Whitepaper

High current, high voltage DC switching

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Abstract:

An increasing number of DC applications, such as battery charge and discharge systems, renewable energy storage etc. require adequate and powerful DC switches. In contrast to AC switching, where zero-crossing of voltage and current facilitates quenching and in some cases prevents arcing, only the high power switch can extinguish the arc generated by a DC source. The power dissipated inside the switch due to arcing is the most significant parameter that determines service life and reliability of the switch. The following paper describes a new gas-filled contactor with excellent arc quenching capabilities, thus increasing performance and service life.

Introduction

Electric vehicles and the corresponding infrastructure are an excellent chance for modern society to reduce CO_2 emissions and improve air quality. Especially the development of high capacity batteries was a barrier for electric vehicles in the past. While motors and inverters are a mature technology, batteries are the challenge to address. In recent years, we have seen a development of high-voltage lithium-ion batteries that have a capacity that is high enough to compete with traditional internal combustion engines.

High-voltage lithium-ion batteries require complex battery-management-systems (BMS) to achieve maximum efficiency and guarantee a reliable safety level. Safety is a crucial aspect, as lithium-ion batteries can fail, and in worst-case, burn or explode as a result of over-temperature, over-voltage, external impacts (such as accidents), or other causes. To ensure safety, batteries need to be disconnected from any charge or load in case of malfunction. This is the task of the battery disconnect unit (BDU), which is part of the BMS.

The BDU contains a fuse and DC high-voltage contactors. In case of a failure, the BMS sends a command to the high-voltage contactor to disconnect the battery. Such a contactor is able to disconnect faster than the fuse and can survive disconnection under load more than once, whereas fuses are used in addition as a safety measure against high short-circuit currents.

The critical factors for modern high-voltage contactors are small size and low weight in combination with high performance switching capability. Furthermore, contactors need gas filling for excellent extinguishing characteristics. To avoid wearing out of the contacts and thus achieve a long service life, the contactor must be able to switch high DC voltages and currents while reducing the dissipative power in the interior to an absolute minimum. Especially during emergency switch off under load, the contactor must not fail.

Basics of DC switching

Whenever an electrical high power device is turned off und load (for example, motors, transformers, energy storage or similar power loads), its switch, relay or contactor transitions from a closed to an open state under load and an electrical arc (break arc) occurs between the two contact points (electrodes) of the switch. This so-called break arc typically has a high energy level and is thus destructive.

The temperature of the break arc is also very high (> 5000 K) so that it leads to melting and thus the destruction of the metallic contact material. On the one hand, the metallic melt and plasma is then deposited onto the surroundings and causes a fast degradation of contacts, and on the other hand, the evaporated material can lead to low insulation between the contacts and a short service life.

As stated above, there is no zero-crossing of voltage and current in a DC circuit to help extinguish possible arcs. Therefore, the current must be forced to zero by extraordinary measures.

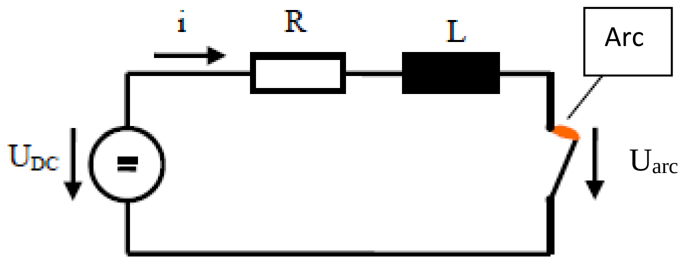


Fig 1: Principle of arc quenching in DC circuits [i]

According to Fig. 1 the following equation applies:

$$U_{DC} = i * R + L\frac{di}{dt} + U_{arc} \quad (1)$$

The condition for arc extinguishing is: $\frac{di}{dt} = \frac{U_{DC}-i*R-U_{arc}}{L} < 0$ (2)

Only when U_{arc} is larger than U_{DC}, the time dependent current I can be forced to zero and the arc can be extinguished.

A detailed analysis of equation (1) results in the time needed to extinguish the arc (arcing time).

$t_{arc} = \sqrt{\frac{2\,U_{DC}}{U_{arc}} * \tau}$ (3) with $\tau = \frac{L}{R}$

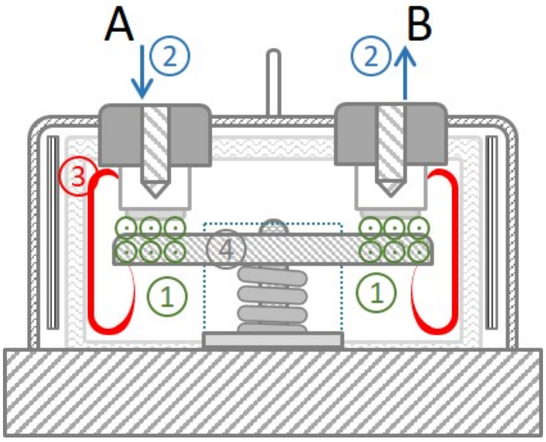
Equation (3) show that a high arc voltage or a small inductance L can reduce the arcing time.

Methods of arc quenching

There are several known methods to increase the arc voltage [ii]:

- Increase the arc length and reduce its diameter
- Separate the arc into several segments
- Cool the arc

Gas-filled contactors with two fixed contacts and one moveable bridge employ all methods mentioned above. The arc length is increased by the moving bridge and by magnetic deflection using permanent magnets. The arc is separated into two segments and is cooled by using a high pressure hydrogen gas mixtures.



1) Direction of Magnetic Field B of permanent magnets used to deflect the arc
2) Direction of Current I
3) Electric Arc
4) Moving Contact Bridge

Fig 2: General principle of gas-filled contactor – inside view

The new TDK HVC gas-filled contactors exhibit excellent arc quenching properties by pushing the arc cooling mechanism to a maximum. This will be shown in the following sections.

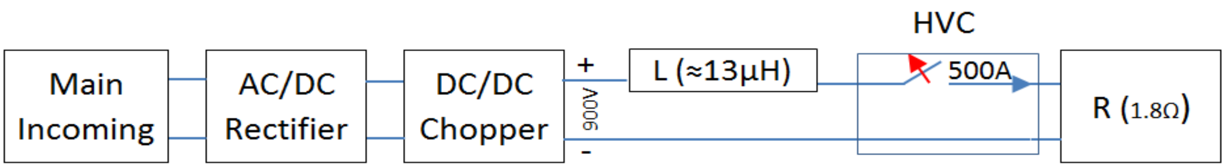
Break testing of the new TDK HVC

Break tests under high voltage and high current require powerful DC sources with short current rise time to simulate the behavior of high voltage batteries. Such a tester (GK ITS 3870) with a maximum power of 650kW was recently installed at TDK's HVC production site in Malaysia.

The following setup was used to study the break performance.

Main contact supply: U=900V, I=500A (P=450kW), R=1.8Ω, L=13µH

Coil voltage U_{coil}=12V



The main voltage is transformed, rectified and filtered into a DC voltage. The load is mainly resistive with a small inductance. The time constant for this setup is below 0.1 ms.

The break process is monitored by measuring the coil voltage, coil current, main (contact) voltage and main (contact) current. *Figure 1* shows a representative measurement for a break performance under load. The process can be divided into two time intervals:

- $\boldsymbol{t_{break}}$: After the coil voltage is switched off, there is a time delay before the magnetic flux of the mechanical system decays and the contactor starts to open.
- $\boldsymbol{t_{arc}}$: After t_{break} the bridge opens and an arc develops between the connections and the bridge.

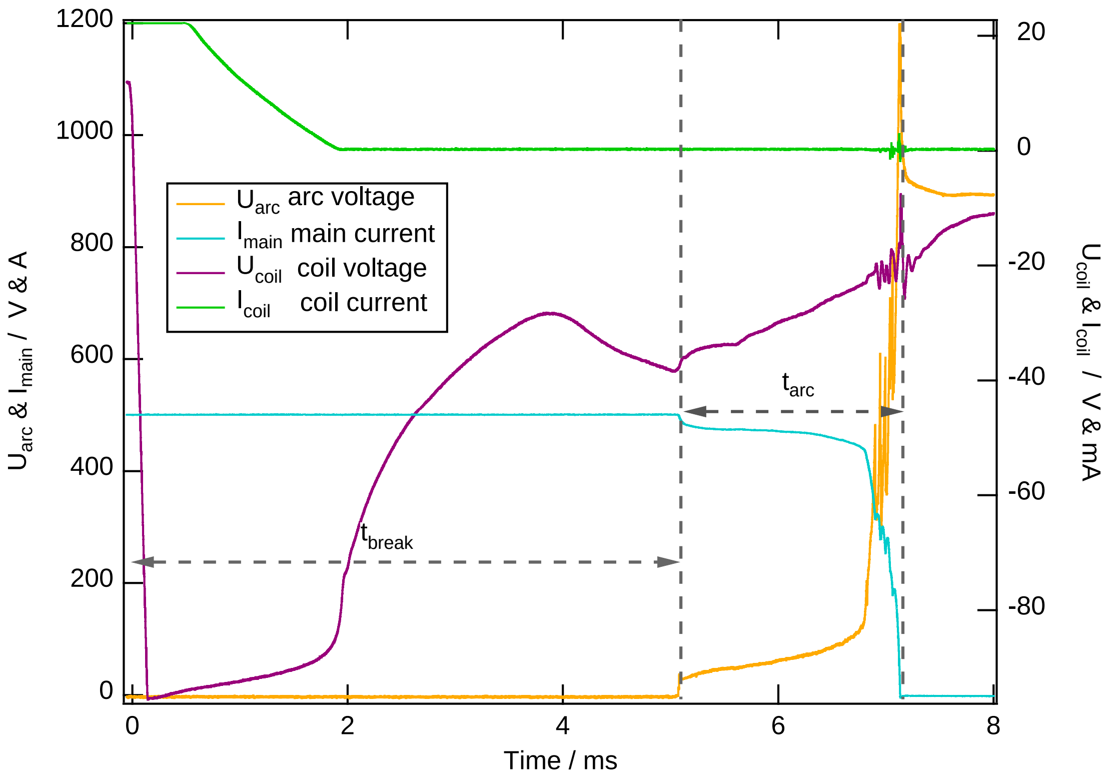


Figure 1: The break process is shown exemplarily with U_{arc} and I_{main} as the voltage and current at the main contacts (left axis) and U_{coil} and I_{coil} as accordingly for the coil (right axis). I_{coil} is shifted by a factor of 10 for better clarity. The time between switching off the coil and the mechanical opening of the main contacts is defined as t_{break} and the actual arcing time is then given by t_{arc}.

A magnified view on the arcing period is displayed in Figure 2. This process can be further divided into two characteristic processes:

- t_{ab}: the arcing is initiated by ionization of the gas in the chamber and a distinct cathode and anode fall can be observed as a steep increase of arc voltage by a few volts[iii]. Over a few milliseconds, the arc voltage only increases slightly and this time interval is characterized as *arc building time* in the present study.
- t_{ext}: after the initial arc building time, the magnetic field of the permanent magnets surrounding the discharge chamber deflects the arc. As a result, the arc length l_{arc} is significantly increased and in turn leads to a steep arc voltage rise U_{arc}. Simultaneously, the main current drops correspondingly and when $U_{arc} > U_{DC}$ (see equation 2), the arc is extinguished. This time period is therefore designated the *extinguish time*.

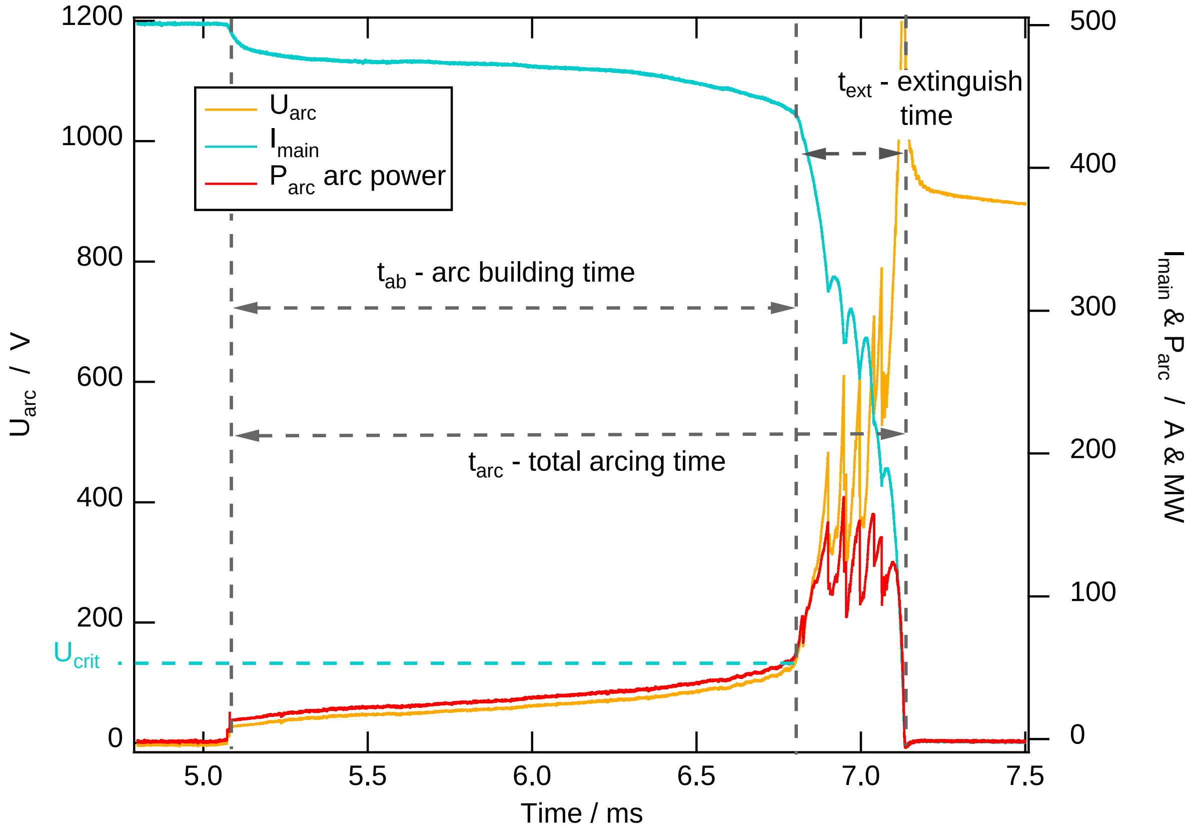


Figure 2: A magnified view of the arcing process in Figure 1 is shown. The total arcing time is divided into two characteristic time intervals: t_{ab} when arc voltage is built up and t_{ext} as the time, in which the arc is extinguished.

Another important parameter that can be derived from the measurements is the arc energy. It is calculated by:

$$E_{arc} = \int_{tarc} P(t)\,\mathrm{dt} = \int I(t) * U(t)\,\mathrm{dt}$$

E_{arc} is the total energy of the time interval t_{arc}. By using t_{ab} and t_{ext} as integration borders, the energies E_{ab} and E_{ext} can be calculated accordingly. The arc energy is a measure that can be used to estimate the damage that can be caused by the arc. For long service life and high reliability is it essential to minimize the arc energy to an absolute minimum.

The present study investigates the impact of different gas pressures in the discharge chamber by using four different pressures P1, P2, P3 and P4, with P1 the lowest and P4 the highest. The experiments were performed on four groups of contactors with the respective gas pressures, and the results were averaged over all parts within one group.

The correlation of arc energy on the arcing time was analyzed for the parameters E_{arc}, E_{ext}, t_{arc} and t_{ext} for all four pressure groups and the result is shown in Figure 3. A clearly positive, strong linear correlation with a correlation parameter of r = 0.9 is observed for the total arcing and arc extinguishing processes (shown in red and green). The slower the arc extinguishes, the more energy is released during this time, which in turn means more stress for the HVC. It is therefore of utmost importance to reduce the arcing time.

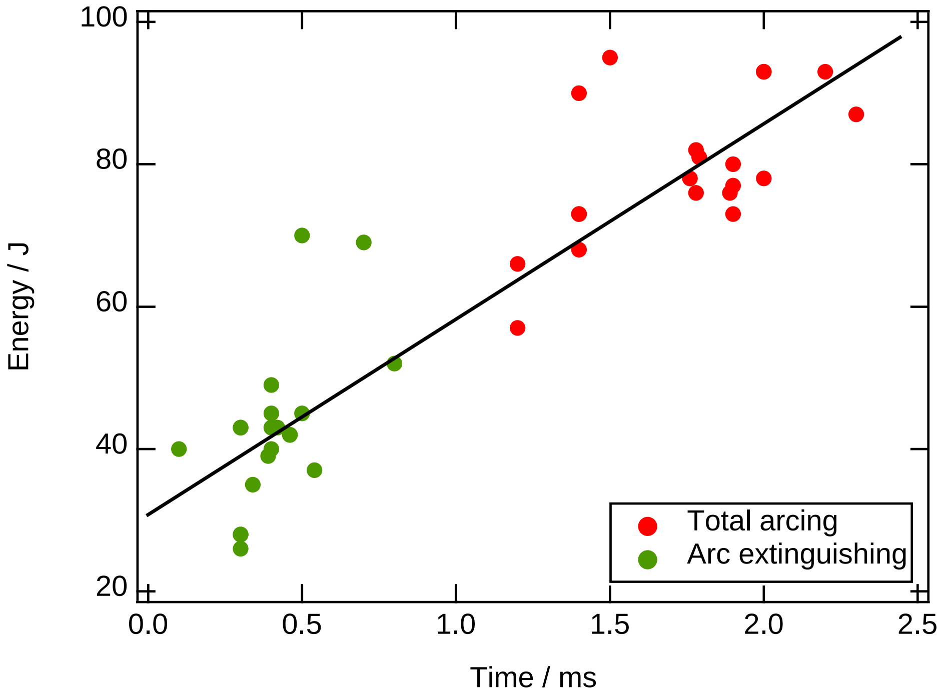


Figure 3: The correlation between arcing time and arc energy is shown over all measured pressure groups. The red and green points represent data for the total arcing and the arc extinguishing processes, respectively. A linear fit is shown as solid line and the linear correlation parameter is r = 0.9.

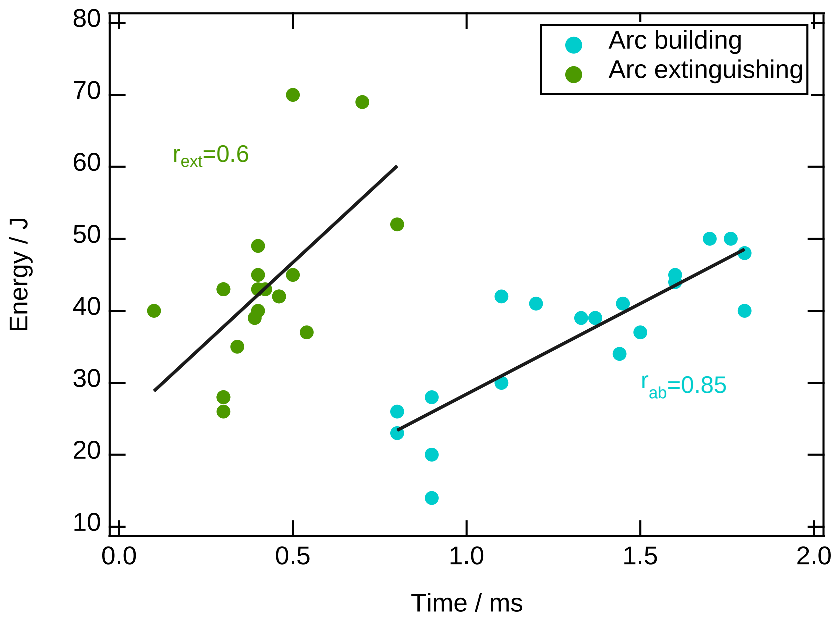


Figure 4: Correlation analysis between arc energy and time of arc building (blue) and extinguishing (green) processes. The extinguishing process is faster but still consumes about the same energy as the arc building process, which is generally longer.

Another interesting correlation is found between the arc extinguishing and the arc building process, as displayed in Figure 4. The arc building process exhibits a strong linear correlation, while the extinguishing process is slightly less correlated and the data is more scattered. This discrepancy is due to the almost chaotic and very complicated extinguishing process during which the arc is extended and fluctuating within the chamber. It is not surprising that the extinguishing process releases the amount of energy in much shorter time compared to the arc building process that is generally longer.

As a clear relation between arcing time and energy level exists, the following analysis only focuses on the arc energy as the most important parameter to evaluate the performance of the contactor.

The relation between arc energy and gas pressure of the arcing chamber is shown in Figure 5.

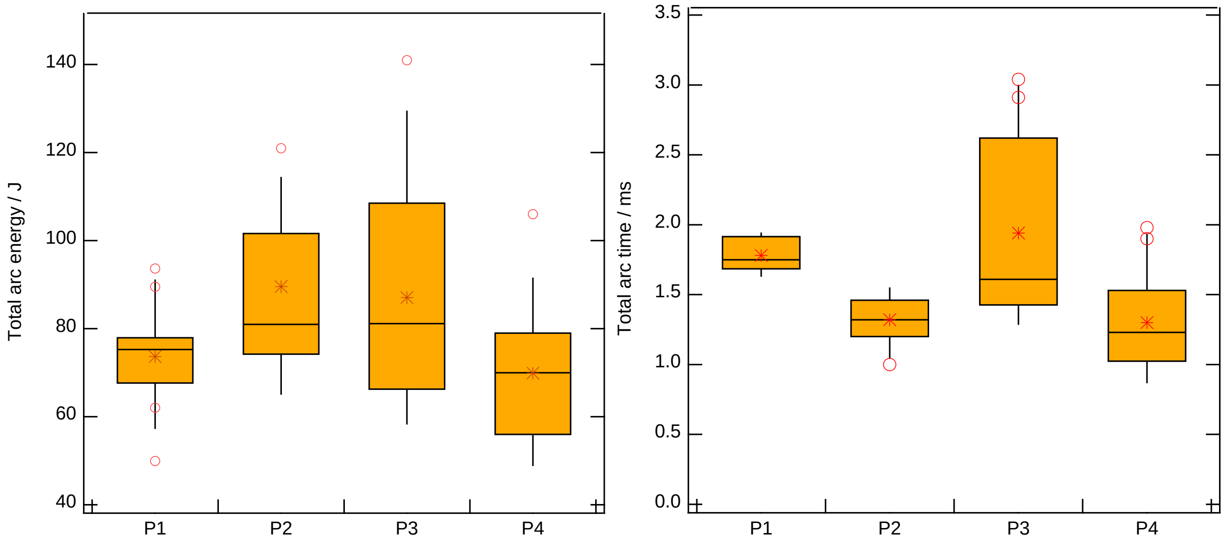


Figure 5: Boxplots showing total arc energy and arc time for different gas pressures P1-P4 within the arcing chamber. Red circles indicate outliers and asterisks the average values.

The boxplots in Figure 5 indicate a non-linear dependency of the arc energy and time to gas pressure, pointing towards a more complicated process than the intuitive linear dependency. Nevertheless, a small tendency of higher pressure leading to shorter arc time is visible despite the wide box at P3. The shortest arc time is observed at P4 with 1.30 ms and closely followed by P2 with 1.32 ms. The energy plot shows the lowest values also at P4, whereas the highest average value is observed at P2. Bearing in mind that minimal arc energy in the contactor during break is desired, it appears that P4 is the most suited pressure for a longer electrical lifetime.

Recently investigations of arc behavior using a model setup based on a TDK HVC gas-filled contactors at the Plasma Institute of Greifswald in Germany showed similar results[iii].

Conclusion

The arcing phenomenon of a contactor was systematically studied as a function of pressure within the discharge chamber. Analysis of the arc voltage and current revealed two characteristic phenomena that occur during arcing: First, an arc building process (measured by t_{ab} and E_{ab}) is observed with a rather constant voltage throughout the whole phase. Second, the extinguishing phase (measured by t_{ext} and E_{ext}) follows, when the arc voltage U_{arc} steeply increases as the arc gains more length due to the permanent magnets used to deflect the arc. Analyzing the dependency of these values on the chamber pressure, a non-linear behavior is observed, pointing toward the complexity of the process. Nevertheless, the most effective arcing with lowest total energy is found at the highest pressure P4.

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[i] Kurrat, Schrank 2009: **“**Arc quenching performance of dc switchgear with annular-gap arcing chamber**”**

[ii] Lindmayer, M. (Hrsg.): Schaltgeräte. Springer-Verlag, Berlin, 1987

[iii] Kim, Wooho et al., *Energies* 2018, 11: **“**Arc Voltage and Current Characteristics in Low-Voltage Direct Current**”**

[iii] INVESTIGATION OF THE ARC CHARACTERISTICS OF SWITCHING DC ARCS ON HYDROGEN CONTAINING GAS MIXTURES. doi:10.14311/ppt.2019.X.1 in Plasma Physics and Technology XX(X):1–4, 2019.