obtained using MAIMD-Model 2.

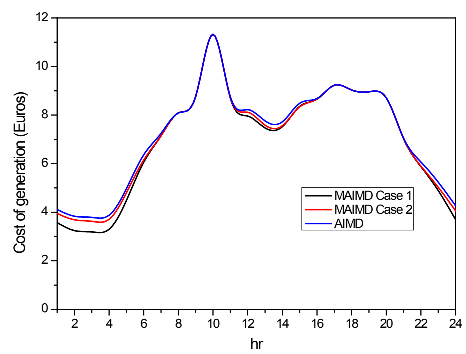

Figure 5. Comparison of cost of generation.

4.1 Application of Two Stage Algorithm for Reducing Grid Dependability in a Grid Connected Microgrid

We have considered a microgrid scenario with one wind mills of 750 kW capacity, two PV plants of 200 kW capacity each, one Fuel cell with 700 kW capacity and one Micro turbine with 700 kW capacity in grid connected mode. A battery storage of 300 kWh capacity, which is approximately 10% of the nominal power capacity of the microgrid, which is optimum storage[15] is connected to reduce the dependency on grid and hence to reduce the cost of power drawn from the grid. The cost particulars of the battery are not considered here as the aim of the paper is to promote the effectiveness of MAIMD algorithm in reducing the grid dependency. The maximum charging and discharging rates of the battery are taken as 100 kW, such that the battery can support at least for 3 hours at the maximum discharge rate and the minimum allowable state of charge is considered as 30 kWh, beyond which the battery has to be disconnected. The state of charge of the battery is evaluated at each hour span using

$$C_{Bat\,(t+1)} = C_{Bat(t)} \pm P_{Bat}\,.\,t \quad (8)$$

where C_{Bat} is the state of charge in kWh, P_{Bat} is the battery power in kW which is taken as positive while charging and negative while discharging and *t* is the time interval. The battery is charged when excess power is available and is discharged when there is deficiency. The load and the generation are sampled at a time interval of one hour. The hourly maximum power availability from wind and solar generators and the demand are as given in Table 6[12], in which Pm denotes the max real power availability. The cost of generation of power are taken from Table 2.

For implementing the proposed algorithm, The Renewable Energy sources are utilized completely and the non-renewable generators (MT and FC) are prioritised based on the hourly cost of generation of one unit of energy in the first stage. Minimum generation from the non-renewable generators is taken as 30kW. In the second stage of algorithm, MAIMD- Case 1 is implemented assuming that the generation facilities are owned by the microgrid owner and there is no need to use all the generators simultaneously. At each hour, the wind and PV sources are utilized completely before scheduling the MT and FC sources.

The graph in Figure 6 summarises the maximum power availability with each plant (Pm) and the power developed by the individual unit (Pg), Power drawn from grid (Pgrid), charging and discharging powers of the battery storage, after implementing the MAIMD-Case 1. The scheduled generation is summarized in Table 7, in which Pg denotes the real power generated. It shows that the renewable energy sources are completely exploited. It also shows that the cheaper source MT is completely exploited before accessing the FC source, whose bidding is on higher side at each hour (Table 2). Table 7 proves that the proposed algorithm is effective in scheduling generation, wherein total generation (*Pgtotal*) is exactly matched by demand plus charging power of the battery (*demand* + *Pcharg*), sparing the error allowed.

Table 6. Hourly generation of wind and PV generators (kW)

Hour	Pmwind	Pmpv1	Pmpv2	Demand
0	429	0	0	1471
1	442	0	0	1325
2	220	0	0	1263
3	39	0	0	1229
4	22	0	0	1229
5	168	0	0	1321
6	352	0	15	1509
7	532	45	71	1663
8	498	83	101	1657
9	504	111	124	1644
10	508	131	147	1644
11	366	144	160	1652
12	373	147	165	1666
13	196	140	160	1639
14	74	130	143	1640
15	23	107	120	1640
16	138	78	86	1676
17	381	42	46	1920
18	617	0	1	2214
19	652	0	0	2382
20	706	0	0	2382
21	744	0	0	2327
22	696	0	0	2174
23	711	0	0	1903
24	721	0	0	1666

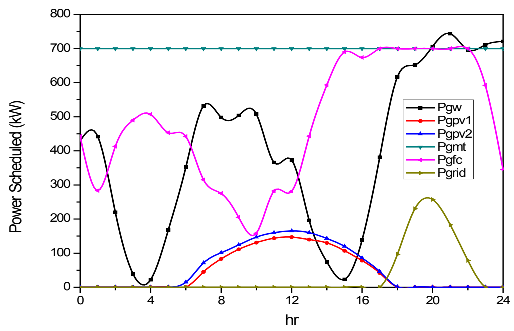

Figure 6. Generation scheduling with storage.

Table 7 also shows that the battery is discharged to meet the excess load before any power is drawn from the grid. Power is drawn from the grid only when the battery discharge is not sufficient to meet the load along with other generators. Figure 7 which shows the grid power drawn in presence and in absence of battery storage, endorses the aim of this work, i.e., application of the proposed algorithm to reduce the grid dependability. Figure 8 validates the application of the algorithm for optimization of cost of power drawn from the grid, which shows the cost of power drawn from grid in presence and absence of the energy storage. The cost of grid power is 100.34 Euros in absence of storage. It is reduced to Euros 82.79 in presence of storage, with net saving of approximately 21% when evaluated numerically. Figure 9 shows the hourly charging and discharging powers of the battery and Figure 10 shows its hourly state of charge. Table 8 shows the summarized generation schedule without a battery storage.

Table 7. Hourly generation scheduling results with storage (kW)

hour	Pgmt	Pgfc	Pgw	Pgpv1	Pgpv2	Pgrid	Pdischrg	Pgtotal	Pchrg	Demand	State of charge of battery	Pgrid cost
0	700	442.19	429	0	0	0	0	1571.19	100	1471	30	0
1	700	283.12	442	0	0	0	0	1425.12	100	1325	130	0
2	700	413.13	220	0	0	0	0	1333.13	70	1263	230	0
3	700	490	39	0	0	0	0	1229	0	1229	300	0
4	700	506.95	22	0	0	0	0	1228.95	0	1229	300	0
5	700	453.15	168	0	0	0	0	1321.15	0	1321	300	0
6	700	442.19	352	0	15	0	0	1509.19	0	1509	300	0
7	700	315.08	532	45	71	0	0	1663.08	0	1663	300	0
8	700	275.14	498	83	101	0	0	1657.14	0	1657	300	0
9	700	205.12	504	111	124	0	0	1644.12	0	1644	300	0
10	700	158.17	508	131	147	0	0	1644.17	0	1644	300	0
11	700	282.13	366	144	160	0	0	1652.13	0	1652	300	0
12	700	281.15	373	147	165	0	0	1666.15	0	1666	300	0
13	700	443.08	196	140	160	0	0	1639.08	0	1639	300	0
14	700	593.14	74	130	143	0	0	1640.14	0	1640	300	0
15	700	690	23	107	120	0	0	1640	0	1640	300	0
16	700	673.91	138	78	86	0	0	1675.91	0	1676	300	0
17	700	700	381	42	46	0	51	1920	0	1920	300	0
18	700	700	617	0	1	96	100	2214	0	2214	249	4.8
19	700	700	652	0	0	230	100	2382	0	2382	149	14.03
20	700	700	706	0	0	257	19	2382	0	2382	49	46.52
21	700	700	744	0	0	183	0	2327	0	2327	30	14.09
22	700	700	696	0	0	78	0	2174	0	2174	30	3.35
23	700	591.95	711	0	0	0	0	2002.95	100	1903	30	0
24	700	345.13	721	0	0	0	0	1766.13	100	1666	130	0
											Total	**82.79**

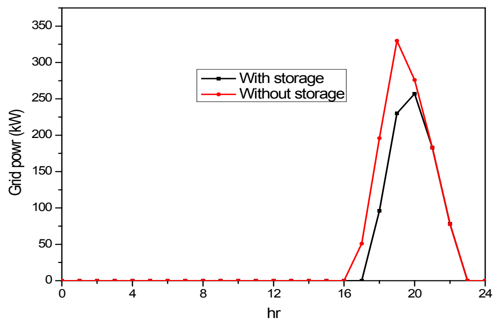

Figure 7. Power drawn from grid.

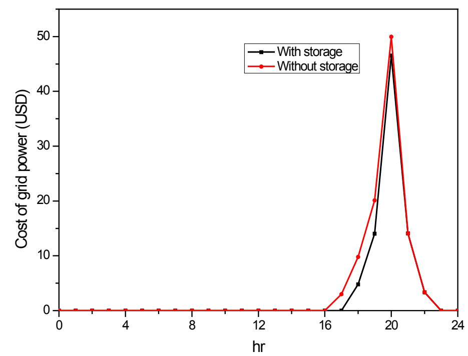

Figure 8. Cost of power drawn from grid.

Table 8. Hourly generation scheduling without storage (kW)

hour	Pgmt	Pgfc	Pgw	Pgpv1	Pgpv2	Pgrid	Pgtotal	Pgrid cost
0	700	342.04	429	0	0	0	1471.04	0
1	700	183.19	442	0	0	0	1325.19	0
2	700	343.07	220	0	0	0	1263.07	0
3	700	490	39	0	0	0	1229	0
4	700	506.95	22	0	0	0	1228.95	0
5	700	453.15	168	0	0	0	1321.15	0
6	700	442.19	352	0	15	0	1509.19	0
7	700	315.08	532	45	71	0	1663.08	0
8	700	275.14	498	83	101	0	1657.14	0
9	700	205.12	504	111	124	0	1644.12	0
10	700	158.17	508	131	147	0	1644.17	0
11	700	282.13	366	144	160	0	1652.13	0
12	700	281.15	373	147	165	0	1666.15	0
13	700	443.08	196	140	160	0	1639.08	0
14	700	593.14	74	130	143	0	1640.14	0
15	700	690	23	107	120	0	1640	0
16	700	673.91	138	78	86	0	1675.91	0
17	700	700	381	42	46	51	1920	3.01
18	700	700	617	0	1	196	2214	9.8
19	700	700	652	0	0	330	2382	20.13
20	700	700	706	0	0	276	2382	49.96
21	700	700	744	0	0	183	2327	14.09
22	700	700	696	0	0	78	2174	3.35
23	700	492.06	711	0	0	0	1903.06	0
24	700	245.17	721	0	0	0	1666.17	0
							Total	100.34

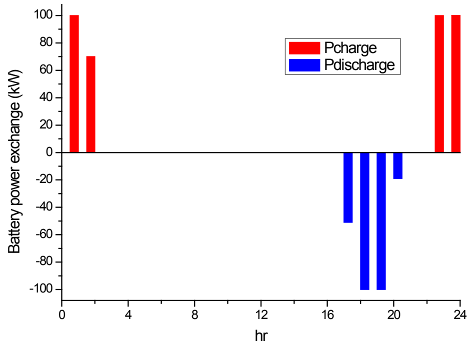

Figure 9. Battery power exchange.

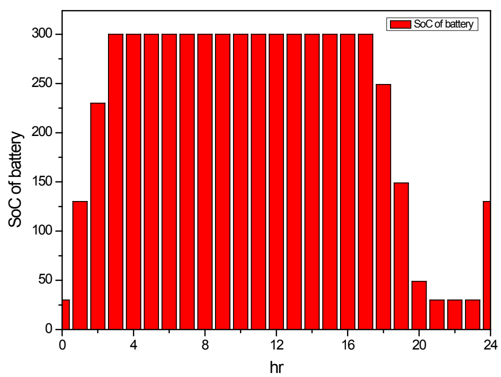

Figure 10. State of charge of the battery.

5. Conclusions

The success of an optimization algorithm for generation scheduling lies in its ability to choose a proper mix of generation among the available sources. Its effectiveness is more challenged in a microgrid with RESs, owing to the uncertainty of power availability. The effectiveness of real time generation scheduling is always restricted by the response of communication system and the electromechanical governors at the far end generators. To overcome this, the optimization algorithm should be able to schedule generation with lesser communication requirements. The Increase/Decrease algorithm is a handy solution for the purpose. This paper introduces a two stage algorithm, which in the first stage prioritises the ESs based on the cost function and schedules power generation among the ESs using a modified AIMD algorithm in the second stage. The algorithm is tested and validated using a test system in a microgrid, comprising of a wind, a solar PV, a micro turbine and a fuel cell as generators with a load curve over 24 hours at a time interval of 1 hour. The proposed algorithm is found to be effective in scheduling generation to meet the demand and in achieving optimality in generation economics. Having established the effectiveness of the algorithm for optimization, it is applied to reduce the dependency on the grid in a microgrid with one wind and two PV generators with battery storage in grid connected mode. Inclusion of storage to an extent of approximately 10% of the nominal capacity of the microgrid is found to reduce the cost of power drawn from the grid by approximately 21% for the chosen scenario. The algorithm can be extended to any optimisation problem, with of course, suitable modifications. Examples are reactive power management, VPP and grid integration etc.

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