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Impact of Electrolyzer on the Operation of a Dual Active Bridge Converter

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***Abstract*—Electrolysis requires a high DC current at low voltage to produce hydrogen from water. Designing power converters for such a load requirement could be challenging while fulfilling the galvanic isolation needs. Therefore, prior knowledge of the electrolyzer's impact on the converter operation should be needed. In this context, this paper investigates the behavior of the Dual Active Bridge (DAB) converter when utilized for electrolysis. A MATLAB simulation of DAB with a 10 kW alkaline electrolyzer is developed. Several converter parameters, such as the phase shift angle, series inductance, peak and RMS currents, and voltage gain, are analyzed during electrolysis. Distinct operating behavior is observed from the analysis.**

***Index Terms*—Dual Active Bridge (DAB) DC-DC converter, Electrolyzer, Hydrogen.**

I. Introduction

Renewable energy has become increasingly important in recent years to reduce greenhouse gas emissions, improve energy security, and promote sustainable development. Many countries have been encouraging the implementation of renewable energy technologies, which could lead to the electrification of many end-use processes with power derived from clean sources [1]. One of the upcoming renewable energy sources is 'green' hydrogen, which can be produced through water electrolysis. Electrolysis is a process in which, by passing a sufficiently high electric current through water, it can be broken down into its constituents, namely hydrogen and oxygen. Due to its high energy density per unit mass, low weight, and easy electrochemical conversion, hydrogen can transport energy over long distances through pipelines or as liquid fuels such as ammonia on cargo ships [2]. In addition, hydrogen can store energy over extended periods, making it one of the few sustainable technologies capable of energy storage throughout the seasons, either in tanks or underground caverns [3].

Renewable energy systems can be integrated with electrical loads or the traditional grid with the help of power electronics interfaces [4]–[6]. They provide control over the power flow between different components of a renewable energy system. Power electronics-based electrolysis systems have enormous potential if renewable electricity is used to produce energy-dense fuels.

Electrolysis requires low voltage and extremely high direct-current (DC) to produce hydrogen from water [7], [8]. Converters for such applications must have galvanic isolation between the input and output stages per ISO:22734:2019 and ISO:19880-1:2020 standards. Moreover, the DC-DC converter candidate must be capable of allowing bidirectional power flow in the case of a hybrid system containing the electrolyzer in conjunction with a fuel cell.

Among the isolated dc-dc converters reported in the literature [9], the dual active bridge (DAB) converter provides galvanic isolation, allows bidirectional power flow, and has the ability to undergo soft-switching without the presence of additional resonant components. Moreover, it also offers the ability to have a series-parallel arrangement [10]. Authors in [8] provided a comprehensive review of DC/DC converter topologies that could be utilized for electrolyzer. However, DAB topology was not covered in this review. Moreover, this study does not consider the ISO:22734:2019 and ISO:19880-1:2020 standards, which is an essential requirement for converters in such applications. Thus, the literature indicates that none of the work has been carried out for high-power electrolysis using DAB converters.

Therefore, this paper presents a preliminary study showcasing the behavior of a dual-active bridge converter for high-power electrolysis. The rest of the paper is organized as follows: Section II explains the modeling approach for the alkaline electrolyzer and the DAB converter. Section III discusses the impact of electrolysis on the operation of the DAB converter using the MAT-

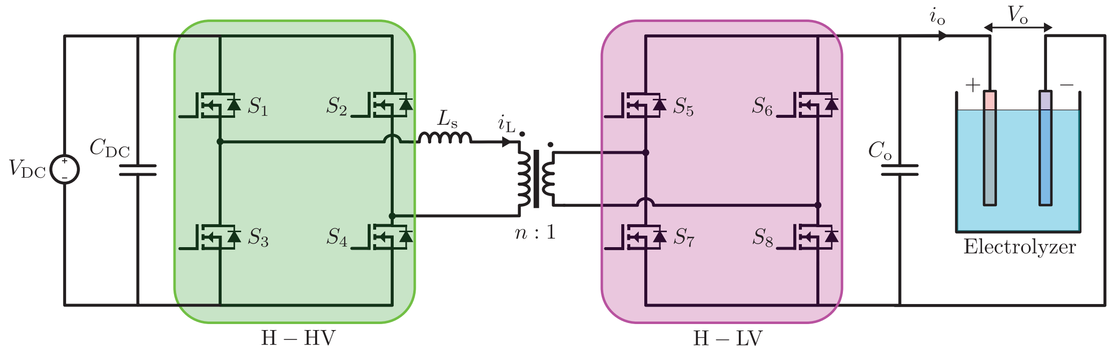

Fig. 1: DAB converter with electrolyzer.

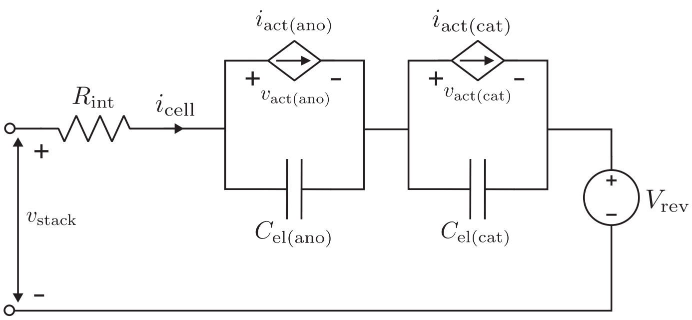

Fig. 2: Electrical Representation of an Alkaline electrolyzer.

LAB Simulink model. The impact of electrolysis as a process on the transformer currents within the current has also been explained briefly. Section IV presents the simulation studies by showcasing the impact of the electrolysis on various DAB converter parameters, such as phase shift angle, RMS, and peak currents, and voltage gain by performing a sweep over the operating power and the series inductance. Finally, Section V provides conclusions and future work.

II. Modeling Approach

A. Alkaline Electrolyzer

Being the most mature and commercially available technology, an alkaline electrolyzer has been chosen as the electrical load for the DAB converter, as shown in Fig. 1. Several modeling approaches have been reported in the literature [11]–[13]. The modeling approach reported in [11] is utilized in this paper. Fig. 2 shows the electrical representation of an alkaline electrolyzer used in the modeling.

The reversible cell voltage V_{rev} can be defined as

$$V_{rev} = V^0_{rev,T_k} + \frac{RT_k}{zF} \ln\left(\frac{(P - P_{KOH})^{1.5}}{a_{H_2O,KOH}}\right) \quad (1)$$

$$v_{act(ano)} = s \ln\left(\frac{i_{act(ano)}}{t} + 1\right) \quad (2)$$

$$v_{act(cat)} = v \ln\left(\frac{i_{act(cat)}}{w} + 1\right) \quad (3)$$

$$v_{int} = i_{cell} \cdot R_{int} = i_{cell} \frac{r}{A_{elect}} \quad (4)$$

$$v_{stack} = N_s \cdot (V_{rev} + v_{act(ano)} + v_{act(cat)} + v_{int}) \quad (5)$$

where V^0_{rev,T_k} is the temperature-dependent reversible voltage, R is the universal gas constant (in $JK^{-1}mol^{-1}$), T_k is the cell temperature (in K), P is the absolute pressure (in bar), z is the number of moles of electrons transferred for 1 mol of product, F is the Faraday constant (in C mol^{-1}), P_{KOH} is the vapor pressure of KOH (in bar), and $a_{H_2O,KOH}$ is the water activity of KOH solution. Moreover, $v_{act(ano)}$ and $v_{act(cat)}$ are the anode and cathode activation potentials respectively. The variables s, t, v, and w are temperature-dependent constants. $i_{act(ano)}$ and $i_{act(cat)}$ are activation currents for anode and cathode respectively. N_s is the number of series connected cells. v_{int} is the ohmic potential, v_{stack} is the stack voltage, r is the area-specific resistance of one of the electrolysis cells (in Ωm^2), i_{cell} is the cell current, A_{elect} is the electrode surface area (in m^2), and R_{int} is the internal resistance of the electrolyzer cell (in Ω).

B. Dual Active Bridge Converter

The dual active bridge isolated dc-dc converter, as shown in Fig. 1, consists of two H-bridges, H-HV and H-LV, representing the high-voltage side bridge and the

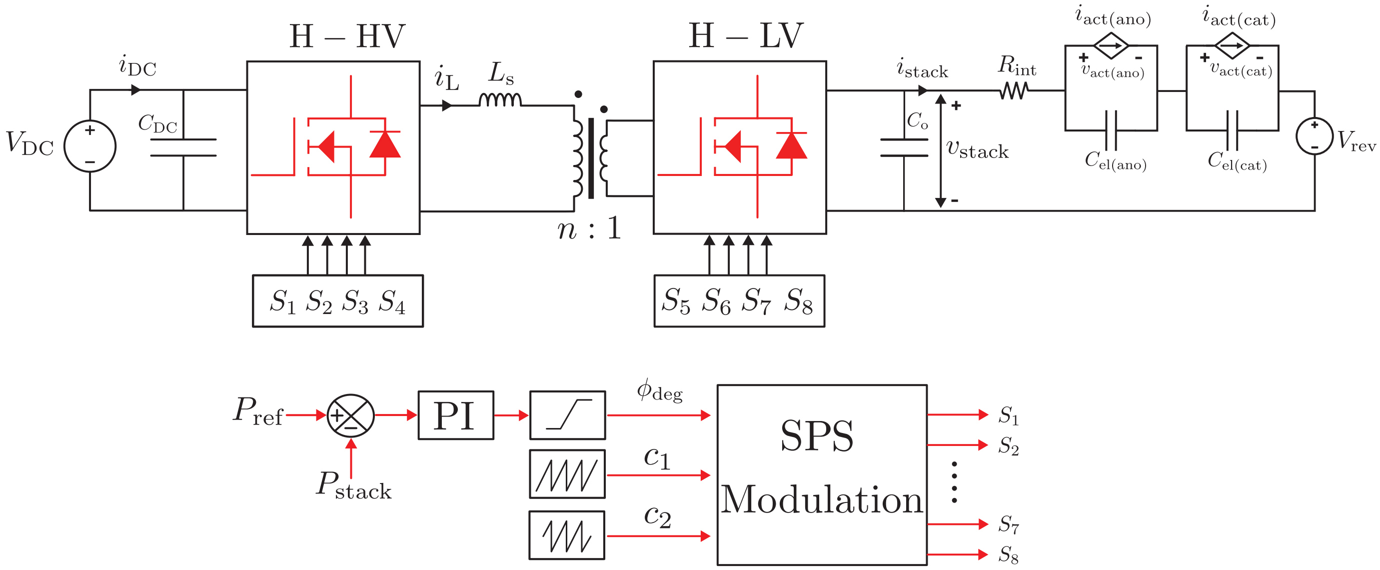

Fig. 3: Block diagram representation of the simulation model of a DAB converter integrated with an alkaline electrolyzer.

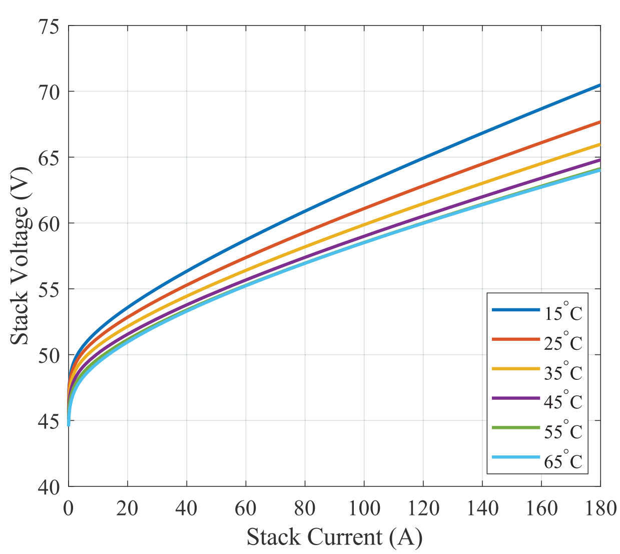

Fig. 4: Electrical characteristics of a 10 kW alkaline electrolyzer.

low-voltage side bridge, respectively. Each bridge is isolated using a high-frequency (HF) transformer designed to either have a unity turns ratio or a step-up/step-down function, depending on the application.

Several modulation techniques have been reported in the literature for dual-active bridge converter [14]–[16]. For this study, the single-phase shift (SPS) modulation strategy has been chosen. The SPS strategy is a classic modulation technique for DAB converter. In this method, the duty cycle or the pulse width of the switching signals sent to both bridges is maintained fixed. However, the switching signals sent to one of the bridges are phase-shifted by an angle ϕ.

The governing equations of the DAB with single phase shift modulation are presented below:

$$P_{op} = \frac{(D \cdot (1 - D)) \cdot V_{DC} \cdot V_o \cdot n}{2 \cdot f_{sw} \cdot L_s} \tag{6}$$

where D is the phase shift duty cycle that can be expressed in terms of the phase angle, ϕ,

$$D = \pi \cdot \phi \tag{7}$$

$$D = \left| \frac{1}{2} \cdot (1 - \Delta) \right| \tag{8}$$

$$\Delta = \sqrt{1 - \left(\frac{8 \cdot P_{op} \cdot L_s \cdot f_{sw}}{V_{DC} \cdot V_o \cdot n} \right)} \tag{9}$$

TABLE I: Specifications of DAB

Parameter	Symbol	Value
Rated Power	P_{op}	10 kW
Input Voltage	V_{DC}	1400 V
Output Voltage	V_o	70 V
Switching Frequency	f_{sw}	100 kHz
Turns Ratio	n	20
Series Inductance	L_s	50 μH - 200 μH

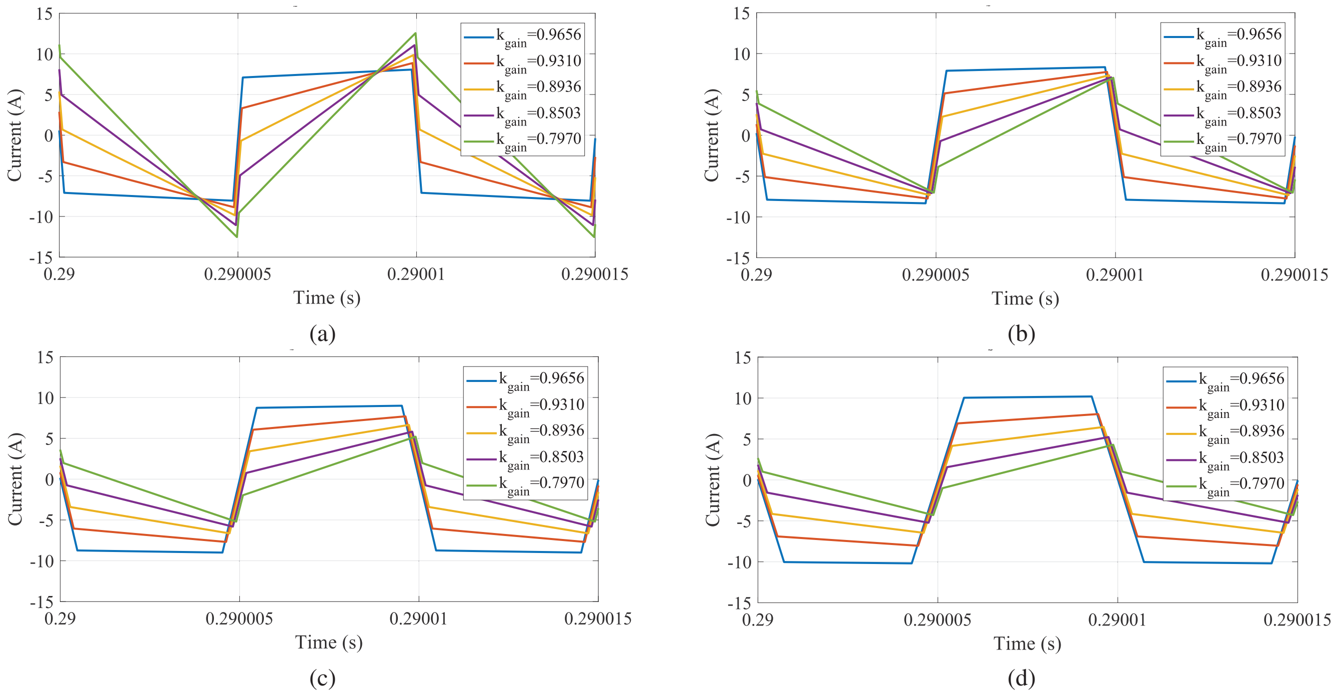

Fig. 5: Primary transformer currents of the DAB converter during electrolysis for variation in voltage gain (k_{gain} = $v_{\text{stack}}/V_{\text{o}}$) for different series inductances, such as (a) L_s = 50 μH, (b) L_s = 100 μH, (c) L_s = 150 μH, and (d) L_s = 200 μH.

III. Impact of Electrolysis on DAB converter

To understand the impact of electrolysis on the DAB converter, a MATLAB Simulink model of an SPS-based closed-loop controlled DAB converter is developed, as shown in Fig. 3. Here, the used specifications of DAB are listed in Table I, and the electrical characteristics of a 10 kW alkaline electrolyzer are obtained from (5).

As a process, electrolysis is quite straightforward to understand. However, the requirement of low voltage and extremely high current imposes challenges for converter design. As the chemical reactions within an electrolyzer continue, the stack voltage and current no longer remain fixed but decrease with time. This behavior of an electrolyzer is seen on the converter side in the form of voltage gain deviation from unity, i.e., $V_1 > \frac{V_2}{n}$. Time is not the only factor that can lead to deviation in voltage gain. Five main parameters govern the electrical characteristics of an electrolyzer, namely, molar concentration, temperature, pressure, number of series connected cells, and electrode surface area. However, for a given electrolyzer system, only the molar concentration of the electrolyte and temperature can influence the electrical characteristics since the number of series connected cells and the electrode surface area can no longer be changed. At the same time, the pressure within the system has no impact on the electrical characteristics, experimentally validated in [11]. Moreover, the deviation in voltage gain is not only influenced by the electrolyzer alone. The series inductance L_{s} has an impact too, as it affects the wave shape of the transformer current and, therefore, the peak value of the current. This can be seen in Fig. 5, which is the simulation results of the transformer currents during the electrolysis operation for variation in stack voltage for a given series inductance.

IV. Simulation Results

A MATLAB simulation model of a DAB converter with an electrolyzer, as shown in Fig. 3, is used for the simulation study. The following assumptions have been made for this simulation study:

- The transformer magnetizing inductance is sufficiently large to prevent saturation.
- The switching is instantaneous and lossless.

Fig. 6(a) illustrates the phase shift angle variation in a DAB converter for the considered range of series inductance and operating power. Trend exhibits a linear relationship between the series inductance and phase shift angle at a given operating power. Additionally, a linear relationship exists between the operating power and phase shift angle for a given series inductance.

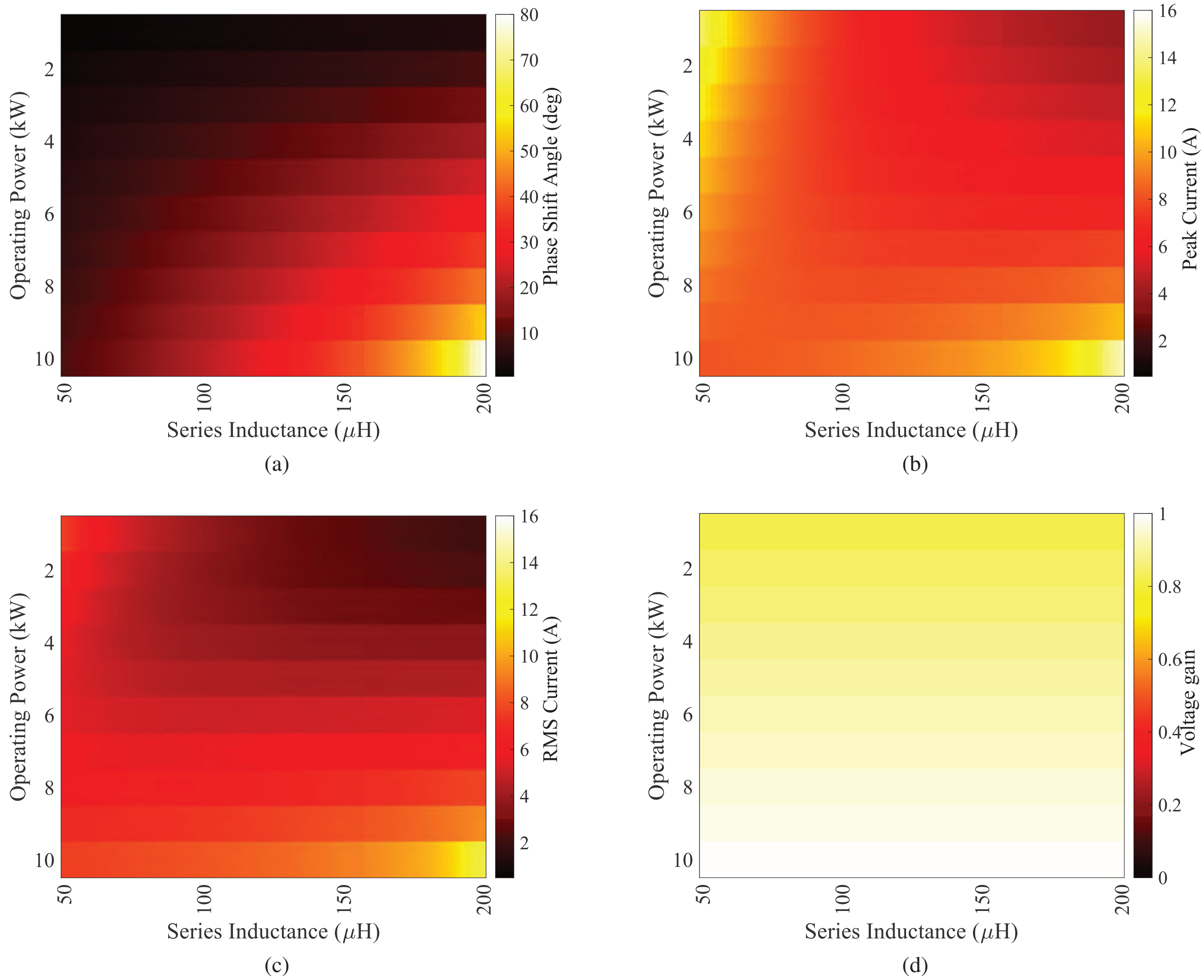

Fig. 6: DAB converter behavior during high power electrolysis. (a) Phase shift angle. (b) Peak Current. (c) RMS current. (d) Voltage Gain.

Fig. 6(b) illustrates the peak current variation in a DAB converter. The peak current hot spots were identified at two operating points, at the lowest series inductance and lowest operating power and at the highest series inductance and highest operating power. A similar trend is evident in the case of RMS currents, as shown in Fig. 6(c). Fig. 6(d) shows the voltage gain variation. On the other hand, in electrolysis operation, as operating power increases, the output voltage increases as well, and the voltage gain tends to unity.

V. Conclusions and Future Work

This paper has investigated the impact of an electrolyzer on the operation of a DAB converter. Initially, the modeling of the considered electrolyzer (specifically, Alkaline) is discussed. Subsequently, the modeling of a DAB converter is explained. A MATLAB simulation of a 10 kW DAB converter integrated with the alkaline electrolyzer is developed to comprehend the impact on the DAB converter's operation. Various results from the MATLAB simulation are presented to understand the behavior of transformer primary currents, phase shift angle, and voltage gain in DAB. The results demonstrated that the converter exhibits a distinct behavior, as evidenced by the trends observed in peak and RMS currents. The presence of hot spots at minimum and maximum operating power gave a preliminary insight with regard to choosing the series inductance, but this choice may not apply to every electrolyzer system.

Hence, in the future, it is essential to develop converter design guidelines that can be universally applied to various electrolyzer systems and architectures (series, series-parallel, parallel), while considering electrolyzer parameters such as molar concentration and temperature as well. These guidelines will assist in determining the optimal series inductance for the converter, consequently determining the choice of semiconductor switch current ratings and so on.

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