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Research Article

Design and implementation of a peer-to-peer energy trading scheme in multi-microgrid network with photovoltaics and wind energy

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Abstract: Expected widespread deployment of Peer-to-Peer energy transactions through affective utilization of Renewable Energy Sources require efficient energy transaction mechanism among the microgrids. We propose a scheme to establish peer-to-peer energy trading in multi-microgrid network by considering photovoltaic and wind energy systems. The research objectives are to minimize overall cost of all microgrids in multi-microgrid network and minimize the loading on centralized power network. Various parameters of photovoltaics and wind energy systems are modeled to explore their impact on P2P energy trading. Energy Management Unit establishes the smart contracts among microgrids, manages power transactions and calculates the cost based on dynamic pricing scheme in the multi-microgrid network. Two different cases are considered with respect to the types of power transaction among the microgrids in the multi-microgrid network and main grid. The effectiveness of the proposed scheme is validated by implementing on local small-scale power distribution system.

Keywords: *Energy management, Peer-to-peer energy trading, Microgrid, Renewable energy, power system optimization*

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1. INTRODUCTION

The demand supply gap of electrical energy is increasing in Pakistan due to ever-increasing population and infrastructure. There is required for development of renewable energy systems, which can decrease demand-supply gap and carbon emissions. Some efforts done for Integrated Energy Modeling (IEM) considering various factors related to energy planning and gaps in IEM were presented in [1]. Long range Energy Alternatives Planning System (LEAP) based models of China-Pakistan Economic Corridor (CPEC) power projects were discussed in [2] where forecasting and policy constraints were presented considering economic and environmental effects.

Potential of wind power at various locations in Pakistan was investigated in Ref. [3] by considering wind speed, power density and capacity factor of different turbines. A study to analyze potential of wind energy along coastal area of Pakistan was presented in Ref. [4]. In Ref. [5], authors presented a study to prioritize the locations for wind projects, which indicates that Jamshoro and Sindh are the most suitable candidates. According to Ref. [6], the analysis of steps taken for clean energy systems development in Sindh, Pakistan for the recommendation of the integration of wind energy with national grid. Different scenarios for development of renewable power plants based on LEAP model were elaborated in Ref. [7] by considering plans of power expansion, emissions and cost of fossil fuels. Wind energy model based on Weibull distribution was developed in [8] to find optimal location considering wind turbulence intensity, capacity factor and shear exponent. A feasibility analysis was presented in Ref. [9] to investigate effectiveness of wind energy potential along coastal line of Pakistan and Artificial Neural Network (ANN) based model was implemented to evaluate operational, geographical and financial factors.

Many schemes have been implemented by the research community to develop and optimize integrated microgrid systems by using RES. In Ref. [10], authors presented a hybrid Photovoltaic (PV) and wind integrated simulation model using intelligent controller in microgrid network. Cooperative control scheme considering both plug in hybrid vehicles (PHEVs) and wind generators was proposed in [11] to investigate most suitable frequency regulation technique. A multi-objective optimization model for energy management was presented in [12] in order to cater the uncertainties of wind energy forecasting in microgrid and solved by using AAN. To enhance the forecasting accuracy of wind power generation, a two stage hierarchical approach was proposed in [13] considering various meteorological parameters in microgrid structures. In Ref. [14], authors developed a wind turbine emulator to simulate its behavior in laboratory, when integrated with microgrid. Model predictive control (MPC) to address uncertainty of energy prices of microgrid is proposed in [15] by considering electrical vehicles and local wind power generation. In Ref. [16], authors presented distributed control structure for load sharing of non-active components of PV and wind integrated microgrid. An economic dispatch (ED) model for energy intensive industries (IIE) was developed and simulated in [17] to minimize energy cost by integration PV and wind energy sources with microgrid. A microgrid model including PV, wind and energy storage system (ESS) was designed in [18] by using hierarchical control strategy and verified considering various operational modes. A scheme for power sharing control was proposed in [19] to coordinate PV and wind energy in system dispatch considering uncertainties of renewable energy systems. In [20], demand response (DR) program for time-of-use (TOU) tariff was implemented with the objectives to maximize customer benefit and price elasticity considering wind with energy storage system integrated Microgrid network. A heat gas integrated network for microgrid was modeled in [21] as nonlinear optimization problem to accommodate wind power to minimize operating and wind curtailment cost. In Ref. [22], authors presented an optimal scheduling model for integration of wind power generation with hybrid microgrid considering uncertainties in wind power, market pricing and power demands. A survey on 20 simulation softwares was presented in [23], which was used globally to investigate various efficiency parameters of microgrid with wind power generation. The authors proposed an agent based approach in [24] to model, simulate and forecast wind power integrated microgrid for cost effective energy solution.

Currently, a large number of research studies have been carried for effective implementation of P2P energy trading concept. A model for information and communication standards was presented in [25] for the development of P2P business model in a small scale microgrid network to minimize cost and carbon emissions. A P2P business model between cooperatives was presented in [26] considering smart contracting through block chain technology. Dual decomposition optimization based approach was proposed in [27] for optimal trading decisions considering privacy of prosumers in microgrid. In [28], the authors presented a P2P model for energy trading agreements based on day ahead scheduling and quoted price. Various simulation methods for P2P energy trading were reviewed in [29] considering distributed generation through renewable energy resources. A bi-level stochastic programming model was proposed in [30] to establish P2P energy trading between wind power producer (WPP) and demand response aggregator (DRA). Similarly, P2P model was implemented in [31] using smart features of consortium blockchain for power transactions and contract management in microgrid. To handle uncertainties in WPPs, a P2P trading model was proposed in [32] in order to manage mutual contract for energy transactions. P2P energy trading for prosumer community based on blockchain technologies was proposed in [33] considering uniform price and double auction mechanisms. A study was conducted in [34] to investigate effectiveness of P2P energy trading mechanisms in zero energy buildings considering wind and solar energy generations.

The concept of P2P for Multi-Microgrid (MMG) is recently developed by research community to enhance efficiency, effectiveness and reliability of power system. A hierarchical P2P (HP2P) approach was implemented in [35] to minimize energy cost for all users connected with community distribution network. A non-cooperative pricing mechanism based on multi-dimensional willingness considering time pressure in Multi-microgrid system was proposed in [36]. To enhance the utilization of renewable energy though distributed generation, a Nash bargaining problem was modeled and implemented in [37] for P2P trading between multi-energy interconnected microgrids. In Ref. [38], deep neural network (DNN) based algorithm was implemented to design hybrid invertor for efficient utilization of renewable energy i.e. photovoltaic and wind based power generation in smart grid. A similar technique based on maximum power point tracking (MPPT) and DNN was presented in [39] to improve quality of output power from PV and fuel cell in microgrid paradigm.

Despite many studies already conducted for multi-microgrid P2P energy trading, still there is a need for development of comprehensive wind and solar power generation models and incorporation of developed model in MMN. The developed schemes focusing on P2P trading through competition among users, which limits the energy utilization for remaining users. A centralized scheme may be required, which can treat all users equally to mitigate the competition. The main contributions of the present paper are summarized in the following:

Mathematical model of PV and wind energy is developed to study effects of various parameters.
Mathematical model of MMN-EMU is developed to manage power transactions and contract establishment in MMN.
The pricing scheme based on DPS is developed and implemented for costing of energy transactions in MMN.
P2P energy trading in MMN algorithm is developed incorporating centralized contracting and pricing features facilitating all networked microgrids equally.
Proposed scheme is implemented on four networked microgrids and validated considering various cases.

The rest of paper is organized as follows: Section 2 provides mathematical model for MMN-P2P energy trading. Section 3 provides the proposed solution scheme. The simulation results are elaborated in Section 4 and conclusion are furnished in Section 5.

2. MATHEMATICAL MODELLING

Mathematical model of Wind Energy, PV power system and MMN-P2P energy trading scheme is presented in this section considering various system parameters. Typical system model is presented in Fig. 1 indicating power and data flows in multi-microgrid network.

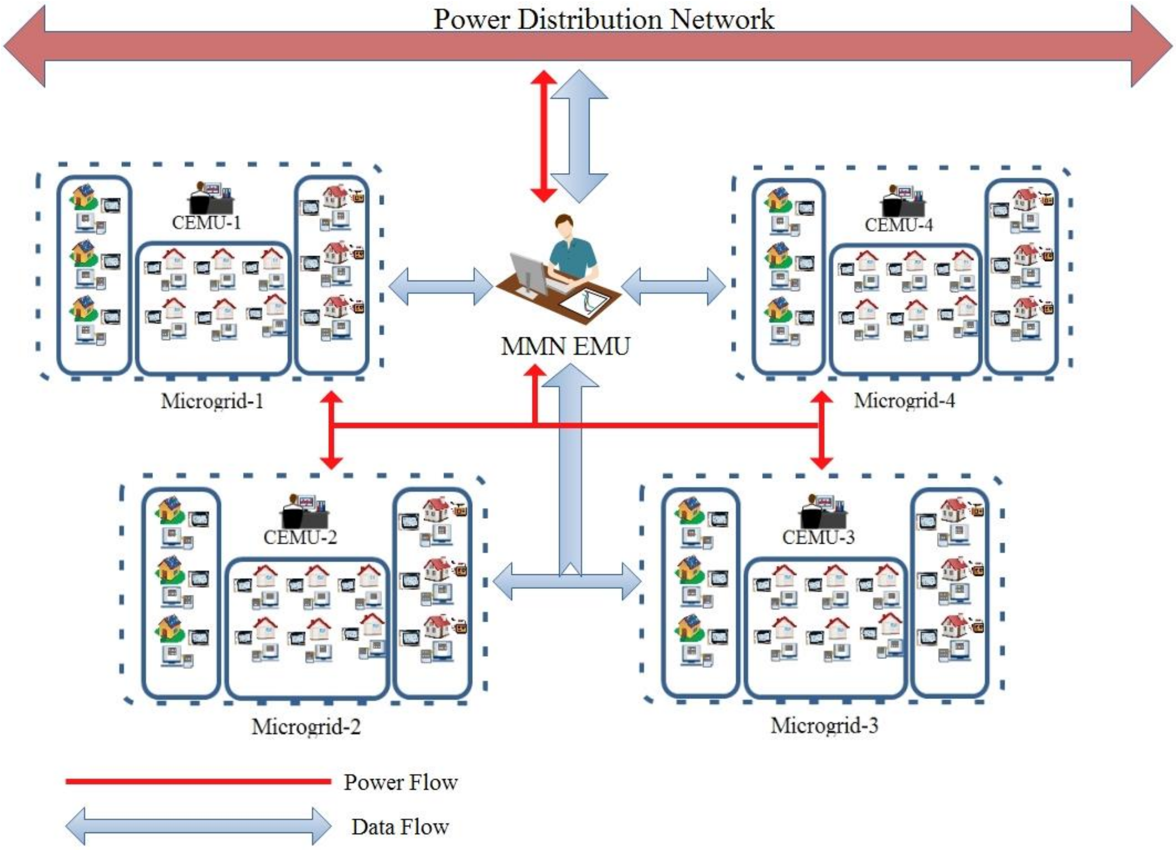

Figure 1. The schematics of multi-microgrid system model.

2.1. Wind Power Generation (WPG) Model

Mathematical model for WPG will be elaborated in this section, which calculates kinetic energy produced by wind turbine at specific wind speed. Kinetic power in wind can be calculated by Eq. (1):

$$P_w = \frac{dE}{dT} = 0.5\left(\frac{dm}{dT}\ v^2\right) \tag{1}$$

where P_W is kinetic power of wind, dE/dT is mass flow rate and can be written as pAv in which p is mass density, A is surface area and v is the wind velocity. Using these parameters, Eq. (1) can be written as:

$$P_w = \frac{p.A\,v^3}{2}, \tag{2}$$

where p(kg/m^3) can be defined as air density, blade cross-sectional area is represented by A(m^2) and $v(m/s)$ is wind velocity. Considering Betz limit for efficiency of wind turbine, Eq. (2) can be represented as follows:

$$P_T = \frac{p.\pi r^2\, v^3\, c_p}{2} \tag{3}$$

According to Betz Law, maximum possible conversion of wind energy into mechanical energy, defined as power coefficient is 59%. It is noteworthy that c_p is having dynamic properties based on aerodynamic design of turbine blades rather than a static value. It is function of pitch angle (β) of blade and tip speed of blade. Tip speed can be defined as,

$$t_{speed} = \frac{v_T}{v}, \tag{4}$$

where t_{speed} tip speed of blade, v_T is turbine speed and v is the wind speed. The parameter v_T depends upon angular speed of blade and diameter of wind turbine.

$$v_T = \frac{\omega \pi d}{60}, \tag{5}$$

where angular speed of blade is denoted as ω and d is wind turbine diameter. Similarly, torque induces in wind turbine rotor is expressed in Eq. (6).

$$\tau_T = \frac{P_T}{\omega} = \frac{0.5\, p\, \pi r^2\, v^3\, c_p\left(t_{speed}, \beta\right)}{\omega} \tag{6}$$

In Eq. (6), τ_T (Nm) is torque generated in wind turbine due to wind with velocity v. The variations in wind speed directly affect power generation of wind turbine. To understand true behavior of wind turbine, the probability distribution function (PDF) of wind is an important consideration. A mathematical model for wind speed/ power using famous Weibull distribution is presented in Eq. (7).

$$f(V_{mean}) = \frac{k}{\gamma}\left(\frac{V_{mean}}{\gamma}\right)^{k-1} \exp\left\{-\left(\frac{V_{mean}}{\gamma}\right)^{k}\right\}, \tag{7}$$

where V_{mean} is mean wind speed and γ is parameter for Weibull scale which measures characteristics wind speed in m/sec. the form parameter k specifies shape of Weibull and its value determines wind variations (Larger k for constant wind and small k for high variations).

2.2. Solar Power Generation (SPG) Model

Power generation model of PV is presented in this subsection. The SPG is mainly dependent on solar irradiance.

$$I_{p.c} = \{I_{sc} + I_{t=25}(T - 298)\}\, \frac{I_{irr}}{1000} \tag{8}$$

In Eq. (8), $I_{p.c}$ is photo current, I_{sc} is short circuit current, $I_{t=25}$ is current at 25°C, T is operating temperature and I_{irr} is solar irradiation. Reverse saturation current of module can be calculated by using Eq. (9).

$$I_{rev.sat} = \frac{I_{sc}}{\left\{\exp\left(\frac{qV_{oc}}{N_C knT}\right) - 1\right\}}, \tag{9}$$

where q represents electron charge, V_{oc} is open circuit voltages, N_c is number of series connected cells, k is Boltzmann's constant and n is ideality factor of photo diode.

$$I_{sat} = I_{rev.sat}\left(\frac{T}{T_{nominal}}\right)^3 \exp\left\{\frac{q\, E_{bg}}{nk}\left(\frac{1}{T} - \frac{1}{T_{nominal}}\right)\right\} \tag{10}$$

In above equation, I_{sat} is saturation current of diode and E_{bg} is band gap energy of semiconductor (1.1 eV). The output current of module is modeled in Eq. (11).

$$I_{o/p} = N_{pv}\, I_{p.c} - N_{pv}\, I_{sat} \left\{ \exp\left(\frac{\frac{V}{N_c} + I\, \frac{R_{series}}{N_{pv}}}{n\, V_t} \right) - 1 \right\} - I_{shunt} \tag{11}$$

Thermal voltage for diode (V_t) can be modeled as,

$$V_t = \frac{k\, T}{q}, \tag{12}$$

and shunt current can be defined as

$$I_{shunt} = \frac{V\, \frac{N_{pv}}{N_c} + I_{\frac{o}{p}}\, R_{series}}{R_{shunt}} \tag{13}$$

2.3. Wind and PV Integrated Multi-Microgrid P2P Energy Trading Model

In MMN, users in each microgrid have their power demands. In Eq. (14), the power demands of N Microgrids are indicated where time T approaches to 24 hours. The power demands of all networked Microgrids stored in P_D, which is based on day-ahead energy forecasting.

$$P_D = \left[P_{d,i}^1, P_{d,i}^2, P_{d,i}^3 \dots, P_{d,i}^T\right] \quad i\epsilon[1,2,3 \dots N] \tag{14}$$

Each microgrid have its own sources of energy generation. This generated energy can be utilized inside microgrid, as well as, surplus energy can be shared with other microgrids through MMN. In Eq. (15), power generation of all networked microgrids is presented for 24 hours. P_G contains the power generation information of each networked microgrid.

$$P_G = \left[P_{g,i}^1, P_{g,i}^2, P_{g,i}^3 \dots, P_{g,i}^T\right] \quad i\epsilon[1,2,3 \dots N] \tag{15}$$

The deficit energy ($P_D - P_G > 0$) is calculated for each microgrid. This shortfall of energy can be fulfilled through MMN or main grid. In proposed solution, first priority to given to energy available in MMN. In Eq. (16), the information of energy deficiencies in each microgrid is stored in D_{DEF}.

$$D_{DEF} = \left[D_{def,i}^1, D_{def,i}^2, D_{def,i}^3 \dots, D_{def,i}^T\right] \quad i\epsilon[1,2,3 \dots N] \tag{16}$$

In prosumer community, each microgrid have some energy generations and power demand. During some hours of the day, any microgrid may have its power demand lower then power generation. This extra generated energy can be defined as surplus energy($P_G - P_D > 0$) of Microgrid. In MMN, surplus energy of connected Microgrids can be utilized by other microgrids having energy deficiencies. The information of surplus power for each networked microgrid is stored in S_P as shown in Eq. (17).

$$S_P = \left[S_{p,i}^1, S_{p,i}^2, S_{p,i}^3 \dots, S_{p,i}^T\right] \quad i\epsilon[1,2,3 \dots N] \tag{17}$$

In Eq. (18), the available surplus energy for each microgrid in MMN is calculated where D presents the set of MGs with deficit energies. The total surplus energy of all MGs is equally distributed among deficit energy microgrids. This approach eliminates competitions between MGs and ensures availability of power to each microgrid.

$$S_{AVAIL} = \frac{\sum_{i=1}^{N} S_{p,i}^{t}}{D} \tag{18}$$

$$S_{AVAIL} = \left[S_{avail,i}^{1}, S_{avail,i}^{2}, S_{avail,i}^{3} \ldots., S_{avail,i}^{T}\right] \;\; i\epsilon[1,2,3 \ldots..N]$$

After calculation of surplus energy for each microgrid, it is evident that there may be some energy deficiencies, which cannot be fulfilled using available power in MMN. This shortage can be defined as energy requirement from main grid. The information of energy requirement from main grid can be stored in D_{MAIN} as shown in Eq. (19).

$$D_{main,i} = D_{def,i} - S_{avail,i} \tag{19}$$

$$D_{MAIN} = \left[D_{main,i}^{1}, D_{main,i}^{2}, D_{main,i}^{3} \ldots., D_{main,i}^{T}\right] \;\; i\epsilon[1,2,3 \ldots..N]$$

During contracting for P2P energy trading in MMN, maximum and minimum limits of various parameters (power demand, power generation, surplus power and deficit power) will be defined by each microgrid as presented in Eq. (20).

$$P_{d,i,min}^{t} \leq P_{d,i}^{t} \leq P_{d,i,max}^{t}$$

$$P_{g,i,min}^{t} \leq P_{g,i}^{t} \leq P_{g,i,max}^{t}$$

$$S_{p,i,min}^{t} \leq S_{p,i}^{t} \leq S_{p,i,max}^{t} \tag{20}$$

$$D_{main,i,min}^{t} \leq D_{main,i}^{t} \leq D_{main,i,max}^{t}$$

Eq. (21) presents total power demand of multi-microgrid network. Power demand of individual MGs depends upon energy users in respective microgrid.

$$PD_{total}^{t} = \sum_{i=1}^{N} P_{d,i}^{t} \quad t\epsilon T \tag{21}$$

In prosumer community, some users in MGs may have capacity of power generation. The sources of power generation will be different such as SPG, WPG and diesel generators. In Eq. (22) total power generation of MMN is calculated considering all types of generation in microgrids.

$$PG_{total}^{t} = \sum_{i=1}^{N} P_{g,i}^{t} \quad t\epsilon T \tag{22}$$

Surplus power in MMN at any instant can be calculated using Eq. (23). Some energy from PS_{total}^{t} can be send to main grid when excessive energy is being produced in MMN.

$$PS_{total}^{t} = \sum_{i=1}^{N} S_{p,i}^{t} \quad t\epsilon T \tag{23}$$

At some instants, MMN requires some energy from main grid to fulfill power demands of users in microgrid. It can be calculated using Eq. (24) where PE_{total}^{t} presents excessive energy requirements from main grid at any instant t.

$$PE_{total}^{t} = \sum_{i=1}^{N} D_{main,i}^{t} \quad t\epsilon T \tag{24}$$

Supply to demand ratio of each microgrid in MMN can be calculated using Eq. (25), which presents energy efficiency of each MG.

$$SD_{ratio}^{t} = \frac{P_{g,i}}{P_{d,i}} = \frac{\sum_{i=1}^{N} P_{g,i}^{t}}{\sum_{i=1}^{N} P_{d,i}^{t}} \quad for\ all\ t\epsilon T \tag{25}$$

Finally, the daily energy cost of each microgrid in MMN can be calculated using Eq. (26). Each MG defines hourly based per unit energy cost and a normalized cost has been calculated by multi-microgrid network-energy management unit (MMN-EMU). The cost of energy utilized from main grid is calculated according to utility tariff.

$$Cost_{daily} = \sum_{t=1}^{24} (S_{avail,i}\, Cost_{MG}) + \sum_{t=1}^{24} (D_{main,i}\, Cost_{utility}) \tag{26}$$

3. SOLUTION SCHEME FOR P2P ENERGY TRADING IN MMN

A novel scheme to solve P2P Energy Trading in Multi-Microgrid Network is proposed in this section. An algorithm is developed to solve optimization problem considering various input parameters of prosumers community. The research work is an extension of P2P energy trading mechanism in microgrid, presented in [40]. Proposed MMN algorithm creates contracts among MGs, manages power transactions among MGs, monitors power transactions from/to main grid to/from MMN, calculates penalties upon violations of contracts, calculates energy cost for each microgrid. The flowchart of solution algorithm is shown in Fig. 2.

3.1. Optimization Objectives

The definition of optimization objectives is first stage of development of scheme. In this problem, two objectives are considered as *i*) Minimization of Energy Cost in MMN and *ii*) Minimization of Load on Main Grid. Total cost of utilized energy can be minimized using P2P in Microgrid and P2P in MMN. The cost minimization can be achieved by minimizing line losses in transmission and distribution networks, effective utilization of renewable energy and implementation of advanced smart metering technologies.

To achieve second objective, the load on main grid can be minimized using P2P energy transactions among various users in Microgrid/Multi-microgrid system. The prosumers of the network sell their surplus energy to the nearby consumers/Microgrids, which decreases power requirements from main grid.

3.2. Algorithm Inputs

The parameters of all interconnected microgrids are considered as algorithm inputs. It includes power generation, power consumption, available surplus energy, excess energy requirements and per unit energy cost of each microgrid. Energy cost of each microgrid depends on the source of power generation (i.e. Solar, wind or diesel generator). The power generation may also depend on environmental conditions and can be intermittent due to use of renewable energy resources. Similarly, power demand of consumers in any microgrid will vary based on energy utilization.

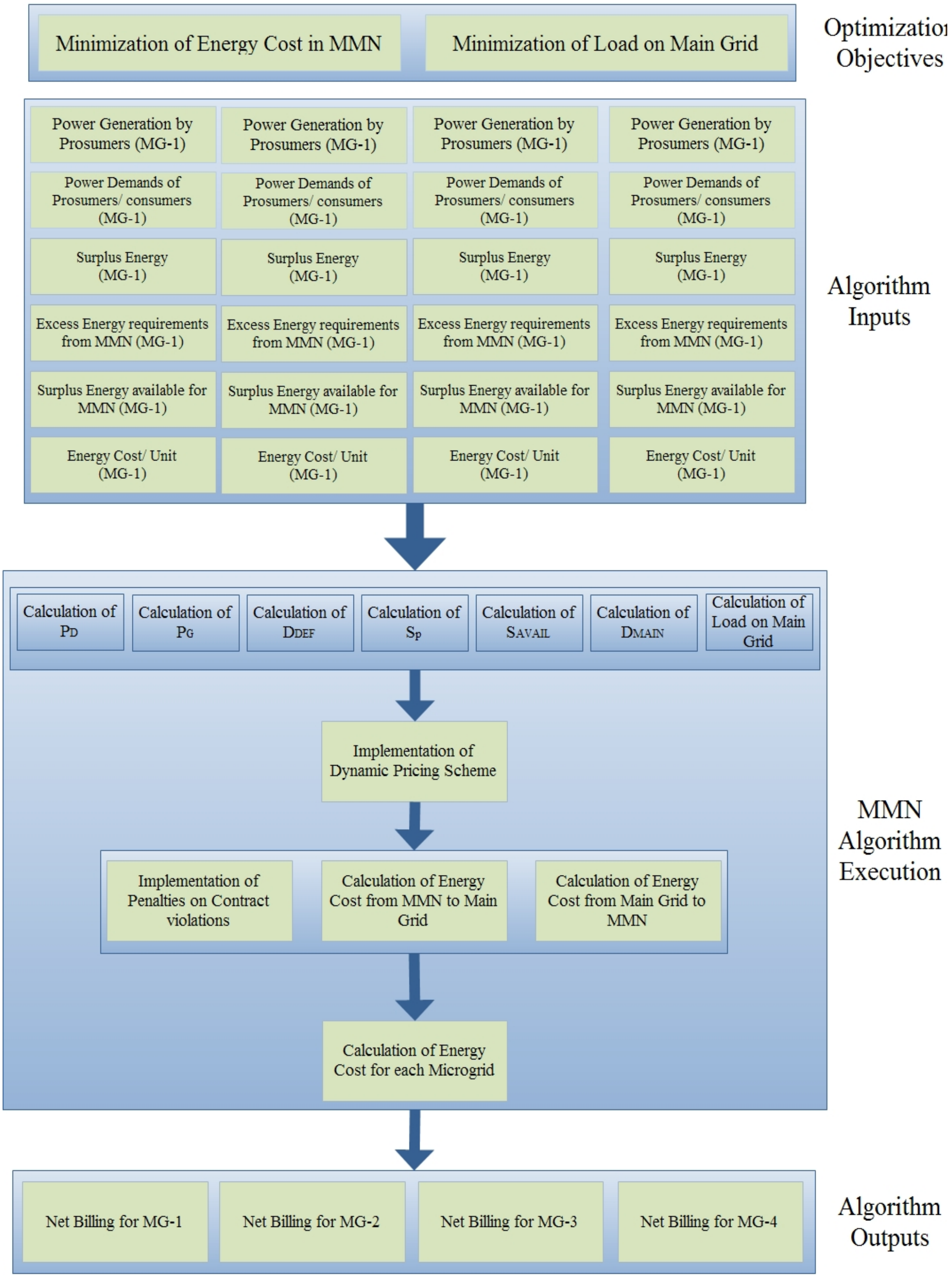

Figure 2. Flowchart of Solution Approach

3.3. Execution of MMN Algorithm

As shown in Fig. 2, the MMN algorithm is responsible for overall contracting and power transaction process in network. It works in following steps:

1. *Calculation of* P_D, P_G, D_{DEF}, S_P, S_{AVAIL}, D_{MAIN} *and* L_{MAIN}
2. *Contract establishment among Microgrids*
3. *Implementation of Dynamic Pricing Scheme (DPS) for uniform cost definition in MMN*

4. *Implementation of penalties on MGs violating contractual obligations*
5. *Calculation of energy cost of power transactions from/ to MMN to/ from main grid*
6. *Delivery of billing information to all Microgrids/ main grid*

3.4. Algorithm Outputs

The output of algorithm is the pricing and costing signals which are generated based on processing and power transaction in the MMN algorithm. At the end, the algorithm also calculates the parameters defined by all MGs (w.r.t generation and demand) and penalties are included in final energy cost of respective microgrid.

Table 1. Power generation and demand profiles of Microgrids in MMN

Time (Hours)	PG MG1 (KW)	PD MG1 (KW)	PG MG2 (KW)	PD MG2 (KW)	PG MG3 (KW)	PD MG3 (KW)	PG MG4 (KW)	PD MG4 (KW)
1	29	61	45	53	44	35	34	36
2	29	54	48	41	42	35	35	30
3	29	53	52	42	40	50	31	39
4	26	67	52	65	41	37	42	45
5	28	62	52	40	42	42	37	58
6	27	56	51	41	40	42	45	33
7	51	69	57	56	49	35	42	33
8	58	50	57	70	52	50	42	33
9	57	68	63	60	51	36	43	59
10	52	58	58	57	49	41	52	57
11	54	70	66	48	53	50	52	42
12	54	50	58	42	53	40	56	30
13	56	50	59	61	54	48	52	59
14	58	70	60	49	53	49	50	59
15	56	55	63	40	52	48	49	35
16	53	65	66	68	51	34	42	32
17	55	53	61	52	48	36	42	33
18	55	66	57	45	47	44	42	46
19	29	58	55	47	45	47	36	31
20	28	67	45	44	43	49	30	35
21	26	67	46	54	43	32	44	56
22	28	54	47	50	42	34	31	58
23	29	55	54	62	45	42	36	49
24	26	55	55	67	43	32	40	30

4. SIMULATION RESULTS

4.1. Important Assumptions

1. *ESSs are not considered in Multi-Microgrid Network.*
2. *All Microgrids in network are working in grid-connected mode.*
3. *The prosumers and Microgrids in MMN can update their information (power demand, generation surplus, energy price etc.) on hourly basis.*
4. *Fixed energy pricing tariff of main grid is considered.*
5. *Solar-based prosumers define minimum/ maximum power only during solar hours.*
6. *The algorithm is implemented on MMN with four (04) Microgrids as a test case and all calculations are performed for one day (24 hours). Same algorithm can be used to simulate more number of MGs for calculation of monthly energy pricing.*

4.2. Power Generation Profiles of Microgrids

Power generation and power demand profiles of microgrids in MMN are presented in Table 1. The power generation capacities of all microgrids are presented in Fig. 3. MG-1 is having 30 KW PV, 10 KW Wind and 20 KW diesel power generation capabilities. The energy-pricing tariff of MG-1 is 10 PKR/KWH. In MG-2, the power generation capacities are 15 KW PV, 30 KW wind and 25 KW diesel generator with energy costing as 12 PKR/KWH. Microgrid MG-3 has 10 KW photo voltaic (PV), 15 KW wind and 30 KW diesel power generation with pricing tariff of 15 PKR/KWH. Similarly, MG-4 is having 15 KW PV, 25 KW wind and 20 KW diesel power generation capacity. The energy cost of MG-4 is 11 PKR/KWH when sold as surplus power.

4.3. P2P-MMN Energy Trading - Various Cases

The effectiveness of proposed MMN algorithm is validated by considering two different cases in integrated microgrid network. In the first case, the excess power requirements of all microgrids are fulfilled through energy transactions from main grid. In this case, the surplus energy of each microgrid is sent to main grid during low load periods. The energy cost of all MGs and loading on main grid is calculated for Case-1. In Case-2, the power requirements are fulfilled through P2P transactions among Microgrids in network. Cost calculations are performed and comparison of both cases is presented at the end.

4.3.1. Case-1: All Power Transactions From/ To Main Grid

This case presents a conventional power transaction strategy to fulfill power demands and sell surplus energy. In this case, it is considered that all microgrids buy/ sell their excess/ surplus energy from/ to main grid. The total power demand of all connected microgrids varies from 160KW to 227KW as shown in Fig. 4. The variations in power demands depends upon intermittent nature of renewable energy generation resources and loading profiles of consumers in MGs.

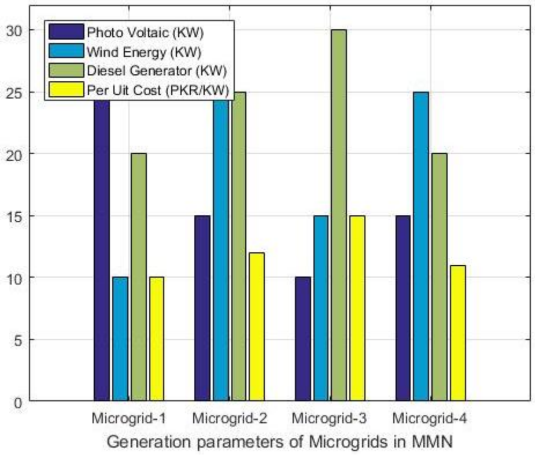

Figure 3. Power generation parameters of microgrids in MMN.

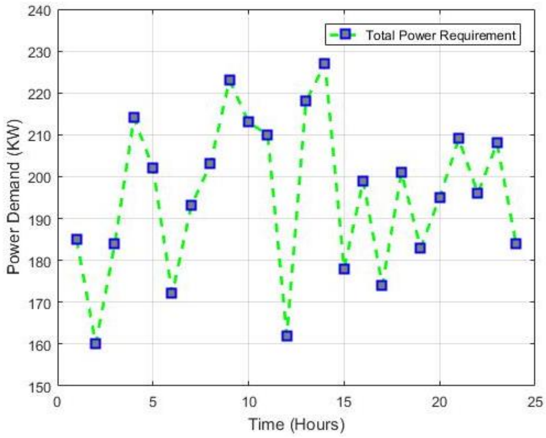

Figure 4. Total power demand of microgrids in MMN.

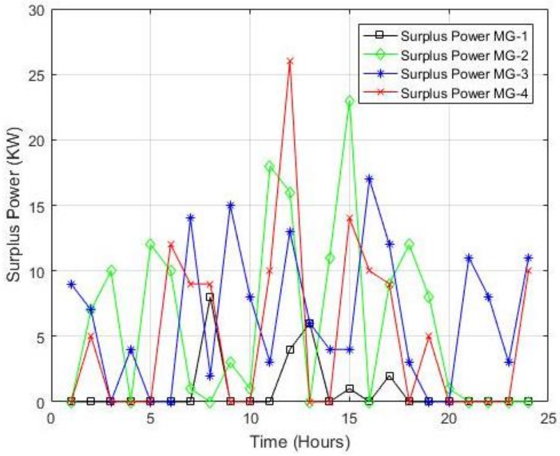

Figure 5. Surplus profiles of microgrids in MMN.

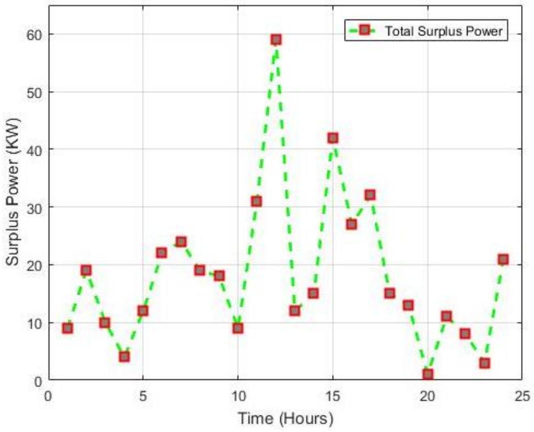

Figure 6. Available total surplus power.

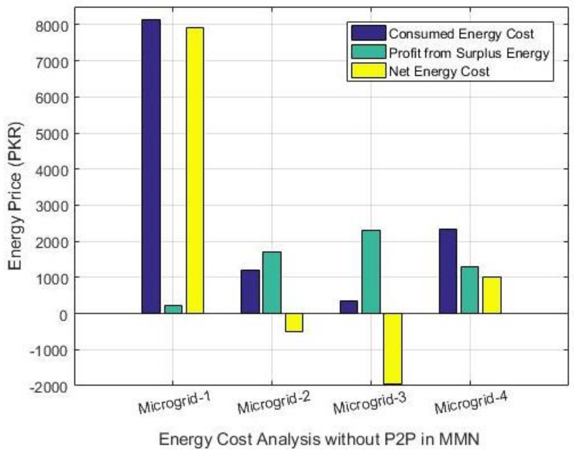

Figure 7. Case-1: Cost analysis of MMN w/o P2P

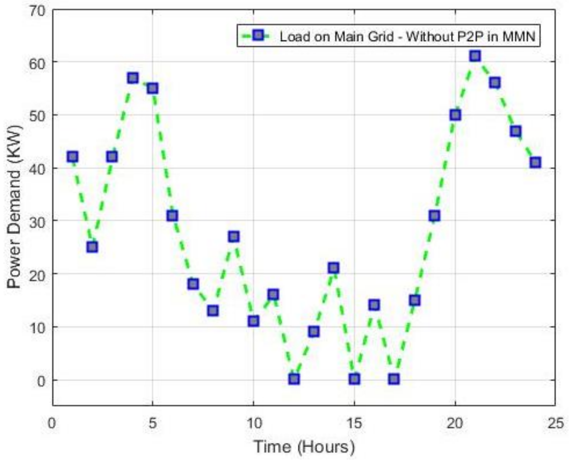

Figure 8. Case-1: Load on main grid w/o P2P energy trading.

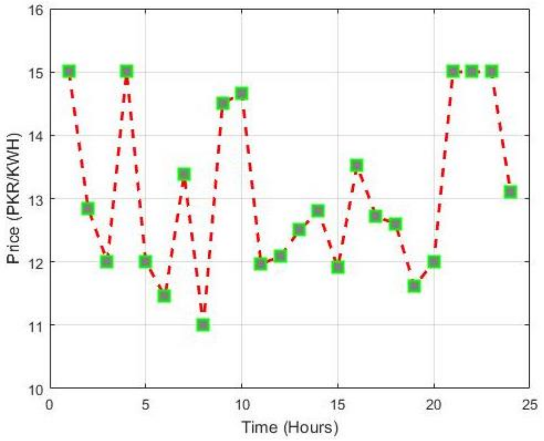

Figure 9. Dynamic pricing scheme in MMN.

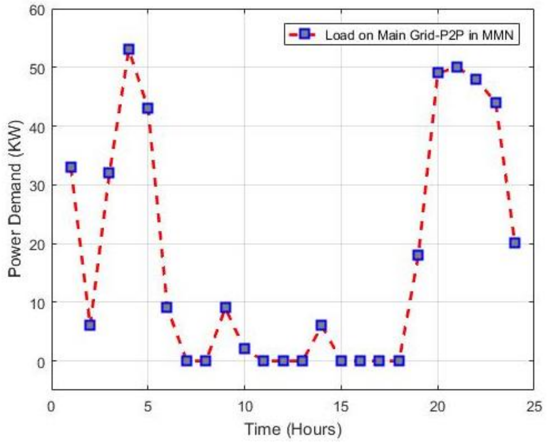

Figure 10. Case-2: Load on main grid with P2P. energy trading

The surplus power profiles of microgrids are shown in Fig. 5, presenting that MG-4 is having maximum surplus energy at 1,200 hours. It is noted that some MGs having zero surplus at some times of the day. The total surplus energy of all connected microgrids is shown in Fig. 6, indicating the minimum surplus as zero at 2,000 hours and maximum surplus energy of 59 KW at 1,200 hours. It is notable that surplus is more during solar hours as compared to off-solar hours due to PV generations.

The cost analysis of all microgrids in MMN is presented in Fig. 7. It represents that MG-1 has maximum daily energy cost of 8122 PKR. The profit of surplus energy from MG-1 is 210 PKR, hence net cost is 7912 PKR. The net cost of MG-2 and MG-3 is negative i.e. -489 PKR and -1985 PKR, respectively. Negative cost means that the daily utilization of energy is less as compared to total power generation of energy in respective microgrid. The net energy cost of MG-4 is 1016 PKR. The total cost of daily energy purchased from main grid 12016.84 PKR.

The main grid load due to MMN is presented in Fig. 8. The maximum load occurs at 2,100 hours, which is 61KW. On contrary, minimum main grid power (0 KW) is required at 1,200, 1,500 and 1,700 hours. During these hours, power generation of MMN is sufficient to meet the requirements of all microgrids. The total daily power requirement is 682 KW with the energy price of 12,016.84 PKR.

4.3.2. Case-2: P2P Energy Trading in Multi-Microgrid Network

In this case, the surplus energy is used to meet the requirements of MMN. It enables P2P energy transactions among microgrids upon availability of surplus energy. The excess energy (after fulfilling requirements in MMN) sent to main grid. Similarly, the energy demands of microgrids are preferably fulfilled by available surplus in MMN and excess energy demand will be fulfilled from main grid.

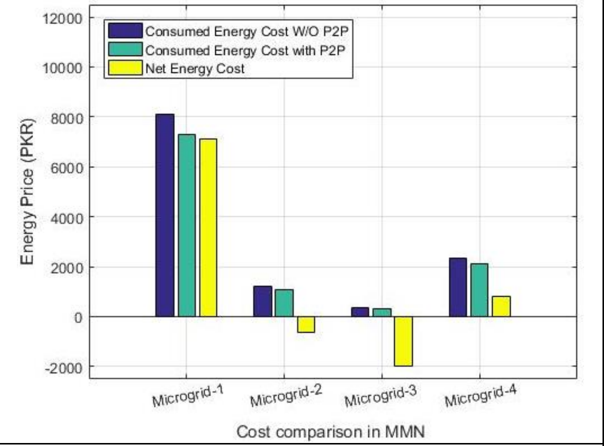

Figure 11. Case-2: Cost analysis of MMN with P2P energy trading.

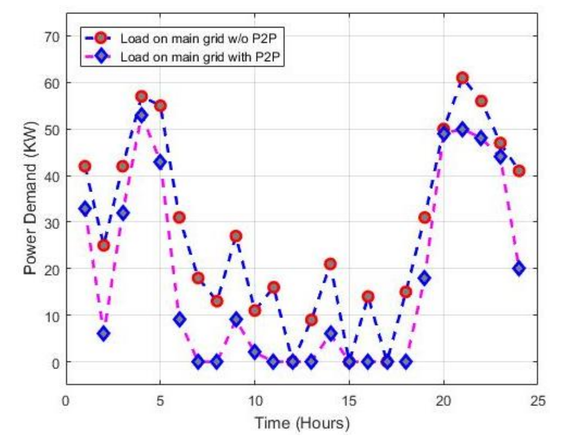

Figure 12. Comparison of load on main grid.

In MMN, the tariff for available surplus energy is set through dynamic energy pricing scheme (DPS), as shown in Fig. 9. As per DPS, maximum energy price in MMN is 15 PKR per KWH at 400, 2,100, 2,200 and 2,300 hours. The energy rates depends on availability and type of surplus energy. The minimum energy cost in DPS is 11 PKR/KWH at 800 hours.

A considerable decrease in main grid load is observed in Case-2, as presented in Fig. 10. The maximum energy requirement from main grid is 53 KW at 400 hours. On the other hand, the minimum power (0KW) is required from main grid at 700, 800, 1,100, 1,200, 1,300, 1,500, 1,600, 1,700 and 1,800 hours. It is notable that minimum load on main grid occurs during effective solar hours.

4.4. Comparison

The comparison of both cases with respect to energy cost is presented in Fig. 11. The result shows that energy cost for all micrograds is decreased by implementing P2P energy trading mechanism in MMN. The results show that proposed P2P-MMN scheme decreases the total cost of energy by 11%. The total daily energy cost of MMN reduced to 10821.5PKR from 121016.8PKR. The comparison of main grid load is shown in Fig. 12. It presents that the load on grid is decreased to a great extend using P2P energy trading in MMN. The total daily power required from main grid is reduced to 422 KW from 682 KW. The reduction in main grid load is about 61.6%, which mitigated the needs of expansion of distribution network due to ever-increasing power demands.

5. CONCLUSIONS

A detailed study on small-scale distribution microgrid network was conducted in this paper to identify and validate the benefits of proposed P2P-MMN energy trading scheme. The proposed scheme is centralized. It also considers RES penetrations due to wind and PV generations. The optimization problem is modeled mathematically and then simulated based on proposed methodology. The MMN algorithm is responsible to manage energy transactions among MGs, establishment of centralized contracting, establishment of DPS based energy tariff and calculation of bills and payments for all MGs in network. The algorithm solves energy trading problem considering two (02) key objectives *i*) Energy cost minimization and *ii*) Minimization of main grid load. Simulation results validate the effectiveness of proposed algorithm to achieve both objectives as, cost decreased by 11% and main load grid decreased by 61.6%.

Although, proposed algorithm is proved very effective for P2P energy trading mechanism in MMN, still some limitations related to Energy Storage System (ESS) needs attention of research community. The charging/ discharging dynamics of energy storage system can be modeled to enhance overall efficiency of P2P energy trading mechanism and RES utilization. The proposed MMN P2P mechanism can be extended by considering ESS and electric vehicle charging stations to increase the benefits of RES and shared economy concept for society.

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