# Design and analysis of a rooftop PV system for an apartment building in Newfoundland


Asif ur Rehman
Department of Electrical and Computer Engineering
Memorial University of Newfoundland
St. John's Canada
aurehman@mun.ca

Hashem Elsaraf
Department of Electrical and Computer Engineering
Memorial University of Newfoundland
St. John's Canada
hasmaelsaraf@mun.ca

Atefeh Zare
Department of Electrical and Computer Engineering
Memorial University of Newfoundland
St. John's Canada
azare@mun.ca

Tariq Iqbal
Department of Electrical and Computer Engineering
Memorial University of Newfoundland
St. John's Canada
tariq@mun.ca



***Abstract*—This research describes the design of a rooftop photovoltaic system to meet the partial energy needs of an apartment building in Newfoundland. A residential apartment building consisting of 54 apartments at fresh water road, St. John's is selected for this work whose average energy demand is 54KW (building is heated using oil). A grid-tied solar photovoltaic system without any battery backup has been deigned for this site because local grid is available and some net-metering laws are in place. The system has been designed by keeping in mind that the produced energy must not be greater than the average energy consumption of the building. Detailed system design, steady state modeling, dynamic modeling, control system design, analysis and required protection system are explained in this paper. Some cost analysis and installation details are also included in the paper.**



***Keywords— Solar photovoltaic power system, Grid-tied photovoltaic system, Renewable energy system***


## I. INTRODUCTION AND LITERATURE REVIEW

Global energy demand is increasing gradually due to the growing population. This increasing demand of energy is leading towards environmental hazards because major portion of energy is generally produced by fossil fuel. Renewable energy resources can provide carbon free energy, but they can't be used to fulfil the requirements of energy sector due to their extraordinary initial cost and energy production limitations [1]. Energy can easily be converted from one form to another and most common energy carrier is electricity. As per International Energy Agency (IEA) total energy consumption of the world will increase 1.3% each year to 2040 with 2.3% growth in 2018. Fossil fuel has been a major source of energy, but it is available in a limited quantity. We have used 60% of fossil fuel storage since last 200 years so relying on this kind of technology is not a good choice [2]. Presently, Power is generated in a centralized facility and distributed to the distant areas through transmission lines. Adopting renewable energy resources is the best solution for all energy demand and climate change problems but implementing these technologies in existing centralized power system is very costly. Distributed power system and micro renewable energy units can make it easy to adopt these renewable technologies at relatively lower cost [3].

Grid-tied solar photovoltaic system is emerging as one of the leading renewable energy technology. Many researchers working in this field e.g [4] evaluates a 100KW grid-connected solar photovoltaic system for Nagar Nigam Kota Rajasthan. This study also discusses the guidelines and technical specification of various components of grid-connected PV system installed at the same site. It analyzes the feasibility of that system resulting 167,822 KWH production annually by using PVsyst software. In [5] the author attempts to highlight the steady state integration impacts of solar photovoltaic (PV) generation to existing transmission and distribution grids. That study shows a model of existing transmission and distribution grid in the Northern Cape region of South Africa, known as the solar corridor using Matlab Software. The study concluded that the amount of PV generation integrated to the grid has a limit if the steady state stability of the existing grid is to be maintained. The study [6] presents a robust control strategy for a solar photovoltaic (PV)-based distributed generation system (DGS) with seamless transition capabilities from islanded to the grid-connected mode and vice versa. The proposed DGS consists of a solar PV array, a dc-dc boost converter, voltage source converter (VSC), and local nonlinear loads. In grid-connected mode, VSC regulates the dc-link voltage and the boost converter operates the solar PV array at the maximum power point. Test results of that study demonstrate the system capabilities under the abnormal grid and unbalanced nonlinear load conditions.

A combined grid-connection and power-factor-correction technique for a photovoltaic (PV) system is proposed in [7]. The author used maximum power point tracking dc/dc converter served as a charger for the battery bank. That study applied a bidirectional inverter as a generator during sunlight, supplying power to the load. The inverter is also used as a charger to maintain the voltage level of the batteries in the absence of sunlight. the experiments performed by author on a 1-kW PV system show satisfactory results of the power management and the unity power factor at the utility side. Our research is about the designing of a grid-tied solar photovoltaic system to meet he energy needs of a residential building. The 285-Freshwater road apartment's building has been selected for the designing of solar photovoltaic power system. As per the electric bill of a particular apartment, the average 3-bedroom apartment in that building is


XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

consuming 872 KWh monthly in winter. Detailed system design, steady state modeling, dynamic modeling, control system analysis and protection designing of this system is being carried out in this research.

## II. System Design

The basic site parameters that are required for the designing a solar photovoltaic system are solar irradiance of that area, average temperature of the location, available space on roof top, local grid specifications and energy consumption of the building. This specific location has solar irradiance of 3.15 KWh/m2/day and average temperature of 5.56C. This data has been calculated with the help of a software named HOMER by putting the location of this building. Total Available area on the roof of this building is 763 m2 which can be used for the installation of solar panels. The electric bill of an apartment shows 872 KWh monthly consumption of an apartment in winter. There are total 54 apartments in this building so the average power consumption is calculated below.

Total hours in a month = 24×30 = 720 hours

Avg. hourly demand of 1 apartment = 872/720 = 1.2 KWh

There are also some double bedroom apartments in the building so we can take this value as a round value of 1 KWh per apartment.

Avg. hourly Electrical demand of the building = 1x54 = 54 KWh

The building space and water are heated by oil. The basic components of a grid-tied solar power units are Solar panel, Power Inverter, PV Combining box, PV roof-top mounting frames, connection cables, lightening protection equipment, grounding pit and Metering and protection panel. If there are 20% system losses then required solar panels are

Solar Panel required for system = 54/0.8 = 67.5 KW

The calculation shows that any value near to 67.5KW is good for solar panel sizing to get required power after compensating losses. Total 228 solar panels (390W each) are used in this project making 12 strings of 19 panels each with a total 66.1KWp DC capacity of this system. There are also some losses due to stationary solar panels but we are not considering those losing for this calculation. The second most important part of this system is PV inverter. Grid-tied solar inverter is always selected as per the capacity of solar panels and voltage specifications of local utility grid. SMA Sunny Tripower CORE1 62-US Inverter is used in design because output efficiency of this specific inverter is maximum in Helioscope. This inverter provides 62KW at 208VAC, 60Hz so it is compatible with local utility grid. Selected inverter has 6 MPPT trackers with maximum current input capacity of 20A each and every tracker has 2 DC input strings. The voltage range of MPPT tracker is 550VDC-800VDC [8].

Total MPPT trackers of the inverter = 6
PV string input for each MPPT tracker = 2
Total string of inverter = 12
Total number of solar panels = 228
Solar panels for each string = 228/12 = 19
Open circuit voltage for each panel = 39.5VDC [9]
Total VOC of each string = 39.5 x 19 = 750.5VDC

There are total 12 input strings in this inverter and 19 solar panels in series will be connected to each string making 750.5VDC each. Other calculations of wire size, PV combining box size and steady state model of the system is carried out in HelioScope software.".

## III. Steady State Modeling of the system

Helioscope is an online Solar PV designing and analysis tool which provides steady state modeling data of the designed system. System is designed after selecting freshwater apartment building in Helioscope. The user just need to select desired PV inverter, PV panels, location of the building, placement of solar panels, and allowable wiring losses of the system in the software then this will automatically calculate the required wires, protection and control equipment for the system. Fig. 1 shows the string connections and placement of solar panels on roof of the selected building. Space between each row of solar panel is selected 1.3 meter to avoid shading on any solar panel due to the other row. The tilt angle of solar panels is set to 32 degrees which is 15 degrees less than latitude to get the more output in summer.


Fig. 1. Solar panel placement and connections

Fig. 2 shows the expected monthly production graph of the system by considering solar irradiance and temperature factors for selected location. This graphs clearly shows that the maximum production is in summer (June, July) and minimum production is in winter (Nov, Dec). This graph shows that designed system can produce 77,432 KWh per year at selected location.

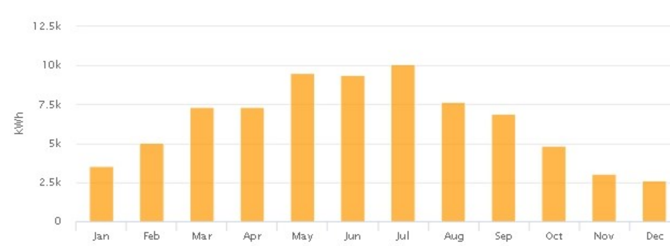


Fig. 2. Monthly energy production of the system

Fig. 3 shows all the losses in the system including inverter losses, wiring losses, shading losses, mismatch losses, solar irradiance losses, soiling losses and reflection losses. There are total 12.5% losses and the system are operating at 87.5% performance ratio. There are no temperature losses in the system because average temperature of the site is always within the ambient temperature of the solar panels.

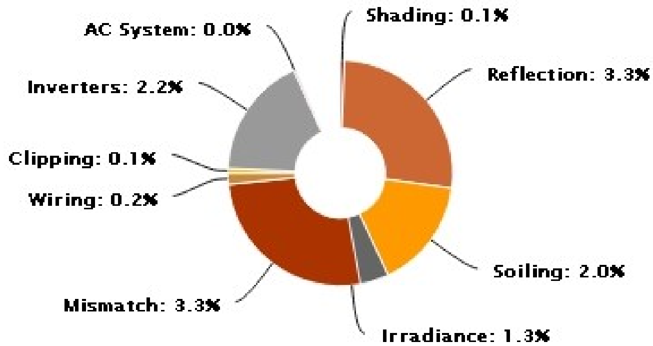


Fig. 3. System Losses

## IV. DYNAMIC MODELING AND ANALYSIS

Dynamic modelling is conducted to study the effects of the proposed system on the grid. Matlab software is used for dynamic modeling of the designed system. The default solar irradiance model of Matlab is attached to the PV block through a rate limiter which converts the sudden change in irradiance from 250 to 750 W/m2 into a slower buildup with a slope. This setup is however unrepresentative of real irradiance which varies every hour and does not follow a stable value throughout time. Therefore, hourly irradiance for St. johns is obtained from HOMER. The values are saved in an excel file. There is a total of 8760 irradiance data points each representing 1 hour in a year. The data is plotted in MATLAB as a variable named "Irradiance". Fig 3 shows the irradiance plot for the entire year. This is accomplished by running the simulation for 87.6 seconds and inputting the irradiance output through an integrator (accumulator) block to obtain the energy density which in this case is 1.15 *106 Wh/m2. By dividing (1000 * 365) using the gain block, the average daily energy density is obtained as 3.15 kWh/m2-day which is the exact same value given by HOMER.

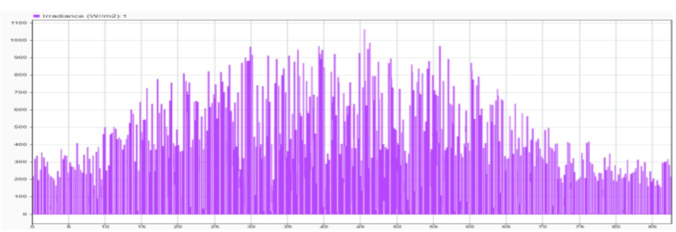

Fig. 4. Hourly irradiance plot

In the original Simulink file, the temperature block is a constant block set at 25 degrees Celsius. Similarly, this approach is unrepresentative of real temperature variation. Gaining the real-time temperature data is accomplished by obtaining hourly temperatures in St. john's and compiling them into one variable with 8760 data points (saved as temp). The panel used in this project is not saved as an option in MATLAB so it is plotted manually from the datasheet. A few values are changed in the default inverter model to simulate the current project. The nominal power of the inverter is set to 75000 VA. The DC voltage is set 750 volts. The upper and lower output limits of the inverter are set to 800 and 550 respectively as per the datasheet of the inverter [11]. Perturb and Observe technique is used to achieve MPPT in this system. Fig. 5 shows the dynamic simulation design of the designed system in Simulink. The numbers in yellow highlight show the results of 0.24 seconds simulation time (first day of January).

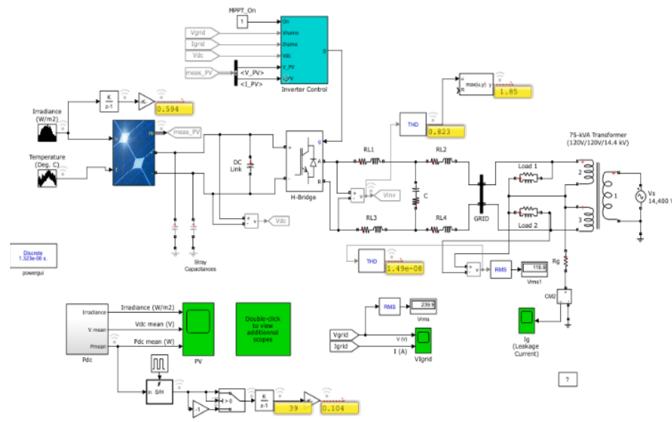

Fig. 5. Simulated system in Simulink

Voltage sensors attached to an RMS block and a display at multiple points show that the RMS voltage at the load is 119.9 volts while the line to line RMS voltage of the grid 239.9 volts. The THD levels before and after the filter are shown in fig. 6. Before the filter the maximum THD level was 1.85 however after the filter this number dropped to zero.

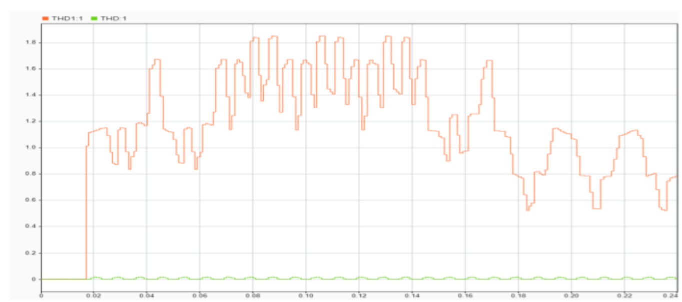

Fig. 6. THD before filter (red) and after filter (green)

Fig. 7 shows Irradiance, mean DC voltage and mean DC power of the PV module. It can be observed from fig. 7 that Dc voltage and power output of the system is totally dependent on solar irradiance. The power output of the designed system does not change immediately after change in solar radiations. The simulation results show that total irradiance for that day is 0.594 kWh/m2-day which is much less than January's average of 1.28 kWh/m2-day. The energy of the PV panels is 39 kWh/day, While the energy density is 0.104 kWh/m2-day making the efficiency of the panel 17.5%. Fig. 8 shows the voltage and current outputs of the installed inverter. The output voltage of inverter is always stable but the value of current is changing as per the availability of sunlight and electrical demand of the building.

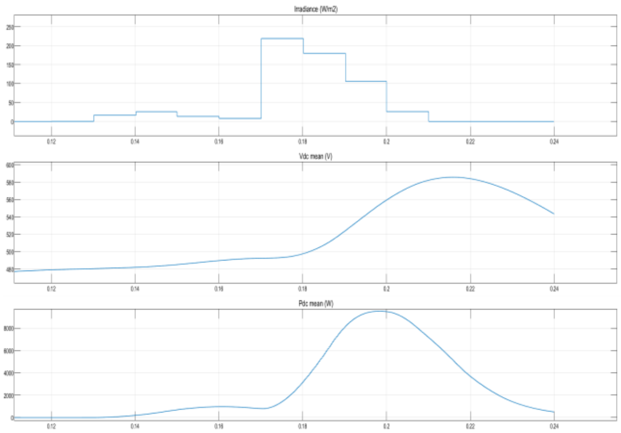

Fig. 7. Irradiance (top), Vdc mean (middle), Pdc mean (bottom)

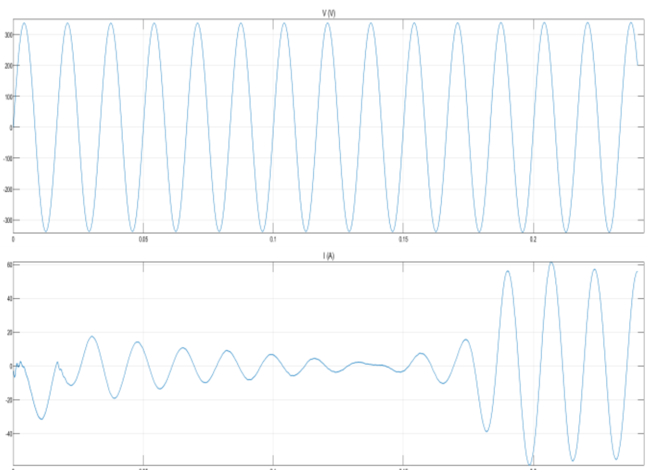

Fig. 8. Voltage (top) and current (bottom) at the grid

## V. CONTROL SYSTEM DSIGN AND ANALYSIS

A controller is designed to control the inverter based on maximum power point tracking (MPPT) algorithms and pulse width modulation (PWM). Normally, MPPT controller is used to control DC-DC converters, in this design it is utilized to generate modulating signal [12][13].

### A. Inverter Control

The inverter, coupled to the PV source, converts DC power from the PV to AC power. Inverter switches are controlled using PWM. In order to generate an activation signal, the comparator receives a modulating signal and carrier signal. The carrier signal is a high-frequency triangular wave. The controlled modulating signal is generated in order to achieve the desired inverter output. Control stage obtain a sinusoidal modulating signal with a frequency equal to the desired output frequency of the inverter. Every time the carrier signal crosses the modulating signal, the activation signal is toggled to the switches [14]. A control system consists of four control loops that generate the modulation signal: a phase lock loop (PLL), a maximum power point (MPP) controller, a voltage controller, and a current controller. Fig. 9 shows the desired circuit diagram of the system.

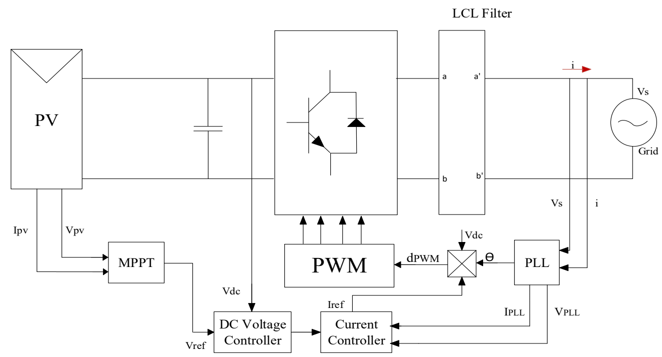


Fig. 9. Block diagram of the inverter control system

### B. Incremental conductance algorithm for MPPT controller

Incremental conductance (IC) is another conventional two sensors algorithm. The algorithm is illustrated in Fig. 10. The basics for this algorithm are that (∂I/∂V) at MPP is zero, positive when the voltage is below Vmpp, and negative when the voltage is higher than Vmpp. Current and voltage are sampled in order to calculate the value of (∂I/∂V). The MPPT regulates the PWM control signal of the DC-AC inverter until the condition: (∂I/∂V) + (I/V) = 0 is satisfied [15].

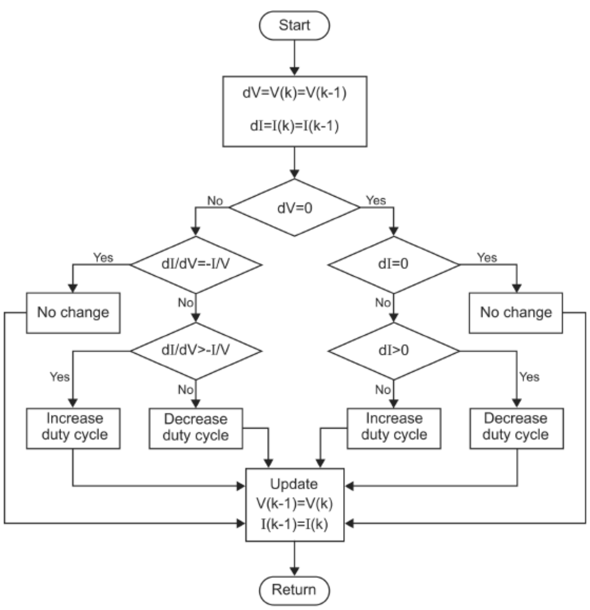


Fig. 10. Flowchart of incremental conductance algorithm

### C. Simulation results

Different solar irradiance values are entered into the solar panel at 25 Degree Celsius to evaluate the designed system. The most important dynamic simulation results are shown in fig 11 and fig. 12. Fig. 11 shows the relation between solar radiation and power output of solar panels. Lower portion of Fig.11 shows the comparison between actual output of solar panels and power output of inverter. Fig.12 shows the voltage and current of local grid after connecting the designed system to it.

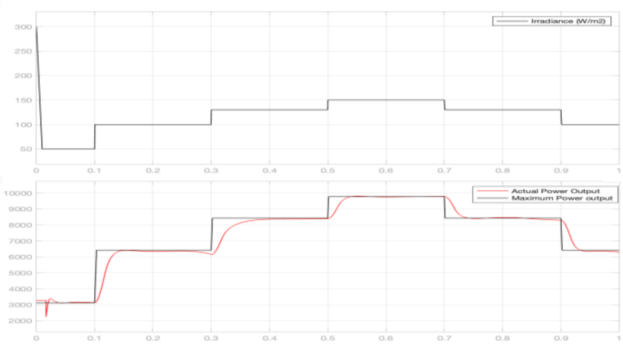


Fig. 11. Solar irradiance & PV output.

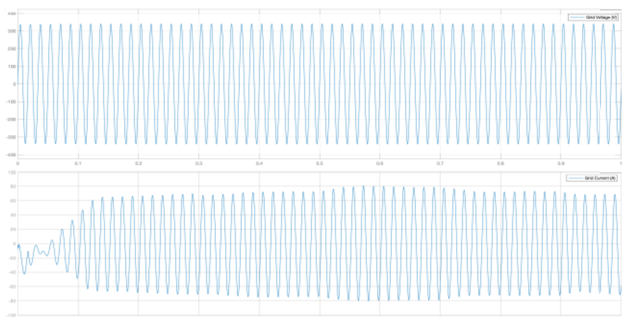

Fig. 12. Grid voltage and current.

## VI. COST ANALYSIS

System advisory model (SAM) software is used for cost analysis of this system. Major equipment used in this system are solar panels, grid-tied inverter and solar panel mounting frames. The estimated prices of these items are mentioned in table 01. In this table the balance of the system equipment means PV combiner boxes, DC & AC breakers, solar PV cables, inverter cables, grounding pits, surge arresters, fuse boxes and other minor material required for installation. The prices of balance of the system equipment, labor and installation overheads are estimated by SAM software.

TABLE I. TABLE TYPE STYLES

| Item | Price C$ | Qty | Total C$ |
|---|---|---|---|
| Solar Panel | 261 [18] | 228 | 59,508 |
| Inverter | 6875 [19] | 01 | 6,875 |
| Mounting Frames | 68 [20] | 228 | 15,504 |
| Balance of system equipment | 23,823 | 01 | 23,823 |
| Installation labor | 26,470 | 01 | 26,470 |
| Installation margin | 66,174 | 01 | 66,174 |

### *A. Simulation results of cost analysis*

SAM result shows that the total cost of this system is 211,283 CAD which seems to be a bit higher than the average solar PV installation prices worldwide. SAM calculated the prices for balance of the system equipment, installation labor and installation margins by default. 52% of direct cost is considered under sales tax and the sales tax rate is considered 5% which is default by the software as per local region. The mortgage setting for final cost analysis of the system is at 100 percent debt fraction with loan terms of 25 years. Fig 13 shows the summary of results calculated by SAM. The results in SAM shows that this system will produce 78,789 KWh per year with a performance ratio of 87 percent which is almost near to the results calculated in Helioscope. The capacity factor of this system is 13.6 percent and all investment will be recovered in 24 years in form of electric bill savings with the installation of this system.

| Metric | Value |
|---|---|
| Annual energy (year 1) | 78,789 kWh |
| Capacity factor (year 1) | 13.6% |
| Energy yield (year 1) | 1,191 kWh/kW |
| Performance ratio (year 1) | 0.87 |
| Levelized COE (nominal) | 14.58 ¢/kWh |
| Levelized COE (real) | 11.64 ¢/kWh |
| Electricity bill without system (year 1) | $60,582 |
| Electricity bill with system (year 1) | $52,892 |
| Net savings with system (year 1) | $7,690 |
| Net present value | $-19,655 |
| Simple payback period | 24.0 years |
| Discounted payback period | NaN |
| Net capital cost | $211,283 |
| Equity | $0 |
| Debt | $211,283 |

Fig. 13. Result summary of SAM

Figure 14 shows the demand and supply graph of the system which shows that this system can provide a minor fraction of power to the building and almost 8000 CAD per month can be saved in electricity bill

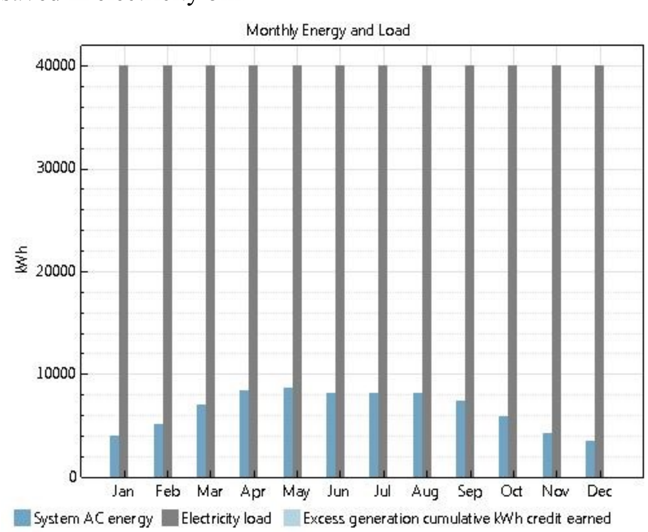


Fig. 14. Demand and supply graph of the system

## VII. CONCLUSION

The designed system will generate 77,432 KWH per year at installation cost of 3.19 CAD per watt. The DC rated power of the system is 66,120 watts so the total initial cost of the system is approximately 211,000 CAD. As per the local electricity rates, the pay-back period of this project is 24 years and the capacity factor of designed system in 13.8 %. The results of the dynamic simulation show that the PV efficiency is 17.5% with low harmonics injected into the grid (after the filter) and rms voltage are grid compatible at 119.9 VAC phase to neutral and 239.9 VAC phase to phase. Two models were proposed for irradiance and temperature simulation and compared against hourly data in which the results showed more than 90% similarity. The system used P&O and IC algorithms for MPPT controller in inverter. Protection devices are selected by considering Photovoltaic protection standards. This system will reduce a significant amount of electricity from the local grid, which eventually contributes towards the environmental improvement.

## REFERENCES


[1] D. Singh, N. K. Sharma, Y. R. Sood, and R. K. Jarial, “Global status of renewable energy and market: Future prospectus and target,” in International Conference on Sustainable Energy and Intelligent Systems (SEISCON 2011), 2011, pp. 171–176.

[2] R. Wang, H. Zhang, F. Shi, Y. Zhang, and L. Zhang, “Empirical study of the relationship between global energy consumption and economic growth,” in 2017 China International Electrical and Energy Conference (CIEEC), 2017, pp. 394–399.

[3] M. Alipour and H. Seyedi, “Enhancement of power system voltage stability using new centralized adaptive load shedding method,” in 2015 30th International Power System Conference (PSC), 2015, pp. 223–227.

[4] G. Saxena and L. Gidwani, “Estimation of Energy Production of Grid Connected Rooftop Solar Photovoltaic System at Nagar Nigam Kota, Rajasthan,” in 2018 3rd International Innovative Applications of Computational Intelligence on Power, Energy and Controls with their Impact on Humanity (CIPECH), 2018, pp. 45–49.

[5] N. Dhlamini and S. P. D. Chowdhury, “Solar Photovoltaic Generation and its Integration Impact on the Existing Power Grid,” in 2018 IEEE PES/IAS PowerAfrica, 2018, pp. 710–715.

[6] S. Singh, S. Kewat, B. Singh, B. K. Panigrahi, and M. K. Kushwaha, “Seamless Control of Solar PV Grid Interfaced System With Islanding Operation,” IEEE Power Energy Technol. Syst. J., vol. 6, no. 3, pp. 162–171, 2019.

[7] Y. Lo, T. Lee, and K. Wu, “Grid-Connected Photovoltaic System With Power Factor Correction,” IEEE Trans. Ind. Electron., vol. 55, no. 5, pp. 2224–2227, 2008.

[8] SMA Solar Technology AG, “SUNNY TRIPOWER CORE1,” SMA Solar. [Online]. Available: https://www.sma-america.com/products/solarinverters/sunny-tripower-core1.html. [Accessed: 09-Apr-2020].

[9] “Canadian Solar Inc.,” Datasheet. [Online]. Available: https://www.bluepacificsolar.com/picture_library/tech-specs/canadian-solar-CS6K-290ms-300ms-datasheet.pdf. [Accessed: 09-Apr-2020].

[10] Bluepacificsolar.com, 2020. [Online]. Available: https://www.bluepacificsolar.com/picture_library/tech-specs/canadian-solar-CS6K-290ms-300ms-datasheet.pdf. [Accessed: 09- Apr- 2020].

[11] S. AG, "SUNNY TRIPOWER CORE1 | SMA Solar", Sma-america.com, 2020. [Online]. Available: https://www.sma-america.com/products/solarinverters/sunny-tripower-core1.html. [Accessed: 09- Apr- 2020].

[12] Mahmood, H., Michaelson, D. and Jiang, J., 2015. Decentralized Power Management of a PV/Battery Hybrid Unit in a Droop-Controlled Islanded Microgrid. IEEE Transactions on Power Electronics, 30(12), pp.7215-7229.

[13] AbdelHady, R., 2017. Modeling and simulation of a micro grid-connected solar PV system. Water Science, 31(1), pp.1-10.

[14] M. Lasheen and M. Abdel-Salam, "Maximum power point tracking using Hill Climbing and ANFIS techniques for PV applications: A review and a novel hybrid approach", Energy Conversion and Management, vol. 171, pp. 1002-1019, 2018. Available: 10.1016/j.enconman.2018.06.003.

[15] H. Fathabadi, "Novel high-efficient large-scale stand-alone solar/wind hybrid power source equipped with battery bank used as storage device", Journal of Energy Storage, vol. 17, pp. 485-495, 2018. Available: 10.1016/j.est.2018.04.008.

[16] “Electrical Standards.” [Online]. Available: https://library.e.abb.com/public/40abe76927e9e01dc12576ba003c22bf/Solar Cat LR v.06.pdf. [Accessed: 09-Apr-2020].

[17] “Codes and conducts.” [Online]. Available: http://www1.cooperbussmann.com/pdf/1b416a65-f5ac-4730-ab77-9e2faa147945.pdf. [Accessed: 09-Apr-2020].

[18] “Canadian Solar 290W PV Module CS6K-290MS,” The Solar Store. [Online]. Available: https://thesolarstore.com/canadian-solar-290w-pv-module-cs6k-290ms-p-2456.html. [Accessed: 09-Apr-2020].

[19] SMA Solar Technology AG, “SUNNY TRIPOWER CORE1,” SMA Solar. [Online]. Available: https://www.sma-america.com/products/solarinverters/sunny-tripower-core1.html. [Accessed: 09-Apr-2020].

[20] “TILT MOUNT PRICE,” RICH SOLAR.[Online]. Available: https://richsolar.com/collections/mounts/products/tilt-mount. [Accessed: 09-Apr-2020].