Household Type Load's Effects on Photovoltaic Systems

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Abstract: - The solar energy is one of the most important energy sources available because, besides the fact that it is not polluting the environment and it helps to the reduction of green house effect, it is free of charge and it can be easily converted to other forms of energy. Clean and renewable energy production is getting more attractive due to global warming, environmental factors and decrease in conventional energy sources. Photovoltaic cells will be a good alternative against the conventional energy sources in the near future, with their decreasing costs and increasing efficiencies. Photovoltaic cells (PV) are exposed to a lot of various loads depending on their increasing usage areas. Among the energy expenses for a building, the lighting system can contribute up to 50% of the total electrical consumption, and especially large quantities of energy are used in schools and office buildings. For that reason lighting devices are important energy consuming units in our daily life. In this study different load effects on PV cells are examined experimentally. D.C. and A.C. load behaviors are analyzed in switching and in steady state regime and their power-time curves are obtained for the demand of system power. Negative effects of the inverter circuit, which is used for feeding A.C. loads on the system, are expressed experimentally.

Key-Words: - Photovoltaic System, A.C. Loads, D.C. Loads, Power LED, Compact Fluorescent Lamp.

1 Introduction

Solar energy is one of the most important renewable energy sources. As opposed to conventional resources such as gasoline, coal, etc solar energy is clean, inexhaustible and free. The main applications of photovoltaic (PV) systems are in either stand-alone (water pumping, domestic a street lighting, electric vehicles, military and space applications) or grid-connected configurations (hybrid systems, power plants).

Unfortunately, PV generation systems have two major problems: the conversion efficiency of electric power generation is very low (9÷17%) especially under low irradiation conditions, and the amount of electric power generated by solar array changes continuously with weather conditions [1].

Photovoltaic systems are generally designed for operating hybrid, grid connected or stand alone. Their most importing advantages against the conventional energy production systems are their modular structures, silence operation property, having no moving parts, less maintenance needs and having no harmful gas emissions. For that reasons PV systems are good alternatives to diesel generator systems that have been widely used in rural areas in recent years [1].

The most important disadvantage of these systems is high initial investment costs. Although, the investment costs of PV cells have decreased 10 times in the last twenty years, they are still not an alternative to conventional energy production systems in grid connected networks. PV cells had the biggest share in initial investment costs for PV systems [2].

Main components and system block diagram for stand alone PV systems are shown in Fig. 1.

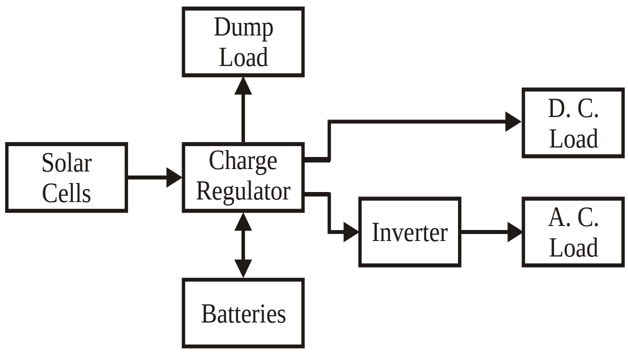

Fig. 1 Basic components of stand-alone PV systems

Nowadays PV systems are designed to feed very different types of loads. Most of the time those loads are lighting devices or electric machines. Loads effects on system can be changed. For example first ignition characteristic of the fluorescent lamp with electronic ballast is very different from the electric machines. Furthermore an inverter circuit effect on system for A.C. loads has been taken into consideration.

Over the last decade, task forces on photovoltaic systems have delineated international recommendations for adequate interconnection to the electricity supply. Harmonic distortion in the current injection is one of the most relevant points included in these standards. Several studies have focused on the impact of harmonics on the network, ranging from parallel resonance to inefficient power consumption [3].

Photovoltaic (PV) power generation is becoming increasingly attractive for conforming to renewable energy targets. Setting the example are countries like Germany and Japan with annual installations in the range of 300MW. This remarkable feat is in part due to government incentives but also due to the maturation of the PV industry and the development of interconnection standards. Inverter manufactures, for instance, comply with IEC recommendation 61727 which is, in many cases, adopted by individual countries. Other recognized standards are IEEE 929 for photovoltaic generators and IEEE 1547 for distributed generators [3].

It is well known that energy producing companies are obliged to supply excellent energy quality to the customers following the national and international limits and standards. High harmonic existence represents a possible source of faults and troubles for loads (motors, home electrical appliances, computer systems etc.) and for the electric system equipment (capacitors, cables etc.). All harmonic sources and effects have been well identified and presented in the past.

The increased use of renewable energy sources and energy saving measures follow worldwide accepted strategic guidelines. Most renewable energy sources that produce electric power use power electronics (converters, inverters), which represent also a harmonic source [4].

1.1 Characteristic and Efficiency of PV Cell

General expression for the current produced by a solar cell

$$I = I_{SC} - I_{o1}\left(e^{qV/kT} - 1\right) - I_{o2}\left(e^{qV/2kT} - 1\right) \qquad (1)$$

In equation (1), I is the cell current, I_{o1} is the dark saturation current due to recombination in the quasi-neutral regions and I_{o2} is the dark saturation current due to recombination in the space-charge region. $q = 1.602 \cdot 10^{-19} C$ is electron charge, $k = 1.3806 \cdot 10^{-23} J/K$ is the Boltzmann's constant; and T is absolute temperature The short circuit current $\left(I_{SC}\right)$ and dark saturation currents depend on the solar cell structure, material properties, and the operating conditions. A full understanding of solar cell operation requires detailed examination of these terms. However, much can be learned about solar cell operation by examining the basic form of equation (1). From a circuit perspective, it is apparent that a solar cell can be modeled by an ideal current source $\left(I_{SC}\right)$ in parallel with two diodes – one with an ideality factor of "1" and the other with an ideality factor of "2", as shown Fig. 2. Note that the direction of the current source is opposed to the current flow of the diodes – that is, it serves to forward-bias the diodes. Diode 1 represents the recombination current in the quasi-neutral regions $\left(\alpha \quad e^{qV/kT}\right)$, while diode 2 represents recombination in the depletion region $\left(\alpha \quad e^{qV/2kT}\right)$

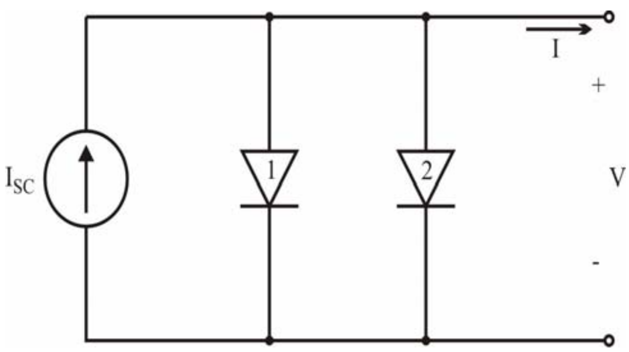

Fig. 2 Simple photovoltaic cell model

The current–voltage $\left(I - V\right)$ and power–voltage $\left(P - V\right)$ characteristics of a typical silicon solar cell are plotted in Fig. 3. For simplicity, the dark current due to the depletion region (diode 2) has been ignored (a reasonable and common assumption for a good silicon solar cell, especially at larger forward biases). It illustrates several important figures of merit for solar cells the short circuit current, the open-circuit voltage, and the fill factor. At small applied voltages, the diode current is negligible and the current is just the short circuit current $\left(I_{SC}\right)$, as can be seen when V is set to zero in equation (1).

When the applied voltage is high enough so that the diode current (recombination current) becomes significant, the solar cell current drops quickly.

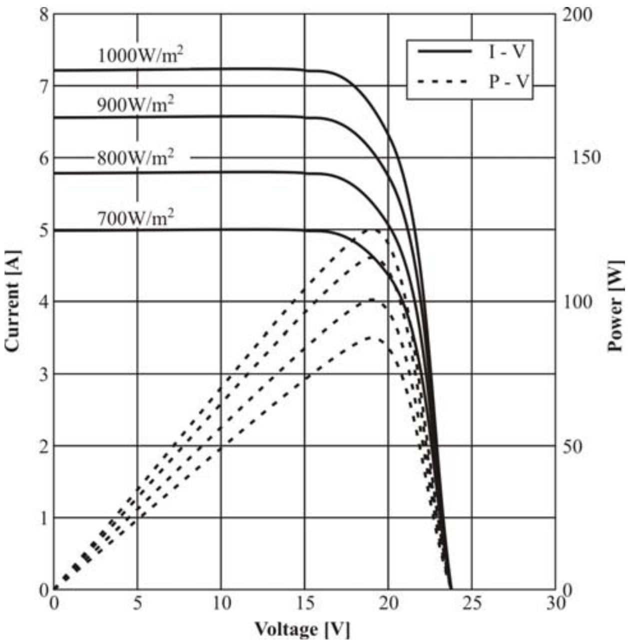

Fig. 3 $I-V$ and $P-V$ characteristics of PV cell

There is a huge asymmetry between the n-emitter and the p-base in a typical solar cell. The emitter is ~1000 times thinner, ~10000 times more heavily doped, and its diffusion length is ~100 times shorter than the corresponding quantities in the base.

At open circuit $(I=0)$, all the light-generated current $(I_{SC}=0)$, is flowing through diode 1, so the open-circuit voltage can be written as

$$V_{OC}=\frac{kT}{q}\ln\frac{I_{SC}+I_{o1}}{I_{o1}}\approx\frac{kT}{q}\ln\frac{I_{SC}}{I_{o1}} \quad (2)$$

Where $I_{SC} \gg I_{o1}$. Of particular interest is the point on the $I-V$ curve where the power produced is at a maximum. This is referred to as the maximum power point with $V=V_{MP}$ and $I=I_{MP}$. This point defines a rectangle whose area given by $P_{MP}=V_{MP}\cdot I_{MP}$, is the largest rectangle for any point on the $I-V$ curve. The maximum power point is found by solving for $V=V_{MP}$,

$$\left.\frac{\partial P}{\partial V}\right|_{V=V_{MP}}=\left.\frac{\partial(IV)}{\partial V}\right|_{V=V_{MP}}=\left.\left[I+V\frac{\partial I}{\partial V}\right]\right|_{V=V_{MP}}=0 \quad (3)$$

The current at the maximum power point (I_{MP}), is then found by evaluating equation (1) at $V=V_{MP}$. The rectangle defined V_{OC} and I_{SC} provides a convenient means for characterizing the maximum power point. The fill factor (FF) is a measure of the squareness of the $I-V$ characteristic and is always less than one. An empirical expression for the fill factor is

$$FF=\frac{V_{OC}-\frac{kT}{q}\ln\left[\frac{qV_{OC}}{kT}+0.72\right]}{V_{OC}+\frac{kT}{q}} \quad (4)$$

Arguably, the most important figure of merit for a photovoltaic cell is its power conversion efficiency (η), which is defined as

$$\eta=\frac{P_{MP}}{P_{in}}=\frac{FF\cdot V_{OC}\cdot I_{SC}}{P_{in}} \quad (5)$$

The incident power (P_{in}), is determined by the properties of the light spectrum incident upon the PV cell.

Using these figures of merit, the properties of a good (efficient) solar cell can be ascertained. From equation (5), it is clear that an efficient solar cell will have a high short circuit current, a high open circuit voltage, and a fill factor, as close as possible to 1.

As seen in equation (2), the open circuit voltage is logarithmically proportional to the short circuit current (I_{SC}) and to the reciprocal of the reverse saturation current (I_{o1}), (the same is true for I_{o2}). Therefore, reducing the saturation current will increase the open-circuit voltage. From equation (4) it is clear that increasing V_{OC} will increase the fill factor. Thus, the design and the operation of an efficient solar cell have two basic goals:

1. Minimization of recombination rates throughout the device.
2. Maximization of the absorption of photons.

It is evident that, despite the apparent complexity of the expressions describing the operation of solar cells, the basic operating principles are easy to understand. Electron–hole pairs are created inside the solar cell as a result of absorption of the photons incident on the solar cell from the sun. The objective is to collect the minority carriers before they are lost to recombination [5], [6].

1.2 Incandescent Lamps
Researches show that, incandescent lamps have lowest values for the electromagnetic interference (EMI) and total harmonic distortion (THD) among the light sources. However, the utilization of incandescent lamps is decreasing in all over the world because of their low efficiencies (10 lm/watt)[2].

Incandescent Lamps: hot light, emitted from a (tungsten) filament at around 2800° K

Advantages:
- Radiant cooling
- Cheap 0.0005$/lumen
- klm per package

Disadvantages:
- mostly infra-red
- glass vacuum envelope & filament both break easily
- <15 lm/W luminous (<5% power) efficiency
- fire hazard, burnt fingers, maintenance
- no chance to come close to daylight (6500°K)[7].

1.3 Compact Fluorescent Lamps
In the past few years there is a global transformation on technology and researches which aims to energy savings through the usage of renewable sources in many applications. Solar energy can be used for lighting usually in cases of low consumption applications. Compact fluorescent lamps are ideal lighting sources with low energy consumptions for these applications.

Compact fluorescent lamps (CFL) with electronic ballast are widely used in energy saving lamp market. Usage areas are increasing rapidly due to their high efficiencies (70-80 lm/watt) and their long lives. Grid voltage has important effects on the live of fluorescent lamps due to electronic circuits. Voltage fluctuation on the grid voltage affects the lamp operation efficiency. For that reason grid voltage has been stabilized by the regulator to increase the THD ratio under the 0.1% to measuring performance of the lamp [8], [9].

There are many published works that give detailed information on different layouts for internal electronic circuits; their goals are generally to obtain low-cost circuits that improve the power factor and reduce the harmonic distortion of the current waveform [10]-[12].

Energy saving measures includes the replacement of incandescent lamps with CFL with electronic gear. CFL consume 80 % less energy than incandescent lamps, but they are a nonlinear load and inject into the network high harmonic currents. CFL are defined as highly non-linear loads producing a high current THD factor, while CFL with electronic gear have extremely distorted current with a THD usually exceeding 100%. That is the reason why there is a limitation for their share in the total installed load. This share is determined by the requests from international standards concerning compatibility levels for voltage harmonics. On the other hand, all electric power corporations world-wide suggest the use of energy saving (low energy consumption) lamps such as the CFL [4].

Fluorescent Lamps: cold light, emitted by phosphors excited by gas discharge.

Advantages:
- High efficiency 80^{+}lm/W & High Flux klm/lamp
- Moderate cost for large lamps 0,002$/lm
- Any color temperature possible by tri-color mixing

Disadvantages:
- Lifetime short <10,000 hrs resulting in high maintenance.
- Glass vacuum envelope leaks/breaks, ballast noisy.
- Poisonous (Mercury)[7].

1.4 High Power LED's
Light-emitting diodes (LEDs) are nowadays widely used in special lighting areas like e.g. traffic lights, signaling, signage, and outstanding architectural implementations. However, these are niche applications compared with general illumination. There is a strong interest in using LEDs for general illumination due to the potential they offer for energy saving, environmental friendliness, new opportunities in lighting design, and control of the intensity, color, and spatial distribution of light. Next to improving the LEDs' efficiency and reducing their cost, improved thermal management and color control are considered to be the key challenges lying ahead.

LEDs are light sources with narrow spectra that are typically a few ten nanometers wide. As a consequence of this they emit light with saturated colors and their color points are located close to the perimeter of the chromaticity diagram.

General illumination requires primarily white light located in the center of the chromaticity diagram. There are two basic alternative solutions for making white light using LEDs, either color mixing or using phosphors for down converting the light of ultraviolet or blue LEDs. Whilst down conversion can be implemented in a more straightforward way, color mixing enables color adjustability, which is considered to be a most attractive feature of future LED lamps. Mixing e.g. the light of red, green, and blue LEDs, any color can be created inside the triangle defined by the LEDs' chromaticity coordinates. However, color reproducibility and stability issues remain to be solved for both alternatives. Lamps with nominally identical color points will have to be operated next to each other without noticeable color differences. Replacing one of these lamps, even after some years, also must not result in noticeable color differences [14].

Besides the compact lamps, high power LED's third generation lighting devices, attracts attention with their high efficiencies (approximately 80 lm/watt) and 50.000-100.000 hours theoretical life spans. They are used often in automotive sector, three-dimensional imaging systems, and signal circuits [15].

They should be driven by a constant current source so they need an extra power source. LED's are produced with semi conductor technology so they have problems depending on heating more then the other light sources. The LED junction temperature depends on the power input; the environmental conditions (ambient temperature, humidity, and wind), the heat sink and the lighting fixture design [16].

Moreover, high power LED's are still too expensive. Their costs are increasing with the addition of extra appliances. Therefore they could not compete with CFL's yet. But they will be taking a big place in our daily life for general lighting with their long theoretical life spans and low power consumptions in the near future [17]-[19].

Led Lamps Advantages

- White point determined by phosphors ONLY! (i.e. tolerant to variation)
- Excellent color rendering possible,
- Theoretically "Simple to manufacture" (Looks like TV or Fluorescent lamp except for pump is now UV LED rather than electrons.)
- Temperature stability of phosphors.
- Controlled radiation pattern and efficient optics.

Disadvantages

- Potential for damaging UV light leakage.
- Fundamental limits on efficiency due to phosphor conversion efficiency, Stokes shift, self absorption [7].

1.5 Permanent Magnet D.C. Motors (PMDC)

Permanent Magnet D.C. (PMDC) motors are increasingly being used in a wide spectrum of applications such as domestic equipments, automobiles, information technology equipment, industries, public life appliances, transportation, aerospace, defense equipment, power tools, toys, vision and sound equipment and medical and health care equipment ranging from microwatts to megawatts. It has become possible because of their superior performance in terms of high efficiency, fast response, light weight, precise and accurate control, high reliability, maintenance free operation, brushless construction, high power density and reduced size. Recent developments in PMDC motor technology in terms of availability of high performance rare earth PM materials, varying motor constructions such as axial field, radial field, package type, rectangular fed, sine fed motors, improved sensor technology, fast semiconductor modules, low cost high performance microelectronics devices, new control philosophy such as robust, adaptive, fuzzy, neural, genetic algorithm based controllers, have been a boon to their widespread use in the large speed ranges from few revolutions to several thousand revolutions per minute [20].

1.6 Induction Motors

Induction motors have been widely recognized as the workhorses of industrial applications in the pulp and paper/forest products industry. Over the past 30 years, there have been clear trends in motor utilization that demand higher power density and increased energy efficiency.

In many industrial applications motor size and inertia are critical. Motors with high power density can offer a performance advantage in applications such as paper machines. However, high power density must not compromise reliability and efficiency.

Induction motors have been able to incrementally improve energy efficiency to satisfy the past requirements. Both mandated (legislated) efficiency (EPACT) and voluntary levels (NEMA Premium®) have been provided using products derived from general purpose induction motors. Another method considered for enhanced induction motor efficiency is through the use of cast copper rotors in place of aluminum for medium size ratings. [19].

2 System Description

In this study, several different load behaviors are examined experimentally in switching and in steady state regime which feed from PV cells and similar D.C. and A.C. loads are compared. For this purpose experiment set was setup as shown in Fig. 4.

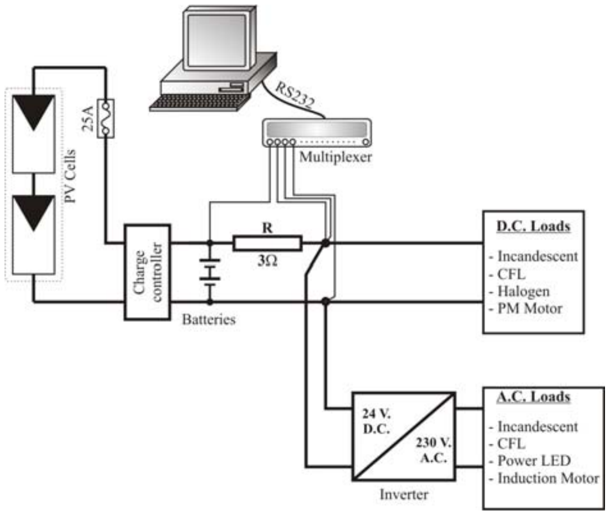

Fig. 4 Experimental setup for measurements

High Speed multiplexer is used to measure current and voltage changes in short duration (0.1 second periods). A constant resistor (3 ohm) is added to the circuit to measure current which drawn from system as a voltage. There were two 51 watt PV cells and two 100 Ah accumulators in the system. Convenient diameter copper electric cables are used to set up system. Fig.5 shows image of experiment system.

Fig. 5 Experiment system with incandescent lamps

3 Experimental Results

Experiments were done in two categories. In first categories D.C. loads (Fig. 6) and second categories A.C. loads (Fig. 7) were examined. D.C. loads are incandescent lamp, CFL, halogen lamp and permanent magnet D.C. motor and A.C. loads are incandescent lamp, CFL, power LED and induction motor.

Fig. 6 D.C. loads; incandescent lamp, CFL, halogen lamp and permanent magnet D.C. motor

Fig. 7 A.C. loads; incandescent lamp, CFL, power LED and induction motor

Loads were put in to circuit and energized with order approximately for one minute during the experiments. Power-time curves are obtained for each load. Incandescent lamps power consumptions can be seen in Fig. 8 for A.C. and D.C. Similarly, the characteristics of compact fluorescent lamps are shown in Fig. 9.

As it is known, incandescent lamps are forcing the power systems lesser than the CFL's in terms of harmonic distortions. In the literature, in systems especially with many incandescent lamps, as a result of replacement of incandescent lamps with CFLs, it is expressed experimentally that THD has increased significantly. [7] THD is 0.024% for current and 0.07% for voltage, in systems where all lamps are incandescent. These values are rising to 23.6% for current and 3% for voltage, when these lamps are changed with the CFLs at 90 percent [22]. These negative effects of CFLs on the system can be realized in experimental studies.

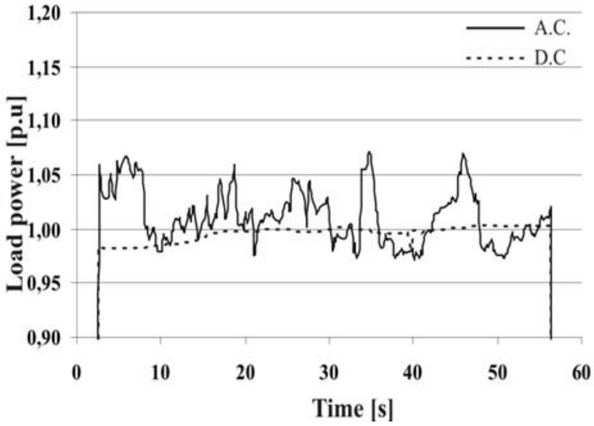

Fig. 8 Power consumptions of d.c. and a.c. incandescent lamps

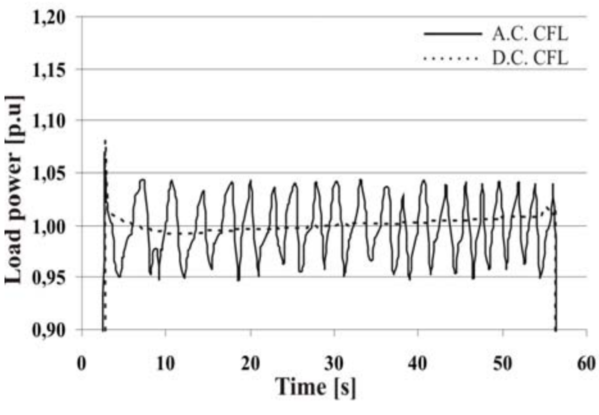

Fig. 9 Comparison of d.c. and a.c. CFLs

Power LED is used in AC system by reason of its constant current source need. The comparison of LED with halogen lamp fed from D.C. shown in Fig. 10. It could be expressed that, the effect of halogen lamp on the system would be identical to the effect of incandescent lamp. Power consumption of incandescent lamp is rising at a small rate, and halogen lamp is demanding an additional low value of power. The negative effect of inverter circuit could be observed clearly in the power consumption of Power Led similar to the other A.C. loads.

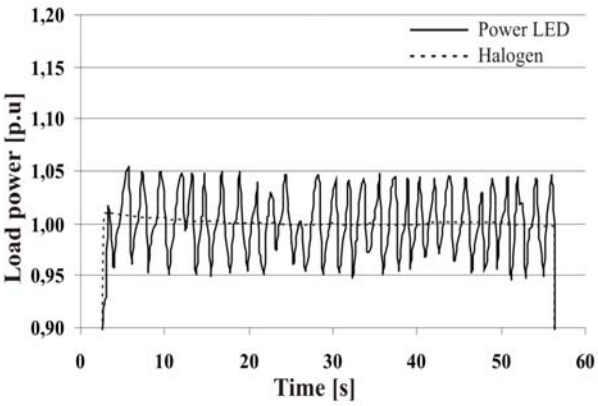

Fig. 10 Power consumptions of halogen lamp and power LED

Comparison of permanent magnet D.C. (PMDC) motor and shaded–pole induction motor power consumptions are shown in Fig. 11. Both two machines are demanding high power that forcing the system at start up. These characteristic aspects should be taken in to consideration at PV systems designs which feed the frequently cycling on-off loads.

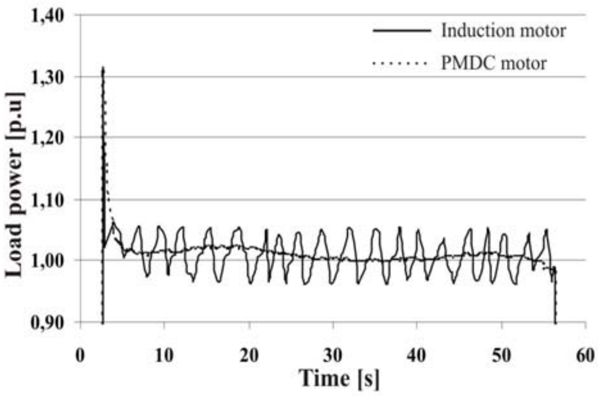

Fig. 11 Induction motor and PMDC motor comparison

Comparison of D.C. and A.C loads among themselves are shown in Fig. 12 and Fig. 13.

Doğru akımla beslenen yüklerde PMDC haricindeki yüklerin benzer özellikler gösterdiği görülmektedir. CFL'nın ilk kalkınma anında ve sürekli rejimde özellikle çok sayıda lamba içeren büyük sistemlerde harmonik açısından olumsuz etkileri olabilir. Ancak küçük güçlü sistemlerde dikkate değer bir etki yapmamaktadır.

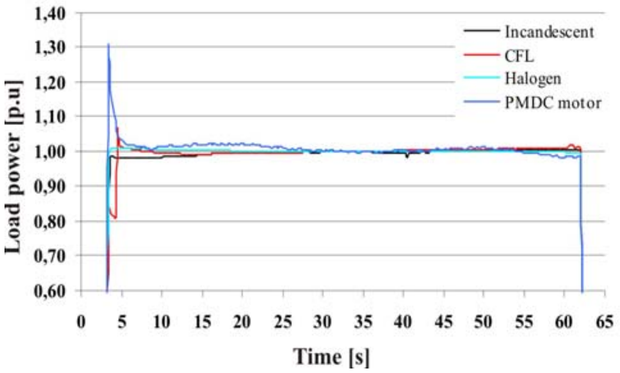

Fig. 12 Comparison of D.C. Loads

It could be said that incandescent lamp is the most balanced load to the system among the A.C. loads. Other loads made approximately ±5% power fluctuation especially with the inverter circuit negative effects.

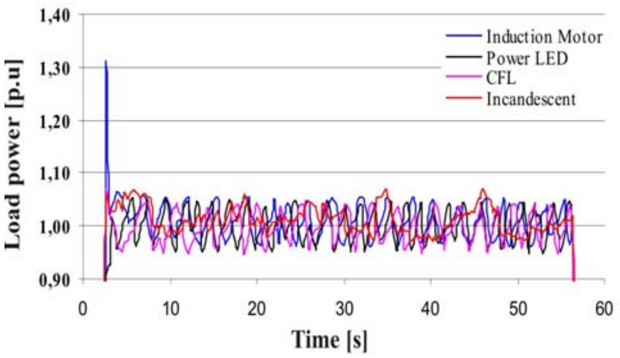

Fig. 13 Comparison of A.C. Loads

4 Conclusions

Photovoltaic systems have a high potential of application in various areas of today's world. The features of the receivers fed from PV systems have a direct impact on the cells; namely, the power generators of the system. Such impacts can be more evident particularly in the systems in which the load is directly connected to cells. System behavior may change in receivers equipped with electrical machines fed from photovoltaics (water pumps and storage systems, cooling systems, ventilation systems, satellite systems, etc), depending on the characteristics of the machine used. According to experiment results, electric motors were the most forcing loads to the system both in A.C. and D.C. loads. Both motors have taken 130% of nominal power in the first start-up. This ratio is an important value especially for frequently switching systems.

D.C. halogen lamp and incandescent lamp were the most ideal loads within the lighting sources in terms of their load changes with time. But it has very important disadvantages like high power consumption and low efficiency. For that reason their usages are constrained all over the world. CFL has taken more power then nominal power while ignition, but this value is 107% of it. This is not a so much important value to affect PV system design. Therefore CFL can be used in PV systems which are designed to use halogen lamp or incandescent lamp. But the effects on the system should be taken into consideration, when an increase in THD, in the systems, comprising many lamps, will take place. Negative effects of inverter circuit could be observed obviously in all load types in A.C. systems. Most convenient inverter circuit can be found with experiments doing by different inverters. However, there will be still fluctuations although the suitable inverter circuit would be used. Also extra costs and low efficiency will be caused to the system when an inverter circuit will be used. D.C. would be preferred in system design if there would not be a significant cost difference taking whole negative effects into consideration.

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