Solar-Powered Ultra-Light Aircrafts: An Overview on Power System Technology

P. Guarino, G. L. Cascella, S. Stasi, M. Dassisti and M. Chimienti

***Abstract*—**This paper surveys the proposed solutions for the design of an ultra-light Unmanned Aerial Vehicles, showing the most recent advances in technology for the power system of the design. In particular this paper focuses on the electrical components of the project, showing a brief review of the single objects and their applicability for the design of a Solar-Powered Airplane. The aim of this paper is to collect all the useful information for people who wants to begin a design process for an ultra light aerial vehicle with electric propulsion system and a solar energy conversion source, giving basic information about the state of the art of the UAV projects and the requirements for the power system management elements.

***Keywords*—**Solar Energy Aircraft, Electric Motor Drives

I. Introduction

Solar Energy is certainly the cleanest energy in the world. Usages of solar energy are widespread in military, industrial and commercial applications. Among these, the usage of solar energy to power an unmanned aerial vehicle (UAV) seems to be a very interesting application [1], which requires a complex engineering approach for the design and the optimization of the project [2]-[4]. In this field, recent projects have successfully accomplished their missions, laying some milestones for the research in Manned and Unmanned Aerial Vehicles [5]-[7].

Though the primary issues of this kind of project resides in the mechanics and aerodynamics of the vehicle, such as the sizing of the airfoil and the reduction and distribution of the weights, which are very well discussed in other references [8], [9], this paper focuses on the aspects related to electric and electronic devices, i.e. the actual propulsion system equally challenging and influent on the success of the project [10]-[12]. This paper provides a short discussion of the main design and optimization issues for each of the electrical components of a solar powered airplane; in particular it analyzes the applicability of the latest developments to the general design problem. We start discussing the propulsion systems (Section II), then about the batteries (Section III), the photovoltaic panels (Section IV), and the control systems and strategies (Section V). Conclusive remarks are given in Section VI.

The innovative contents described in this paper are disclosed after the permission of INGENIA & PARTNERS. S.r.l. company, which committed to Laboratorio KAD3 S.c.a.r.l. the research project called “Analisi e studi per lo sviluppo di una metodologia per la progettazione assistita dei velivoli ultraleggeri a propulsione solare”, co-funded by Italian Government (Legge 12 luglio 2011, n. 106 – Credito di imposta per le imprese che finanziano progetti di ricerca in Università o enti pubblici di ricerca).

P. Guarino, G. L. Cascella and S. Stasi are with the Dipartimento di Ingegneria Elettrica e dell’Informazione, Politecnico di Bari Via E. Orabona 4, 70125 Bari (cascella@deemail.poliba.it, stasi@deemail.poliba.it).

M. Dasissti is with Dipartimento di Meccanica, Matematica e Management, Politecnico di Bari (m.dassisti@poliba.it).

M. Chimienti is with Laboratorio Kad3 – Organismo di Ricerca, C.da Baione S.C. - 70043 Monopoli (BA) (m.chimienti@laboratoriokad3.com).

II. Propulsion System

In the design of the power system for an aerial vehicle, the weight of each component plays a fundamental role, since the performances of the vehicle and the power requirements will be strictly related to the overall weight of the UAV. Therefore, much care has to be put on the power-to-weight ratio in the choice of the type of motor to be used. Based on this crucial parameter, Permanent Magnet Brushless DC motors (PMBLDC) are commonly considered the best possible choice for the propulsion of an Aerial Vehicle [13]. In fact, PMBLDC motors have many advantages over other motors due to their high efficiency, low weight, silent operation, compact size, high reliability and low maintenance requirements. Due to these features they are the most used motors in vehicle and pumping applications. This make PMBLDC motors very interesting even for research activity, aiming to improve their performances for various applications, ranging from low-cost and low-power applications to fields requiring high precision [14],[15].

The Permanent Magnet Brushless Machine (PMBL) is a synchronous machine with permanent magnets, displaced on the rotor surface or buried in the rotor body, replacing the excitation windings, slip rings and brushes. The absence of these elements makes the machine shorter, thus reducing not only the size, but also the distance between the bearings; by this way the machine is more rigid and can reach higher speeds.

PM Brushless machines can be divided into two categories. The first is called PM ac, brushless ac, or sinusoidal-fed PM machine, and uses continuous feedback of rotor position to supply the armature windings with sinusoidal voltages and currents by pulse width modulation of the supply voltage. The ideal motional EMF is sinusoidal, so that the interaction with sinusoidal currents produces constant torque with very low ripple.

The latter category of PM Brushless machine is called brushless dc, trapezoidal brushless machine, or rectangular-fed machine. The three-phase quasi square wave currents of duration 120 electrical degrees are supplied to the machine, in which the ideal motional EMF is trapezoidal and synchronized with the current waveform, i.e. the constant part of the back EMF waveform coincides with the intervals of constant phase current (Fig. 1). For this type of machine, rotor-position information is needed only at the commutation points that are every 60 electrical degrees.

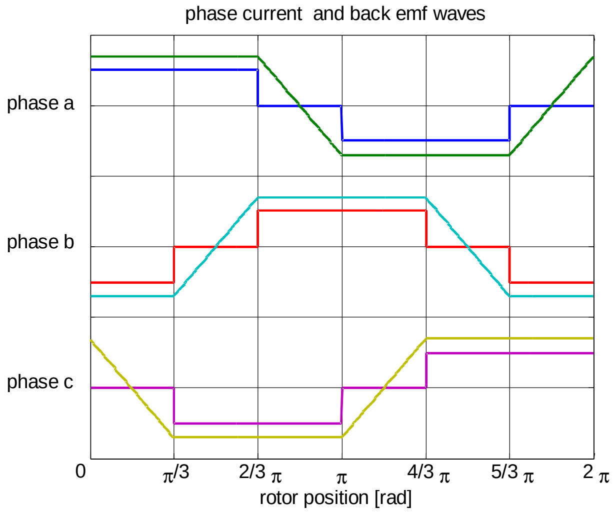

Fig. 1 – Phase currents and back EMF waves of a PM brushless dc machine

In absence of magnetic saliency (isotropic rotor), both the trapezoidal and sinusoidal machines can be represented by the same equivalent circuit for each phase winding (Fig. 2), in which the source voltage *v* supplies current *i* to the phase circuit consisting of series-connected resistance *R*, equivalent inductance L_{eq}, and motional back EMF *e*. The motional EMF is due to the movement of the PM rotor and is proportional to the rotor speed, and therefore is dependent on the rotor position.

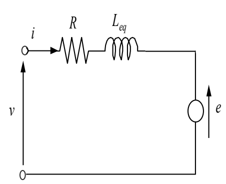

Fig. 2 – Equivalent circuit of isotropic PM brushless machine

The phase voltage equations of the machine are as follows:

$$\begin{cases} v_a = R\cdot i_a + \frac{L\cdot di_a}{dt} + \frac{M\cdot di_b}{dt} + \frac{M\cdot di_c}{dt} + e_a \\ v_b = R\cdot i_b + \frac{L\cdot di_b}{dt} + \frac{M\cdot di_c}{dt} + \frac{M\cdot di_a}{dt} + e_b \\ v_c = R\cdot i_c + \frac{L\cdot di_c}{dt} + \frac{M\cdot di_a}{dt} + \frac{M\cdot di_b}{dt} + e_c \end{cases} \quad (1)$$

where *L* and *M* are the self-inductance of each phase and the mutual inductance between phases, respectively. In a star-connected three-phase winding with isolated star point, the sum of the three currents must be equal to zero, and therefore (1) may be rewritten as

$$\begin{cases} v_a = R\cdot i_a + \frac{(L-M)\cdot di_a}{dt} + e_a \\ v_b = R\cdot i_b + \frac{(L-M)\cdot di_b}{dt} + e_b \\ v_c = R\cdot i_c + \frac{(L-M)\cdot di_c}{dt} + e_c \end{cases} \quad (2)$$

where $(L-M) = L_{eq}$.

In a BLDC machine the most common way to supply the phase windings with quasi square wave currents synchronized to the trapezoidal waveforms of back EMF, is through voltage-source current-controlled inverters. The magnitude of the current waveform, I_{max}, is proportional to the machine shaft torque. Then, by controlling the phase-currents in magnitude and frequency, torque and speed can be controlled.

Current control can be realized using one of the simplest control strategies available, the ‘‘triangular carrier modulation strategy’’ [16], which offers additional advantages:

- the switching frequency depends on the triangular carrier;
- the ability to follow the current references is quite accurate;
- the hardware implementation is very simple.

The PWM modulation frequency is generally in the range 4-10 kHz, but inverters using IGBT can reach a frequency of 30 kHz and over. The commutation sequence is generated by the controller according to the rotor position which is traditionally sensed using Hall sensors, resolvers or optical encoders. These sensors increase the cost and size of the motor and a special mechanical arrangement is required for mounting the sensors. Furthermore, Hall sensors are temperature sensitive, and so represent an operation limit for the system. The cost reduction of controllers for PMBLDC motor drives can be accomplished by two approaches: in the topological approach, the number of switches, sensors and associated circuitry used to compose the power converter is minimized; in the control approach new algorithms are designed and implemented in conjunction with the converter to produce the desired characteristics.

Another completely different idea for reducing the size, the weight and the cost of the controller, is to avoid the use of sensor to detect the actual position of the rotor [17]. The position is then estimated by the sensing of voltage and current values, elaborated by an additional dedicated circuitry. The lack of a direct sensor causes the needs for higher performances of the calculator and bigger memory for the data elaboration. To estimate the position of a PM brushless machine, many schemes are possible for the sensorless control. The three main methods used are briefly summarized in the following.

A. Position Detection by Motional Back EMF

The instantaneous magnitude of the EMF depends on the actual position of the rotor and therefore information about position is contained in the EMF waveform. However, it is hard to extract information on back EMF, due to rapidly changing current in the windings and induced voltages during commutation phases. Furthermore, the motional EMF is proportional to rotor speed and then it cannot be detected during the starting operation, until the speed has reached a threshold value. The absence or the reduced value of motional EMF at zero or very low speed can be addressed by accelerating the motor to a suitable speed with a preset sequence of excitation. In trapezoidal brushless machines the rotor position information can be obtained detecting the zero-crossing points of the back EMF wave, which is “measured” across the terminals of each of the three machine phases. These zero-crossing points are phase shifted of 90 electrical degrees through the rotor positions where commutation between phases takes place. Therefore, they have to be phase shifted before they can be used for commutation. This method is usually used in low cost application [18],[19].

An improved method [20] utilizes the third-harmonic component in the EMF waveform, in order to reduce the phase-shifting problem mentioned above. This third-harmonic component has a frequency three times that of the fundamental component and its peak values are in phase with the rotor positions where commutation between phases takes place. For this reason, the third harmonic waveform is shifted through a rotor position of 30 electrical degrees by integration, so that the zero crossings of the integrated waveform (third harmonic flux component) correspond to the rotor positions at which excitation must be switched between the phases.

B. Position Detection by Inductance Variation

This method involves monitoring of the rate of change of winding currents, which depends on the winding inductances that, in turn, are a function of rotor position and the same currents. Then rotor position information can be extracted from winding currents and their rates of change. An important advantage of such a scheme is that it can be used even at zero speed, in absence of motional EMF. Detection of rotor position by inductance variations in isotropic PM brushless machines is not simple, because of the absence of an inherent magnetic saliency, so any variation of inductance with rotor position arises only from magnetic saturation. Furthermore, this incremental inductance variation undergoes two cycles per single electrical cycle of the machine, causing an ambiguity of 180 electrical degrees in sensed position. In fact, the minimum value of incremental inductance occurs at rotor positions 0° and 180°, while the flux linkage is maximum positive at 0° and maximum negative at 180°. Despite these obvious difficulties, there have been numerous attempts to use inductance variation to detect rotor position in PM machines.

To solve the rotor orientation ambiguity, the most used approach consists in considering the effect of magnetic saturation on the incremental inductance. If a positive current pulse is injected in the winding when the rotor is aligned at the 0° position, the effect of the pulse is to increase the total positive flux linkage, but if the rotor is at the 180° position, the current reduces the total negative flux linkage. Therefore, the difference between the flux amplitudes for the two alternative rotor positions, to which corresponds a difference level of magnetic saturation, can be used to discriminate the two positions. If magnetic saturation increases, the incremental inductance is lower and the amplitude of the current pulse is larger. This scheme is widely used in high-performance motors, and is often applied with the motor stopped, since the back EMF is zero [21].

C. Position Detection by Flux-Linkage Variation

This last method is based on the phase voltage equation of the machine

$$v = R\, i + \frac{d\lambda}{dt} \tag{3}$$

The total flux linkage λ is a function of the current and position of the rotor, and can be estimated by integration of the phase voltage after subtracting the resistive voltage drop [22], [23].

$$\lambda = \int \left(v - Ri \right) dt \tag{4}$$

III. Batteries

For using batteries in application based on the solar energy as the power source, the power system design needs crucial considerations concerning the battery management [24]. In this kind of application batteries are often the most limiting component in terms of lifetime: photovoltaic panels, for their own characteristics and electrical behavior, are not the ideal source for battery recharge operation, and this means, as for lead-acid batteries, a strong reduction of their lifetime. Therefore the charging method and strategies become an essential issue for granting a long enough lifetime. Depending on the kind of batteries chosen for the design of the UAV, the design of an optimized battery charging scheme is required [25],[26].

The most simple system, that could give the best efficiency in terms of accumulated charge to incident power ratio, is based upon the load line method: the idea is to have the intersection between the solar panel V-I characteristics and the battery load line in the point of maximum power extraction from the PV, the same of the optimal recharge condition for the battery [25]. But this system is not really suitable for applications like an UAV, in which the environmental conditions, and so the illumination flux on the panels, are rapidly varying, introducing the need for a constant maximum power point tracking of the photovoltaic panel.

The charging system represents a strong issue, and many theoretical and technical solutions have been suggested during several years [26].

The charger has three main functions: delivering charge to the battery, optimizing the charge rate, and terminating the charge. The charging process can be realized through different schemes and algorithms, depending on the battery chemistry (single- and multi-chemistry battery chargers).

A. Single-chemistry algorithms

The single-chemistry battery chargers are the most widely used; the batteries are mainly nickel-cadmium (Ni-Cd), nickel-metal-hydride (NiMH), and lithium-ion (Li-ion) types.

Ni-Cd / NiMH batteries

Ni-Cd and NiMH batteries have almost the same voltage cutoff and charging performances, so they can be charged by the same battery charger using the same charging algorithm. The difference consists in the charge termination method, so that many algorithms have been proposed to let a single charger to operate correctly with both types. In [27] the author suggests to use a constant current until an inflection point occurs: at this time, the charger turns the charging mode in trickle charging, in order to avoid overcharging. Another solution [28] consists in 3 steps: first a battery voltage sensing is performed to determine the state of the battery; then the battery is charged with a high current or a low one, according to voltage and temperature conditions; finally a very low current is used to charge the battery until it will be disconnected from the charger.

Other solutions have been proposed in the case of solar charging of the batteries [29]: one of these is based on the continuous observation of the battery voltage and current in a time window of 5-10 minutes. The charging process will be ongoing until the variations in current and voltage derivatives will be confined in predetermined thresholds. Another solution is based on the separation of battery in two legs, and on the comparative detection of temperature and its derivative in both the legs, using the temperature variation as the parameters which determines which one of the two legs has to be charged, or both.

Besides these algorithms there are many others, more complex, which need the knowledge of the capacity of the battery to be performed. So the charger will act differently in different situations; mainly three cases are provided: fully charged, half charged and discharged. Once the state of charge (SOC) has been detected, different operation methods could be performed. For example, if the battery is completely discharged, it will be first charged with a trickle current to avoid damages due to high current, and then completely charged with a high current, while if it is half charged, it will be first completely discharged to prevent memory effect [30]. Other works proposed different charging methods, like the pulse charging [31].

Li-ion batteries

Li-ion batteries have many critical problems regarding the charging process, in order to avoid overcharging. They are charged with a constant voltage and the current should be limited to prevent overheating at the beginning of the charging process. Furthermore the equal distribution of charge between the cells in the battery is continuously checked to have a balanced voltage.

An algorithm [32] is based on the initial check of the state of charge, through the initial open-circuit voltage measurement, and the continuous temperature control: if the battery is completely uncharged (voltage lower than a threshold), it will be charged with a low current until it is half charged, and then the charge is completed with an high current. If the temperature rises up over a certain value, the battery is electrically disconnected from the charger, until the temperature come back in the predetermined bounds.

Another method [33] is to control, after the total charge, the open circuit voltage of individual cells, to detect whether there are some unbalanced or not. The more charged cells are selectively discharged, until the voltage difference across all the cells is lower than 0,1 V. Now, if the temperature is in the allowed range, the cells are charged applying a continuous voltage, until a voltage threshold is reached: at this point the charging mode is switched to continuous current one. When the current limit is reached, the charge stops.

B. Multi-chemistry algorithms

In multi-chemistry chargers the main goal consists in detecting the type and size of the battery, in order to choose the most suitable charging scheme. Many techniques have been proposed to allow the controller to operate in safe charging conditions.

Many solar battery chargers are based on the principle of the interrupt charge control (ICC)[34]: the battery is charged with current pulses at a 50% duty cycle, that increases the accuracy in the voltage sensing at the end of each rest cycle. Charging speed can increase if there are two batteries to charge at the same time, since all the available solar power is used to charge each battery in its charging cycle. Chargers use the power obtained by the solar array to charge the battery during the charge cycle, while during the rest cycle the battery is disconnected. Voltage and voltage drop are checked at the end of every rest cycle. If the voltage increases and is not within a certain range, the algorithm still charge the battery. If the voltage drop is higher than a certain threshold, the charge stops. If there is no voltage drop, and the battery voltage is within the security range for Li-ion batteries, the constant voltage charging mode begins, until the voltage drop is under a certain threshold.

Another algorithm [35] is based on an open circuit voltages (OCV) lookup table, established for different possibilities of battery cells. The possible battery type is determined by sensing the OCV and comparing it to the values of the lookup table. To prevent damage in case of Li-ion battery a safety limit voltage is set. Then the charger starts the charging operation in constant current mode and an hysteresis measurement test begins to detect the battery typology. The test is based on a discharge-charge cycle of 30s+30s. If the differences in OCV after this cycle is higher than a certain value, the battery is a Ni-Cd or a NiMH one. In this case, the constant current mode will continue until the battery is completely charged. If the test is not able to detect the chemistry of the battery, the Li-ion nature is supposed, and the constant current mode will stop when the safety limit voltage is reached.

A last algorithm [36] is based on the inflection point principle to identify the typology of the battery. The constant current mode is used to charge the battery, and the voltage and its derivative are checked at each time step. Nickel based batteries have a voltage peak of 6-7% over the inflection point, while Li-ion ones have a peak of 10%. So the constant current mode is ongoing until a voltage drop occurs (6-7% above the inflection point), or until the voltage goes 10% or more above the inflection point. In the latter case the constant voltage charging is switched on to complete the Li-ion battery charging.

In solar powered airplane applications a very common problem dealing with batteries is the uncertainty about the remaining charge, as the battery capacity decreases with the time and the utilization. To avoid conditioning of the charging and powering processes of the batteries, proposed systems that aim to predict the state of charge of the batteries usually operate with algorithms that collect all the available data of the airplane status and estimate the SOC using a pre-described model of the charge consumption. The reliability of the system depends on the accuracy of the collected data, and on the complexity of the model, that has to be recorded on the on-board embedded processor which executes the algorithm. The battery behavior model itself is not enough to determine a complete SOC prediction algorithm with a good reliability, since many parameters could affect the battery behavior, and many of these are not simply predictable as linear parameters, or white noise, or Gaussian. So the choice of the filtering method to manage these parameters is crucial to the reliability of the algorithm. Many solution have been proposed in literature, like Statistic Based Baseline models, Probabilistic Regression Models or Particle Filters [37].

Depending on the mission tasks the UAV is designed for, it will need a different amount of stored charge to accomplish its goal. But surely an issue regarding the storage of electrical power onboard still be valid. From the literature we know that the batteries represent the heaviest component inside the power management system for a solar powered UAV.

As for the other components of the power system, batteries are still under ongoing investigation to improve their performances, fabrication processes and energy management [38]. So the energy stored to weight ratio becomes the crucial parameter for the choice of the batteries for the design of the Unmanned Aerial Vehicle. This requirement obviously paves the way for the choice of Fuel Cells [39].

Comparing to other batteries technology, like Lithium ions, or Nickel Cadmium batteries, Fuel Cells have a very higher energy density, due to their capacity of converting chemical energy in electrical one. Fuel Cells systems are widely used in aerospace missions, because they are 25%-50% lighter than a battery system [40].

Generally, for electric vehicles, the propulsion system is powered by an hybrid power source, in which the Fuel Cell system is coupled to a battery, usually a Lithium-ion battery stack. The battery has the role of energy buffer: it power assists the fuel cell system during peak power demands (acceleration) and allows shifting the operation point of the fuel cells to optimize the efficiency [41]. Recently it has been analyzed the feasibility for realizing a powertrain drive system with a passive hybrid control scheme, without the utilization of buck DC\DC transformers for the power sharing of the two power sources [42].

The most promising fuel cells seem to be the electrolyte ones, but these kind of cells could show some more problem for the utilization in an aerial vehicle: since the working principle is based upon the capability of the electrolyte to generate power form H_2 and O_2, giving water as byproduct, the need for hydrogen and oxygen storage has to be approached considering the pressure variations when the vehicle is flying at different altitudes. In general an Oxygen tank is not suitable for aircraft operations. For the application of the fuel cells on the aerial vehicles many studies have been performed, also because the aim of reducing the weight of the batteries is still valid for the conventionally motored airplane, used in commercial flights [43]. Novel technology for fuel cell systems can be explored, like the methanol fuel cells, which can avoid the problem of managing pressure requirements [44].

In 1998 NASA began the development of a H_2-O_2 Fuel Cell with regeneration cycle: during the daylight the PV panel converts the solar light into electricity, which powers the airplane motor and the electrolyzer also. This one takes the stored water, the result of precedent electricity production from electrolysis, and divides it in H_2 and O_2, which are stored for the next use in the Fuel cell [45].

IV. Photovoltaic

For a solar powered UAV, which has only the solar irradiance as power source, the importance of the choice and the sizing of the photovoltaic panel is evident.

The solar energy conversion is one of the most explored research fields nowadays, and focuses both on modeling and technological improvements.

The ideal model of a solar cell is characterized by a current generator with a diode. The current equation is given by:

$$I = I_L - I_0\left(\exp\left(\frac{qV}{kT} - 1\right)\right) \tag{5}$$

where I_L is the cell's photocurrent, that depends on the solar irradiation and temperature, I_D is the diode current, I_0 is the reverse saturation current of the diode, q is the electron charge, k is the Boltzmann's constant, and T is the temperature of the solar cell.

A more detailed model adds a series resistance R_S to represent the electric behavior of the cell. In this case (5) becomes:

$$I = I_l - I_0\left(\exp\left(q\frac{(V + IR_S)}{kT}\right) - 1\right) \tag{6}$$

Moreover, a parallel resistance is introduced in the model, and the current equation becomes:

$$I = I_L - \left(V + \frac{IR_S}{R_P}\right) - I_0\left(\exp\left(q\frac{(V + IR_S)}{kT}\right) - 1\right) \tag{7}$$

This model is the simplest available to study a real solar cell; however, it is not complete enough, since many processes occur in a solar cell, and they are often depending on the technology the solar cell is made with. In this model the R_S parameter indicates all the current losses in the cell that do not allow all the charge collected by the junction to reach the outer circuit (ideal value is 0), while the R_P parameter indicates all the possible current paths in the cell between the two regions of the junction, that should be avoided (ideal value is infinite).

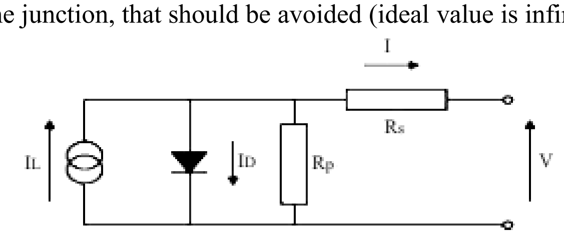

Fig. 3 - Equivalent circuit of a solar cell

To perform a correct prediction of the solar cell behavior, many parameters have to be considered and represented in a model which is expected to be valid. Among these parameters, the most commonly considered is the temperature. The effect of temperature on solar cell efficiency is strong and complex, since it affects the solar cell operating principle in many way. First, the temperature affects the diode reverse saturation current as follows

$$I_0 = I_{0r}[T/T_t]^3 \exp(\frac{qE_G}{kA}[\frac{1}{T_r} - \frac{1}{T}]) \quad (8)$$

where T_r is the cell reference temperature, I_{0r} is the reverse saturation current at T_r, and E_g is the band-gap energy of the semiconductor used in the cell. The photocurrent I_L also depends on the temperature as follows:

$$I_L = [I_{scr} + k_i(T - T_r)]\frac{S}{100} \quad (9)$$

where I_{scc} is the cell short circuit current at T_r, k_i is the short circuit temperature coefficient and S is the solar radiation.

To take into account the influence of temperature, a diode ideality factor A is introduced in the expression of the diode current as follows:

$$I_D = I_0 \exp(\frac{qV}{Akt}) - 1 \quad (10)$$

The ideality factor is set to achieve the best I-V curve match.

Other parameters which influence the behavior of solar cell are the radiation incidence angle and the dust concentration in the air. Many studies have been performed to model the behavior of solar cells taking into account these parameters [46], with good results in terms of prediction of variation of solar cell efficiency and energetic output; however, regarding the design of a solar panel installation on an ultra-light aircraft, the flight dynamic represents a new variable which strongly influence the performance of the photo-conversion.

The application object of this study also demands many other requirements: because of the lightness requisites and the frequent variations of illumination conditions, the purpose of pursuing the best efficiency has to be balanced by other needs, in particular the need of a very light weight, but also of a good average efficiency which takes into account the frequent changes of weather and orientation.

So it is necessary to analyze very well all the parameters involved in the design of the UAV for the best choice of the power source [47]. This is why thin film photovoltaic panels are the suggested technology for the utilization in application characterized by the ultra-light oriented design.

There are different technologies for the realization of thin film solar cells: the major ones, already well explored by researchers, are those based on Silicon (amorphous or polycrystalline), on Cadmium Teluride and on Copper [48]. The organic solar cells also appear promising as a solution for ultra-light projects, especially solid state DSSC [49], but they are still in a research stage, and so longer studies about stability are necessary to predict their behavior in hard environmental conditions like those expected for an aerial vehicle.

While the sizing and the installation of the photovoltaic panels is submitted to mechanic and dynamic evaluations, from the power management point of view what is critic is the optimization of the output power from the panels. The single solar cell, and therefore a solar panel, realized as a series-parallel combination of solar cells, has a single point of maximum power output, and so it is needed to make the panel work at that point. Of course, this condition cannot be permanently achieved, especially for UAVs, flying in hard environmental conditions and fast varying atmospheric conditions, which may generate frequent and wide variations of the power produced by the solar panels. So the need for a good Maximum Power Point Tracking (MPPT) system is evident [50].

The MPPT operation can be accomplished following one of the many algorithms proposed in the years [51]-[53]. The most used algorithms, as observed in literature, are those based on the direct readings of the output variables of the source, current and voltage: in particular, the P&O algorithm (Perturbation and Observation) is based upon the idea of periodically changing the operating voltage (perturbation) of the solar cells, and then reading the variation of the generated power (observation): if the power increases after the voltage variation, then the successive voltage step will have the same direction of the previous one; else if the power reduces, the successive variation will go counter side. It is a simple and very efficient method, but has many problems, in particular an intrinsic one: it always needs to apply a voltage variation, and so the maximum power point will never be established in a constant way, leading, in the best case, to a ripple in the output power signal, whose envelope is the maximum power available, resulting in a power extraction loss. Moreover, the ability of this scheme to follow correctly the maximum power point in rapidly changing environmental condition is strictly dependent from the sampling frequency of the system.

Beside this scheme, the other one widely used is that proposed by Hussein [54], named Incremental Conductance: the idea is to evaluate the sign of the derivative of the power with respect to the voltage. Being this derivative, as definition, equal to zero in the maximum power point, the sign of the derivative indicates whether the actual operation voltage is higher or lower than the actual maximum power point voltage. As the instantaneous power is equal to $P=V\,I$, evaluating the sign of the derivative of the power with respect to the voltage means comparing the instantaneous equivalent conductance (given by the I/V ratio, with negative sign, due to the position of the V-I curve in the fourth quadrant for a solar cell in operating conditions), and the incremental conductance, given by the dI to dV differentials ratio, with positive sign. From a mathematic point of view, this algorithm is surely better than the previous one, as it potentially avoid the output power ripple present in the P&O algorithm. The disadvantage resides in the complexity of the control system, which has to manage more operations.

An even more efficient algorithm, with extraction efficiency reported in the order of 99%, is the Parasitic Capacitance one [55]: it is very similar to the Incremental Conductance one, as it aims to bring to zero the derivative of the power respect to the voltage, but takes into account also the effect of the shunt parasitic capacitances of the cells within the module, that are the cause of the output power ripple signal from the PV panel. To calculate the incremental conductance, a frequency discrimination between the power contribution from the solar power source is necessary, and so the introduction of a dedicated hardware (high-pass filters and multipliers) and a higher computation capacity for the determination of the harmonic components will be necessary.

These three methods reside on the availability of direct measuring both output voltage and current from the solar power source. Beside these methods, others have been proposed, based on the reading of only one of these two variables, at predicted time intervals, and on electrical and mathematical models of the solar panels, more or less complicated. For instance a method consists in the disconnection of the cell for a certain time interval, during which the open circuit voltage (V_{OC}) produced by the cell is measured [56]. This voltage value is then scaled by a predefined parameter (<1), that identify the ratio between the maximum power point voltage and open circuit voltage, calculated by an a priori analysis of the cell electrical behavior. The so calculated voltage value will be the next operating voltage applied to the cell. An analog method has been proposed, based on the reading of the short circuit current (I_{sc}) [57]. The advantages of these methods, by a computational point of view, are clear and evident; but they have also evident disadvantages. First, they need a time interval during which the cell, though working, is not giving energy to the load, but only acts as a device under test to extract the needed variable. Second, the efficiency of this scheme strongly depends on the definition of the cell model, and it assumes constant the ratio V_{MAX}/V_{OC} in different lighting, temperature and lifetime conditions, resulting quite loose. In other proposed schemes, the evaluation of the operating voltage from the observed variable is a more complex function that takes into account different environmental conditions, that makes a more complete cell model, but also needs bigger memory space to consider many model parameters. Other proposal consists in having a control test cell, completely apart from the power generation system, whose electric characteristic perfectly match the operating panel ones, and so managing with an indirect control driven by a twin cell: the performances of this method are totally dependent from the matching between the operating panel and the test cell, not simple to achieve really, and there are intrinsic losses due to the presence of the test cell, that occupy an illuminated area and has its own mass, fundamental parameters in the design of an UAV, without performing a power generation.

For the implementation of these algorithms, many proposal have been offered by literature, for stand-alone systems [58], and also for system characterized by the combination of a PV power source followed by a DC motor, in water pumping application [59]-[61] and in solar powered vehicles [62]-[64]. In this last case, in addition to the MPPT dedicated controller, there is the presence of the motor driving system, generally a DC\DC converter, whose sizing depends on both the output power features of the solar power source system (made by the panels followed by the MPPT) and the motor driving requirements. The design of such a control system can vary for the typology of the cells [64] and for the configuration chosen for the series-parallel connection between cells [65],[66].

In [67] the PV MPPT system adopts a boost converter to transfer power from solar array to load. Fig. 4 shows the PV array characteristic, while fig. 5 shows the circuit diagram of PV DC-DC converter system. In fig. 5 the power switch D controls the output energy of the solar array. When D is opened (D=0) power will be switched to open, when D is closed (D=1) power will be switched to close.

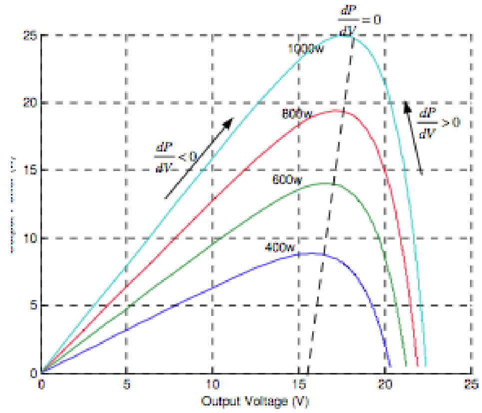

Fig. 4 – PV array characteristic

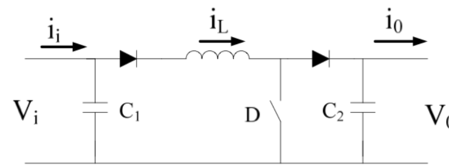

Fig. 5 – Circuit diagram of PV DC-DC converter system

In [68] the authors proposed an interleaved boost DC-DC converter to transfer the low DC voltage of the cell to high DC voltage in DC link. The converter has a parallel structure with two voltage-doublers boost converters by interleaving their output voltages to reduce the voltage ripple ratio.

In [69] an artificial neural network (ANN) is used to estimate the global solar energy, having latitude, longitude, day number and sunshine ratio as inputs.

V. Energy Flow Control System

For the global energy control system point of view, the principal issue is the evaluation of cost and benefits, in terms of power, of a control system implemented on the vehicle. For the costs, actually, the principal impact to evaluate is the weight of each single added driving component on the airplane, as a greater mass means greater power needing in the motor design. The relation mass-power is crucial in the design of the UAV. In the Zephyr project [70], for example, first the introduction of an additional driving system with a mass of 1 kg has been taken into account with a penalty function of the motor power performances equal to 5%; but the design of the UAV with this penalty function led to a failure, and so the penalty estimation has been corrected, and the new value was 10%, which allowed the design to become consistent.

There is the need for a control system which can allow the UAV's motor to work in stability, sourcing the energy from the batteries without minding about the environmental and illumination condition of the solar panels. The energy flow scheme for the UAV generally consists in a photovoltaic power source, followed by a MPPT scheme (for managing the output power from the panels), the battery pack (to store energy when the output power exceeds the power needs, and to provide energy during the power need peaks), the PMBLDC motor, and a power control circuitry, for granting a constant energy supply to the motor [71].

For the power control system, the requirements reside in the regulation of output voltage, in order to properly feed the motor. This is generally obtained by a feedback control realized by a PID Dual loop controller, identified by two loops, one sensing the value of the rotor speed, the other sensing the rotor current. The weighted sum of the errors measured by these two loops is the input total error for the PID network. The current loop acts as a limiter, more than a controller, as it avoids current peaks and high rippled currents in the motor, which could cause irreversible failures. The PID output is still valid until both the loops error signal are not zero. Generally the PID output signal is used to drive a PWM modulator, which manages a two-quad chopper, that supply the motor with the proper voltage. In the solar powered vehicles, however, the two-quad chopper can be substituted by a couple of DC\DC boost converter in series, in order to have a low current input range for the motor[72],[73].

VI. Conclusions

As it has been discussed, the design of an UAV is not a unique process: it depends on the tasks the vehicle is designed for (weather monitoring, plantation fields observance,…) and then on the altitudes it has to reach and the time it has to fly for. As the power system of the UAV consists in many blocks, there are many ways to improve the system performances. For some parts of the system, like the motors, the advances in research and development of PMBLDC motors offer many options for an optimized design, already with good performance in terms of power to weight ratio, that is the most important parameter in the design of the UAV. Also for the MPPT algorithms there are plenty of solutions available from literature that are suitable for the design of the UAV. For other parts of the system design, like the photovoltaic panels and the battery pack, there are, of course, many technological issues to solve to optimize the power (or energy) to weight ratio, but the design of custom devices for the UAV could be very important for the improvement of the vehicle performance. At the end, the driving control system involved in the energy flow system can be improved applying many techniques already studied and used for the driving of field electric vehicles.

Acknowledgements

The innovative contents described in this paper are disclosed after the permission of INGENIA & PARTNERS S.r.l. company, which committed to Laboratorio KAD3 S.c.a.r.l. the research project called “Analisi e studi per lo sviluppo di una metodologia per la progettazione assistita dei velivoli ultraleggeri a propulsione solare”, co-funded by Italian Government (Legge 12 luglio 2011, n. 106 – Credito di imposta per le imprese che finanziano progetti di ricerca in Università o enti pubblici di ricerca).

References

[1] Vashishtha, V. K., Kumar, A., Makade, R., Lata, S., “Solar Power the future of aviation industry”, International Journal of Engineering Science and Technology, 2011, vol. 3, n° 3, pp. 2051-2058.
[2] Noth A, Siewwart R., “Design of Solar Powered Airplanes for Continuous Flight,Advances in Unmanned Aerial Vehicles: State of the Art and the Road to Autonomy”, Springer, 2007.
[3] Eun-Mi Kwon, Kee-Ho Yu, Myoung-Jong Yoon, Gu-Young Jeong, “Design considerations and modeling of a small and low altitude solar powered UAV”, Control, Automation and Systems (ICCAS), 11th International Conference on, 2011, pp. 1085-1088.
[4] Meyer, J., du Plessis, J.A.F., Ellis, P., Clark, W., “Design considerations for a low altitude long endurance solar powered unmanned aerial vehicle”, AFRICON 2007, pp. 1-7.
[5] Perriard, Y., Ragot, P., Markovic, M., “Round the world flight with a solar aircraft: complex system optimization process”, Electric Machines and Drives, 2005 IEEE International Conference on, 2005, pp. 1459-1465.
[6] Mecrow, B. C., Bennett, J.W., Jack, A.G., Atkinson, D.J., Freeman, A.J., “Drive Topologies for Solar Powered Aircraft”, IEEE Transactions on industrial electronics, vol. 57, Jan 2010, n°1, pp. 457-464.
[7] Romeo, G., Pacino, M., Borello, F., “First Flight of Scaled Electric Solar Powered UAV for Mediterranean Sea Border Surveillance Forest and Fire Monitoring”, Aerotecnica Missili & Spazio, The Journal of Aerospace Science, Technology and Systems January-June 2009, Vol.88, No.1/2.
[8] Reinhardt, K.C., Lamp, T.R, Geis, J.W., Colozza, A.J., “Solar-Powered Unmanned Aerial Vehicles”, Energy Conversion Engineering Conference, 1996, IECEC 96, Proceedings of the 31st Intersociety, 1996, Volume 1, pp. 41-46.
[9] Leutenegger, S., Jabas, M., Siegwart, R., Solar Airplane Conceptual Design and Performance Estimation, Journal of Intelligent & Robotic Systems, vol. 61, 2011, n° 1-4, pp. 545-561.
[10] Jaw-Kuen Shiau, Der-Ming Ma, Pin-Ying Yang, Geng-Feng Wang, Jhij Hua Gong, “Design of a Solar Power Management System for an Experimental UAV”, Aerospace and Electronic Systems, IEEE Transactions on, Oct. 2009,vol. 45, no. 4, pp. 1350-1360.
[11] Torabi, H.B., Sadi, M., Varjani, A.Y., “Solar Power System for experimental unmanned aerial vehicle (UAV), design and fabrication”, Power Electronics, Drive Systems and Technologies Conference (PEDSTC), 2011 2nd, 2011, pp. 129-134.
[12] Colozza, A.J., “Effect of Power System Technology and Mission Requirements on High Altitude Long Endurance Aircraft”, NASA CR 194455, February 1994.
[13] Ragot, P., Markovic, M., Perriard, Y., “Optimization of Electric Motor for a Solar Airplane Application”, IEEE Transaction on Industry Applications, 2006, vol. 42, n° 4, pp. 1053-1061.
[14] Bhim Singh, “Recent advances in permanent magnet brushless DC motors, Sadhana,1998, vol. 22, part 6, pp. 837-853.
[15] Bhim Singh, Sanjeev Singh, “State of the Art on Permanent Magnet Brushless DC Motor Drives”, Journal of Power Electronics, January 2009, Vol. 9, No. 1, pp. 1-17.
[16] Karthikeyan, J., Dhana Sekaran, R., “Current control of brushless DC motor based on a common dc signal for space operated vehicles”, Electrical Power and Energy Systems, 2011, vol. 39, pp. 1721-1727.
[17] Acarnley, P.P., Watson, J.F., “Review of position-sensorless operation of brushless permanent-magnet machines”, Industrial Electronics, IEEE Transactions on, April 2006, vol.53, no. 2, pp. 352- 362.
[18] Matsui, N., “Sensorless PM brushless DC motor drive”, IEEE Trans. Ind. Electron., vol. 43, April 1996, no. 2, pp. 300-308.
[19] J. X. Shen, Z. Q. Zhu and D. Howe, “Sensorless flux-weakening control of permanent-magnet brushless machines using third harmonic back EMF”, IEEE Trans. Ind. Appl., vol. 40, Nov-Dec 2004, no. 6, pp. 1629-1636.
[20] Moreira, J.C., “Indirect sensing for rotor flux position of permanent magnet AC motors operating over a wide speed range”, IEEE Trans. Ind. Appl., vol. 32, Nov./Dec. 1996, no. 6, pp. 1394–1401.
[21] G. H. Jang, J. H. Park, J. H. Chang, “Position detection and start-up algorithm of a rotor in a sensorless BLDC motor utilising inductance variation”, IEEE Proc –Elec. Power Appl, vol. 149, March 2002, no. 2, pp. 137-142.
[22] R. Wu, Slemon, G. R., “A permanent magnet motor drive without a shaft sensor”, IEEE Trans. Ind. Appl., vol. 27, Sep./Oct. 1991, no. 5, pp. 1005–1011.
[23] Batzel, T.D., K. Y. Lee, “Slotless permanent magnet synchronous motor operation without a high resolution rotor angle sensor”, IEEE Trans. Energy Convers., vol. 15, Dec. 2000, no. 4, pp. 366–371.
[24] Glavin, M., Hurley, W.G., “Battery Management System for Solar Energy Applications”, Universities Power Engineering Conference, UPEC '06. Proceedings of the 41st International, vol. 1, Sept. 2006, pp. 79-83.
[25] Gibson, T.L, Kelly, N.A, “Solar photovoltaic charging of lithium-ion batteries”, Journal of Power Sources, vol. 195, 2010, no. 12, pp. 3928-3932.
[26] Hussein, A.A.-H., Batarseh, I., “A review of Charging Algorithms for Nickel and Lithium Battery Chargers”, IEEE Transactions on Vehicular Technology, vol. 60, 2011, no. 3, pp. 830-838.

[27] Nicolai, J., and Wuidart, L., "From nickel-cadmium to nickel-hybride fast battery charger", Power Electronics and Drive Systems, 1995., Proceedings of 1995 International Conference on, IEEE, 1995, pp. 786-791.

[28] Mundra, T. S., and Kumar, A., "An innovative battery charger for safe charging of NiMH/NiCd batteries", Consumer Electronics, IEEE Transactions on, vol. 53, n° 3, 2007, pp. 1044-1052.

[29] Boico, F., Lehman, B., and Shujaee, K., "Solar battery chargers for NiMH batteries." Power Electronics, IEEE Transactions on, vol. 22, n° 5, 2007, pp. 1600-1609.

[30] Gonzalez, M., Ferrero, F.J., Anton, J.C., Perez, M.A., "Considerations to improve the practical design of universal and full-effective NiCd/NiMH battery fast-chargers", Applied Power Electronics Conference and Exposition, 1999. APEC'99. Fourteenth Annual. Vol. 1. IEEE, 1999, pp. 167-173.

[31] Díaz, J., Martín-Ramos, J.A., Pernía, A.M., Nuño, F., and Linera, F.F., "Intelligent and universal fast charger for NiCd and NiMH batteries in portable applications," IEEE Trans. Ind. Electron, vol. 51, n° 4, 2004, pp. 857-863.

[32] Datasheet, Panasonic Lithium-Ion Charging. "Jan. 2007."

[33] Elias, M. F. M., Nor, K. M., and Arof, A. K., "Design of smart charger for series Lithium-Ion batteries", Power Electronics and Drives Systems, PEDS 2005, International Conference on, Vol. 2, IEEE, 2005, pp. 1485-1490.

[34] Hussein, A.A-H., Pepper, M., Harb, A., Batarseh, I., "An efficient solar charging algorithm for different battery chemistries", Vehicle Power and Propulsion Conference, 2009, VPPC'09, IEEE, 2009, pp. 188-193.

[35] Barth, H., Schaeper, C., Schmidla, T., Nordmann, H., Kiel, M., van der Broeck, H., "Development of a universal adaptive battery charger as an educational project", Power Electronics Specialists Conference, 2008. PESC 2008, IEEE, 2008, pp. 1839-1845.

[36] Sung-Yeul Park, Miwa Hidekazu, Clark Brian T., Ditzler Danielle S. K., Malone Greg, D'souza Neil S., and Lai Jih-Sheng, "A universal battery charging algorithm for Ni-Cd, Ni-MH, SLA, and Li-Ion for wide range voltage in portable applications", Power Electronics Specialists Conference, 2008, PESC 2008. IEEE, 2008, pp. 4689-4694.

[37] Bhaskar Saha, Edwin Koshimoto, Cuong C. Quach, Edward F. Hogge, Thomas H. Strom, Boyd L. Hill, Sixto L. Vazquez, Kai Goebel, "Battery health management system for electric UAVs", Aerospace Conference, 2011 IEEE, 2011, pp. 1-9.

[38] Divya, K.C., Østergaard, J., "Battery energy storage technology for power systems—An overview", *Electric Power System Research,* vol. 79, 2009, pp. 511-520.

[39] Thomas, C.E., "Fuel cell and battery electric vehicles compared", *International Journal of Hydrogen Energy,* vol. 35, 2009, no.15, pp. 6005-6020.

[40] Khalig, A., Zhihao, L., "Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art", *IEEE Transactions on Vehicular Technology*, vol. 59, 2010, no. 6, pp.2806-2814.

[41] Markel, T., Zolort, M., Wipke, K.B., Pesaran, A.A., "Energy Storage System Requirements for Hybrid Fuel Cell Vehicles", *Advanced Automotive Battery Conference*, Nice, France, June 2003.

[42] Bernard, J., Hofer, M., Hannesen, U., Toth, A., Tsukada, A., Buchi, F.N., Dietrich, P., "Fuel cell/battery passive hybrid power source for electric powertrains", *Journal of Power Sources*, vol. 196, 2011, pp. 5867-5872.

[43] Nishizawa, A., Kallo, J., Garrot, O., Weiss-Ungentum, J., "Fuel cell and Li-ion battery direct hybridization system for aircraft applications", *Journal of Power Sources*, vol. 222, 2013, pp. 294-300.

[44] Halim, F.A., Hasran, U.A., Masdar, M.S., Kamarudin, S.K., Daud, W.R.W., "Overview on Vapor Feed Direct Methanol Fuel Cell", *APCBEE Procedia*, vol. 3, 2012, pp. 40-45.

[45] Bents, D. J. "Solar Airplanes and Regenerative Fuel Cells." (2007).

[46] Cortez, L., Cortez, J. I., Adorno, A., Cortez, E., and Larios, M., "Progress on the problems of the study in the performance of a solar module under conditions of random changes of radiation", *International Journal Of Energy*, Issue 2, Vol. 3, 2009, pp. 17-24.

[47] Lubkowski, S., Jones, B., Rojas, E., Morris, D., "Trade-off analysis of regenerative power source for long duration loitering Airship", *Systems and Information Engineering Design Symposium (SIEDS), 2010 IEEE* , April 2010, pp. 25-30.

[48] Aberle, A.G., "Thin-film solar cells", *Thin Solid Films*, vol.517, 2009, pp. 4706-4710.

[49] Bin Li, Liduo Wang, Bonan Kang, Peng Wang, Yong Qiu, "Review of recent progress in solid-state dye-sensitized solar cells", *Solar Energy Materials & Solar Cells,* vol. 90, 2006, pp. 549–573.

[50] Van der Merwe, L., Van der Merwe, G.J., "Maximum Power Point Tracking-Implementation Strategies", *Proceedings. ISIE '98. IEEE International Symposium on Industrial Electronics*, vol. 1, 1998, pp. 214-217.

[51] Hohm, D.P., Ropp, M.E., "Comparative Study of Maximum Power Point Tracking Algorithm", *Progress in photovoltaic: Research and Applications*, vol. 11, 2002, no. 1, pp. 47-62.

[52] Salas, V., Olias, E., Barrado, A., Lazaro, A., "Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems", *Solar Energy Materials and Solar Cells*, vol. 90, 2006, no. 11, pp. 1555-1578.

[53] Esram, T., Chapman, P.L., "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques", *IEEE Transactions On Energy Conversion*, vol. 22, June 2007, no. 2, pp. 439-449.

[54] Hussein, K.H., Muta, I., Hoshino, T., Osakada, M., "Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions", *IEEE Proceedings, Generation, Transmission and Distribution*, vol. 142, 1995, pp. 59-64.

[55] Brambilla, A., Gambara, M., Garutti, A., Ronchi, F., "New approach to photovoltaic arrays maximum power point tracking", *Proceedings of the 30th IEEE Power Electronics Conference*, 1998, pp. 632–637.

[56] Lafferty, D., "Coupling network for improving conversion efficiency of photovoltaic power source", US4, 873,480, 1989.

[57] Alghuwainem, S.M., "Matching of a dc motor to a photovoltaic generator using a step-up converter with a current-locked loop", *IEEE Trans. Energy Conversion,* vol. 9, 1994, no. 1, pp. 192–198.

[58] Bhuiyan, M.M.H., Ali Asgar, M., "Sizing of a stand-alone photovoltaic system at Dhaka", *Renewable Energy,* vol. 28, 2003, pp. 929-938.

[59] Putta Swamy, C.L., Singh, B., Singh B.P., "Dynamic performance of a permanent magnet brushless DC motor powered by a PV array for water pumping", *Solar Energy Materials and Solar Cells*, vol. 36, 1995, pp. 187-200.

[60] Singh, B., Putta Swamy, C.L., Singh B.P., Analysis and development of a low-cost permanent magnet brushless DC motor drive for PV-array fed water pumping system, *Solar Energy Materials and Solar Cells*, vol 51, 1998, pp. 55-67.

[61] Mozaffari Niapour, S.A.KH., Danyali, S., Sharifan, M.B.B., Feyzi, M.R., "Brushless DC motor drives supplied by PV power system based on Z-source inverter and FL-IC MPPT controller", *Energy Covnersion and Management*, vol. 52, 2011, pp. 3043-3059.

[62] Ustun, O., Ylmaz, M., Gokce, C., Karakaya, U., Tuncay, R.N., "Energy Management Method for Solar Race Car Design Application", *in Proc. Electric Machines and Drives Conference*, *2009, IEMDC '09, IEEE International*, 2009, pp. 804-811.

[63] Wolfs, P., Tang, L., Senini, S., "Distributed Maximum Power Tracking for High Performance Vehicles Solar Arrays", *Proc. IEEE PESC*, 2005, pp. 165-171.

[64] Quan Li, Wolfs, P., "A preliminary study of the distributed maximum power point tracker designs for different types of solar cells in solar and electric vehicle arrays", *Power Engineering Conference, 2007, AUPEC 2007,. Australasian Universities*, Dec. 2007, pp. 1-6.

[65] Wolfs, P.J., Tang, L., "A Single Cell Maximum Power Point Tracking Converter without a Current Sensor for High Performance Vehicle Solar Arrays", *Power Electronics Specialists Conference, 2005. PESC '05. IEEE 36th*, June 2005, pp. 165-171.

[66] Yasuro Haseo, Fujisawa, T., "Evaluation on tracking capability of MPPT for running solarcar", *Control, Automation and Systems, 2008. ICCAS 2008. International Conference on*, Oct. 2008, pp. 2933-2936.

[67] Jui-Liang Yang, Ding-Tsair Su, Ying-Shing Shiao, "Research on MPPT and Single-Stage Grid-Connected for Photovoltaic System, WSEAS TRANSACTIONS on SYSTEMS, Issue 10, Volume 7, October 2008, pp.1117-1131.

[68] Long-Yi Chang, Kuei-Hsiang Chao, and Tsang-Chih Chang, "Application of High Voltage Ratio and Low Ripple Interleaved DC-DC Converter for a Fuel Cell", WSEAS TRANSACTIONS on CIRCUITS and SYSTEMS, Issue 1, Volume 12, January 2013, pp. 26-35.

[69] Tamer Khatib, Azah Mohamed, M. Mahmoud, K. Sopian, "Estimating Global Solar Energy Using Multilayer Perception Artificial Neural Network", INTERNATIONAL JOURNAL OF ENERGY, Issue 1, Vol. 6, 2012, pp. 25-33.

[70] Mecrow, B., Bennett, J., Jack, A.G., Atkinson, D.J., Freeman, A., "Very high efficiency drives for solar powered unmanned aircraft", *in Proc. Int. Conf. Elect. Mach., Vilamoura, Portugal*, Sep. 2008, pp. 1–6.

[71] Vas, J.V., Venugopal, S., Nair, V.G., "Control scheme for electrical drive of solar powered vehicles", *India Conference, 2008. INDICON 2008. Annual IEEE*, vol.1, Dec. 2008, pp. 75-80.

[72] Sharaf, A.M., Elbakush, E., Altas, I.H., "Novel Control Strategies For

Photovoltaic Powered PMDC Motor Drives", Electrical Power Conference, 2007. EPC 2007. IEEE Canada, Oct. 2007, pp. 461-466.
[73] Sharaf, A.M., Elbakush, E., Altas, I.H., "An Error Driven Pid Controller for Maximum Utilization of Photovoltaic Powered PMDC Motor Drives", Electrical and Computer Engineering, 2007. CCECE 2007. Canadian Conference on, April 2007, pp. 129-132.