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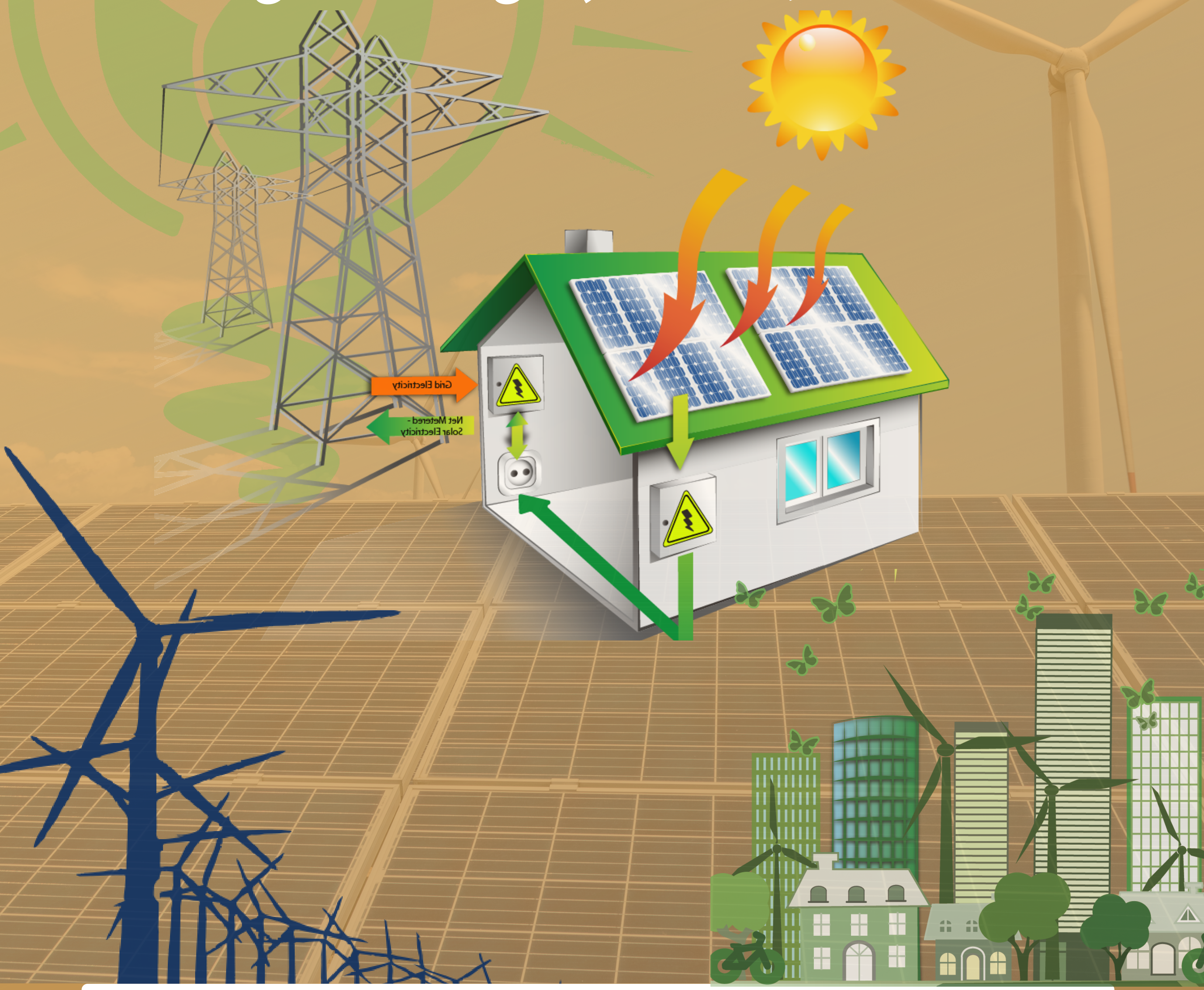

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Solar Irradiance & On Grid Solar Power Systems with Net Metering in Pakistan

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ABSTRACT

This paper presents a case study of solar irradiance and scope of on-grid solar power systems with net-metering in Pakistan. Detailed analysis of solar irradiance in Pakistan is being carried out by developing the dedicated solar excel sheets. The need of on grid solar power systems for the present energy crisis in developing countries like Pakistan is also discussed. It also presents the inclination of many countries especially USA and Europe towards it. Identification of barriers for implementing on grid net metered solar power systems in Pakistan along with solutions of these barriers is carried out.

1. Introduction

Pakistan is one of those countries around the world having maximum solar irradiance throughout the year. The solar energy needs to be exploited on very large scales in order to overcome the severe energy shortfall. This paper establishes the fact that solar irradiance in most cities of Pakistan ranges between 5 to 7 kWh/m^2 per day. In this research, dedicated excel sheets have been designed that gives the solar irradiance anywhere on the globe by just entering latitude, longitude and altitude of a particular location. In order to exploit this energy, large scale solar power plants need to be installed. But conventional solar power systems make use of batteries to store the excessive power, which makes the system expensive, less reliable and requires maintenance on a large scale. Batteries also reduce the overall efficiency and redundancy of the system. So the modern techniques are being employed in solar power systems to get rid of the batteries and feeding the excessive power to the grid directly. This makes use of the sophisticated techniques for synchronization between solar power system and the grid.

In order to promote the concept of distributed generation using renewable energy sources for the customers, an innovative approach of "net-metering" is employed. This helps to enhance the power production at commercial level, thus decreasing the net load on national grid. Net-metering allows two-way power flow between the utility and distributed generators (solar power plants). Two way power flow helps the distributed generators (DGs) to feed the surplus power to the grid (preferably during the day when sunlight is abundant) and get the required power from the grid (mostly at night) so it prevents wastage of electrical power. To implement this technique, smart energy meters are used that measure amount of power fed to the grid and also the amount consumed by DG. Fig. 1 is showing that how net metering is employed on the currently functional conventional system.

Since the conventional sources of energy (fossil fuels) are depleting rapidly, so it is necessary to rely on renewable energy sources as well. Developing countries like Pakistan also are facing substantial energy shortage should shift its maximum load to solar plants as it has one of the highest solar irradiance in the world. The effective way of using solar energy without use of batteries is "Net Metering".

2. Solar Irradiance in Pakistan

Pakistan is situated in a very favorable location as far as solar radiation is concerned with peak solar hours. In many parts of the country the sun shines for 7 to 8 hours daily and solar energy is available for approximately 2300–2700 hour per annum and there is sun shine for more than 300 days in a year [1]. Pakistan has Solar Irradiance of 2400 kWh/m^2 per year on average [2]. US National Renewable Energy Laboratory developed solar maps of Pakistan which indicates that many regions of the country are blessed with higher solar irradiance averaging from 5-7 kWh/m^2 per day [3].

Fig. 2 clearly shows that average solar irradiance in Pakistan is about 4.5-5 kWh/m^2 per day and the irradiance of South-Western part goes as high as 6.5-7 kWh/m^2 per day.

Data of Solar Irradiance for various cities of Pakistan is shown in table 1.

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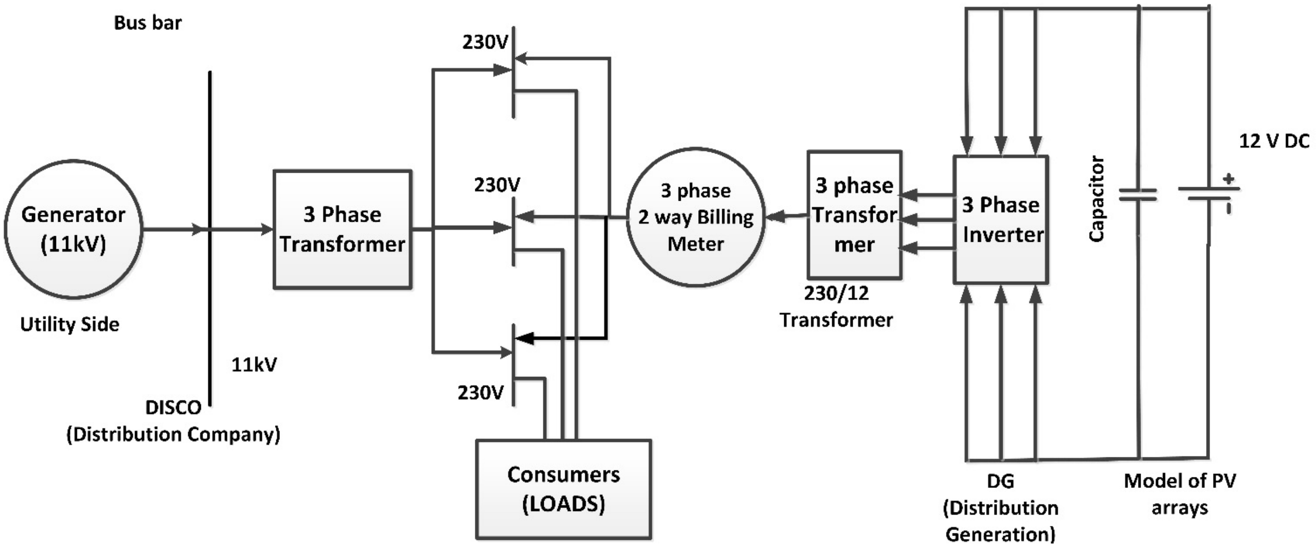

Figure 1: Schematics of two way net metering

Table 1: Annual solar irradiance in various cities of Pakistan

City	Solar Irradiance (kWh/m^2)
Lahore	1806
Bahawalpur	1981
Karachi	2168
Mardan	2143
Chiniot	1820
Faisalabad	1816
Multan	1961
Quetta	2287
Islamabad	2135
Gujrat	1854

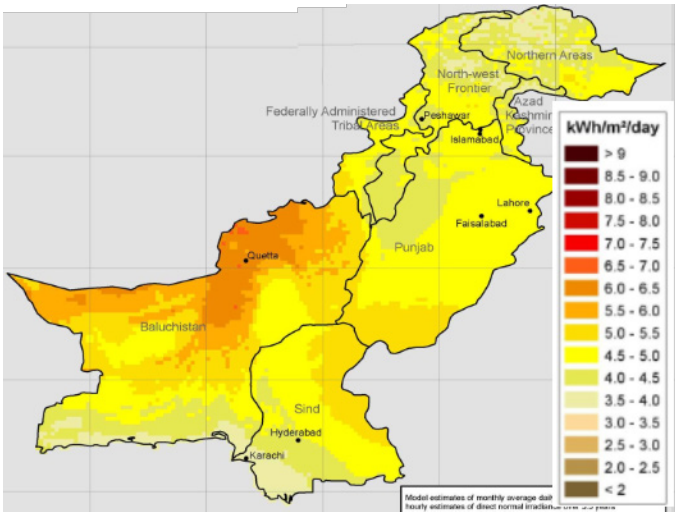

Figure 2: Solar irradiance map of Pakistan

Values from Table 1 show that various cities of Pakistan have high irradiance throughout the year. If the solar energy in these cities is utilized effectively, then the short fall of electricity will not be a problem anymore. When solar irradiance is sufficiently high, then it can be used to solve large scale energy crisis. The excess power produced is fed to the grid using net metering, thereby reducing load on national grid considerably.

In this research, excel sheets have been designed that give us the solar irradiance of any location after every 15 minutes throughout the year. The inputs to that excel sheet are latitude, longitude and altitude of some location. The sheet computes intensity for every 15 minutes and then we can get irradiance of a day, month or year as per requirement.

Table 2 shows the inputs provided to the excel sheet for the computation of solar irradiance. All the inputs i.e., latitude, longitude and altitude for any location are easily available.

Table 2: Data input for excel sheet to get solar irradiance

Location	Mardan (Pakistan)
Latitude	34.198°
Longitude	72.04°
Standard longitude	60
Altitude (m)	286
Degrees to radians	0.017453293

The daily solar irradiance curves for Mardan for three random days (Fig.3, 4 and 5) show compliance with the annual solar irradiance graph. The graph for annual solar irradiance is discussed in results and discussion chapter.

3. Trend of On Grid Solar Power Systems with Net Metering around the world

Solar energy technologies experienced the second highest annual growth rate of 28% among Renewable Energy Technologies (RETs) after wind energy during last decade [3]. According to the

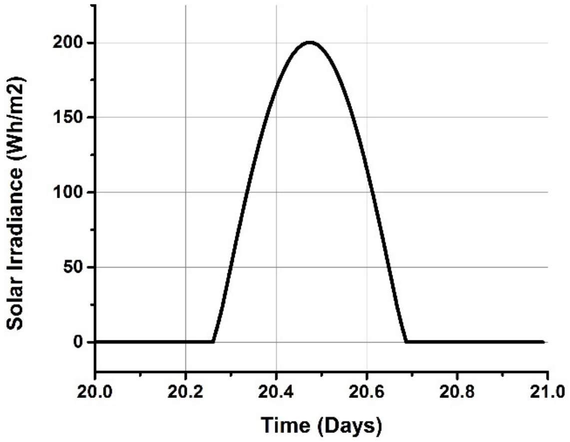

Figure 3: Graphical representation of solar irradiance of a day (21^{st}, January) in Mardan

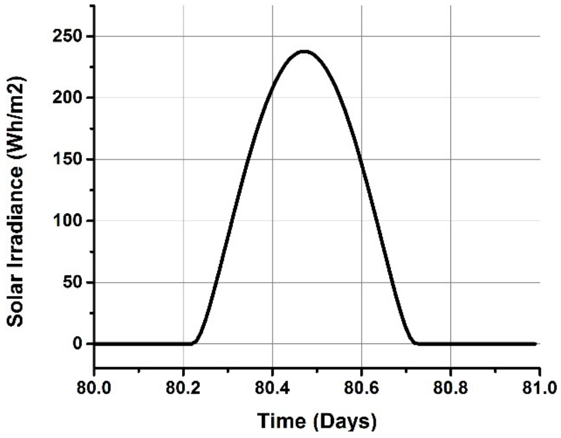

Figure 4: Graphical representation of Solar Irradiance of a day (March 21) in Mardan

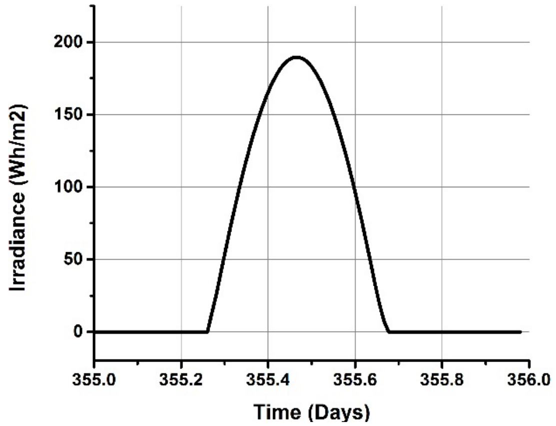

Figure 5: Graphical representation of Solar Irradiance of a day (December 21) in Mardan

European Photovoltaic Industry Association,[4] solar photovoltaic power increased by 16 GW in 2010 around the world, approximately doubled the increase seen in 2009. Also there is a growing interest for electricity generation from solar thermal energy and in 2008 over 6 GW of solar thermal based projects has been announced by various countries [5]. Many countries around the world are meeting their major electricity demand by the use of Solar Energy. Percentage of electricity produced by Solar Energy in different countries is shown below:

Table 3: Percentage of electricity produced by solar energy

Countries	%age of electricity produced by solar energy
Germany	21.58%
Italy	10.43%
China	15.10%
USA	10.33%
Japan	13.16%
Spain	12.00%
Austria	1.80%
India	1.67%

On Grid Solar Power Systems along with Net Metering is very common in the world especially in USA and Europe. Many states of USA and many countries of Europe like Austria, Belgium, France, Germany and Denmark etc. (Table 4). are successfully converting their solar energy into electrical energy and feeding surplus energy into the grid.

Many countries already producing electricity from solar energy have shifted their off-grid solar systems to on-grid solar systems using net metering [6].

Table 4: Percentage of solar power systems

Countries	% of on-grid	Yearly Solar irradiance
Germany	73%	1146.1
Italy (Genova)	78%	1400.38
China (Beijing)	70%	1561.89
USA (Orlando)	78%	1678.08
Japan (Tokyo)	63%	1371.18
Spain (Almeria)	15%	1827.73
Austria	90%	1115.08
India (Delhi)	23%	1823.47

Table 4 show the solar irradiance in many countries around the world and the corresponding exploitation of solar energy by using Net Metering. [7]

Globally, solar technologies share a growth of 18% in renewables energy generation. Many other countries rely on solar energy to meet their energy demands tremendously. Undoubtedly Germany, USA, Austria, Italy and China are the biggest players in this market. Other than these, some countries like Greece and Brazil are now exploiting high solar irradiance in the various cities. For example, The NEB (Brazilian Northeastern region) has the largest solar energy resource in Brazil, presenting an average global radiation of approximately 5.9 kWh/m^2 per day according to the Brazilian Atlas of Solar Energy [8, 9]. Greece has a strong potential of solar electricity generation, especially during cloudless summer days. For example, a typical crystalline silicon PV system established in an urban residential area in Greece can produce annually between 1100 and 1330 kWh/m^2 peak [10, 11]. Lebanon also has very high solar irradiance throughout the year. On average, Lebanon has solar irradiance of 5.28 kilo watt hour per square meter per day and an annual irradiance of 1928.7 kilo watt hour per square meter [12].

4. Identification of barriers and solution for implementation of grid solar systems in Pakistan

The exploitation of Solar Energy along with Net Metering is one of the main solutions of electricity crisis in Pakistan but still it is not being harvested at a large scale. Pakistan is moving towards RETs at a snail's pace. There are many barriers in the way of tapping solar energy with net metering. Stated below are those barriers and their possible solutions [13, 14];

4.1. Discouragement by Utility

The unwelcoming approach of utility (WAPDA) in Pakistan is a major setback to the promotion and installation of net-metered solar power systems. This is due to the fact that if the Distributed Generators (DGs) offset their electricity usage from utility by sufficient production of electricity from solar panels, then utility would have no usage based revenue. If DG is producing more electricity than required and feeding excess to Grid, then it will not be willing to pay utility rather expect utility to pay it. As a matter of fact, DG uses Utility's transmission lines for the purpose of feeding power to the grid or getting power from the grid during night [15].

So DG and utility should come in an agreement where DG will pay utility a fixed amount for the maintenance of transmission line and grid irrespective of its own production. In this way, Utility will not be in deficit anymore and will encourage its users to adopt net-metered solar power systems.

4.2. Lack of local production of equipment & technical staff

The back bone of net-metered solar power systems is comprised of solar panels, Grid-Tied Inverter (GTI) and two way energy meters. Unfortunately, none of this equipment is locally produced in Pakistan. Thus, we have to import them which increases the net cost of the system exponentially. Likewise, there is no dedicated staff for the installation and maintenance of such systems. This causes the plants to be unsustainable.

The possible solution to this problem is the development of local industries for the production of above stated equipment. This will help lower the net cost of the system. Users will not have to pay any additional charges that incurred in the import of equipment. Moreover, the local engineers should be trained to install and maintain such systems in order to ensure sustainability of the system [16].

4.3. Lack of awareness

In Pakistan, there is an extreme crisis of awareness in all people, from policy makers to the public, from technical staff in the Utility to the consumers. To implement a grid connected system with net metering, DG is responsible for extra cost associated with the installation and protection. Due to lack of awareness, DG does not feel safe investing that huge amount of money. He does not actually believe in the pay-backs associated with the system. The people in rural areas do not have access to electricity. They do not know the natural resources available to them. They have adapted themselves to live without the basic need of life, i.e., electricity [17].

To handle this problem, awareness campaigns must be carried out. The technical staff in the utility must be given special training courses about the on grid net metering system. Moreover, awareness has to spread in the public regarding the reliability, sustainability and pay back associated with such a system. Factors like green energy and independent generation should be exploited. Lastly, the rural population should be taught that they should not rely on the far off grid stations for power. They should generate power of their own in order to meet their energy demands. Media can play an important role towards general acceptance of Renewable Energy Technology (RET) and confidence building of people. Once people are convinced about the advantages associated with this, only then such a system will be able to thrive in Pakistan [18]-[22].

4.4. Financial Barrier

Right now, the equipment associated with on grid net metering system costs too much to be used by a common man in Pakistan. The equipment that is imported costs sky high. Obviously installing the local industries in Pakistan will be a long term solution to this problem. But development of industries takes

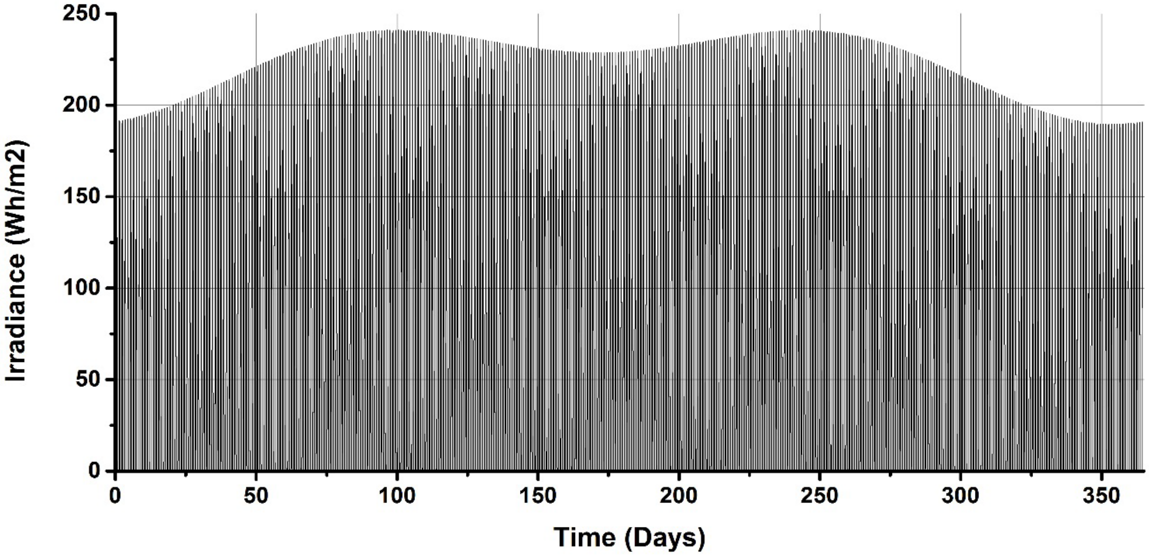

Figure 6: Graphical representation of Annual Solar Irradiance in Mardan (in 2012)

ample amount of time. So the short term solution to this problem is that government steps in and subsidizes the import of equipment needed to install on grid net metering systems in order to encourage the users to adopt this. This way cost of the system incurred to users will be quite less and they will be encouraged to install them.

5. On-going research on Net-metered Solar Power Systems

On Grid solar power systems with net-metering have high initial cost due to Solar Panels, protection system, grid-tied inverters and smart meters. Research is being carried out to reduce the cost of individual components so that cost of the system can be reduced. Moreover sustainability of the system is also a problem. Solar panels have to be replaced after every 20-25 years whereas life of a conventional system is along as 40 years. So intensive research is being conducted throughout the world to optimize between the reliability and cost of the system. When a Distributed Generation is installed on already existing conventional system, then a threat is posed to stability of the system if already installed transmission lines are unable to cope up with the additional power flow. So researchers are looking ways to increase the transmission capacity and system stability efficiently and prevent cascading disturbances.

Innovative solutions involving power electronics with both HVDC and FACTS solutions have the potential to cope with these challenges. They provide the necessary features to avoid technical problems in heavily loaded AC systems; they increase the transmission capacity and system stability very efficiently and assist in preventing cascading disturbances [23].

Net-metering is the technique of grid connection that will be practiced in the near future in Pakistan. Pakistan is at the verge of adopting net metering systems on large scales. The utility in Pakistan i.e., WAPDA (Water and Power Development Authority) and NEPRA (National Electric Power Regulatory Authority) have come up with the set of guidelines that helps to establish the agreement between utility and the customer for net-metering.

6. Results and Conclusion

Pakistan is facing an acute shortage of electricity despite the fact it has one of the highest solar irradiance in the world. In this research, the yearly solar irradiance of a city of Pakistan i.e., Mardan was plotted. Fig. 6 is showing irradiance of Mardan city for a complete year. So it is observed that it has high solar irradiance and variation of irradiance is small throughout the year. The data points of solar irradiance were obtained after every fifteen minutes by the excel sheet and then plotted against time. Using the same techniques, a complete day irradiance is also observed and discussed already in fig. 3, 4 and 5.

Fig. 6 is drawn for one complete year just to observe the variation in irradiance throughout the year. High solar irradiance throughout the year except December and January when winter causes high humidity and foggy weather.

Solar power systems with net metering are used world widely for the production because of many advantages like clean energy, substantial reduction in bills and elimination of batteries from the system. All these points are discussed in previous sections. There are certain barriers in implementing on grid solar power systems with net-metering. But certainly these problems can be solved by awareness, technical expertise and with the upgrade of infrastructure.

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Robust μController Implementations for a Linear Pneumatic Actuator Interaction

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ABSTRACT

Over the years, pneumatic systems have recorded a remarkable performance in automated applications, based on their cost to efficiency ratio and ease of energy transmission. Therefore, their drawback of not being totally controllable devices in terms of position accuracy, still represents a challenge task for engineers. In this paper, a traditional three term controller (PID) is designed for the task which is implemented in the system with an intelligent and not straightforward manner. The Integral term of the controller is not operating all the time during and parallel to the pneumatic piston stroke. The I-term will be switched 'on' and 'off', considering the system performance and needs. This ensures a robust control algorithm design, a faster system response and the avoidance of chattering around the demand position of the piston set point. In addition to this, an electrical board will be designed and produced in order to host all electronics like, a microprocessor, various amplifiers and converters, and a serial port for communication between the user and the system. An interface window is also implemented for the user to be able to export information of the system and record all data acquisition results as well as provide to an engineer a useful tool for re-programming the controller and download multiple versions of control code to the system. All results of the system performance are monitored and a representative pack of them are illustrated in the main body of this paper.

1. Introduction

Servo pneumatic systems play an indispensable role in industrial applications thanks to their variety of advantages, like: simple operation, clean, low cost, high speed and easy maintenance. Generally, The dynamics of these systems are highly nonlinear and their models inevitable contain parametric uncertainties and unmodeled dynamics. The pneumatic servo system is a very nonlinear time-variant control system because of the compressibility of air, the friction force between the piston and the cylinder, energy and thermal effects inside the cylinder, the flow rate through the servo valve, etc. In recent research work like [1-3], all the above problems are highlighted as well as that the application of nonlinear robust control techniques is a necessity for successful operation of pneumatic systems. Although PID (Proportional, Integral, Derivative) controller is still the most widely used approach due to its ease of implementation, the need for overcoming highly nonlinear phenomena turns away the use of classical PID controllers nowadays.

Therefore modern control techniques were designed and tested in pneumatic actuators in order to improve the performance of such systems considering position accuracy and repeatability as the two main performance characteristics. Fuzzy logic control, neural networks method, adaptive control, self-tuning or gain scheduling, the so-called "Soft Computing" control techniques, are approaches that have been already used for the task with remarkable outcomes. Among these techniques, much previous work from the above authors proved to be very confident in solving position control problem of a pneumatic servo system and all non-classical control methods have attracted considerable attention because they provide a systematic approach to the problem of maintaining stability and consistent performance in the face of modelling imprecision and disturbances. To implement a technique like them, though, requires high expertise from an engineer, high level of

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computing programming knowledge and control design skills. In an industrial environment this cannot always be succeeded due to multiple production line circumstances like low cost demand and the ability of a non-expert engineer to operate and control pneumatic systems for actuation. In this paper, our scope is to investigate and afterwards demonstrate how the all-time classic PID controller and its transformations can be robust and effective enough to control the position of a pneumatic cylinder based on a simple mathematical model of the system. At the top of all these, the most important part of the system is an interface board which will host the controller and all electronics peripherals. The interface card will be designed and assembled in order to be used for long term operations of the system. The criteria for choosing these specific microprocessor and electronics, details are provided in the following paragraphs, are low cost, reliability and multitasking capabilities. The ease of use in terms of programming was taken under consideration since the multiple input positioning system requires long control algorithms to be compiled by the microcontroller. One of the interface board main purposes is also data acquisition and real time data monitoring on a computer screen. In this paper, the pneumatic positioning system description and the control method implementation are given in the first paragraphs. The electronic interface board parts and assembly details will follow and finally the results and some further future applications will be discussed.

2. System Description

The pneumatic positioning system under investigation consists of a double acting pneumatic cylinder (type DSW-32-80PPV-A), stroke of 80mm, combined with a pneumatic proportional control servo-valve (type MPYE-5-1/8). The controller of the plant will have to read the current position of the pneumatic piston and correct the input of the system in order to minimize the error. The position sensor is a Linear Variable Differential Transducer (LVDT) and pressure sensors are also included in the system to increase the performance of the controller, by providing more data to it. This type of position sensor was selected among others as in [4-6], due to its simple assembly and unbeatable repeatability. The main layout of the system with all its parts connected is provided in Figure. 1.

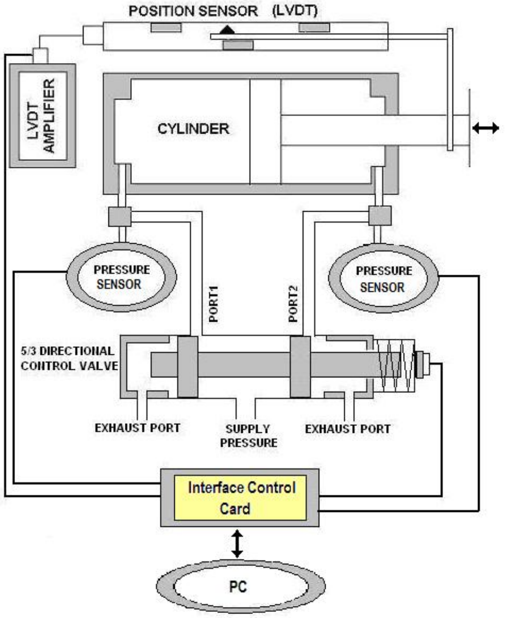


Figure. 1. The system main layout

It is obvious that the inputs of the system are the actual piston position provided by the LVDT and the two different air pressure values given by the pressure sensors. The output of it is the control signal in Volts produced by the microprocessor as a result of the control algorithm implementation that drives the servo-valve. The last one is the control device of the plant, which operates the whole system under the controller's commands. The valve opens and closes its ports in order to compress or decompress air in the two cylinder chambers and therefore move the piston. At this point the difficult part of the system dynamics and controlling occur, since the air compression is a highly nonlinear phenomenon. The mathematical model of the pneumatic cylinder and the valve consists of third order system equations and in fact they are also switching depending on the air pressure. All mathematics and system modeling can be found in [7-8]. It must be stated that 100% position accuracy of any pneumatic piston has not be achieved yet and therefore there is still area for more research like the one in this project.

3. The Interface Board

In order to be able to control and record the behaviour of the pneumatic plant, an interface card was designed and assembled. This should be able to convert the analog and continuous signal into digital words and also the digital input into an analog control signal to drive the pneumatic servo valve. Criteria like low cost electronics and multiple power supplies for the microcontroller and its peripheral equipment should be kept. The pneumatic valve response time is 50msec so the interface card should be faster than that to drive the valve properly. The controller reads the current position of the pneumatic piston and corrects the input of the system according to the control algorithm in order to minimize the error.

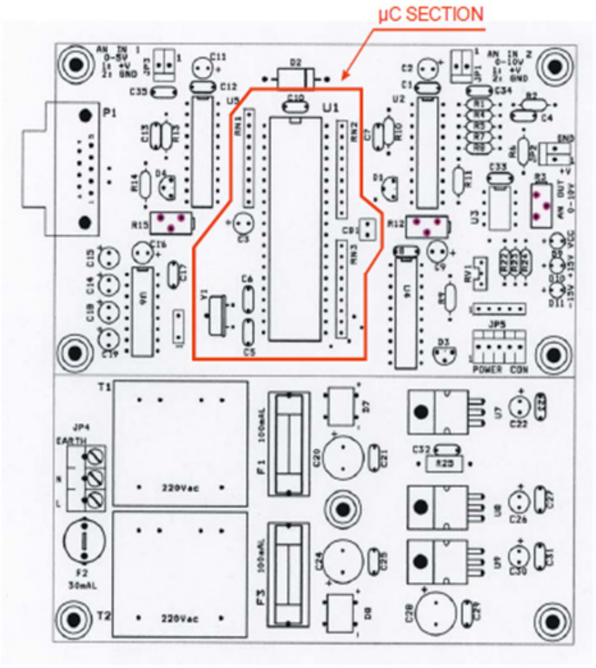


Figure. 2. The interface board drawing with the microcontroller section highlighted

Pressure sensors are also available to increase the performance of the controller. The first sensor, the LVDT, produces an analog signal of 0-5 Volt. An Analog to Digital Converter is used, specified to the highest accuracy for such a signal. The pressure sensor, varies between 0-10 Volts, so the Analog to Digital converter needs to be circuited a different way, to produce the maximum accuracy like [9-11]. If its input is 5-10Volts then it moves down. At the exact input of 5Volts there is no action. A Digital to Analog Converter transmits the digital control input into a continuous signal. The interface board consists of four main stages. The first is the microcontroller (μC) stage, which is the AT89C51. The second stage is the 5V input Analog to Digital Converted (ADC). The third one is the 10V input Analog to Digital Converter. The fourth stage is the 10V output Digital to Analog Converter (DAC). The microprocessor, a flash AT89C51, is responsible to synchronize the communication between the sensors and the computer and an overall view of the interface board that highlights the microcontroller section is provided in Figure. 2.

At this point it was considered as necessary to include another copy of the board schematics in order to illustrate the power supply management section of it. Therefore Figure 3 is added below to present the part that the 220VAC main input is transformed to lower DC voltages in order to supply the microcontroller and its peripheral electronics.

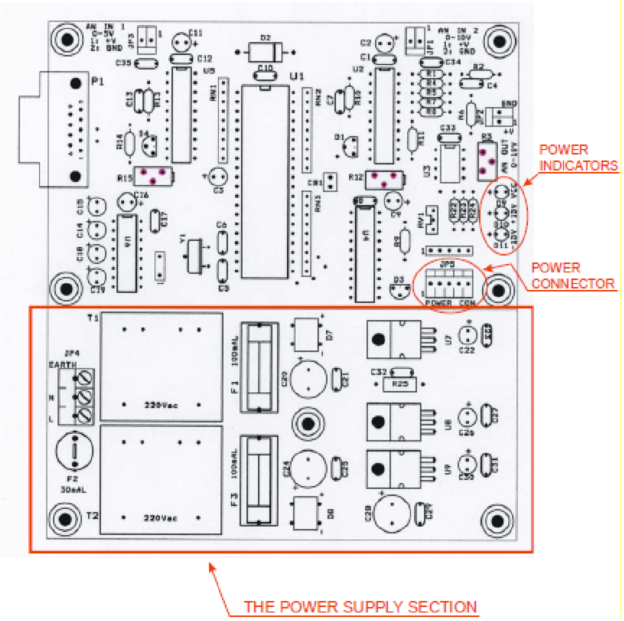
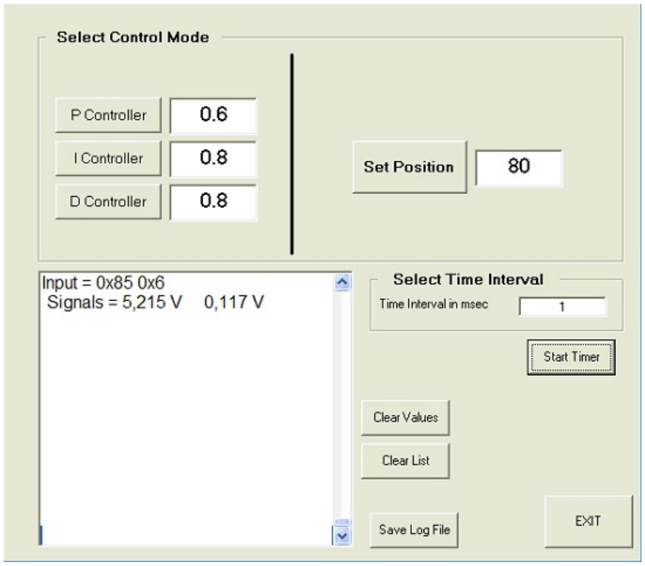


Figure. 3. The interface board drawing with power supply section highlighted

The serial interface and the control of the converters are being controlled in this stage. The clock frequency is selected to be 11.0592 MHz so it can be divided exactly for the RS-232 serial communication. A circuit breaker, which is shorted on power up, is used for downloading every new program code to the microcontroller. For the second and third design stages, the Analog to Digital Converters, a ADC0803 8 bit μC compatible is used. This is a common ADC, with excellent characteristics. It's a successive approximation A/D converter that uses a potentiometric ladder. This converter appears as a memory location to the Input-Output ports of the μC and so no interfacing logic is needed. In addition to this, the voltage reference input can be adjusted to allow encoding any smaller analog voltage span to the full 8 bit resolution. Another significant feature is that this converter has an on-chip clock generator and the conversion time is 100 μsec. For the 10 V input ADC stage the same converter is used with just a voltage divider added to the input of the converter. The fourth stage of the interface control board is the DAC0830, which is used as a Digital to Analog converter in a voltage switching configuration. In this configuration the ladder is operated as a voltage switching network and not as the standard current switching. The reference voltage is connected to one of the current output terminals and the output voltage (V_{ref}) is provided by the normal reference pin of the microcontroller. The converter output is a voltage in the range from 0V to 255*V_{ref}/256 as a function of the applied digital code. In this configuration the applied reference voltage must be always positive to prevent unacceptable behavior. There is also a dependence of conversion linearity and gain error on the voltage difference between the supply voltage and the voltage applied to the normal current output terminals. This is a result of the voltage drive requirements of the ladder switches. The power supplies voltages needed for the Interface board are +5V, +15V and -15V. A power supply providing all these voltages is included on the card. If an external power supply is to be used then the card can be further minimized and the part with the power supply equipment can be removed. Then the voltages needed for the interface board can be supplied to it through a power supply connector. Assembling this kind of boards with ADCs and DACs, it is critical to design in a certain way the power lines, especially ground connections, to ensure proper operation. In this board, special care has been given to this. In addition, it would be useful at this point to highlight the interface controls between the user-engineer and the system. The micro-processor provides a user friendly environment for programming, which is illustrated in Figure 4.



P Controller 0.6
I Controller 0.8
D Controller 0.8
Set Position 80

Input = 0x85 0x6
Signals = 5,215 V 0,117 V

Time Interval in msec 1

Figure. 4. The programming interface panel

In the above figure, there are three different buttons corresponding to the three terms of the controller gains. There are also buttons to set the piston target position, to start the experimentation timer and the log window that monitors the system's signals. In Visual Basic 6.0 (vb6) is quite simple to build an interface software. The functions needed are few which makes it even easier. This program is built in order to test the interface card's functionality. The interval of the control signal and the PID's parameters can be selected. There is an ability to save out logs in an Excel File where an analysis of them can take place afterwards. The gains of each parameter and the Desired Position of the system (mm) can be shown then. On the left part a list shows the input and output signal, values presented as hex and volts. The user sets the parameters and the desired position in mm while by pressing the Start Timer button, the control begins. The Timer stops when the system reaches the desired position or if the user stops the control by pressing the same button. In order to save the information of the response, the button "Save Log File" needs activation and all information is saved in an excel sheet. In the first two lines of this sheet, the Starting Position and the Desired Position are saved. The parameters of PID Controller are logged in lines 5, 6, 7. Then, from line 10 and after the system response and the control signal are saved. The control signal in mm is saved in the same column with the previous information. In the next two columns is the response of the plant, in mm and volts. Experiments have an empty column between them. The maximum length of the data logged is 1000. If the plant has not settled in desired position in 1000msec then the control automatically stops, and so do the data being logged. Else, the column length depends in the time the user stops the timer (the samples are taken when the timer overflows). The user can save up to ten experiments this way and all following data will be overwritten. The layout of the interface was a custom design that meets the requirements of this specific task. The versatility of the interface design in this project is a helpful tool for an engineer in order to communicate and control multiple dynamic systems.

4. System Performance

Although the design of the classical three-term control for nonlinear multivariable systems has been extensively studied in many books and papers, the design procedures for such high order nonlinear systems, like the pneumatic systems, may be complicated and vary from case to case. A simple approach to robust control, and the main topic of this chapter, is the implementation in the system of a classical controller which would automatically choose whether or not all terms of control P, I, D are appropriate for the application. During experimentation we managed to witness that the system operates satisfactory with the use of PD control and that the existing steady state position error was the main unwanted characteristic of the system behavior. The solution to that was to address the I-term control in the controller so that the steady state error would be eliminated. The need for retuning three rather than two control gains on one hand and the fact that the overall system behavior became oscillatory under the influence of the I-term, turned us to implement a clever idea of using the I-term only for beneficiary results. The new technique, which was addressed in the system, is based on "switching" the Integration term 'on' and 'off' according the value of the steady state error. Although the integration term is limiting the steady state error to tiny values close to zero over short periods, it is also producing the unacceptable system response over long time periods of operation. This technique introduces another secondary 'zone' of the steady state error which is placed in the middle of the primary 'zone' of 4mm (+/- 2 mm) when the I-term switches on, discussed earlier in this section. The secondary zone of values is, like the primary zone, split into two parts, 0.5 mm above and 0.5 mm below the demand piston position respectively. The idea of the new control algorithm is that the I-term is switched on when the error is within the primary zone (2mm above the demand position and 2mm below it) but when the error values are very small, i.e., within the secondary zone of values, it switches off. When the system performs without the influence of the I-term, the behavior is not oscillatory, and therefore if the steady state error remains always in the secondary zone, the response is considered to be acceptable. The new algorithm is based on the generic PID algorithm with this slight modification allowing the existence of the secondary zone and in fact this method provides the privilege to the system of 'deciding', according to the value of steady state, error whether to perform with or without the integration influence. The operation of the system required the implementation of manual retuning, but the undesired oscillations of the system were eliminated. In Figure 5 the system response when this method is applied to it, is shown.

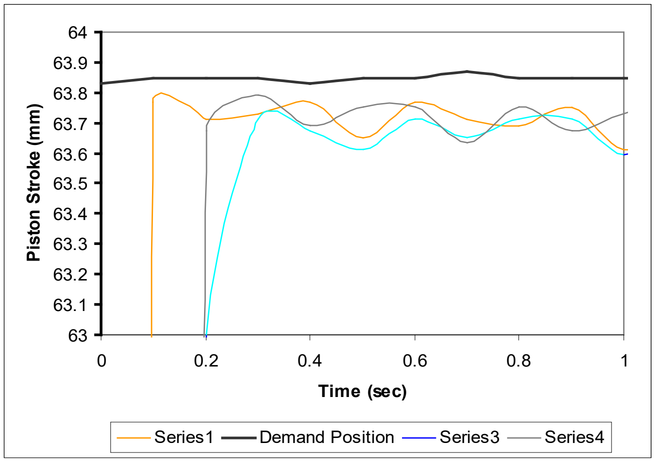


Figure. 5. The system performance focused around target position

In order to estimate the steady state error, the position axis of the plot is extremely focused around the desired position value (64mm). The system responses, as well as the demand position signal, therefore appear noisy. There are three different system responses, test1 (orange line), test2 (gray line) and test3 (light blue line), which are the average curves of ten different experiments each, with the same control gain values and the desired target position is set to the ¾ of the piston stroke. The system with the new method of the secondary zone of error values performs rather well, there are no oscillations during long time operations (50 sec) as there were before, with the simple PID control and the critical factor of this research project, the position accuracy, is minimized in values between 0.16mm and 0.2mm of the demand position.

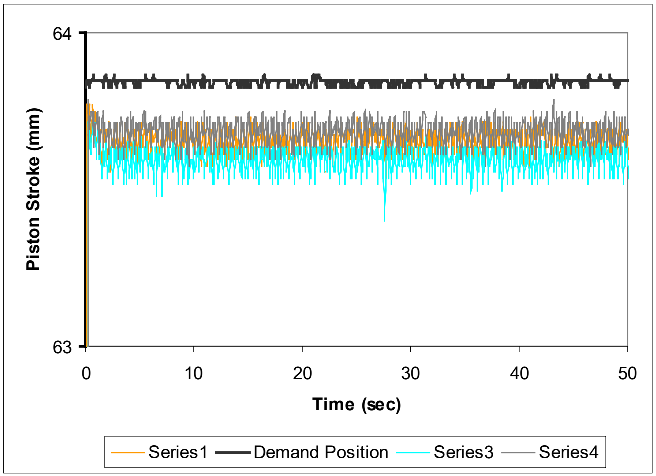


Fig. 6. The system performance

The piston position percentage accuracy is calculated as the 0.28% of the overall stroke of the piston, a value that is excellent considering the nature of the system. After all, this new method of control improved the overall system response and the time spent on retuning the re-designed algorithm was worth it for the aim of this project. The experimentation to back-up our results was designed as follows. During 8 hours continuous operations of the system all responses of the PD, PID, Auto-selective I-Term, were recorded. Then, an average response of each one of the techniques was plotted and an illustration of that is provided in Figure 6.

5. Conclusions and Further Applications

Throughout experimentation and during all tests the system proved its robustness in position accuracy of the piston and repeatability of it. The control algorithm supported that fact and never failed to be compiled and downloaded to the micro controller. Therefore this smart and innovative control technique is a more than acceptable solution to control a highly nonlinear system such a pneumatic positioning actuator. Given the fact that the 100% percentage accuracy has not been yet achieved in a worldwide level, there is still a small gap for further improvements referring to the controller's performance. Perhaps an Intelligent Control Method could assist in that and be adopted in the system for further experimentation.

On the other hand, a significant advantage of the work presented in this paper is the interface board. Its versatility allow for more complex controller design experimentations without any upgrade in the hardware of this specific interface card. The microcontroller source code, as the software part, is the only bit that needs to be re-designed in order to adopt the new control method algorithm. Furthermore, the ability of these electrical components is proven to be stable and capable enough to host multiple control tasks and monitor their performance successfully and experimentations with methods as found in [12] will follow.

As a summary, it can be stated that this research work introduced a versatile and reliable interface board to host any kind of controller design in order to control the position of a linear pneumatic actuator with highly standards of robustness.

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Energy Management and Simulation of Photovoltaic/Hydrogen/Battery Hybrid Power System

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ABSTRACT

This manuscript focuses on a hybrid power system combining a solar photovoltaic array and energy storage system based on hydrogen technology (fuel cell, hydrogen tank and electrolyzer) and battery. The complete architecture is connected to the national grid through power converters to increase the continuity of power. The proposed hybrid power system is designed to work under classical-based energy management algorithm. According to the proposed algorithm, the PV has the priority in meeting the load demands. The hydrogen technology is utilized to ensure long-term energy balance. The battery is used as a backup and/or high power device to take care of the load following problems of hydrogen technology during transient. The dynamic performance of a hybrid power system is tested under different solar radiation, temperature and load conditions for the simulation of 24 Hrs. The effectiveness of the proposed system in terms of power sharing, grid stability, power quality and voltage regulation is verified by Matlab simulation results.

1. Introduction

Today, pollutants in the atmosphere are progressing in parallel with the increasing demand of energy. The continuous increasing demand for fossil fuels such as natural gas, crude oil and coal is motivating society towards the development of Renewable Energy Sources (RES) power generation. Many such renewable energy sources like Wind Turbine (WT) and solar Photovoltaic (PV), which are clean and abundantly available in nature, are now well developed, cost effective and are being widely used, while some others like Fuel Cells (FC) are in their advanced developmental stage [1]–[3]. The applications PV systems have become more common in both developed and developing countries. The world's primary energetic consumption is only 1/10,000 of the one available on the surface of sunny countries. If adequately exploited, solar energy may become sufficiently powerful, providing enough energy for future mankind [4]. PV is scaleable from very small to very large and easy to integrate with existing power converters [5], [6]. However, The output power generated by PV systems is highly dependent on weather patterns. For instance, during a particular period of time (e.g., cloudy or at night), a PV system would not generate any power. Natural variations in solar irradiance and temperature causes power fluctuations in a PV system. Apart from this, the power generated by a PV system is difficult to store for backup [7]. The best way to address this problem is to propose hybrid power system with proper energy management.

A Hybrid Power System (HPS) utilizes two or more energy sources, power converters and/or storage devices. The main purpose of HPS is to combine multiple energy sources and/or storage devices which are complement of each other. Thus, higher efficiency can be achieved by taking the advantage of each individual energy source and/or device while overcoming their limitations [8]. Recent advancement in FC technology for grid enhancement has exposed its significant potential and consider an indispensable energy source for the future power system. FC is a static energy source that generates electricity from hydrogen through electrolysis. The superior reliability, with practically zero noise level or no moving parts is an extra advantage of FC system as compared to the diesel generator. Main characteristics of FC include modularity, near zero emissions, fuel flexibility, premium power quality, high efficiency and practically low noise levels. Other advantages of FC are the distributed and centralized

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configurations, diversity of fuels, cogeneration options and reusability of exhaust gases for heating of buildings [9]. The combined use of FC with an Electrolyzer (ELZ), hydrogen storage tanks and compressor unit provide a new energy storage concept. Since, hybridization of FC stacks with PV panels will, therefore, form an alternate energy conversion system where the FC acts as back up during low PV outputs to satisfy sustained load demands. There are several types of FCs which are classified on the basis of their operating temperature ranges and type of electrolyte. In this study, Solid Oxide Fuel Cell (SOFC) is selected, because, it works at high temperatures (800 – 1000 °C) [10]. But, the main weak point in SOFC is their poor dynamic response, gas starvation and load tracking delays [11]. When a SOFC is subjected to a step increase in load, it shows an instant drop off of the voltage in the V-I curve and take several seconds to provide the desired power. In the meantime, the SOFC may be starved of fuel, which can seriously affect the life time of SOFC [12]. This problem can be addressed by using a high energy density device such as a battery. Therefore, the SOFC should be utilized under controlled steady-state environment while the battery is supplying the demanded power. Without the battery bank, the SOFC system must provide all the power demand, thus oversize and increase the cost of the SOFC power plant.

2. Literature Review

A considerable literature on hybrid power systems are discussed and published in academia at other active forums too. For example, a hybrid photovoltaic fuel-cell generation system employing an electrolyzer for hydrogen generation and battery for storage purpose is designed and simulated in [13]. The performance of a hybrid system using an ELZ/FC/diesel generator are given in [14]. The simulation results of a grid dependent hybrid system integrating a FC, PV and wind for distributed energy applications are shown in [15]. The designing of PV/FC/wind hybrid system for proper energy management is presented in [16]. A wind based power system with hydrogen storage is simulated in [17]. In [18], the author design a management system for FC with a battery hybrid tramway. References [19]–[22], proposed an autonomous control scheme for the interlinking converter whose responsibility was to link AC and DC sub-microgrids together to form the hybrid AC/DC microgrid. The work performed in [15], dealt about the hybrid system which contains wind/PV/FC. The main purpose of this research paper is to provide uninterrupted supply to the load, it is achieved by using FC which operates at rated power of 10 kW, in the event of worst environmental conditions where there is no generation from wind and PV resources. The proposed system is simple, easy to control and low cost. In [23], the dynamic behavior and performance of the hybrid system is evaluated. The hybrid system consists of wind and PV resources and the system is grid-connected. The overall system consists of DC–DC converter, grid interface inverter, hybrid system and appropriate power control strategy, which draws maximum power from the wind turbine by using a variable speed control method and extracts maximum energy from the PV array using the Maximum Power point Tracking (MPPT) technique. The simulation models are developed in PSCAD/ EMTDC environment and the results showed very good performance of hybrid system in response to variations in solar irradiance and wind speed. In [24], the authors presented modeling and control of photovoltaic/wind/fuel cells hybrid generating system. The overall work is divided into two parts. In the first part the authors focused on each subsystem and different parameters are identified for each subsystem. The second part dealt with the design and installation of various equipment which includes voltage and current sensors, the data acquisition is made possible by using National Instruments cards which allowed to obtain real time data in LabVIEW environment. Similarly, several authors focused on hybrid power system on different issues various such as the size and cost optimization [25]–[27], power management [28]–[31], power quality and reliability [32]. There are some drawbacks in all the above mentioned studies. For example, some authors include short energy system in their studies, while others concentrate on long term storage medium. Some authors describe power control of PV system while others attempt to address the energy management without providing power sharing among different energy sources and/or storage system. In addition to this, most of the authors supported their studies on the basis of virtual generated solar irradiance, temperature and weather patterns.

This work presents a grid connected HPS combining PV, SOFC, battery and ELZ while considering the real wind speed and load variations for the hundred households at Peshawar, the capital of KPK, Pakistan. The proposed HPS works under the supervision of Classical-based Energy Management and Control Algorithm (CEMCA). The proposed algorithm effectively managed all the energy sources and storage system according to different weather patterns and load conditions. The proposed combination and algorithm ensures 24 Hrs power flow with better reliability and stability. The said combination signifies the most suitable option which ensures to maximize the output energy, continuity of power and decrease the variations in output power.

This paper is organized as follows. First, system description is focused in Section 3. Next, Section 4 explains the control of system components. Section 5 focuses on the energy management of the entire system. Simulation results are given in Section 6 followed by the conclusion in Section 7.

3. Description of Proposed Hybrid Power System

The complete system is designed in two buses i.e., DC and AC bus. PV, SOFC, ELZ and battery make the architecture of DC bus, and the power conversion and transferring occurs between these components through a CEMCA. Domestic load and national grid are the parts of AC bus. The output voltages of PV and SOFC are regulated and adjusted through two non-isolated DC–DC boost converters. The boost converter is controlled through Proportional Integral Differentiator (PID) controller. The bidirectional power flow of battery with the rest of the system occur through a buck boost converter. The buck boost converter is controlled through Proportional Integral (PI) controller. The output of DC bus provides the required power to the grid and grid-connected load through three phase inverter even if only one source is available. The inverter is controlled via hysteresis current control strategy.

It is important to describe that the proposed HPS is flexible and, therefore, easily upgradable as long as a new PV, SOFC and battery are added to the existing ones without increasing the circuit complexity. Furthermore, it is also possible to add another parallel inverter to expend the said design with high efficiency. The assessment of the performance and stability of the proposed CEMCA necessitates the simulation of the integrated system over a period of time. Therefore, steady-state simulation models have been employed for each distinct unit.

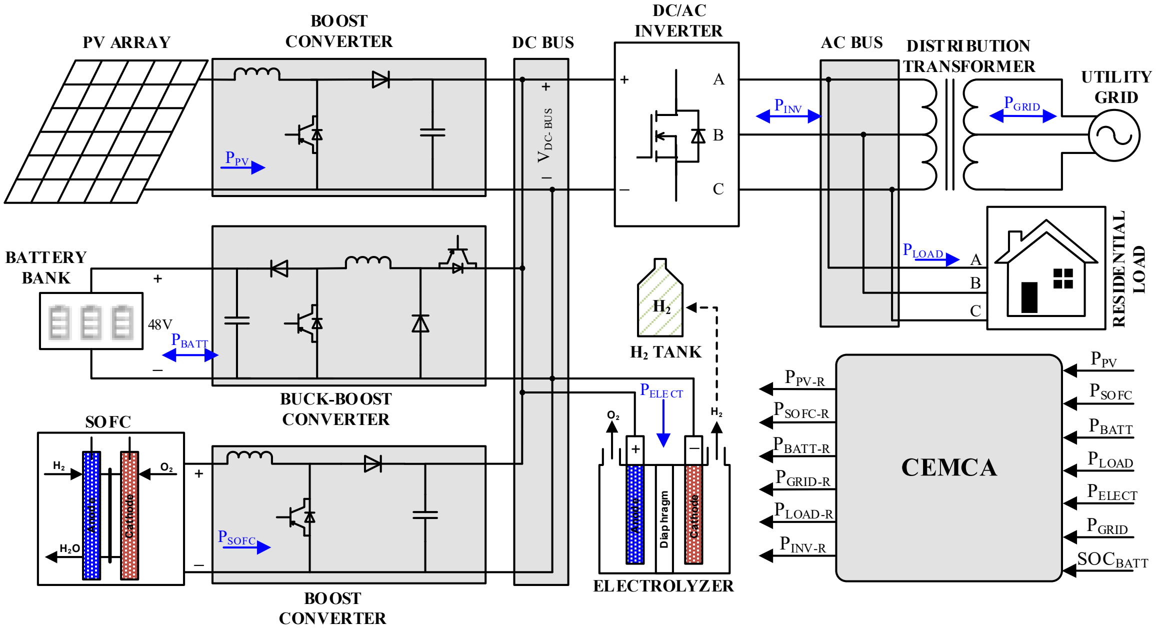


Figure 1: Architecture of proposed hybrid power system

4. Control of System Components

4.1. Control of PV System

The output power of PV depends upon the atmospheric condition, therefore, to track the maximum power point (MPP) of the PV, a single boost stage is applied to boost the PV voltage. The output current and voltage of the PV are used to compute MPPT error denoted as "e" in figure 2. The MPPT error is calculated using an incremental conductance algorithm. The boost converter is controlled by proportional integral differentiator (PID) controller. The PID controller tries to minimize the MPPT error. The output of PID represents the variation in duty cycle.

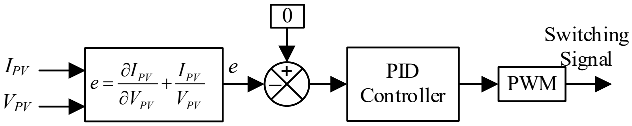


Figure 2: Control diagram of PV system

4.2. Control of SOFC System

The assembly of SOFC is linked with DC bus through boost converter. Here, the boost converter is controlled via PID controller. The PID controller tries to reduce the error, which is the difference of reference voltage by CEMCA and actual voltage of SOFC. The output of PID controller denotes the variation in duty cycle. The output voltage generated by boost converter is based on duty cycle provided by PWM generator. The control system for SOFC is depicted in figure 3.

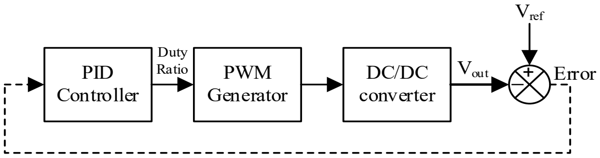


Figure 3: Control diagram of SOFC/ELZ system

4.3. Control System of Electrolyzer

The output power of ELZ is controlled by controlling its input current. A buck converter is used to regulate the input current of ELZ which consequently control the output power. The buck converter is itself controlled by a PI controllers. The control system for ELZ is shown in Figure 3.

4.4. Control of Battery System

The linking of the battery to the DC bus is established though DC-DC buck-boost converter. The power flow from the battery to the DC bus is made via boost mode while the buck mode is used to charge the battery from DC bus. The PID controllers are used to control the battery buck-boost converter. The control diagram of buck-boost converter is depicted in figure 4. I_R is the reference current calculated as $I_R = P_{BATT-R}/V_{BATT}$.

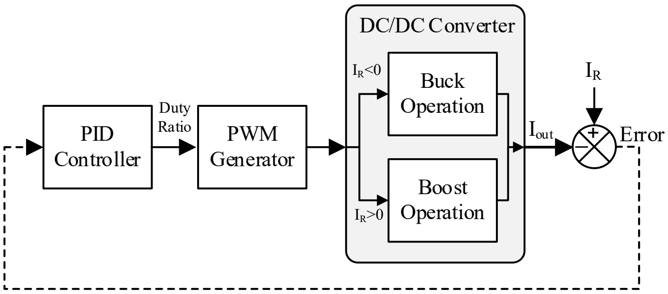


Figure 4: Control system of battery

4.5. Control of Inverter

The DC bus of the HPS is connected to the grid through a three phase inverter. Here, the inverter is controlled using PI controllers followed by hysteresis current control scheme as depicted in figure 5. The proposed control scheme generates suitable pulses for driving the controllable switches of the inverter. The PI controllers try to reduce the error which is the difference between the reference and actual values of the active and the reactive powers. The PI controllers adjust the error and thus control the corresponding powers. It is essential for the grid current to be in phase with the grid voltage and has unity power factor. Therefore, a phase locked loop is used which estimates and adjusts the phase angle of grid voltage. The estimated phase voltage angle is then used to synchronize the inverter to the grid.

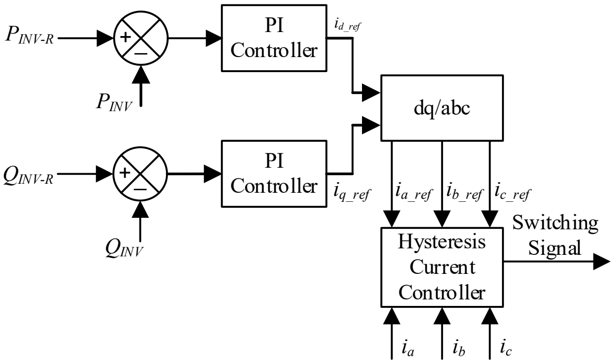


Figure 5: Control system of grid connected inverter

5. Operation of CEMCA

The PV system selected in this work is capable of providing 261 kW of power at best radiation and temperature while the fuel cell (FC) is a 200 kW power plant. In this research work, a SOFC is selected, because, among the various types of FCs, SOFC has the maximum efficiency of about 50-65%. A pressurized 50 kW alkaline ELZ is used for hydrogen production. The hydrogen is stored in a tank for later use in the SOFC. A battery bank of capacity 50 Ah is used in parallel with SOFC. The function of the SC bank is to store the excess power from DC bus and then supply it back in case it is needed. Apart from this, the mismatches and load following problems of SOFC are compensated by SC. A control approach is designed to meet load demands throughout the day and after sunset by using the PV/SOFC/ ELZ/battery hybrid system. The CEMCA controls the whole energy measurement. Based upon the required measurement, the CEMCA generates the commands for the power converters attached to the inputs/outputs of the components used in the hybrid system.

The operating strategies employed in the CEMCA are as follows:

- The use of power generated by the PV system has the priority in meeting load demand over that delivered by the SOFC system or by the battery bank.
- If the power generated by PV system is higher than the demand, the excess power will be used to charge the battery bank.
- If still excess power is available, then it will be sent to ELZ to produce hydrogen for SOFC.
- Similarly, if the total power generated by the PV system is less than the demand, power will be delivered from the SOFC.
- If the load demand exceeds the power generated by the PV/SOFC combination, the difference is supplied by the battery bank.

For explanation of algorithm shown in figure 6, it is better to divide the operation of CEMCA into several modes. Mode I: PV disconnected SOFC disconnected Battery discharging (PDSDBD), Mode II: PV disconnected SOFC connected Battery discharging (PDSCBD), Mode III: PV connected SOFC disconnected Battery charging (PCSDBC), Mode IV: PV connected SOFC disconnected Battery disconnected (PCSDBD).

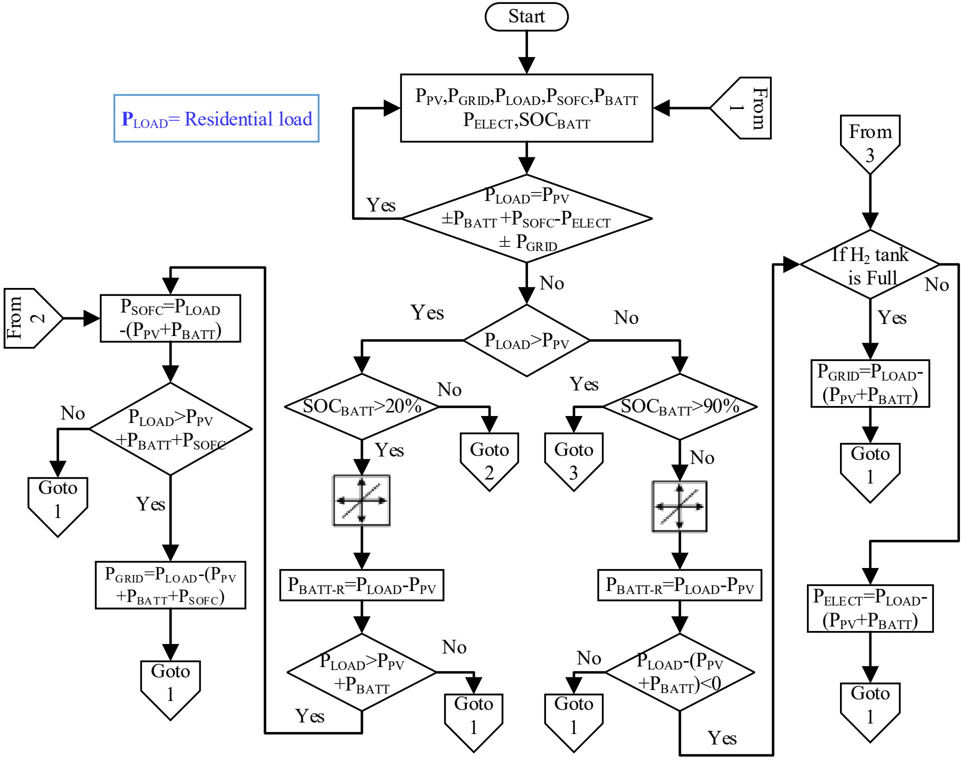


Figure 6: Flow chart of proposed algorithm

5.1. Mode I: PDSDBD

In this operating mode, the power generated by PV is zero due to low irradiance or bad weather i.e., $P_{PV} < P_{LOAD}$. Thus, the need of battery and SOFC is essential. The CEMCA checks the battery SOC and if sufficient charge is available, CEMCA controls the buck-boost converter to deliver its maximum power and applying a reference $P_{BATT\text{-}R} = P_{LOAD} - P_{PV}$ as shown in figure 6. Hence all the power demand is provided by the battery itself.

5.2. Mode II: PDSCBD

This mode is similar to the mode I, but the difference in both modes is the involvement of SOFC which is absent in mode I. Alike mode I, the PV and battery goes in same fashion. As the power demand is not satisfied with the battery alone, so, SOFC is acting as an active player in this mode. The remaining power demand reference is given to the boost converter of SOFC by CEMCA which is $P_{SOFC\text{-}R} = P_{LOAD} - P_{PV} - P_{BATT}$ as shown in figure 6.

5.3. Mode III: PCSDBC

This mode is applicable when PV is generating excess power i.e., $P_{PV} > P_{LOAD}$. So in this mode, there is no need of SOFC. The excess power generated by PV system is sent to the battery with reference power $P_{BATT\text{-}R} = P_{PV} - P_{LOAD}$ as shown in figure 6. The electrolyzer will consume any excess power present inside the system. Here, there are two conditions for excess power (a) when battery is charging on its maximum power (i.e., 30 kW) remaining excess power is still inside the system (b) the battery is fully charged and then the remaining power exists inside the system. From the above two conditions, the first condition is incorporated in this mode while the second condition will be employed in next mode. Hence, in this mode, the battery is charging with its maximum power and remaining power is consumed by the electrolyzer as shown in figure 6.

5.4. Mode IV: PCSDBD

In this operating mode, the PV is generating power greater than the load demand. Therefore, the excess power is sent to battery bank or electrolyzer depending upon the status of the state of charge (SOC) of battery i.e., $SOC_{BATT} < 90\%$ and tank pressure. If the SOC of the battery reaches its maximum value, the second condition (discussed in previous mode) is fulfilled.

6. Simulation Results and Discussion

In this section, first weather and load data are discussed. Secondly simulation results of various modes are described and validated.

6.1. Weather statistics

The weather data used in this HPS are ambient temperature (°C) and solar irradiance (W/m^2). The temperature is collected on hourly basis while solar irradiance is taken at the interval of half an hour. The weather data used in this paper are of a typical summer day in Islamabad as shown in figure 7.

6.2. Dynamic Load

In this paper, HPS is grid connected and standalone. The HPS provides power to Residential Load (RL). In Peshawar, fixed power is determined by inflexible loads like ceiling fan, air conditions, refrigerators etc. For lighting load, the power consumption is calculated by using averaging. The peak load and average load are calculated as 2.8 kW and 2.02 kW per home. The peak load starts from 18 Hrs and ends at 21 Hrs.

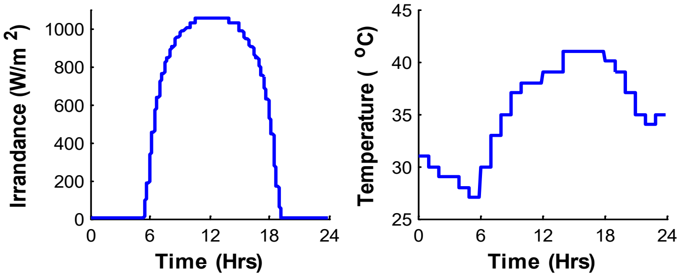


Figure 7: Weather statistics of Peshawar

The simulation is carried out under different circumstances .viz. irradiance, temperate, peak and off-peak load. The simulation time is divided into various sections based on the behaviour of different energy sources.

The powers of PV, SOFC, battery, electrolyzer, Utility Grid (UG) and RL at different intervals are shown in figures 8-13. The first time interval is selected such that when the irradiance level is zero i.e., from midnight to 6 Hrs and it represents the mode I. In the same fashion, others are selected and described later on. From figure 8(a) the RL varies from 70-140 kW. The reference is represented by dotted lines while actual power is shown with solid lines. According to the algorithm, the PV first tries to stratify the load, but due to no radiation, PV does not generate any power as depicted in figure 8(c). After PV, the battery delivers its maximum power (30 kW) as illustrated in figure 8(e) but the battery does not fulfill the load demand. Therefore, the remaining power demand is shared between SOFC and grid as shown in figure 8(b) and (d). To keep the system stable, this excess power is consumed by the electrolyzer as shown in figure 8(f).

The second range of interval is selected in which irradiance level starts increasing gradually (i.e., 6-7 Hrs) and mode II also lies in this interval. The PV starts generating power as shown in figure 9(c). From figure 9(a), the RL is 130 kW whereas PV production is 100 kW. The remaining power demand of load is satisfied from battery, SOFC and grid as shown in figure 9(e), (d) and (b). After 6.5 Hrs, the PV generates 150 kW power which is greater than load demand. Therefore, the excess power is first sent to a battery for charging and then sent to electrolyzer as shown in figure 9(e) and (f). This interval contains a switching of mode I to II to III. Mode I ends at 6.1 Hrs whereas mode II lies between 6.1-6.5 Hrs and after that mode III begins.

The third and fourth time slots are selected in such a way that the PV generates power greater than RL demand. Third and fourth slot contains mode III and mode IV respectively. Figure 10 describes the mode III which starts from 7-12.5 Hrs. In this interval, RL varies from 150-200 kW whereas PV output power varies from 180-260 kW as shown in figure 10(a) and (c). Thus, PV is generating sufficient power to meet the load demand and excess power is first sent to a battery for charging (30 kW) and remaining excess power is sent to the grid and electrolyzer as explored in figure 10. As there is no need of SOFC, because, all the load demand is satisfied with PV, so its output power is zero throughout this interval as depicted in figure 10(f).

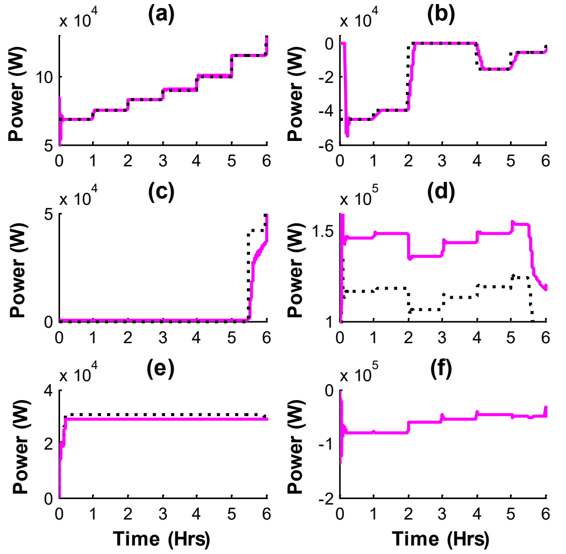


Figure 8: Matlab Simulink output powers with references for Mode-I (a) RL (b) UG (c) PV (d) SOFC (e) Battery (f) Electrolyzer

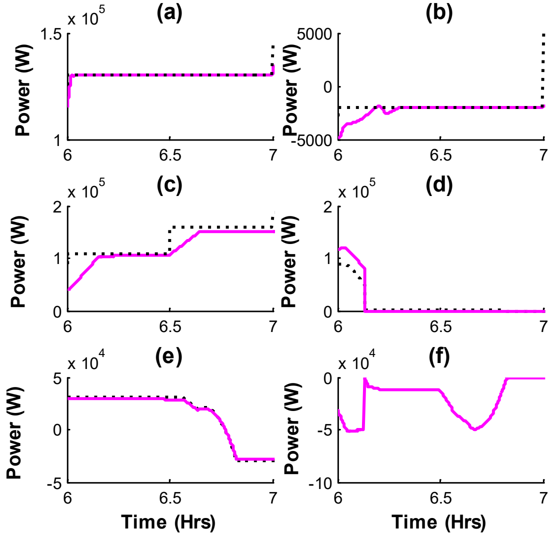


Figure 9: Matlab Simulink output powers with references for Mode-II (a) RL (b) UG (c) PV (d) SOFC (e) Battery (f) Electrolyzer

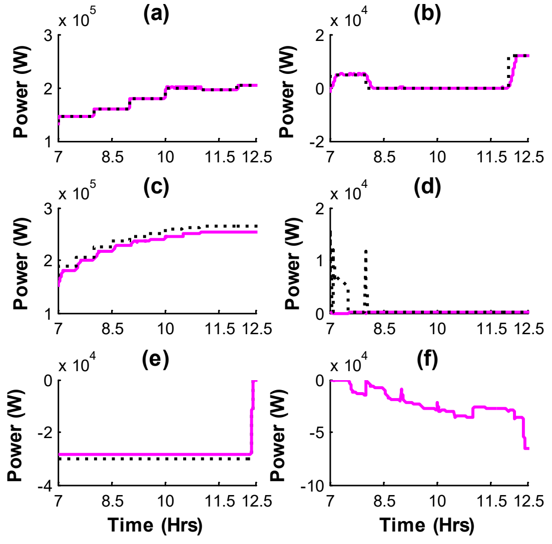


Figure 10: Matlab Simulink output powers with references for Mode-III (a) RL (b) UG (c) PV (d) SOFC (e) Battery (f) Electrolyzer

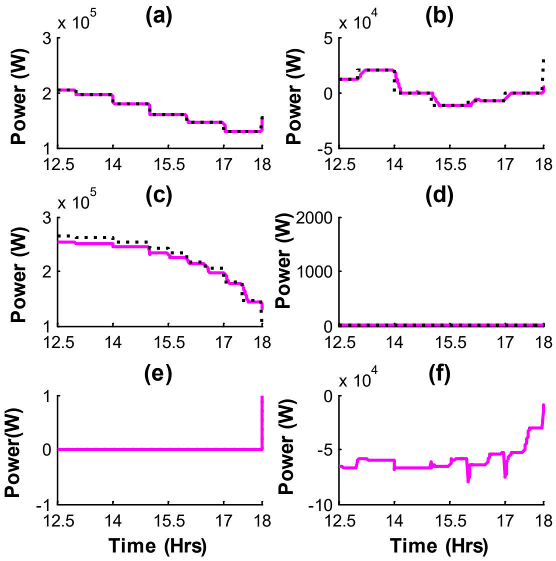


Figure 11: Matlab Simulink output powers with references for Mode-IV (a) RL (b) UG (c) PV (d) SOFC (e) Battery (f) Electrolyzer

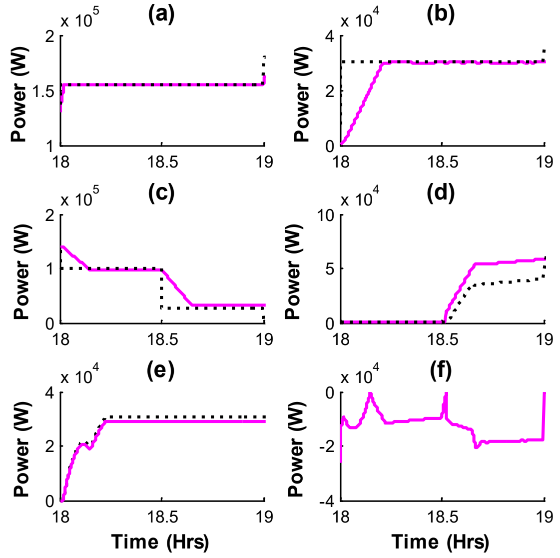
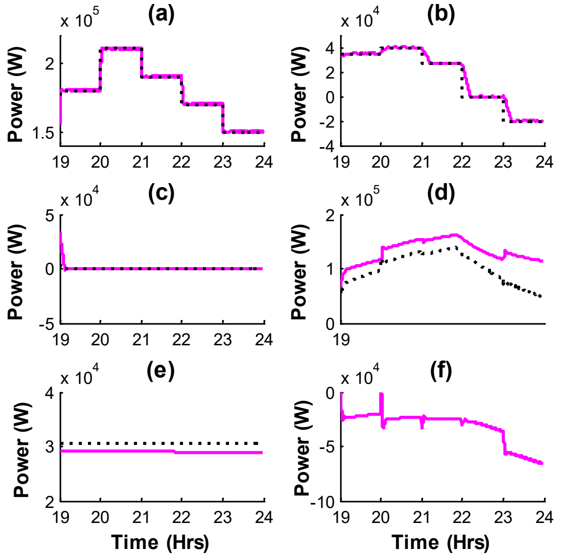
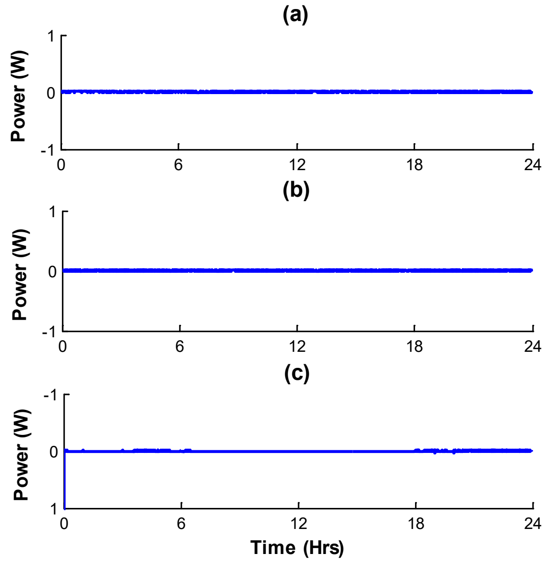


Figure 12: Matlab Simulink output powers with references for switching of modes (a) RL (b) UG (c) PV (d) SOFC (e) Battery (f) Electrolyzer

than it reference which is consumed by the electrolyzer to keep the system stable as shown in figure 12(f).

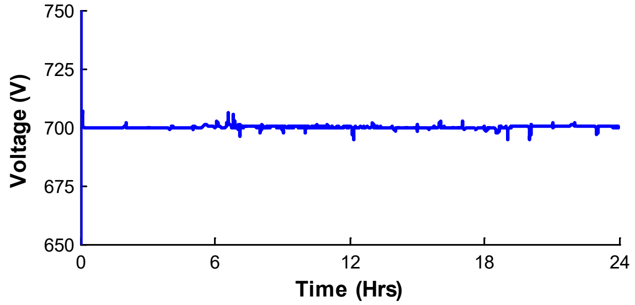
The final time slot starts from the evening (i.e., 19 Hrs) to midnight and contains mode I. This time interval contains the peak load of the day, i.e., 210 kW and PV is off. In the same fashion during peak load, rather than taking power from the UG, it's a better option to take power from the battery and SOFC to satisfy load demand. Hence, figures 13 reveals that the battery is providing its maximum power and SOFC satisfies the remaining load demand and excess power is sent to the UG and an electrolyzer.





The system is called as stable one when all the power inside it is zero. If a system contains real power, then it alters the line- to-line voltage of the load while if a system contains reactive power, it alters the frequency of load voltage. It is clear from figure 14 that the net real and reactive powers on the AC side and net DC power on DC side are zero during peak and off-peak hours. This analysis shows the effectiveness of the proposed system in terms of stability and power quality.

Similarly the net power on the DC bus alters the DC bus voltage which causes in harmonics. From figure 15, it is clearly revealed that the net real and reactive powers on the AC side and net DC power on DC side are zero. Furthermore the figure 15 shows that the DC bus voltage is inside standard limits [33].



7. Conclusion

This paper concludes a classical based energy management and power control of HPS, which is composed of renewable energy source (PV), hydrogen energy (SOFC), and battery. The proposed CEMCA removes the deficiency of a single power source and provides a PV/SOFC/ELZ/Battery HPS which meets the load demand for 24 Hrs without any interruption. The dynamic behavior of the proposed HPS is tested under real-world record of wind speed and load variations. Matlab simulation is performed to confirm the effectiveness of the developed system in terms of load tracking, voltage regulation, power quality and grid stability

Conflict of Interest

The authors declare no conflict of interest.

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