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Control of Optimal Operation with Hybrid Energy System

Muhammad Waseem[1] Dr. Abdul Basit[1], Imran Khan[1]
[1]US Pakistan Center for Advanced Studies in Energy, UET Peshawar
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***Abstract*—**Fossil fuels is the main energy resource now a day with the advantage of generating gigantic electricity at a given location. Fossil resources, however, are subject to exhaustion rendering energy resources risks. The process of electricity generation from fossils fuels may be less costly compared to other schemes however this advantage comes at the expense of increased pollution, greenhouse gases emission contributing to overall global warming. Sustainable energy production requires reusable energy resources. Each renewable energy resource is characterized by a unique characteristic set and advantages, making it suitable for application of specific nature and location. In a hybrid system, the cummulative sum of the powers generated by the constituent systems should match the load demand rendering its implementation complex mainly due to the non linear behavior of the renewable energy resources and the non linearity of the fuel consumption curve. The dissimilar load demand pattern and the limit on the operation of the battery also poses a constraint. Controlling the process of any compound power source system in an optimal manner is essential and challenging to achieve low overall system cost.

***Keywords*—** Renewable Energy Resources, Hybrid System, System Cost.

I. INTRODUCTION

A hybrid energy system has many renewable energy sources, back-up, battery systems, that is designed to provide power to a given load. The fact that renewable energy resources are variable, whose variation is dictated by factors such as changes in wheather, seasons etc.; and the fact that load demand is also variable; optimally controlling all the constituent renewable resources to provide energy to a fluctuating load is one of the fundamental challenge of such a hybrid system. An optimal central control system is thus required to manage each renewable resource in a manner such that the overall system is able to deliver energy efficiently to a fluctuating loads with renewable energy resources, battery back-up and energy storage mechanism. Current research in the hybrid system optimization mainly aims at the sizing aspect of the renewable hybrid system. This section highlights challenges and possible developments that will have an impact on the enhanced performance and optimized control of the hybrid energy system. This section also summarizes the hybrid systems optimization module available in the literature.

Hybrid system designing and controlling often employ conventional methods such as Rule of thumb methods [1] and Paper-based methods [2]. These approaches are based on reformist experience and trials, characterized by errors. They are, however, limited as they only provide a broader picture that may still very likely be open to improvements [3]. Many research works have assumed numerical approaches for the sizing and optimal cost calculations of the hybrid system, based on the load and resources of energy at a given location [4]. These techniques, however, are time-consuming and complex in implementation, and their complexity is an exponential function of the variables (number of constituents etc) in the hybrid system [5]. Using these approaches, the sizing and optimal initial cost could be determined but the running cost of the average optimized control could not be determined with accuracy. Researchers have coined techniques such as" Graphic method"," Probability based models" which are derivative-based and have shown promising results and efficiency towards improved optimal solutions of optimization problems, however they lack application when applied to advance optimization problems (joint sizing and optimal control) [6].

These techniques employ pure analytical methods, but they may not be best suited for practical problems with high non-linearity. The gradient and Newton methods are limitted as they can't handle inequality constraints. Linear programming techniques have oscillatory problems and their convergence is slow for an improper iteration step when optimizing both objective function and constraints [7]. Non-linear programming methods have complex implementation, stability problems, and bad convergence. Mixed integer programming are highly complex and their computation time is poor [8].

A number of software platforms are available that are used to optimize given hybrid renewable energy system. These softwares are designed taking the analytical models of the components systems. Simple linear or complex models are employed in these tools and their design varies within a predetermined interval in a random fashion; still producing sub-optimal results due to the inherent complexity in the system [9].

As hybrid systems are complex and highly non-linear, artifi-cial/computational intelligence based techniques are coined to cope with the high degree of complexity in hybrid systems [10]. To use these modern optimization techniques in an efficient manner, comprehensive and precise models of the hybrid renewable energy system is mandatory [11]. Also the complex interaction between constituent systems sizing and optimal operation control is required.follow.

II. Related Work

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Many researchers have conducted surveys on optimal con-trol operation of hybrid renewable energy systems. We briefly summarize them in the following paragraphs. A review of the state of the design, functioning, and control for the stand-alone PV solar-wind hybrid energy systems was conducted by [12] using conventional back-up sources such as Diesel Generator (DG). State-of-art control mechanism (like artificial intelligence) was suggested for future use to optimize hybrid renewable energy system and for managing energy efficiently. A summary of techniques for renewable energy systems setup, optimal control, managment, and sizing was proposed by [13]. The author also highlighted future developments of how renewable resources can be used to generate energy and challanges due to mass scale growth in future renewable energy systems. Optimization algorithm for renewable energy system de-signs, planning, and controlling were reviewed by [14]. The authors concluded that there is an increased surge for tradi-tional and huerestic algorithms to solve the optimum control problems in hybrid renewable energy generation and control systems.

A number of optimization techniques were investigated by ranging from software based to sophisticated optimization algorithms [15]. The modeling of Solar and wind renewable energy system models were discussed by [16]. These authors describe the models of the constituent of the hybrid system. They further review the contributions from many other au-thors and concludes that most publications are not discussing control. A detailed review in core areas of constituent unit sizing, optimization, management of the energy flow, and modeling of the components hybrid system for the last 10 years was presented by [17]. Their work provides a summary of the important parameters and factors which helps in deciding an optimized energy management mechanism. A comprehensive description of the optimal operation control is not presented in this work. A stand-alone hybrid solar-wind energy system in conjunction with battery system was reviewed for simulations, control, and optimization by [18]. They concluded that there is still space for enhancement of the system performance; al-gorithm establishment for enhancement of accurate prediction of their outputs, and their integration with other conventional or renewable energy generation systems.

III. Motivation

In a hybrid system, the cumulative sum of the powers generated by the constituent systems should match the load demand rendering its implementation complex mainly due to the following problems.

A. Sub-Problem 1: Non-linear renewable resources

Since renewable energy resources at a given location are function of season and time, the corresponding power provided by such sources to loads is variable. In a hybrid system, the fraction of energy generated by constituent renewable sources have a high impact on the fuel consumption of DG, which further depends on the alternate resources and fluctuating load demand. The problem of calculating approximate operation cost has been considered in the literature and mostly average monthly renewable resources are used to calculate it. In most cases, however, the interaction between load and non-linear renewable powers on comparatively lesser scale have not yet been considered. This work assumes comprehensive time series data and uses realistic non-linear resource profiles.

B. Sub-Problem 2: The non-linearity of the DG fuel consumption curve.

The efficiency of DG is optimal when they operate either at 80% or above their measured capacities and show very poor performance when operate at 30% or below the rated capacity. The DG fuel comsumption while operating thus is a function of the instantaneous output power and the span of time for which it is running. Many established models related to fuel consumption (the model adopted in HOMER software etc.) assumes a linear behavior between the fuel usage and the corresponding output power of the DG according to:

$$fc = FoYgen + F1.Pgen \quad (1)$$

Equations above represent linear behavior but when the true response of generator is considered, the expressions given above for the fuel usage response become exceedingly non-linear.

C. Sub-Problem 3: The Load demand pattern is dissimilar

The work in the literature assumes load demand and oper-ational cost to be fixed, from which monthly and yearly costs can be inferred. This assumption however is not valid when the consumer behavior is dependent on days, months and seasons which ask for a more accurate, precise and practical cost model that explains consumer behavior on daily basis.

D. Sub-Problem 4: Limitation on Battery Operation

The extent when the load demand is fulfilled the surplus energy is stored in battery system. The battery system is calliberated having a paramount charge limit, and can be discharged to a minimum allowed limit in the event of energy deficit at which point the DG is turned on. The following battery operation settings however are conflicting:

- If a battery discharges in longer time, DG run-time and fuel consumption are reduced at the cost of reduced battery life and frequent battery replacement.
- If a battery discharges in short time, DG run-time and fuel consumptions are maximized, though the battery life span is increased.

The impact of battery operation and maximum and minimum discharge rating is necessary to be inspected and checked.

IV. Model Formulation

A hybrid power system is characterized by multiple sources, with multiple variables, exhibiting high non-linearity, and constraints where the objective is minimal cost and enhanced system performance. The operation cost is also highly non-linear and is a function of the constituent sizing, load, re-sources, and dispatch strategy.

We suggest a hybrid system with components; DG system, Photo Voltaic (PV) system, wind turbine, Hydro Kinetic (HK) system, and battery system as depicted in Fig. 1. The operation model is a representation of how the components of the hybrid power system interact, how energy flows between the components, the losses that occur in the transformation of energy, and control of the overall system [19].

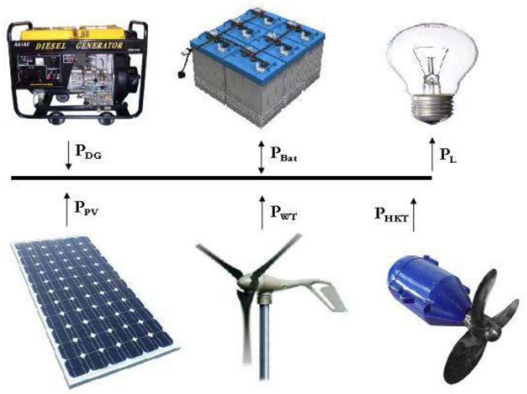

Figure 1. Components of the Proposed Hybrid System

The battery charging is only from HK turbines, the wind turbines, or from PV cells, and DG if used will only be supplying to the load and battery charging will not occur from DG. This configuration has the significance of effectively using renewable resources and the energy is optimally used when the DG is switched on since it satisfies the load demand. For economical usage of the hybrid system and available resources, a plan is required such that the DG fuel usage is minimized, meeting the satisfaction of the load and constraints of the hybrid system. The long span cost of the system includes maintenance, fuel, lubricant, components replace, supply, and repairs. For a short span, however, the only significant cost is the fuel usage cost of the DG.

A. Objective Function

We wish to reduce the fuel cost of the DG in the hybrid power system. We wish to minimize the following:

$$\min[\int (uP_{DG}(t) + vP_{DG}(t) + w)dt] \quad (2)$$

where u, v, and w comes from the consumption plot of the DG and PDG(t) is the power at the output of the DG.

B. Constraints

A list of the constraints is given below with a brief description where necessary:

- The power supplied by the hybrid system must meet the load demand.

$$\sum(P_{DGt} + P_{HKt} + P_{PVt} + P_{BSt} + P_{WTt} = P_{Lt} \quad (3)$$

where the symbols are mostly self representative, showing powers from different components are the control variables which must sum to the load demand at any instant of time" t".

- All the components of the hybrid system may be subjected to their maximum output as limiting constraints, as no source is able to deliver power beyond its capacity.
  - $0 \leq P_{HKt} \leq P_{HKt}^{max}$ (4)
  - $-P_{BSt}^{max} \leq P_{BSt} \leq P_{BSt}^{max}$ (5)
  - $0 \leq P_{PVt} \leq P_{PVt}^{max}$ (6)
  - $0 \leq P_{DGt} \leq P_{DGt}^{max}$ (7)
  - $0 \leq P_{WTt} \leq P_{WTt}^{max}$ (8)

- State Variable Limits: Battery SOC At any instant of time" t", the battery SOC should be between the minimum and maximum limits as:

$$SOC_{bat}^{min} \leq SOC_{bat\ t} \leq SOC_{bat}^{max} \quad (9)$$

V. Proposed optimization Algorithm

Almost all optimization techniques use the local minima which is effective for linear problem, but in hybrid optimal control, the problem is highly non-linear in terms of resources output, load demand, and component interaction, which makes the solution to the problem rather complicated, with multiples local minima asking for algorithms to search for global minima instead of local one.

"fmincon" solver from MATLAB is used to solve this problem.

$$min_x[g(x)] \quad (10)$$

Fmincon uses the following strategy while solving the under the restriction that one or more of the following must be true:

$$C(x) \leq 0 \quad (11)$$

and Or

$$C_{equ} = 0 \quad (12)$$

and Or

$$a_x \leq b \qquad (13)$$

and Or

$$C_{equ} \leq 0 \qquad (14)$$

and Or

$$a_{eqx} = b_{eqx} \qquad (15)$$

and or

$$u \leq x \leq v \qquad (16)$$

Fmincon is one of the most sophisticated optimization algorithm with ability to solve" Interior Point" problems, with high constraints, provides Hessian information, and robustness.

VI. Simulation

We present the simulations results of optimal operation control of hybrid power system. We use the fmincon library of MATLAB for our simulations. The simulations results will confirm that, using the proposed optimal control algorithm, the system is optimized for low cost, in a fluctuating load environment. Data sets from different locations with different load profiles are used and sensible cost is computed under varying load conditions.

A. Data Set

We provide a description of the data set used in simulations, extracted from two different sites. We extract data in the form of environment of the site, the load vs energy data, and the size of the constituent of the hybrid power system. The following two case studies are made.

B. Case 1: Rural Household

We collect daily load data from a household usage located at a certain height. The hybrid power system design is to provide electricity to loads in the form of laptop, stove, charging, ironing, freezer, and electric kettle etc. The load profile is a function of the user requirement and behavior and also vastly depend upon the seasonal changes and time of the year. The velocities of the water, the radiations from solar system, and speeds of the wind is recorded. The least velocity of the water is recorded and is noted in the month of September. The size of the HK generator is chosen such that it provides 1 kW when the velocity of the water is 1.4 m/s.

C. Case 2: Base Transmit-Receiver (Transceiver) Station

We chose a base station that use to transmit and receive data. The transceiver needs electrical power for its operation (for heat removal etc). The load profile is a function the daily usage of the power as required for transmission, reception, lighting, antennas, amplifiers, water needs etc. Some of the appliances have specific time usage during the day, say air conditioning, whereas the rest of the transceiver is functioning 24 hours a day. The air conditioning is shut down during winter and is no longer needed. There are two sites at which BTSs are located, making their environment different. The HK system should supply the necessary power to the overall system during a month.

TABLE I. Specification for simulation

Item	Figure
Sampling Time	30 min
Battery Maximum SOC	95%
Battery Minimum SOC	40%
Battery Charging Efficiency	85%
Battery Discharging Efficiency	100%
Diesel Fuel Price	1.4$/1
a	0.247
b	0.1
c	0.4200

D. Component Sizing and Simulation Parameters

As stated earlier, the main focus is cost optimization of the hybrid power system. The optimal sizing of the constituents is done using HOMER. These results serve as inputs to the optimization model. For Case 1 (household load in rural area), the following hybrid system is used.

- Hydrokinetic Turbine of 3kW
- Wind Turbine of 1kW
- Photo-Voltaic system of 1kW
- Diesel Generators system of 1kW
- Battery system of 13 batteries

For Case 2 (Transceiver setup), the following hybrid system is used.

- Hydrokinetic Turbine of 2kW
- Wind Turbine of 1kW
- Photo-Voltaic system of 1kW
- Diesel Generators system of 1kW
- Battery system of 7 batteries

Tab. 1 shows the parameters of DG and battery used for simulations.

The case in which the DG alone is supplying the load is also considered for purposes of comparison.

E. Simulation Results for Case 1 (Rural Household)

To see the impact of climatic changes on the results of the simulations, we consider two different scenarios. Two scenarios are considered in which the hybrid system is operating in different climatic conditions to supply the load. These scenarios are simulated to investigate how the climatic changes of loads and resources can influence the optimal operation of the hybrid system. Fig. 2 to fig. 5 highlight the load demand," Ld", and the power at the output of the components of the hybrid power system (HK, PV, Wind, Battery, DG). The major portion of the power supply comes from the HK system, which significantly reduces the DG fuel consumption and consequent cost of the overall hybrid power system. The results are shown in Fig. 6 to fig. 8.

We conclude from the observation of the results that:
The load demand in the morning and night is small, and is mostly met by the HK system. The wind turbine and PV cells are not operational in these hours as the renewable energy resources are not available at those times. We write the power balance as

$$P_{bal} = \sum(Renewable\ Outputs) - Load_{instanteneous} \qquad (17)$$

TABLE II. DAILY FUEL COST SAVINGS

	Winter		Summer	
	Consumption (L)	Cost ($)	Consumption (L)	Cost ($)
DG Only	122 L	171.03$	40.5 L	56.7$
Hybrid System	1.84 L	2.58$	0 L	0$
Savings	120.16 L	168.45$	40.5 L	56.7$

If Pbal > 0, batteries are charged as we are generating more power than that required by the load, however, if Pbal < 0, we use the battery system for the compensation. If the demand cannot be met by both renewable resources and battery system, then DG is used to fulfill the demand.

During day time, however, due to the availability of renewable resources, major portion of power is contributed by HK, PV, wind and battery system.

The demand is at its peak, in the morning between 8 am and 10 am, and HK, PV are used at their rated capacities, whereas DG is used for compensation when needed. The time for which the DG operates, and the fuel consumption and associated cost, are all functions of the load demand, battery state of charge, and the contributions from the renewable power resources. The batteries are not charged with DG; it only compensates for the surplus demand from the load.

Once the peak demand hours are passed, the batteries get charged upto about 40%, and the power from the renewable resources exceeds the demand from the load. The batteries are charged using this extra power upto 95%.

In evening, the demand raises again, between 5pm and 10pm. A combination of HK, PV at their rated capacities with contribution from DG is used to provide for the load demand. After 6pm, however, the PV system is unable to provide any further significant power, so the contribution from batteries and DG increases.

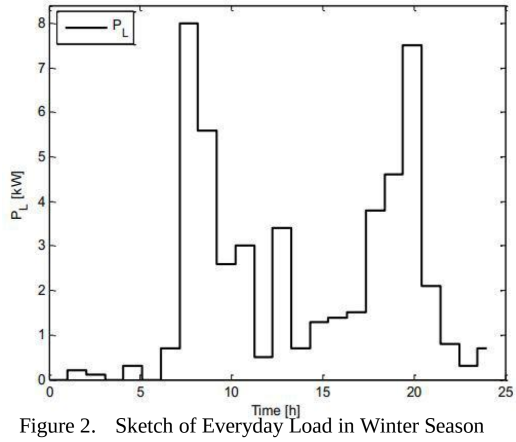

Figure 2. Sketch of Everyday Load in Winter Season

When DG is the only source, the results are shown in the Fig. 9. The DG sizing for this case should be such as it will able to provide for the entire load alone, in the absence of renewable hybrid model.

The model proposed here is helpful in differentiating the

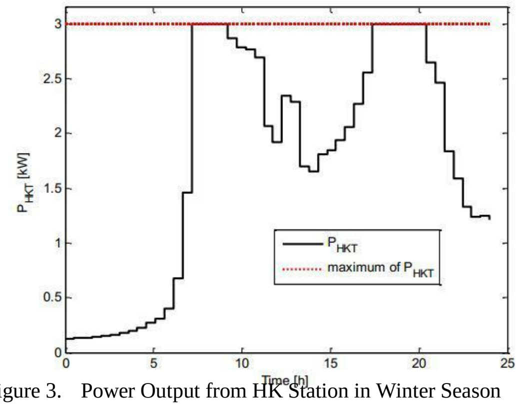

Figure 3. Power Output from HK Station in Winter Season

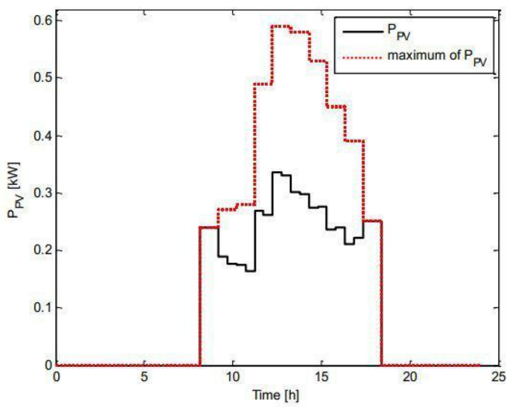

Figure 4. Power Output from PV Setup in Winter Season

behavior of the optimal operation control of the hybrid system under different weather condistions (say summer and winter) which greatly effect the DG fuel consumption and operation hours. The load demand is generally low during summer, and the renewable resources are in high availability, compared to winter. Consequently, DGs operation hours and cost are high during winter compared to summer. During summer, HK, PV, battery SOC all are high, which results in less DG usage and consequently less fuel consumption and cost. The fuel consumption cost can be computed as,

$$Cost_{day} = Price_{diesel} \left[\frac{dollars}{L}\right] xFuel_{used} \left[\frac{L}{day}\right] \quad (18)$$

where the daily fuel consumption is a function of the sizing and type of the DG. Tab. 2 indicates the fuel saving by using a hybrid power system instead of a stand-alone DG system for both winter and summer day.

F. Simulation Results for Case II (BTS)

We again assume two scenarios. The BTS load demand is a function of the BTS transceiver functions and lighting in addition with air conditioning demand, which reduces to 0 during winter, so the load demand is small during winter on the contrary to the Case I.

We make the observations below.

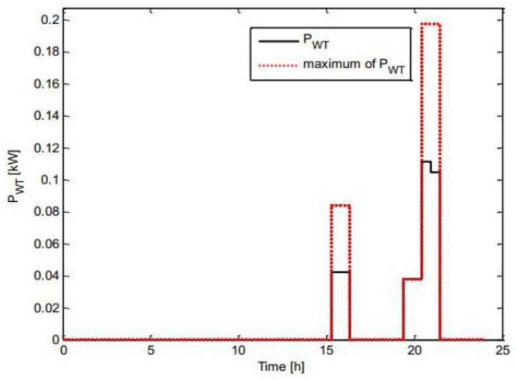

Figure 5. Power Output from Wind Power Station in Winter Season

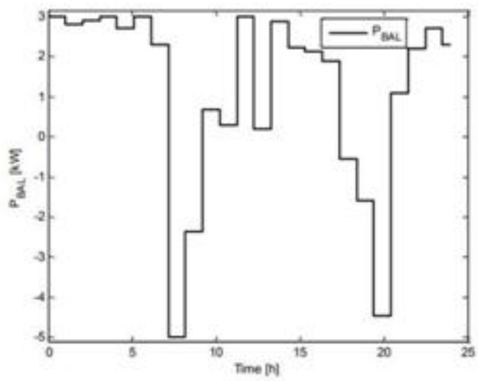

Figure 6. Crosspondenc between Load and Reneable Season during Winter

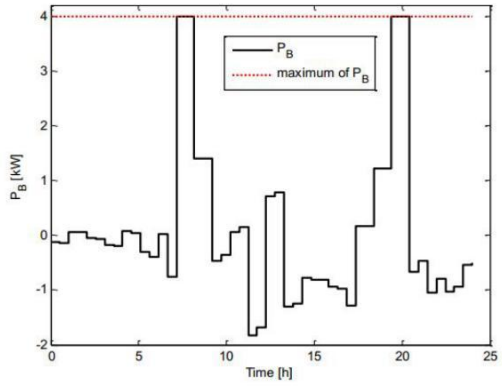

Figure 7. Power Output from battery Source in Winter Season

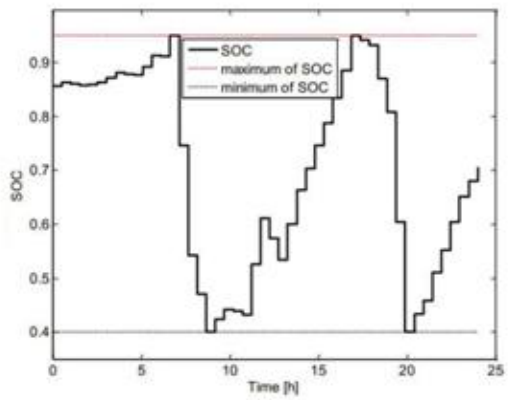

Figure 8. Changing Behaviour of Battery Charging during Winter Season

For most of the time, except when air conditioning turns on, the load demand is constant, and is supplied by the HK and battery systems. When wind, and PV are also supplying power, the surplus energy is used to charge the battery system.

When the demand is at its peak, all the components of the hybrid system, and the better system contributes towards power supply. The DG system is used in the case if there is surplus demand to compensate for the extra power needed. Once the peak demand hours are passed, the SOC reduces to the minimum of 40% and the load demand must be met by the hybrid system renewable resources.

The demand for transceiver is high during summer compared to winter for which a comparison is made on the daily basis. The results show that DG are highly used in summer compared to winter for providing additional air conditioning. The non-linear behaviour of both the loads as well as the renewable resources is evident from the results shown for daily operation cost minimization. Compared to the household Case I, Case II (BTS) uses more diesel fuel in summer day than winter day. We analyse how different DG and battery control settings effect the performance of the simulation results, Even if we have DGs with same kilowatt ratings, their duel consumption plots will differ if they are coming from different manufacturers.

We can customize the limits for battery operation which will have a significant impact on the simulation results of the hybrid power systems operation cost. We use Case 1 which uses data from the household appliances to illustrate the purpose. If the battery can last for longer, the fuel consumption of DG can be reduced and its life span can be enhanced significantly. This, however, may reduce the life of the battery and may need frequent replace. So a trade off has to be made between battery life span, and the fuel consumption and life span of the DG.

We conclude that:

- Compared the operation cost of different DGs from different manufacturers to see which cost is the lowest.
- The impact of battery setting is analyzed on the results of simulations and it is seen that deep charged batteries can enhance DGs performance at the cost of reduced battery life span.
- The impact of load variations due to seasonal changes and the fluctuating behaviour of the renewable resources is considered.
- Highlight the significance of HK module for cost mini-mization of the hybrid system.

The algorithm, and model used in this study is not complex and easy to implement with fast computations and results generation.

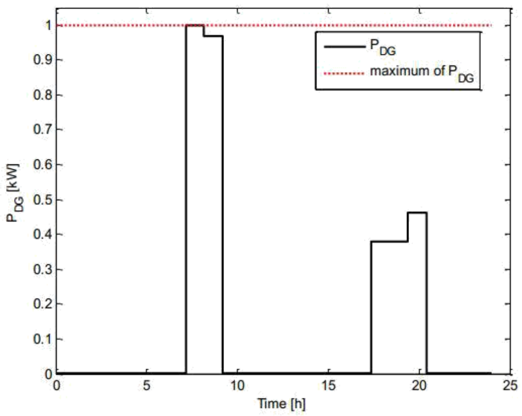

Figure 9. Output Power Vs Optimal Scheduling of DG in Winter Season

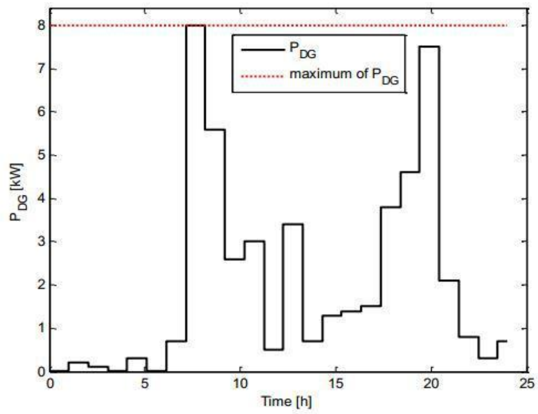

Figure 10. Output Power Vs Optimal Scheduling in Winter Season when Only DG is Considered

CONCLUSION

This section pivots around the results drawn from the optimal and advantageous operation and simulations of a system consisting of many energy sources. The sources includes PV module, wind turbine, HK and DG. Battery bank also makes part of the system. In a compound system consisting of many sources, the variation between weather conditions and load is a main entaglement in the operation of the system. The cost of the system mainly depends on the aforementioned concern. The study was based to find an optimal way to operate either a single unit of power or a combination of different to reduce the cost factor to a minimum value. As a return the cost of daily operation of the standalone system is significantly reduced. The main aim is to reduce the duration of the operation of DG while prolonging the operation of renewable sources. The idea is to use the renewable sources for maximum possible time. The algorithm selected for optimized operation is fmincon solver with Interior Point. Focus is made on the different non linearities involved in the process. Due to the intermittent behavior of renewable sources the solar irradiation, velocity of water at each hour and wind speed date have been used in the simulation. The simulation also includes the load demand and the fuel consumption of the DG system. The introduction of the non linear and intermittent behavior of the renewable sources gives accurate results of the operational cost.

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Muhammad Waseem graduated from COMSATS University Islamabad in 2013. He holds B.Sc degree in Electrical Engineeirng. He is currently enrolled in M.Sc Electrical Energy Systems Engineering at US Pakistan Center for Advanced Studies in Energy (USPCASE) UET Peshawar.His major field of study is Electrical Power Engineering. Currently he is working as Junior Engineer In MEPCO.

Abdul Basit completed his B.Sc. degree in electrical engineering fromUniversity of Engineering & Technology (UET) Peshawar, Pakistan in 2006. He received his M.Sc. degree in electrical power engineering from Chalmers University of Technology, Sweden in 2011 and his PhD from the Department of Wind Energy of the Technical University of Denmark (DTU) in 2015. He is currently working as Assistant professor at U.S. Pakistan Center for Advanced Studies in Energy (USPCAS-E) of the University of Engineering & Technology (UET) Peshawar. His research interests are on protection, power factor improvement, power system operation, renewable power integration and automatic generation control.

Imran khan Khan graduated from University of Engineering and Technology (UET) Peshawar in 2014. He holds B.Sc degree in Electrical Engineeirng. He is currently enrolled in M.Sc. Electrical Energy Systems Engineering at US Pakistan Center for Advanced Studies in Energy (USPCASE) UET Peshawar. His major field of study is Electrical Power Engineering. Currently he is working as Junior Engineer In MEPCO.