Performance Optimization and Development of an Efficient Solar Photovoltaic Based Inverter Air Conditioning System

G. Chaudharya, P. Shrivastavaa, M. S. Alama and Y. Rafatb

aDepartment of Electrical Engineering, Aligarh Muslim University, Aligarh, India; bDepartment of Mechanical Engineering, Aligarh Muslim University, Aligarh, India

ABSTRACT
Presently, Inverter Air Conditioners are becoming popular due to their several advantages. This technology results in consuming less amount of energy for achieving weatherization and has potential to be easily powered by economical energy systems. Few correlated research have been carried out in this field but the outcomes are not significant due to system cost. In this work, the proposed Solar Photovoltaic based Inverter Air Conditioning system using DC motor was designed, modeled and tested for the weather conditions of Aligarh-India. Based on the simulation results, this work formulates an optimization problem depending on the general weather conditions and the time of operation, in order to reduce the operating cost. Optimized design specifications are outlined and verified for onsite implementation.

1. Introduction
In any country power plants play a very important role in improving the economic condition and the life style of the people [1]. In addition to this, electricity being the key ingredient for the socioeconomic development of any country, productivity of the power generation sector has a strong bearing with the competitive advantage of other sectors [2]. Currently, global warming is an alarming situation for the world. This results in disparity in weather conditions, thus causing a change in temperature profile in all parts of the world and in particular, the Heat Islands in urban areas [3]. Thus, a challenge for the world ahead is to control the emissions of greenhouse gases and also to reduce the consumption of energy.

Human beings are getting accustomed to weatherization. A significant amount of the energy consumed by a nation is utilized for the purpose of Heating, Ventilation, and Air-Conditioning. One such device is the Air Conditioning (AC) system which has gradually grown in number over the decades. At present it still consumes a high amount of energy for its operation and has a high operating cost. According to energy usage guidelines by Uttar Pradesh Power Corporation Limited (UPPCL), cost of energy consumed by a conventional AC is INR 10/h [4]. Inverter Air Conditioner (IAC) has several advantages over conventional AC. It has reduced operating cost when compared to conventional ACs, which is still on the higher side, at approximately INR 7/h. ACs are the most suitable means to meet human prospects for weatherization and with advancement in technologies, becoming affordable as well. Thus, the use of AC is increasing rapidly. However, with this increasing number, the gap between the electric
power generation and the demand increases. Due to the heavy dependence of India on fossil fueled electricity generation, rising CO$_2$, SO$_2$, and NO emissions, and increasing demand for emission reductions [5], the situation is becoming difficult to handle.

Further, there are several other disadvantages associated with energy derived from thermal power plants namely running cost is high due to fuel, maintenance, etc., large amount of smoke causes air pollution, fossil fuels are depleting with time and overall efficiency of thermal power plant is low (around 30%) [6] and the energy available from them is costlier [4]. Limited availability of fossil fuel resources and many other environmental problems associated with them have emphasized the need for new sustainable energy supply options that rely on renewable energy resources (RES) [6]. Currently, RESs based power generation in India is 15.9% [7] of the total installed capacity, which is quite low. There are several forms of RESs in India. Some of them are wind power, solar power, small hydro power, bio-power, etc. [7]. Currently, solar energy is the most utilized NRSE source and has a huge potential [11] in India due to several advantages, namely free of cost production, availability, pollution free and it can be used in remote areas. It is estimated that the world’s oil reserves will last for 30–40 years, while, solar energy is forever. With several advantages as mentioned above, solar energy can be realized as an efficient and eco-friendly alternative to the energy derived from fossil fuels mainly from thermal power plants. Photovoltaic (PV) systems are becoming more and more popular as they convert sunlight directly into electricity [8] and their cost has reduced significantly in recent years [9].

India has immense solar energy potential due to its location near equator. The number of hours of sunshine every year is approximately 3000 which is equivalent to 5000 trillion kWh of energy that can generate 1900 billion units of solar power annually which is even sufficient to meet the projected demand by 2030 [10]. The average irradiance/day in a month in India is between 4 and 7 kWh/m$^2$ [11].

There are several types of cooling systems available based on solar power utilization. One such system is solar-assisted air-conditioning system which works on the principle of absorption and uses LiBr/water absorption machine [12]. These systems did not become popular due to their complexity and immature technology. A hybrid air-conditioning system simultaneously connected to the grid and PV modules was tested for its energy efficiency, where the Solar PV based AC system was analysed in terms of energy efficiency ratio and coefficient of performance of system [13]. This system is completely tested for its mechanical performance and no focus was given to the sizing of PV modules.

An IAC powered by PV modules was analysed for its performance both in hot summer zones and cold winter zones for the weather conditions of Shanghai, China [14]. This work did not discuss about the sizing of PV modules required for the optimal minimum cost. Also, the conditions taken for weatherization were not favorable conditions. The earlier researches carried out in this field fails to provide an efficient and eco-friendly system for achieving weatherization. The four main objective of this work are: (1) To reduce the load on grid and matchup with the peak demand in coming years without compromising with the health prospects of human-beings subjected to weatherization. (2) To reduce emissions like CO$_2$, SO$_2$, NOX, particulate matters and ash, etc., generated Thermal power plants. (3) To provide low cost solution through integration of various existing technologies for specific applications to benefit the society of Indian sub-continent.

The objectives mentioned above can be achieved by the solar PV based IAC system (DC Motor based), proposed in this work. A performance optimization problem is formulated for general case of: location and operational hours of AC. This problem can be solved to achieve minimum expenditure for an IAC system, in terms of cost per hour of operation for particular site of interest. This work is categorized in seven different sections. The first section is nomenclature and the second section is introduction. Third section explains how the model employed in this work is designed. Fourth section is about testing the system for weather conditions available at Aligarh, India and results of simulation are discussed. In fifth section, performance optimization problem is formulated based on the simulation results of the proposed model. Sixth section gives the design specifications of hardware setup for site implementation. Final section concludes the work.

2. Proposed IAC Scheme

The proposed scheme is different from the existing technologies in terms of DC motor used to drive the compressor in IAC systems. In the proposed scheme a DC motor is used to drive the compressor, instead of a three-phase AC motor. The advantage of using a DC motor is reduced number of conversion stage. Only a single conversion stage i.e. Buck-Boost converter (variable DC voltage to fixed DC voltage) is essential in proposed scheme. Block diagram of the proposed scheme is shown in Figure 1.

2.1. Modeling of SPVIAC

A physical model for the system is developed for a DC motor based IAC system of 1.5 Tons. Mechanical loading of the system is derived in terms of current drawn from the motor and power requirement of the compressor in commercially available IACs of 1.5 Tons capacity.
DC motor based AC is fed from 3 kWp PV system with the help of a Buck-Boost converter. Small capacity batteries are used in order to fulfill the initial high power requirement of DC motor used to drive the compressor. Maximum power point operation of the system is achieved by deciding the capacity of batteries such that the impedance of the system reaches near to load resistance required at maximum power point of operation. Layout model used for the proposed scheme is shown in Figure 2.

2.2. Simulation of SPVIAC

Model designed in this work is tested for weather conditions of Aligarh at 9:00 AM in the month of April. Simulation was performed on Simulink. The proposed system was simulated for a period of 50 min to test the performance of DC motor based IAC powered by PV system. This time chosen is due to the fact that the amount of time required for the IAC system to switch from full load operation to constant temperature operation is around 40 min. Results of interest are plotted and shown in Figures 3–7.

Figure 3 shows converter output voltage which are applied to motor. As the motor turns-on, voltage in the beginning dips to a value of approximately 150 V due to sudden heavy load. After initial transient time, voltage quickly reaches its nominal value. After transition of state from full load operation to constant temperature operation, voltage rises due to imbalance of power as the power drawn by AC reduces. Still the voltage remains in safe range of operation i.e. under 260 V, with the protection provided to control over voltage.

Figures 4 and 5 show the transient current drawn by motor and the current drawn by motor during stable operation, respectively. Current drawn during transient time is almost 12 times of rated current which is an obvious fact with DC motor and is supplied by the battery. Later, motor draws current at rated value in full load operation for about 40 minutes and a lower value of current is drawn after transition from full load operation to constant temperature operation.

Figures 6 and 7 show the transient power drawn by motor and the power drawn by motor during stable operation, respectively. Power drawn during transient time is almost six times of rated power which is an obvious fact with DC motor and is supplied by the battery. Later motor draws power at rated value in full load operation for about 40 minutes and a lower value of power is required after transition from full load operation to constant temperature operation.

Figure 8 shows the state of charge of battery. Initially, battery was having 40% SOC and dips to near about 39% instantly as high amount of power is drawn from battery to deliver high power required by motor during transient state. After the transition of operation from full load operation to constant temperature operation, battery starts charging quickly as the power available from module is now more than the power required by motor. This rate of charge can be controlled by delivering extra power available to the other storage batteries available for inverter backup supplies used in that particular location. This extra energy utilized can serve as savings in terms of reduction in bills paid to the grid.

3. Performance Optimization Problem

By looking at the power requirement curve (Figure 6) of DC motor based IAC proposed in this work, IAC operation is categorized in two different modes. One is termed as full load operation in which the maximum refrigerant flows through the compressor. Thus, the driving motor runs at full load condition, till the time, set point temperature is not reached. Generally, for a temperature change of 36–16 °C, time taken by IAC is around 40 min for an IAC by Voltas (Model Name: 1.5 T Voltas SAC 18 V DY) and the time taken for temperature change of 36–16 °C is same for the proposed system. Power requirement during this time is the rated power of the compressor motor.

Once the temperature reaches preset value, second mode of operation starts which is termed as constant temperature operation. In constant temperature operation, lesser amount of refrigerant flows through compressor...
Figure 2. Layout of SPVIAC.

Figure 3. Converter output/motor input voltage-vs.-time (complete cycle).

Figure 4. Motor input current-vs.-time (initial transients).

Figure 5. Motor input current-vs.-time (complete cycle).
of 9:00 AM–5:00 PM, the concept of optimization occurs when the insolation starts falling after 12:00 noon and AC has to operate till 5:00 PM. If the AC is run till 5:00 PM from PV modules, the capacity of PV modules required will be very high making the system costlier. Thus, in this work the authors are looking to find that point of time \( t \) from where the AC load should be switched to grid system in order to achieve minimum consumption cost per hour during the lifetime.

The function to be minimized is cost consumption of AC per hour of operation over complete lifecycle, i.e.

\[
\text{Min } C_{\text{per hour}} = \frac{C_{\text{Net}}}{(T_2 - T_1) - T_{\text{Grid}}} \times \text{Number of days AC operate in a year} \times \text{Life Cycle}
\]  

which is sufficient enough to maintain the temperature at preset value and thus, the driving motor consumes lesser power.

The aim of this study is to run IAC initially on grid, where high power is required and then switch on to PV modules as the power required becomes less. Also, the insolation rises with time. Optimization problem is formulated for a general case considering weather condition at a particular location of interest and the timings of offices in those places. For the case of Aligarh with office timings of 9:00 AM–5:00 PM, the concept of optimization occurs when the insolation starts falling after 12:00 noon and AC has to operate till 5:00 PM. If the AC is run till 5:00 PM from PV modules, the capacity of PV modules required will be very high making the system costlier. Thus, in this work the authors are looking to find that point of time \( t \) from where the AC load should be switched to grid system in order to achieve minimum consumption cost per hour during the lifetime.

The function to be minimized is cost consumption of AC per hour of operation over complete lifecycle, i.e.
where: $C_{\text{per hour}}$ is the cost consumption of AC per hour of operation over complete lifecycle, $C_{\text{Net}}$ is the total money spent during life cycle, $T_{\text{Grid}}$ is the time for which AC operates from grid during life cycle, $T_2$ is the time of turning off AC in evening and $T_1$ is the time of turning on AC in morning.

Total money spent during life cycle is given by,

$$C_{\text{Net}} = C_{\text{Buy}} - C_{\text{Bill}} - C_{\text{Aux}} \quad (2)$$

where: $C_{\text{Buy}}$ is the cost of purchase of components, $C_{\text{pv}}$ is the cost of PV modules, $C_{\text{BB}}$ is the cost of Buck-Boost converter, $C_{\text{R}}$ is the cost of rectifier, $C_{\text{AC}}$ is the cost of Air conditioner, $C_{\text{M}}$ is the Miscellaneous cost, $C_{\text{Bill}}$ is the money paid to grid power supplier during life cycle, $C_{\text{Aux}}$ is the benefits achieved during life cycle.

Cost of purchase of components is given by,

$$C_{\text{Buy}} = C_{\text{pv}} + k \quad (3)$$

$$C_{\text{Buy}} = C_{\text{pv}} + C_{\text{BB}} + C_{\text{R}} + C_{\text{AC}} + C_{\text{M}} \quad (4)$$

where,

$$K = C_{\text{BB}} + C_{\text{R}} + C_{\text{AC}} + C_{\text{M}} \quad (5)$$

$$C_{\text{pv}} = P_{\text{pv}} \times \frac{\text{Cost}}{\text{kWh}} \quad (6)$$

Capacity of PV modules required is given by,

$$P_{\text{pv}} = \frac{P_{\text{in}}}{1000 \sin (\omega t) \times 0.85} \quad (7)$$

where: $P_{\text{pv}}$ is the capacity of PV modules required, $t$ is the time of switching from PV Module to grid, $P_{\text{in}}$ is the power required by AC and $P_{\text{in}}$ during full load operation.

Energy consumed by AC during life cycle = 7Unit/Day * Number of days of operation during life cycle. Thus, the optimal solution can be achieved by solving equations from (1) to (11) for minimum value of cost consumption of AC per hour of operation over complete lifecycle subjected to weather conditions and office timings at required place of operation.

### 4. Proposed Design of IAC Scheme

There are two possibilities for implementing the proposed hardware. First one is to use only solar PV system of high capacity for powering the Inverter AC, i.e. in stand-alone mode. The second one is to power IAC with help of grid supply for 35–40 min in beginning. Once the temperature is stabilized, solar PV system of small ratings is used to run the inverter AC, i.e. in grid-tied mode. Detailed specifications of hardware for both the possibilities are presented in this section. Finally, investment and running cost for both possibilities are compared in Cost Analysis and Payback Period section in order to find the optimal operation amongst these two. Based on the results obtained from simulation, hardware to be designed will have the specifications as given below.

### 4.1. Design Specifications of Solar PV System

The design specifications for PV system in stand-alone mode are estimated depending on the requirement of power by IAC in full load operating mode and commercially available modules. Design specifications of solar PV system, when only solar PV system is used to power IAC, i.e. in Stand-alone mode are given in Table 1.
The design specifications for PV system in grid-tied mode are estimated depending on the requirement of power by IAC in constant temperature operating mode and commercially available modules. Design specifications of solar PV system, when both Grid and small rating solar PV system are used to power the Inverter AC, i.e. in Grid-tied mode are given in Table 2.

4.2. Design Specifications of DC–DC Converter

Design specifications of DC–DC converter are estimated based on the power available at the input of converter and the level of voltage available at input of converter and output voltage requirement. DC–DC converter used, when only solar PV system is used and when both grid and small rating solar PV system are used to power the IAC have the same specifications. The design specifications are given in Table 3.

4.3. Design Specifications of Inverter AC

The design specifications of IAC are provided on the basis of power requirement of compressor in commercially available IAC (1.5T Voltas SAC 18 V DY). With the help of power requirement, voltage requirement and efficiency of DC motor, different parameters are estimated for proposed IAC system. Design specifications of IAC are given in Table 4.

4.4. Specifications of Battery Pack, Rectifier and Changeover Switch

The design specifications of Battery pack are given in Table 5. The design specifications of Rectifier and Changeover switch are given in Table 6.

4.5. AC Load Curve

The load curve of proposed IAC and conventional AC are given in Table 7. It is clear from table that the how the energy consumption of an IAC is lesser as compared to the conventional AC systems.

5. Cost Analysis and Payback Period

Cost of hardware is estimated based on the current market price of different required components. The estimated cost of proposed hardware in Stand-alone mode is given in Table 8. The estimated cost of proposed hardware in Grid-tied mode is given in Table 9. Depending on the load curve of IAC two different possible systems are proposed. Firstly, a stand-alone system and secondly a grid-tied system.

These results of interest for practical implication and choice of system for customer over a lifespan of 10 years are being tabulated below in Table 10.
### Table 5. Design specifications of battery pack.

| Parameter | Value |
|-----------|-------|
| number of batteries | 18 |
| nominal voltage of battery pack | 216 V |
| nominal voltage of each battery | 12 V |
| nominal capacity of each battery | 1.5 Ah |

### Table 6. Design specifications of rectifier and changeover switch.

| Parameter | Value |
|-----------|-------|
| Rectifier specifications | 230/50/1 V/Hz/ph |
| Output voltage | 220 V DC |
| Output current | 5.7 A |
| Output power | 1254 W |
| Short time output power | 7165/7.0 W for s |
| Maximum diode reverse biased voltage | 325 V |
| Short time max current Rating | 65/1 A for s |
| Changeover switch specifications | AC–DC |
| Power Rating | 1254 W |

### Table 7. AC load curve

| Load description | Loading condition | Load (Watt) | Time of operation (h) | Energy consumed (kWh) |
|------------------|-------------------|-------------|-----------------------|-----------------------|
| 1.5 Ton IAC (DC motor based) | Full load operation | 1254 | 0.66 | 0.828 |
| 1.5 Ton IAC (DC motor based) | Set point temperature | 700 | 7.33 | 5.131 |
| 1.5 Ton conventional AC | – | 1800 | 8 | 14.4 (at 0.9 pf) |

### Table 8. Estimated cost of proposed hardware in Stand-alone mode.

| S.no. | Item | Rating | Qty | Cost per piece (in INR) |
|-------|------|--------|-----|------------------------|
| (1)   | PV Module | 250 Wp | 12 | 10,000 |
| (2)   | DC–DC converter | 3 kWp | 1 | 5000 |
| (3)   | Inverter AC | DC motor based | 1 | 40,000 |
| (4)   | Battery | 12 V, 1.5 Ah | 18 | 300 |
| (5)   | Installation charges | – | – | 30,000 |
| (6)   | Miscellaneous | Wire, etc. | – | 10,000 |
| Total proposed cost | | | | 210,400 |

### Table 9. Estimated cost of proposed hardware in Grid-tied mode.

| Item | Rating | Qty | Cost per piece (in INR) |
|------|--------|-----|------------------------|
| 1. PV Module | 250 W | 8 | 10,000 |
| 2. DC–DC converter | 3 kW | 1 | 5000 |
| 3. Inverter AC | DC motor based | 1 | 40,000 |
| 4. Rectifier | 230 V (AC In), 220 V (DC Out) | 1 | 2000 |
| 5. Changeover switch | AC–DC (1254 W) | 1 | 400 |
| 6. Installation charges | – | – | 20,000 |
| 7. Miscellaneous | Wire, etc. | – | 10,000 |
| Total proposed cost | | | 157,400 |

### Table 10. Results of interest for practical implication and choice of system for customer.

| Operational mode | Investment cost (in ₹) | Savings (in ₹) | Consumption cost (in ₹/h) | Payback period | Possible turn-on |
|------------------|------------------------|---------------|---------------------------|----------------|-----------------|
| Stand-alone      | 135,400                | 247,920       | 5.8                       | 5.46           | Till 3:00PM     |
| Grid-tied        | 107,400                | 160,400       | 5.4                       | 6.69           | Any time        |
6. Conclusion

The proposed system tested for Solar Photovoltaic based Inverter Air Conditioning (SPVIAC) has the potential to bring a breakthrough in the field of weatherization. The expenditure of running this system is estimated to be around INR5.00/h as opposed to the conventional AC system which runs at INR10.00/h. Reason for reduction in this operating cost is achieved by reducing the number of stages of conversion and thus, reducing conversion losses. The proposed system can help in reducing the load on grid in coming years without compromising with prospects of human-beings for weatherization. Also, the proposed system provides low-cost solution through integration of various existing technologies, namely, a Buck-Boost converter, DC motor driven compressor and solar PV modules, for specific applications to benefit the society of Indian sub-continent. The proposed system helps in providing green and clean energy as the system potentially relies on solar PV system, which is a renewable source of energy. The work, in the end, provides choices for different requirements, like weatherization is demanded only in day time or both in day and night time. The application of SPVIAC is sensitive to local climate conditions, which affects the load profile and requirement of solar PV system significantly. The work has immense future scope, both in terms of practical application and in terms of improvement. Every human wants weatherization at minimum cost and the proposed scheme serves their purpose.

Disclosure Statement

No potential conflict of interest was reported by the authors.

ORCID

M. S. Alam

http://orcid.org/0000-0003-4008-2680

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