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Efficiency Enhancement of PWM Controlled Water Electrolysis Cells

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***Abstract*—**By analyzing the sources of energy and power loss in PWM (Pulse Width Modulation) controlled drivers of water electrolysis cells, it is possible to reduce the power dissipation and enhance the efficiency of such hydrogen production units. A PWM controlled power driver is based on a semiconductor switching element where its power dissipation might be a remarkable fraction of the total power demand of an electrolysis system. Power dissipation in a semiconductor switching element is related to many different parameters which could be fitted into two main categories: switching losses and conduction losses. Conduction losses are directly related to the built, structure and capabilities of a switching device itself and indeed the conditions in which the element is handling the switching application such as voltage, current, temperature and of course the fabrication technology. On the other hand, switching losses have some other influencing variables other than the mentioned such as control system, switching method and power electronics circuitry of the PWM power driver. By analyzings the characteristics of recently developed power switching transistors from different families of Bipolar Junction Transistors (BJT), Metal Oxide Semiconductor Field Effect Transistors (MOSFET) and Insulated Gate Bipolar Transistors (IGBT), some recommendations are made in this paper which are able to lead to achieve higher hydrogen production efficiency by utilizing PWM controlled water electrolysis cells.

***Keywords*—**Power switch, PWM, Semiconductor switch, Water electrolysis

I. INTRODUCTION

AS one of the clean methods of hydrogen production, water electrolysis has been a field of interest to many researches for a few decades. Studying and analyzing the process have been scientifically followed for a long time [1-3]. The required electrical power for decomposing water into hydrogen and oxygen could be harvested from green and renewable sources of energy such as wind farms, solar power plants and nuclear reactors [4].

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The amount of applied power to an electrolysis cell could be controlled in different ways and PWM is one of them. The load power of a PWM controlled system (in this case, the power of a water electrolysis cell) is determined by controlling the “on” to “off” states ratio of a semiconductor switch. Fig.1a shows a typical command signal for the semiconductor switch of a PWM power controller. Voltage and current of an ideal switch with a linear load is illustrated in Fig.1b and Fig.1c respectively.

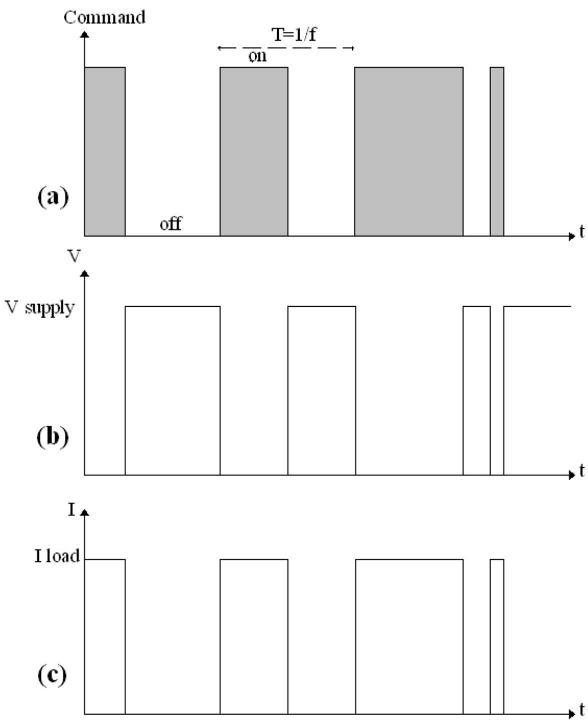

Fig. 1 Typical (a) Command signal from a fixed frequency PWM controller; (b) Voltage drop on the semiconductor switch and (c) Current of the semiconductor switch

In the following sections of this paper, the practical behavior of semiconductor switches is the subject of discussion which will lead to some recommendations regarding to the title of this paper.

As Fig.2 illustrates the practical power dissipation of a semiconductor switch as bellow:

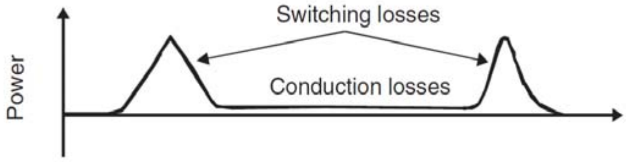

Fig. 2 Power loss elements in a semiconductor switch [5]

Power dissipation of a semiconductor switching device could be fitted into two main categories: conduction losses and switching losses. Switching losses take place during the turn-on and turn-off periods of the switch as a result of non-ideal characteristics of the switching element where conduction losses could be observed during the "on" state of the switch when the voltage level of the switch has its minimum value and load current is passing through it.

II. CONDUCTION LOSSES

An ideal switch is expected to show zero resistance during the conduction stage. In other words, the voltage drop on an ideal switch should be zero for any given level of passing current trough the device. However none of the available semiconductor switches could be fitted into this expression as there is no "ideal switch" available in practice. Bipolar based devices such as BJTs [5] and IGBTs [6] have very exceptional conducting resistance which is much less than the MOSFETs [7] with the same nominal current, switching speed and voltage blocking capacity level. In practice, bipolar devices have a voltage drop of several hundreds of millivolts for low current and up to a couple of volts in the case of high power applications. On the other hand, voltage drop of a MOSFET switch is related to the passing current and the conduction resistance of each device is a known finite value. Voltage drop on a MOSFET switch during the conduction stage could be calculated by the Ohm's law equation as in (1)

$$V=R\,I \tag{1}$$

Where V is the voltage drop, R is the resistance between MOSFET terminals and I, is the current passing through the MOSFET devise. The voltage drop (saturation voltage) of a bipolar power switch ($V_{CE\ sat}$) and the conduction resistance of a power MOSFET ($R_{DS\ on}$) are always among the data which are provided by the device manufacturer. Though bipolar devices, especially IGBTs are most common to be used in high voltage and high current applications, this fact should be considered that in industrial electrolysis of water, the deal is with low voltage and high current levels where the saturation voltage (voltage drop) of a bipolar device is a significant fraction of the total applied voltage. Power dissipation of a switching element is calculated by (2) as below:

$$P= V\,I \tag{2}$$

Where P is the power dissipation, V is the electrical voltage of the device and I, is the current passing through the device. A semiconductor switch is connected to the electrolysis cell in series so it is obvious that passing current trough the switching device is the same as the current level of the electrolysis cell. Considering the voltage drop of a bipolar transistor, this conclusion could be drawn that the power dissipation of the semiconductor switch in a bipolar based PWM power controller is high enough to affect total hydrogen production efficiency. A typical connection diagram of semiconductor switch and electrolysis cell is shown in Fig.3.

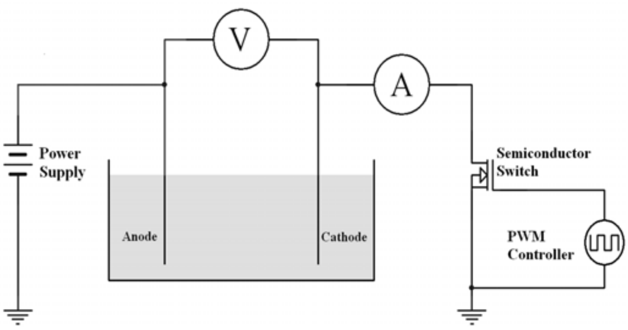

Fig. 3 PWM controlled electrolysis cell typical connection diagram

Current driven BJTs are outperformed by both IGBTs and MOSFETs as the above-mentioned devices are voltage driven in nature. Driving an IGBT or a MOSFET is less complicated process and requires simpler electronic circuitry than a BJT [8]. Moreover, their high input impedance is a plus in order to compare their switching characteristics with BJTs [9].

On the other hand, recent developments in the field of design and fabrication of MOSFETs with ultra low conducting resistance concluded in the availability of devices with a conduction resistance as low as only a few milliohms. This resistance levels are much lower than the conduction resistance of conventional high voltage power MOSFETs [10] which might be as high as a few ohms. These switching devices are able to conduct and cut off currents up to 270A and voltages up to 40V – 75V [11]. The voltage blocking characteristics of this generation of switching devices is absolutely satisfactory for applications in the field of hydrogen production via water electrolysis. Limited maximum nominal current, limits the electrode plate physical size to around 250cm^2 for current densities of 400mA cm^{-2} for a 100A power MOSFET. The maximum size of electrode plates is easily calculable for different current densities and MOSFET switches for any given scenario.

The main drawback of utilizing power switches with smaller maximum nominal current capacity could be limited gas production rate for industrial grade electrolysis units. However, by proper considerations, this drawback could be cancelled and lead to a more efficient conversion. It is known that raising the current density in an electrolysis cell causes more power dissipation [12] and heat generation where control and reduction of the generated heat is also an energy consuming subject. Using electrolysis cells with smaller physical dimensions and electrical ratings as blocks of a larger modular electrolysis plant is a solution for this problem. Moreover, high current / high power industrial electrolyzers have a minimum "turn on" power threshold [13]. As they usually work under low voltage and high current conditions, a very slight change in the applied voltage of the cell, causes a massive drift in cell current level and power demand.

A PWM controlled electrolysis cell of a lower size and power is able to serve as a module for a grid of theoretically any number of cells. Activation / deactivation and production rate of each and every cell could be controlled and monitored by a main processor via some sort of local networking. This method of electrolysis has also some advantages in the field of maintenance and upkeep. A main processor is able to initiate hydrogen production with a fraction of maximum capacity of only one cell as they are PWM controlled and manage to calculate total required cells regarding to available consumable electrical power. This method could be used to store the surplus power generation of time variant power plants such as solar and wind farms in the form of hydrogen. The excess generated power of nuclear reactors could be fed to this kind of water electrolysis grids as it is not possible to vary their energy production regarding to the load electrical demand very fast. Fig.4 is a block diagram of such PWM based electrolysis grid.

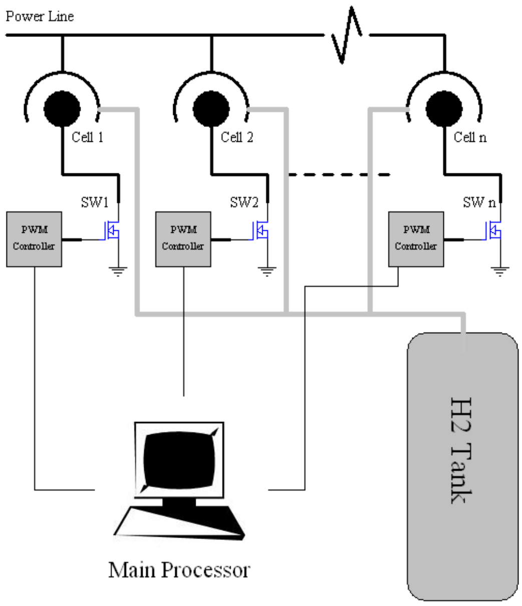

Fig. 4 Modular PWM controlled electrolysis

III. Switching Losses

As it is shown in Fig.2, the peak level of switching loss in a semiconductor device is much higher than the conduction loss. This loss is affected by different variables of the device and connection circuitry [3] such as the device switching speed, switching frequency, switching method and the semiconductor switch characteristics.

Referring to Fig.1a and Fig.1b, in an ideal electronic switching, the switch voltage is supposed to fly from the supply voltage level to zero and start to conduct electrical current after receiving "on" signal and from zero to supply voltage level and block the current flow by receiving the issued "off" signal. This is the reason that the power dissipation of an ideal switch is zero. By using (2) the result of the multiplication is zero because during the on and off periods, either one of the voltage and current values are zero.

In practice, rising and falling times of a switch voltage are not immediate as it is illustrated in Fig.5. Hence, a power loss will be observed during these periods. Reducing the proportion of switching to total cycle of the pulses could cause a remarkable reduction in overall power dissipation. Considering the latter, utilizing semiconductor switches of higher speed with shorter rising and falling timings will reduce overall switching time and as a result, power consumption of electrolyzers, as the applied control signal is periodic and repetitive.

The mentioned source of power loss is also affected by the switching frequency. The proportion of switching time period will enlarge in the case of using any given semiconductor switch as the frequency rises. On the other hand, there might be many other considerations in order to set a frequency value for any PWM controller such as technical requirements, behavior and characteristics of power source, power grid specifications and regional noise and filtering standards of electrolysis cell installation.

In addition to the mentioned, switching method is one of the most important subjects of debate in the field of power electronics. There are basically three different switching categories to discuss: Hard switching, snubbered switching [14] and soft switching [15].

Hard switching is the switching method of the most simplicity. In this method, the power transistor is connected to the load accompanied only with required protective electrical / electronic devices. Fig.5 illustrates typical I-V trajectories of power switches in the case of all three mentioned methods. All trajectories are drawn for a switch which is working in its Safe Operating Area (SOA).

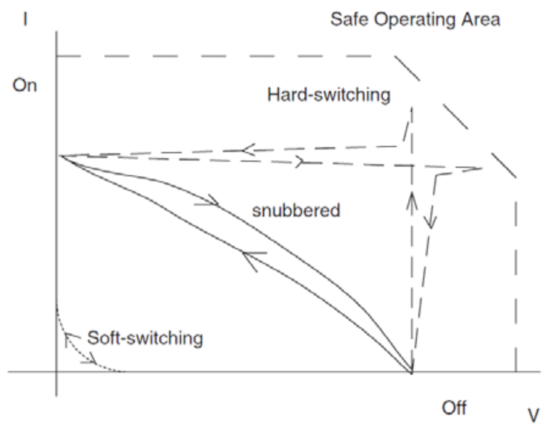

Fig. 5 Typical switching trajectories of semiconductor power switches [15]

High switching loss and stress are attached to this switching method. There are always visible spikes in the current and voltage waveform of a hard switched device. These spikes may become very critical in the cases of high voltage or high current applications and should be controlled in order to prevent causing any damages to the switching element. High power loss in hard switching is mainly because of non-ideal characteristics of a semiconductor switch where it does not immediately change its state.

One way to reduce the losses in hard switching method is to limit the *dv/dt* and *di/dt* of switching elements by adding proper dissipative passive elements to the power electronic circuitry which is called “snubbered” switching. As it could be clearly seen in Fig.5 the I-V trajectories of a snubbed switch is much smoother for snubbered switching than those of hard switching. Moreover, power dissipation of a snubbered switch which could be calculated by multiplication of V and I of the switch for any given point of its trajectory is lower than the result of same multiplication for a hard switch.

Since 1980’s many scientists and engineers draw their attention to improve a new method of switching which was mainly introduced for playing a role in switch mode power supplies (SMPS) [15-18]. As a nearly lossless switching method, soft switching was developed in two main classifications for this switching method [1]: zero voltage switch (ZVS) and zero current switch (ZCS). The main idea behind this method is to keep the switching power loss of a switch to zero by maintaining either one of the elements of (2) to zero. A ZVS soft switch has proper circuitry to change switch voltage to zero right at the time that the switching command is issued by a PWM controller. In the case of utilizing ZCS soft switching, the same act will happen to switch current at the right moment. So, massive *di/dt* and *dv/dt* are not going to be a concern for ZVS and ZCS soft switches respectively [15]. By comparing trajectories in Fig.5 this conclusion will be drawn that soft switching is the best method of choice for PWM based power drivers. On the other hand, proper technical and financial matters should be considered in order to utilize soft switches for PWM based water electrolysis regarding to gas production specifications.

Another benefit of soft switching is its reduced Electro Magnetic Interference (EMI) emission [15, 19]. Utilizing soft switching method is a known choice for EMI reduction in switching power supplies [1, 2]. Measurements clearly show EMI radiation suppression in soft switching method in analogy with those of hard switching.

IV. Conclusion

By reviewing the characteristics and behavior of state of the art BJT, IGBT and MOSFET transistors technology, and considering relationship between their voltage drop and conducting current it is possible to make some recommendations in order to enhance the water electrolysis efficiency in PWM controlled electrolyzers.

Voltage drop of bipolar power switches does not have a linear relation to their conducting current. The voltage drop value is a matter of a couple of volts in the case of high current switching. This fact should be considered that most common industrial electrolysis apparatuses run under low voltage and high current conditions. On the other hand, recent developments in MOSFET fabrication technology introduces power transistors with ultra low conduction resistance with reasonable current conduction capacity. Hence, utilizing power MOSFETS with low voltage drop properties will lead to lower “on state” voltage drop and as a result less heat generation in the semiconductor and higher efficiency.

Regarding the subject of PWM power driving, switching method has a major influence on the total electrical power dissipation of the driver. Hard switches have the most simplified electronics circuitry. However in this method of switching, the semiconductor switching device experiences maximum possible stress and power dissipation. This problem could be reduced by adding a snubber circuit to the switching power transistor which will lower the stress, electrical spikes and power dissipation of the switch where added elements have their own electrical specification. Utilizing soft switching methods such as ZVS and ZCS is highly recommended in order to reach minimum possible power dissipation in the driver circuit.

By manufacturing smaller water electrolysis cells and connect them in parallel under the supervision of a main control system, it is possible to maintain a gas production plant with exceptional characteristics of high efficiency and a wide range of hydrogen production rate. This arrangement also makes the maintenance and upkeep of each cell easier and independent from other cells.

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