VVVF HAJTÁSVEZÉRLÉSŰ NAPENERGIÁVAL HAJTOTT ELEKTROMOS AUTÓ

SOLAR POWERED ELECTRIC CAR WITH VVVF DRIVE CONTROL

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ABSTRACT
The popularity of electric vehicles has been expanding rapidly due to the subsidies and are worldwide used What if, solar panel help us to drive the car? The World Solar Challenge is exemplary. In Australia directly solar powered cars can across the continent during a 3000 km long race. Let's use this technology! Our goal is to create a theoretical model of an electric car, which can directly use solar energy or restore it. We would like to use a three-phase induction motor to drive the electric car. The motor is control by variable voltage frequency drive (VVFD). The solar panel string supplies the inverters DC link.

1. INTRODUCTION

Nowadays energy hunger favours the accelerated expansion of renewables. Of the renewable energy sources, solar electric power generation is one of the least located option. Since the solar panels generate direct current, it is an obvious solution to place them on top of vehicles and connect them to a 12 VDC system. Although solar panels are not suitable for running an electric car in its entirety, however they can provide power to the control circuits or provide a slight increase in range. Over the past decade, many vehicle manufacturers have experimented with solar cars, with greater or lesser success.

The solar panels are always used to charge the vehicle battery pack. For some cars, the charge only works when stationary. Basically, electric cars run on tens of kW electric motors, on the other hand, only a few hundred watts of solar power capacity can be placed on them. It follows that solar panels alone are not enough to charge and operate the vehicle. For this reason, the importance of solar cars lies primarily in the daily commuting of the urban population. If the distance travelled per day is considered and how much energy the solar panels produce daily in unclouded, sunny days, then the difference between consumption and production is less perceptible. It should not be overlooked that most cars are usually used by one person at a time, so it is unnecessary to produce large and powerful solar cars. It would be practical to design these vehicles for daily, low-power commuting, rather than for a family car. It is worth researching in this direction and developing cheaper solar cars.

2. INDUCTION MOTORS

AC induction motors are the most common motors used in industrial motion control systems, as well as in main powered home appliances. Simple and rugged design, low-cost, low maintenance and direct connection to an AC power source are the main advantages of AC induction motors. Various types of AC induction motors are available in the market. Different motors are suitable for different applications. Although AC induction motors are easier to design than DC motors, the speed and the torque control in various types of AC induction motors require a greater understanding of the design and the characteristics of these motors [1].

Like most motors, an AC induction motor has a fixed outer portion, called the stator and a rotor that spins inside with a carefully engineered air gap between the two. Virtually all electrical motors use magnetic field rotation to spin their rotors. A three-phase AC induction motor is the only type where the rotating magnetic field is created naturally in the stator because of the nature of the supply. DC motors depend either on mechanical or electronic commutation to create rotating magnetic fields. A single-phase AC induction motor depends on extra electrical components to produce this rotating magnetic field. Two sets of electromagnets are formed inside any motor. In an AC induction motor, one set of electromagnets is formed in the stator because of the AC supply connected to the stator windings. The alternating nature of the supply voltage induces an Electromagnetic Force (EMF) in the rotor (just like the voltage is induced in the transformer secondary) as per Lenz's law, thus generating another set of electromagnets; hence the name – induction motor. Interaction between the magnetic field of these electromagnets generates twisting force or torque. As a result, the motor rotates in the direction of the resultant torque [1].

2.1. Stator

The stator is made up of several thin laminations of aluminium or cast iron. They are punched and clamped together to form a hollow cylinder (stator core) with slots. Coils of insulated wires are inserted into these slots. Each grouping of coils, together with the core it surrounds, forms an electromagnet (a pair of poles) on the application of AC supply. The number of poles of an AC induction motor depends on the internal connection of the stator windings. The stator windings are connected directly to the power source. Internally they are connected in such a way, that on applying AC supply, a rotating magnetic field is created [1].

2.2. Rotor

The rotor is made up of several thin steel laminations with evenly spaced bars, which are made up of aluminium or copper, along the periphery. In the most popular type of rotor (squirrel cage rotor), these bars are connected at ends mechanically and electrically using rings. Almost 90% of induction motors have squirrel cage rotors. This is because the squirrel cage rotor has a simple and rugged construction. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper, aluminium, or alloy bar. These rotor bars are permanently short-circuited at both ends by means of the end rings. This total assembly resembles the look of a squirrel cage, which gives the rotor its name [1].

The rotor is mounted on the shaft using bearings on each end; one end of the shaft is normally kept longer than the other for driving the load. Some motors may have an accessory shaft on the non-driving end for mounting speed or position sensing devices. Between the stator and the rotor, there exists an air gap, through which due to induction, the energy is transferred from the stator to the rotor. The generated torque forces the rotor and then the load to rotate. Regardless of the type of rotor used, the principle employed for rotation remains the same [1].

2.3. Application

The use of induction motors in electric cars is subservient because of their low maintenance requirements. This is due to the fact, that induction motors do not contain carbon brushes and slip ring, in contrast with synchronous and DC motors. Therefore, only the bearings should be maintained. The induction motor has good starting torque, which gives good acceleration in cars.

2.4. Speed of an Induction Motor

The magnetic field created in the stator rotates at synchronous speed (*equation 1*). Where: f_1 the supply frequency, p the number of pole pairs [1].

$$n_0 = \frac{f_1 \cdot 60}{p} \tag{1}$$

The magnetic field produced in the rotor because of the induced voltage is alternating in nature. To reduce the relative speed, with respect to the stator, the rotor starts running in the same direction as that of the stator flux and tries to catch up with the rotating flux. However, in practice, the rotor never succeeds in "catching up" to the stator field. The rotor runs slower than the speed of the stator field. This speed is called the Base Speed (n). The difference between n_0 and n is called the slip. The slip varies with the load. An increase in load will cause the rotor to slow down or increase slip. A decrease in load will cause the rotor to speed up or decrease slip. The slip is expressed as a percentage and can be determined with the following formula (*equation 2*) [1, 8]:

$$s\,[\%] = \frac{n_0 - n}{n_0} \cdot 100 \tag{2}$$

3. SPEED OF CONTROL

The best way to control the rotor speed is to change the f_1 supply frequency. Variable frequency drives can vary the frequency stepless from 0 Hz to a few hundred Hz. The variable frequency drive is an electronic device which has three main part inside: rectifier, DC link with filter capacitor and inverter. The input and output can be one or three-phase AC voltage. For high power usages, a three-phase motor is recommended which requires a three-phase inverter. The inverter makes AC voltages from DC voltage where the frequency can vary. If the inverter's input is constant voltage, we called it VVFD (Variable Voltage Frequency Drive). The rectifier and the filter capacitor make the constant voltage at the inverter's input.

3.1. Voltage control

The torque will be constant only if the flux is constant as well (*equation 3*). U_{i1} means the induced voltage in the stator, Φ_{max} is the flux amplitude, N_1 is the number of turns, ξ_1 is the winding factor. If we do not reduce the voltage at low frequency, the stator iron core is saturated. So, the frequency and the voltage must also be changed together [8].

$$\Phi_{max} = \frac{U_{i1}}{4{,}44 \cdot f_1 \cdot N_1 \cdot \xi_1} \tag{3}$$

3.2. V/f control

The variable-voltage/variable-frequency (VVVF) drive powered induction motors have several control engineering problems. For optimal utilization of the drive, the slip-frequency should not be bigger than the pull-up slip-frequency.

Current overload must also be eliminated, the slip must remain below the nominal slip. Therefore, it is expedient to measure the slip and, on this basis to control the frequency of the VVVF drive, so that a specific adjustable slip frequency is not exceeded. In addition, it must be ensured that the motor is always supplied with the correct frequency-proportional voltage. This is necessary, on the one hand, to ensure that the machine flux does not exceed the nominal value, on the other hand, to achieve the nominal flux, apply the motor torque with the lowest possible current and reach the nominal torque at any speed. This condition can be achieved by controlling the voltage directly in proportion to the frequency [2].

Figure 1 shows two sections [3]. n the first section, the frequency and the voltage are increased proportionally to the limit frequency, then the flux and the torque are constant. Once the nominal voltage has been reached, the voltage applied to the motor terminals can no longer be increased, but the frequency can.

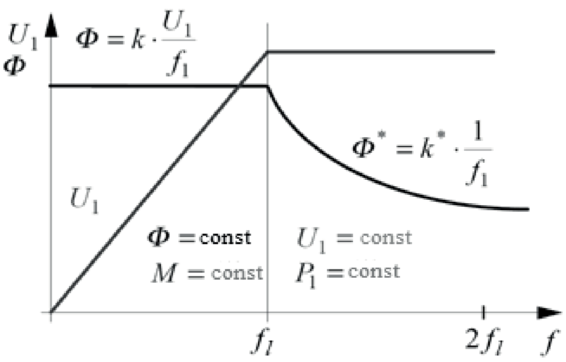

Figure 1. Voltage and flux variations as a function of frequency

This has the disadvantage that the flux is reduced, so that the motor torque and the engine power do not increase further. In the second section we talk about field weakening, not to be confused with that of DC machines. In this case, the field weakens due to constraints, and is not intentionally weakened.

4. POWER ELECTRONICS IN ELECTRIC CARS

In electric cars, the input DC comes from the battery for the inverter. DC/DC converter is needed because the battery voltage is different from the motor voltage. If we charge the battery with solar panel, one more DC/DC converter is required. These converters reduce efficiency due to power dissipations.

In many electric cars, the three-phase inverter consists of IGBT switches. These high power IGBT modules contain driver circuits as well. The modules are mounted on a heatsink.

5. THREE-PHASE INVERTER

A power inverter is an electrical device that converts direct current (DC) to alternating current (AC). The frequency of the generated AC voltage is arbitrary.

Simple control is when modulation of the control voltage is not applied. By simple control neither sine current nor sine voltage can be realized at the output. If a pulsating torque on the motor shaft is not tolerated, a simple controlled inverter is not advisable.

Six IGBT semiconductor switches are connected to the intermediate DC circuit. The alternating voltage is realized by switching these, which forms a three-phase network. The phase is offset from the others by 120°. During one period, one of the IGBT elements is switched off or on six times. An IGBT can take part in driving till 180°. The structure of the inverter is shown in Figure 2, where the induction motor is connected to the output.

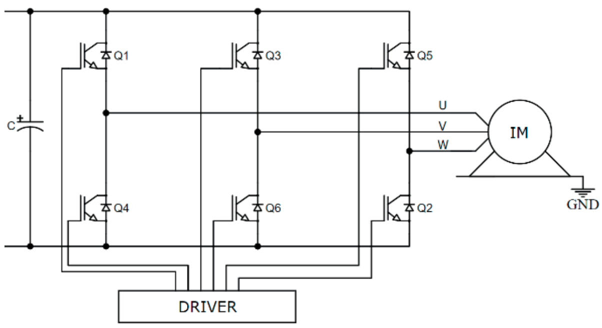

Figure 2. Three-phase inverter

The phase voltages generated on the star-connected power supply are shown in Figure 3. In the case of electric cars, simple control is not allowed because the torque will be pulsating, the car will not accelerate smoothly. The smoothest torque is created by sinusoidal current and flux.

Since IGBT switches are only controlled by rectangular signals, Sine Pulse Width Modulation (SPWM) must be used. This method results that the fundamental frequency of the control signal will be sinusoidal. Therefore, the basic harmonic of the current includes the sine as well as overtones due to the switching frequency. The amplitude of the overtones can be greatly reduced by an LC low-pass filter. The IGBT Gate-Emitter capacity has the following control voltage in case SPWM control (Figure 4), switching frequency is 7,3 kHz.

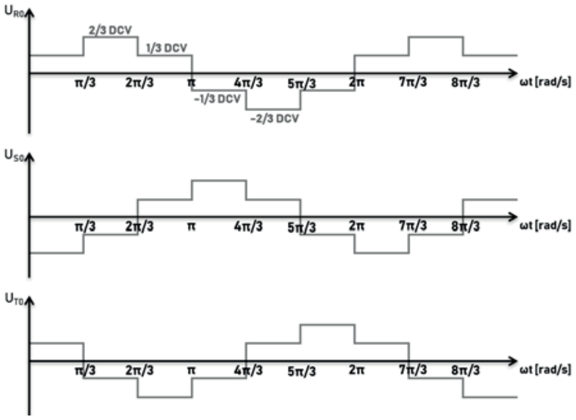

Figure 3. The three-phase voltage

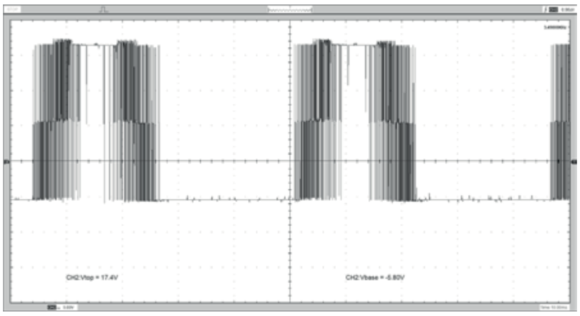

Figure 4. IGBT driver voltage

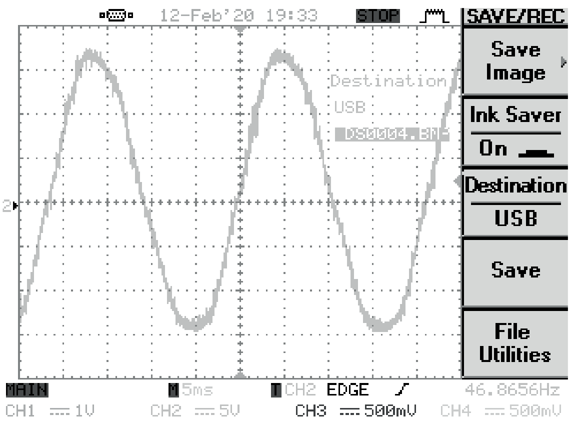

Figure 5. Phase current

If a low pass filter on the inverter output is used, the current of Figure 5 is obtained on one of the motor coils. Of course, THD is not 0% even so, but the amount of overtone content is greatly reduced. During the measurement, the DC/DC converter stably provided a DC voltage powered by the solar cell string.

6. TYPE OF SOLAR CELLS

The solar cell is an electrical device that converts the energy of light directly into electricity, its operational background is the photovoltaic effect. They are more and more popular year after year and their residential and industrial usage is constantly increasing.

As a result of their development, their efficiency is increasing, while their production cost is constantly decreasing. Depending on the type, the efficiency of the solar panel can reach 22%. Under laboratory conditions, efficiency of 30% also has already been achieved. The vast majority of currently used solar cells are based on silicon semiconductors, but there is ongoing research into the development of new technologies to further maximize existing efficiency [4].

<u>The major types of currently applied solar cells:</u>

- amorphous
- polycrystalline
- monocrystalline
- organic.

Nowadays amorphous solar cells are faded into the background, among other things, due to their low efficiency (5 – 8%). In the case of amorphous silicon solar cells, the silicon atoms are less ordered, and atoms are less attached to neighbours, like in the crystalline version. One of the advantages of amorphous silicon solar cells is that they are cheaper to produce than crystalline silicon cells, have thinner layers, thus they can be placed in rigid or flexible frames [5, 7]. They absorb more light, so their power decreases lesser in low-light, cloudy conditions than crystalline types. Among their disadvantages are the lower efficiency, and the degradation of efficiency by aging. The reason for this is the lower stability of amorphous silicon [6].

The use of polycrystalline solar cells is the most common among residential users. This is due to the fact, that they have the most favourable cost per produced energy. Price plays a very important role in the development of silicon based crystalline solar cells. The production of monocrystals is very expensive due to the technology. This led to the development of polycrystalline solar cells. The bottom line of the production of polycrystals, that the electronic grade silicon base material is melted and poured into a graphite crucible and crystallized under controlled cooling. Crystallization starts at several focal points and the solidified material becomes polycrystalline [6, 7].

Their efficiency can reach 18%, and this value is less dependent on the age of the solar panel. Manufacturers generally warrant staying the loss of efficiency within the 20% limit for 25 years [5, 7]. Crystalline solar cells can be easily recognized by their cellular structure, which cells are galvanically coupled to one another and their combined power supplies the electricity of a solar module.

Monocrystalline solar cells produce the highest efficiency. However, their manufacturing technology is very expensive, so their popularity in the residential usage is less significant than the polycrystalline type. Crystalline silicon solar cells, and generally most semiconductor devices are made on a crystalline semiconductor chip, also known as a wafer. Their efficiency can reach 22% [5].

Organic solar panels are the youngest type of solar panels. Their development began in the last decade and has developed significantly during this time. As thin-film technologies, organic cells can be used to coat different surfaces like glass, metal, plastic, or can be print by using 3D printers. Another advantage of organic technology is that it is less sensitive to the angle of incidence of light, thus they are ideal for the not exactly southern orientation. They are also excellent for colouring and patterning. The most important promise, that they will be produced very cheaply, large surfaces will be coated with them, however this could not be proved in practice in the absence of large-scale production [7]. Organic solar panels are now seen as a major, untapped, environmentally friendly possibility for large energy and oil companies. Carbon-based organic polymer solar cells still operate at very low efficiency (<4%), however they were able to achieve 6% efficiency under laboratory conditions. Another disadvantage, that their production is relatively expensive compared to silicon based solar cells. In addition to the high price, there is another problem to be solved, which is their short lifetime. While conventional, crystalline and thin-film solar cells are sold with a 20- to 25-year performance guarantee, organic solar cells operate for 3 to 5 years based on current tests.

In fact, organic solar technology can be divided into two main groups:

- semiconducting organic polymers,
- dye-sensitised cells (DSC) [7].

Solar panels are manufactured in a variety of sizes. There are many categories ranging from the very small cell of a few mm^2 to the module of 1.6 m^2. The solar modules are made up of small cells, usually 100 cm^2 cells connected in series and parallel. While unit price per power in case of a 100 W monocrystalline solar cell is ~602 Ft/W, a polycrystalline solar cell with the same performance is only ~484 Ft/W. Because of this difference in value for money, polycrystalline solar panels are the best choice to use in solar cars. In addition, the dimensions of the solar panel can be selected depending on the location. It is advisable to install fewer but larger solar panels on the roof or engine hood.

Table 1. The parameters of the most commonly used monocrystalline solar cells

Power [W]	Operating voltage [V]	Dimensions [mm]
5	12	220x250x18
10	12	370x250x18
20	12	500x350x25
25	12	500x350x25
30	12	520x510x28
40	12	530x520x28
50	12	630x545x35
80	12	1080x545x35
100	12	1205x545x35
140	12	1480x680x35

Table 2. The parameters of the most commonly used polycrystalline solar cells

Power [W]	Operating voltage [V]	Dimensions [mm]
10	12	245x415x17
20	12	345x535x25
30	12	356x798x30
50	12	655x668x30
80	12	674x950x35
85	12	674x951x35
100	12	674x1131x35
130	12	674x1482x35
140	12	680x1479x35
150	12	674x1482x35
200	12	992x1488x35
250	24	992x1650x40
260	24	992x1640x40
270	24	992x1640x40

Table 2 contains the parameters of the most commonly used solar cells. 10 W polycrystalline solar panel (in uppermost row of Table 2) can generate only ~98 W of electricity per square meter (since the solar panel has a surface of ~ 0.1 m^2), while its value for money is ~895 Ft/W. On the other hand, the capacity per unit surface area of a 270 W solar panel (in undermost row of Table 2) is ~165 W/m^2, while its value for money is ~284 Ft/W. (The used values for money and values per unit surface area are informative average values given the large number of manufacturers and distributors.)

7. CONCLUSIONS

The source of our inspiration was the World Solar Challenge. However, these cars are one-man vehicles and not particularly suitable for daily use. Several companies and universities are already working to resolve this issue. Build a family car powered by solar panels.

Solar powered prototype is currently being developed by the Lightyear company and the German start-up Sono Motors. The Lightyear One is a large hatchback, with 5 m^2 of solar panels. The company Lightyear claims that the car can add 50–65 km of range per day during summer. It seats five adults and luggage.

The Sono Sion (Sono Motors) is an announced solar powered, electric car. The drive will be a three-phase induction motor with a power of 120 kilowatts (161 hp). The top speed of 140 kilometres per hour should be possible. The total area of photovoltaic modules is 7.5 m^2. The daily range gained in Central Europe is at a maximum of 34 kilometres a day under favourable conditions and on average over a whole year about 10 kilometres a day. The production of both vehicles is scheduled to start in 2021.

An induction motor can operate by being powered exclusively by the solar cell string through the DC / DC converter and inverter. The current is sinusoidal, so little torque pulsation occurs on the motor shaft. The solar panel on top of cars can run the motor only at very low power. Therefore, it is best, if only the battery is charged continuously by it. Another option is to supply the auxiliary circuit of the inverter, independently of the battery, from a solar panel. The auxiliary circuit may cover the control power of the IGBTs from the solar panel. IGBT modules require high control power in pulsed mode due to their Gate-Emitter capacity.

Consider an average-sized electric car with a consumption of 200 Wh/km and a roof area of 4 m^2. Ideally 350 W solar capacity can be placed on a surface of this size. On an average summer day, we can expect 3.5 kWh of electricity. This means that our car would ideally be able to cover 17.5 km with electricity from solar panels. Of course, this requires that the roof of the car (where the solar panels are located) is constantly shining by the sun. Annually, this small solar power plant can produce maximally 950-1000 kWh/year of electricity, which is enough to cover 4750-5000 km/year. The annual average is 13 km per day. It should not be overlooked, that the battery pack and electronic devices, charge controllers, and electric motor controllers have efficiency-reducing effect, which can reduce these theoretical distances.

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