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Hybrid Microgrid Load Flow Management using Model Predictive Control

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Abstract—The intermittence of the renewable energy resources coupled with the declining fossil fuel reserves have led to the development of hybrid AC/DC microgrids that not only elevate the benefits of each subsystem, but also curtails the deficiencies of the subsystems. Hence there is a pressing need to explore hybrid microgrid with the help of advanced controllers and techniques to increase the reliability and efficiency of the system. In this paper, we have employed Model Predictive Control (MPC) to control the output of the generators and meet the requirements of the grid with residential, industrial and highly integrated electric vehicle load. The hybrid microgrid system, taken under study, comprises PV system, Wind generator and diesel generator. The capability of the MPC will be observed for a 12-hour duration, with events of the charging/discharging of the electric vehicles and variations in the generated power due to uncertainty in the levels of irradiance and wind speed.

Index Terms— microgrid; model predictive control; pv system; wind generator; electric vehicle.

I. Introduction

In present world, a bulk amount of fossil fuel is used to produce energy and its depletion causes warming, energy crisis, ocean pollution, and many other environmental hazards, which are notice by world level society [1-2]. Renewable energy is reliable approach to solve such issue. Renewable energy includes biomass energy, wind energy, hydro energy, solar energy, etc. In such alternative energy sources, biomass energy attracts a lot for its numerous benefits like for neutralization of CO2 which makes environmental clean [3-5]. In highly developed countries, the residue and waste materials are utilized for combustion process to produce electricity from biomass in future. A survey for biomass is conducted in 2017 which tell 9% to 13% of energy contributes from biomass which is approximately 60 MJ in total amount of energy consumed. Moreover, Biofuels are also producing through biochemical or thermo-chemical reaction in biomass [6].

The energy sources can be classified as renewable and nonrenewable sources, and an additional third subcategory, nuclear energy, can be added. The famous nonrenewable sources are oil, coal and natural gas and the well-known renewable sources are solar radiation, wind power, geothermal heat difference, water flow potentials and biomass.

The production, transportation and storage of the energy are three subtitles in these issues. The aim is not only focus on sustainable energy production, but also its storage and transportation [7].

In the recent years the change in customer demand and the advancement in technologies, the need of reliable and fault resistant distributed network is more important now-a-days.

As energy demand is always increasing in power sector and load management is an important tool for any microgrid to continuously maintain the balance of energy generated and energy consumed by the end consumer. The basic control system in microgrid is used to calculate the total load demand of consumer at particular instant for balancing. The load management in large scale microgrid is actually an emergency plan to supply power to end consumer. The figure 1 shows the division of energy resources, and how the electricity is created from these resources.

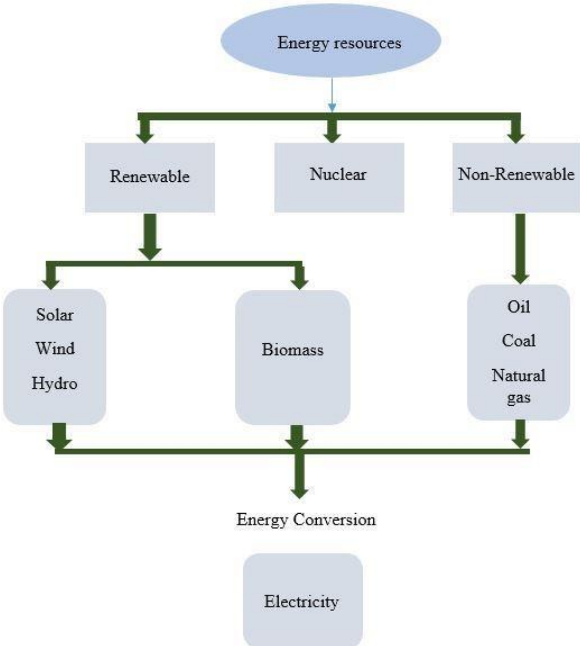


Figure 1: The division of energy resources

The model predictive control is used to solve multiple problems in power sector. The MPC has ability to find the optimal solution point on the basis of constrains, prediction horizon, control horizon and sampling time. The optimal objective function provide by MPC is based on minimum cost. The forecasting by sampling time in renewable energy sources is also one of the applications of MPC controller [8].

In the recent power world, a lot of research is done in photovoltaic cell. The deficiency of losses in photovoltaic cell increase the efficiency of Renewable energy resources, some latest techniques to recover losses by using MPPT algorithm to get maximum output by taking minimum input. moreover, the involvement of power electronics also another factor to increase its efficiency [9].

Most probably the radial distribution system is analyzed for load flow analysis is compiled to satisfy the customer demand, the distributed generator provides active power to radial distribution. The network consists of 12 buses and 69 buses on IEEE standard to compare the analysis of both load operating at constant power to reduce the energy loss at constant power load model which improves the efficiency of radial distributed network in microgrid [10].

As the main issues like change in dynamics and steady state factor faced by all Micro Grids, power electronic also includes HMG due to large amount of natural resources which increase the efficiency and control rate in hybrid microgrid.

II. MODELING OF THE HYBRID MICROGRID SYSTEM

The microgrid model has been taken from the MATLAB simulation [11] but MPC have been applied on the system by us to yield the desired output results.

A. Photovoltaic system

Among all the renewable energy resources, the photovoltaic (PV) power generation system has recently received a great attention from the power society due to its special features including low environmental impact, ease of integration and direct energy conversion. A disadvantage of solar-power generation is that it is difficult to achieve control of the power frequency or voltage when connected to a power grid because the output of solar-panels is unstable, and vary with weather conditions.

In photovoltaic cell the effect of temperature on thermal efficiency of photovoltaic cell can be obtained by using standard equation

$$P_m = V_m I_m = (FF) I_{sc} V_{oc}$$

Where FF is fill factor, I_m and V_m are the current and voltage maximum power point in I-V characteristics of photovoltaic cell.

The electrical efficiency of the photovoltaic cell as a function of temperature is represented by means of the linear expression given blew [12].

$$\hbar_c = hT_{ref}(1 - \mathcal{B}_{ref}(T_c - T_{ref}))$$

Where *h*ref is the electrical efficiency of the cell at the reference temperature, βref is the temperature coefficient, TC is the temperature of the cell and *T*ref is the reference temperature

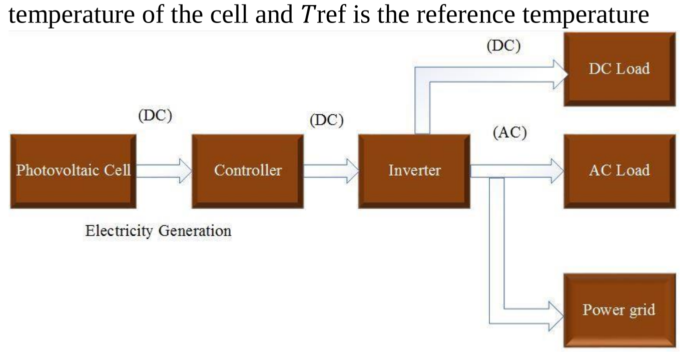


Figure 2: Schematic diagram of photovoltaic system

The figure 2 shows the block diagram of the PV system model. It shows that output is controlled by the controller, which is MPC, in this case, it then gives the three-phase power output to meet the load demand.

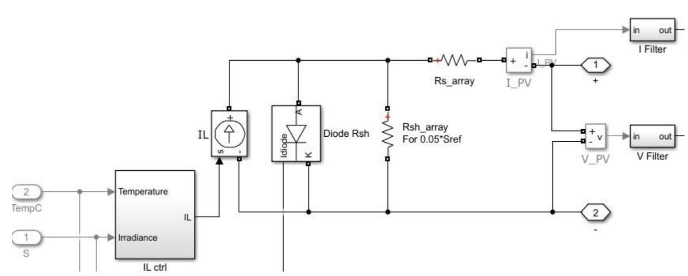


Figure 3: Simulink PV model [11]

The figure 3 shows the single diode PV module model in Simulink library in MATLAB. The rated power of the PV generator is set to be 8 MW at the peak.

In an MPC control approach, a discrete-time finite- horizon optimal control problem is solved at each time step k ∈ N. It provides a sequence of control steps from time k to time k +T −1, where T is the length of the time horizon in the optimization problem. However, only the first step of the sequence is implemented on the system until the time instant k + 1. Then, the optimal control problem is re-calculated using as the initial condition the state of the system at time k + 1 in time horizon.

$$J = \sum_{t=k+1}^{k+T} (Jl(t) + W * \mathrm{Jc(t)})$$

where Jl(t) is the power loss in transmission line, W represents the weights associated and Jc(t) shows the cost of the active power of the system.

B. Wind Turbine

Wind energy is becoming the fastest growing energy technology in the world. Wind power provides a clean and cheap opportunity for future power generation and many countries have started harnessing it. Due to this, it can now be considered as valuable in conventional energy sources. However, the drawback is that wind is a highly fluctuating resource. The maximum penetration of wind power in electricity networks is limited by the intermittency of wind energy. Due to this intermittent nature of the wind, efficient and cost-effective integration of wind power into electricity grid has become the greatest challenge.

The mechanical power of wind turbine can be calculated by using equation

$$P = \frac{1}{2}\rho S V^3 C_P(\Lambda\beta) \qquad [13]$$

Where

- ρ is the air density (Kg/m^3)
- S is surface swept by the turbine (m^2)
- V is wind speed (m/sec)
- C_P is power coefficient

The coefficient related to turbine model is non-linear and vary according to speed ratio of turbine blade.

$$\Lambda = \frac{W_R R}{V}$$

where W_R is mechanical angular velocity of turbine rotor (rad/s), R is blade radius of wind turbine (m), V is wind speed (m/s) and also angular rotation is given as

$$W_R = \frac{2 * pi * n}{60}$$

The output power fluctuation of wind turbines is due to wind speed variations. These power fluctuations can cause many problems to the grid, for example, frequency deviations and the power outage. Fluctuations in wind power production also make it difficult for owners of wind power plants to compete in electricity markets. Therefore, in order to mitigate the power fluctuations, wind power smoothing is required.

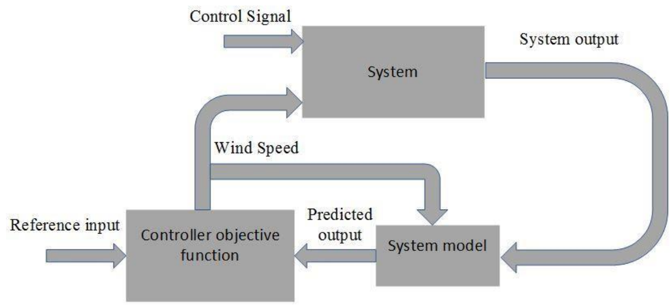


Figure 4: Schematic diagram of wind turbine

The figure 4 shows the block diagram of the wind generator system, where output power is controlled by the controller. We have used the built-in model for the wind generator DFIG system, as shown in the figure 5.

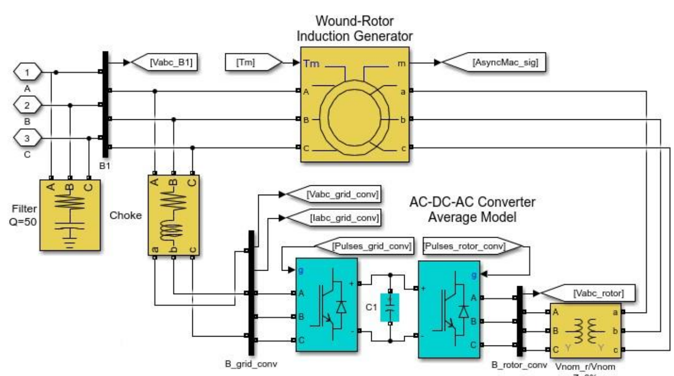


Figure 5: Modelling of wind turbine [11]

The figure 5 shows the wound rotor induction generator used to model the wind power generation and a AC-DC-AC converter used with the generator that converts variable ac to fixed dc and fixed ac output. The wind generator of 4.5 MW is employed in the system. The MPC module controls the output power of the wind turbine.

MPC has also gained popularity in industry since 90's and there is a steadily increasing attention from control practitioners and theoreticians. The practical interest of MPC is mainly due to the fact that today's processes need to be operated under tight performance specifications and more and more constraints need to be satisfied. These demands can only be met when process constraints are explicitly taken into account in the controller design. MPC is the possible solution for that due to its constraints handling capability. Therefore, we are using MPC theory to smooth and regulate the wind power.

$$\min_{u(t)\in S(\delta t),Ws} \int_{tk}^{tk+N} J_{MPC} + W_s \, dT$$

where S(δt) represents the piecewise functions with sampling time N, J_{MPC} is the objective function, and W_s shows the restrictions on the function.

C. Diesel generator

The asynchronous machine block from the Simulink library, as shown in figure, is used as a generator to model the diesel generator. The rated power of the generator is set to be 15 MW.

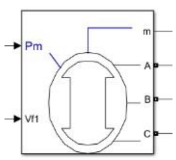


Figure 6: Diesel generator model [11]

D. Load

The load of 10 MW is used. A fixed load coupled with asynchronous machine is employed to meet the characteristics of the residential and industrial load. The machine is modeled as a squirrel cage induction motor. The power factor is set to be 0.95. The electric vehicle load, as shown in figure, is used to study the effects of charging on the hybrid microgrid. The power of each vehicle is set to be 40 kW. A total of 100 vehicles is used in the simulation of the system. Hence the peak load of the system is 14 MW.

The figure 7 shows the model used for the electric load vehicle which works as a load when it uses power to charge itself, and the block charge power generation is used to record the state of charge. The grid regulation is kept in check to avoid a large sudden increase in load, that could lead to a drop-in system frequency. It is assumed that the car is fully charged at the start of the day, it gets discharged when driving to work from home, gets charged again while in parking, and is again discharged when reaching home back from work. It is again charged after reaching the home. Hence the car is discharged and charged twice in a day.

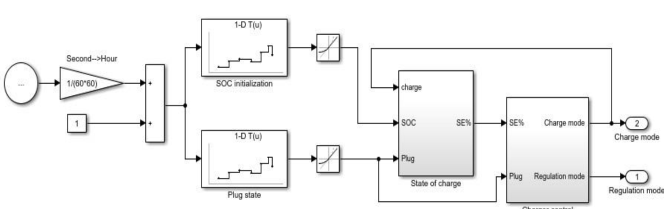


Figure 7: The electric vehicle load model [11]

III. WORKING OF THE HYBRID MICROGRID

The figure 6 shows the hybrid microgrid, comprising PV, Wind and Diesel generators, connected with different types of loads like hybrid electric vehicle, industrial load and residential load. On other hand microgrid are classified by attending following types

- Types of voltage: DC, AC and Hybrid
- Distribution configuration: Single-phase, three phase, three phases + neutral.
- Voltages: Low (LV) and Medium (MV).
- Structure: Radial and Ring.

This paper reflects the optimized hybrid modeling approach for load management flow analysis. The MPC model linearizes the power in wind profile and solar profile. The MPC model allow the system to follow the desired trajectory of the plant for both systems. The linear MPC model with SISO system is used for wind farm and solar farm. The state space model for linear MPC discrete time system is

$$x_{k+1} = Ax_k + Bu_k$$

$$y_k = Cx_k$$

Where $x\in^n$, $u_k \in^m$ and $y_k\in^p$ denotes the system states, inputs and outputs, respectively, at time Tk_s, being T_s the sampling time. The constrains of manipulated variable are considered hard constrains and output constrains are soft. The hard and soft constrains for wind turbine and solar farm are set on the basis of their capacity. The following equation show the constrains for PV and wind turbine. The constrains for manipulated variable in generalize form are given blew.

$$u_{min} < u < u_{max}$$

$$y_{min} < y < y_{max}$$

Constrains for proposed model will be:

$$0MW < U_{PV} < 8MW$$

$$0MW < U_{wind} < 4.5MW$$

$$7MW < Y_{pv} < 8MW$$

$$3MW < Y_{wind} < 4MW$$

The MPC techniques allow solving such constrains regulation problem in a symmetric way to minimize the cost function. The predicted output for linear MPC model for load management analysis can be calculated by given equation:

$$y_{\to k} = H\Delta U_{\to K-1} + PX_{\leftarrow k} \quad [14]$$

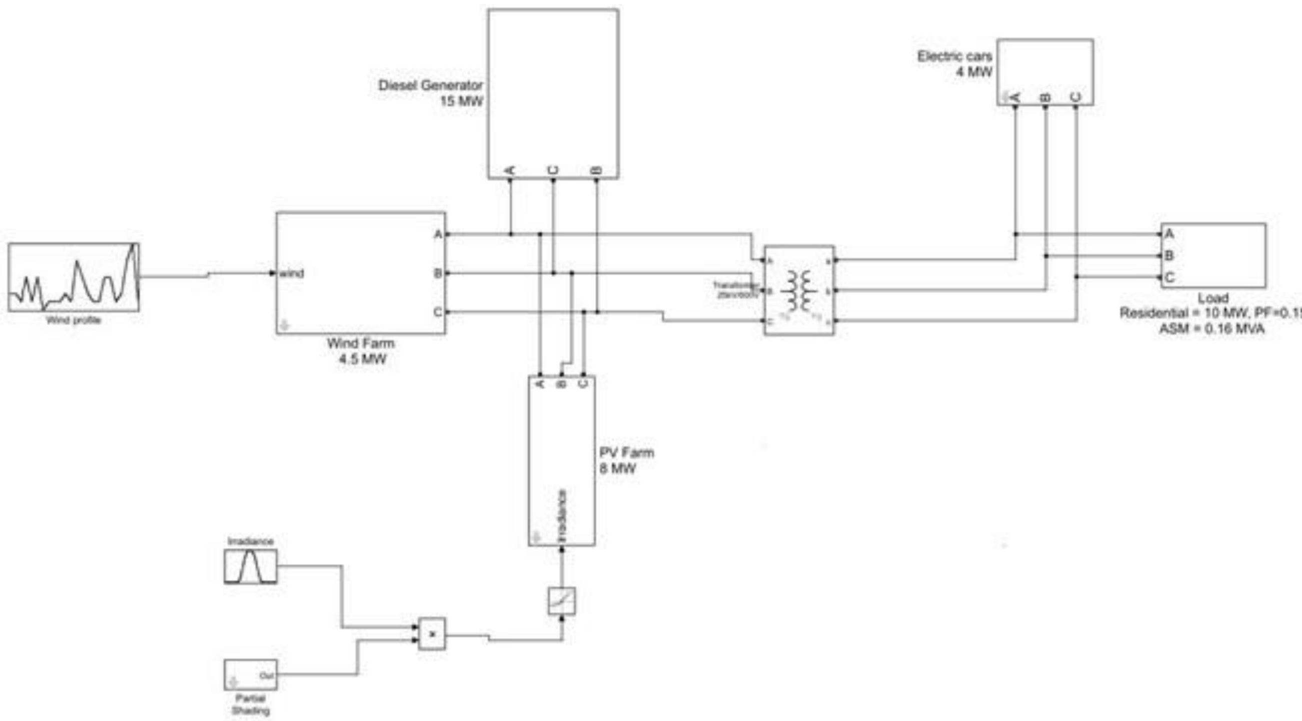


Figure 8: Hybrid microgrid model [11]

Y_{k+2} 0 0 ...
CB 0
$Y_k{}^{+1}$ $CCAA^2{}_3$ CAB CB ...
$CCABCBA_2B$ ...
. .
. . $. u_{k-1}$
Y_{k+3} CA . .
. = . $CA_{n_y-2}B$ $CA_{n_y-3}B$
. .
x_k+ . . ...]
.
.
. . .
$[Y_{k+n_y}]$ $[CA_{n_y}]$ $[CA_{n_y-1}B$
y_k p H

Where,

- H is Toeplitz matrix
- P is a matrix whose coefficients depend on model parameter in a straight forward but nonlinear manner
- Arrow notation for past and future values.
-

However, the order for proposed model predictive control matrix A, B, C, D are given in Table 1 and Table 2. The disturbance is considered negligible for MPC model and the reactive power of plant and the irradiance is taken as reference manipulated input. Moreover, some parameter like prediction horizon is set to be 10, sampling time 0.01 and control horizon is 3. The MPC model improves the irradiance control feed to solar farm while in case of wind turbine the active power and disturbances are ignored. The wind profile is taken as reference to increase the quality of wind quality. The objective of cost function of is to reduce the error between predicted output and target output, the equation for better understanding is given blew

$$Obj = \sum(Y - \bar{\nabla})$$

Where

- Y is actual output
- $\bar{\nabla}$ is Predicted output

The control strategy for load flow analysis is done for 12 hours. The results show that when sudden peak occur then diesel generator come into working at any time, wind turbine is set at base load of the system and solar will work on the day times. The wind farm trips around 22h when the wind speed exceeds the maximum wind value. The table 1 shows the important parameters of the MPC used for the solar PV system, and table 2 shows the parameters of the MPC regarding the wind turbine.

Table 1: Important parameters of the MPC for PV system

Sr.	Parameter	Value
1	Sampling Time Ts	0.1 sec
2.	Prediction Horizon	10
3.	Control Horizon	3

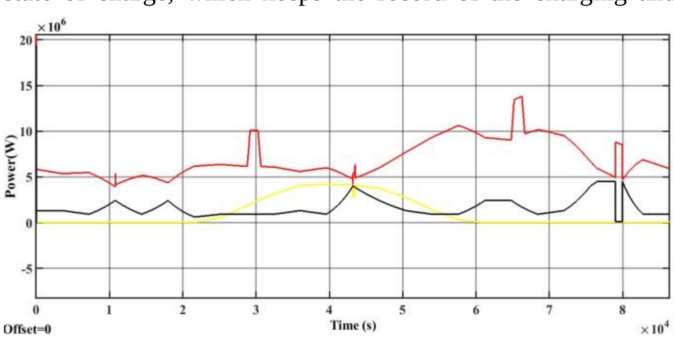
4.	Input Weight	0.1
5.	Output Weight	4
6.	Matrix A	55x55
7.	Matrix B	55x1
8.	Matrix C	1x55
9.	Matrix D	0

Table 2: Important parameters of the MPC for Wind turbine

Sr.	Parameter	Value
1	Sampling Time Ts	0.1 sec
2.	Prediction Horizon	10
3.	Control Horizon	3
4.	Input Weights	0.02
5.	Output Weights	4.95
6.	Matrix A	27x27
7.	Matrix B	27x1
8.	Matrix C	1x27
9.	Matrix D	0

IV. RESULTS AND SIMULATIONS

The figure 8 shows the model of the hybrid microgrid system with the connected loads. It shows the block of the wind, solar and diesel generator. It also shows the electric vehicle and residential load models. The MPC controllers have been employed, in solar and wind generator blocks. The simulation was run for 24 hours, and the results obtained have been discussed below. The vehicles are set to discharge and charge twice in the day, at fixed timings as explained earlier in electric vehicle load section, shown in figure 9. It shows the parameter, state of charge, which keeps the record of the charging and



discharging of the vehicle.

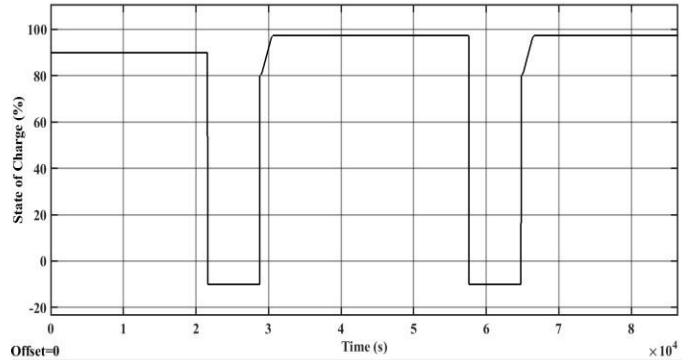
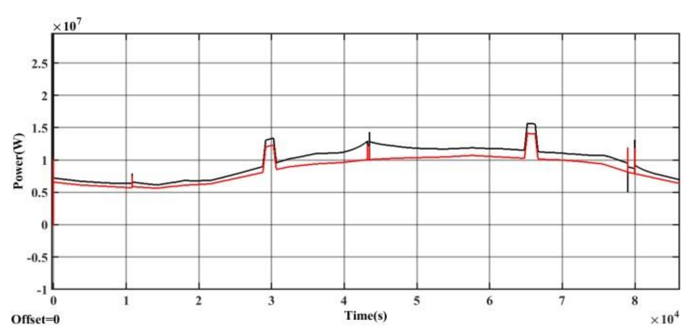


Figure 9: Electric vehicle load state of charge

Figure 12: Total output power of the system

Figure 10: Power of the PV panel

The figure 10 shows the output power of the photovoltaic generator (yellow line), wind generator (black line) and diesel generator (red line). It shows the peak production of the photovoltaic generator reaching at the middle of the day, when the sun irradiance is maximum. The output is controlled by the MPC, keeping in check the uncertainty constraints, and it can be observed that as the solar output decreases, the diesel generator output is increased to coop with the lower PV power production. The wind generator power fluctuates in the day according to the wind speed. As the speed increases beyond the upper limit, MPC controller sheds down the extra power, and in case of reduced power production than the desired production limit, the diesel generator is used to supply the required power. It can be seen between times $1x10^4$ to $2x10^4$, and $4x10^4$ to $5x10^4$, that as the wind supply power increases, the diesel generator power is decreased. At time $8x10^4$, as the wind power decreases, the diesel generator output is increased to mitigate the effect. The figure shows that MPC smoothly regulates the power and efficiently operates the system.



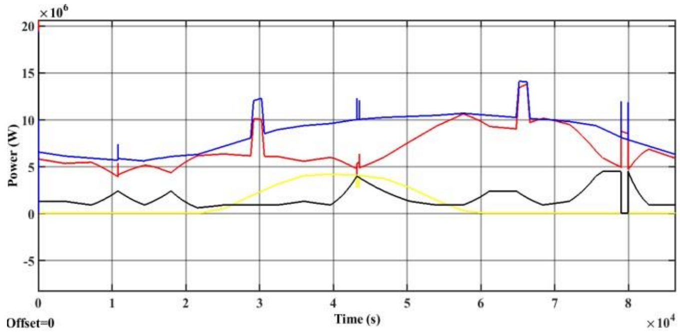


Figure 11: Power from the wind turbine

The figure 11 shows the same output power from solar (yellow), wind (black) and diesel (red) generators, but also shows the waveform of total load (blue). It can be seen that MPC regulates the power if power generated by the wind generator is greater than the maximum limit, or if the power generated by solar and wind power is less than the required power to meet the load demand. It also accurately keeps the power generation in check with the total load demand. The MPC smoothly regulates the output power, in accordance with the reference load power and taking into account all the constraints.

The figure 12 shows the total output power(black) and total load(red) of the system. It shows spikes in the power output, when the load electric vehicles are charging at time instants of $3x10^4$ and $6.8x10^4$ secs. It can be observed that the hybrid microgrid controlled by the MPC, effectively handles all the constraints, and successfully delivers power to the varying loads, and also covers the spikes in the power system arising due to the integration of the electric vehicles load.

V. CONCLUSION

In this paper, MPC was employed to control the load flow in hybrid microgrid. The hybrid microgrid involved intermittent energy resources, whose output power was uncertain, depending upon the environment factors. Although it is computationally expensive to employ MPC, but the results obtained proves that it successfully handles all the constraints regarding the uncertain parameters, and provides a smooth output power of the system, for load variations regarding residential as well as electric vehicles.

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