Model-based analysis and evaluation of 48 V automotive power supply systems regarding to electric arc faults

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***Abstract*—The introduction of 48 V power supply systems into automotive vehicles may lead to critical arcs when a 48 V connection is interrupted (series arc) or shorted to ground or 12 V (parallel arc) and opened again. The high energy dissipation in the arc might damage connectors or even cause fire. The energy dissipation during arc events strongly depend on the power network. In order to understand the arc behavior, a deeper look inside the processes going on during arc faults in typical automotive supply configurations is required. Experimental research on arcs is extensive, and computer simulations are more promising but in the past no appropriate arc models were available. With a new accurate modelling approach complete power network investigations can be done. This paper makes use of the new arc model and analyzes the interaction between the arc and typical power supply systems. Approaches to identify worst-case situations are suggested, both for series and parallel arcs. Furthermore, it is shown, how the influences from the power network on the arc behavior can be utilized in order to suppress arcs in the moment of ignition based on the oscillating circuit properties, or delete arcs through load control.**

Keywords—arc fault, automotive power supply system, 48 V, series arc, parallel arc

I. INTRODUCTION

The ongoing electrification in automotive systems creates a continuously increasing energy demand. Changes from mechanically driven components to electrically supplied ones and new power demanding functions could hardly be realized with the 12 V power level. Due to this reason, the voltage level has been raised to 48 V [1]. Furthermore, highly automated driving requires high power computational systems and complex sensors with a fail-operational power supply. This can be supported by 48 V supply networks, as well.

There has always been a significant number of possible faults in the 12 V wiring harness, namely e.g. short circuits, open circuits, contact aging/corrosion, loose contacts, etc. By introducing 48 V these already known fault scenarios may be extended by arc events. Whereas cable breaks or loose contacts lead to a short interruption in the supply of the electronic control units (ECU) in 12 V networks, series arcs can occur in 48 V networks. Similar to this, momentary short circuits due to vibrations can lead to parallel arcs when short circuit is opened again. For example, this can happen due to a damaged insulation.

It was furthermore found that some power supply networks promote the arc generation and others seem to prevent such failures. In the automotive environment, this means that a variation in cable lengths, cable diameters, load characteristics, load states, additional dynamic components, such as capacitors, and so on can lead to different situations in case of an arc fault.

In order to understand which configurations might be risky and which configurations can be seen as less critical, computer simulation with accurate arc models can be beneficial.

For these reasons, this contribution analyzes the actual properties of arcs when occurring in typical automotive power supply system configurations. In order to create the ability of robust safety case investigations, worst-case situations are identified with varying network components. Additionally, measures are suggested to prevent various arcs, as well as to handle them once occurred.

II. MODELLING APPROACH FOR ARCS IN POWER SUPPLY SYSTEMS

A. Arc Modelling

Experiments with arcs in real car situations or even in laboratories request an enormous effort and safety precautions. Due to extremely high temperatures electrodes can be destroyed quickly and the number of observations has to be large enough in order to identify random and non-systematic results. Actually, arcs are influenced by many parameters such as temperature, surface conditions, humidity, etc. [2] [3]. However, the research into behavioral models of arc faults has already created several approaches that combine these influences in fixed parameters and consider other variables with high influences on the behaviour. Equations like the Steinmetz equation [4], Nottingham equation [5] and Ayrton equation [6] describe the nonlinear behavior of the arc voltage as a function of the arc current or the arc length [7] [8]. Whereby these equations are not focused on 48 V automotive power supply systems, other authors have been working on applications and investigations of arc phenomenon in low voltage DC grids, respectively 48 V automotive power supply systems [9] [10]. In this paper the arc model from [11] was used:

$$v_{arc}(i_{arc}, d) = A + B \cdot ln(C \cdot d + 1) + \frac{D \cdot d}{i_{arc}} \quad (1)$$

The relationship between the arc voltage v_{arc}, arc current i_{arc} and arc length d is given by (1). This modelling approach has been shown to be valid for both, static and transient simulations. The parameter set from [11] is applied here:

$$\begin{aligned} A &= 11\ \text{V} \\ B &= 8.52\ \text{V} \\ C &= 1.3\ \text{mm}^{-1} \\ D &= 2\ \text{VA·mm}^{-1} \end{aligned} \quad (2)$$

These parameters were found for typically used plug materials (copper alloy with silver plating) and are assumed to be mainly independent from arc gap geometry but may vary in other setups with other materials or very different environmental effects.

B. Power supply system modelling considering arc situations

Automotive power supply systems vary regarding to different brands, models or model variants. For a general investigation into automotive power supply systems, though, it is necessary to find similarities to describe the resulting circuits. The model representations of the power network components, chosen to be relevant in this paper, are shown in Fig. 1 for series arcs and Fig. 2 for parallel arcs for simplified power networks.

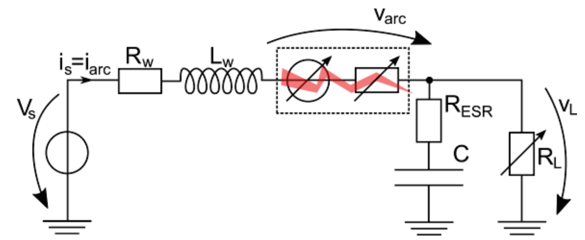

Fig. 1. Simplified power circuit for simulation of series arc events

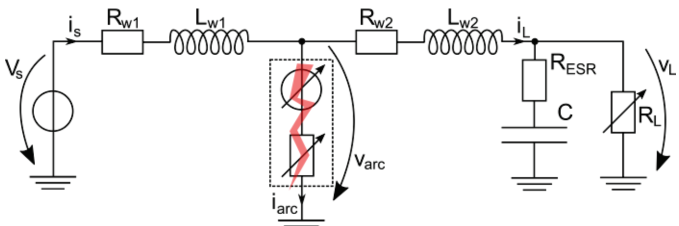

Fig. 2. Simplified power circuit for simulation of parallel arc events

A voltage source V_s represents the power supply, such as a battery, a DC/DC-converter, or a generator. The internal resistance of those components is integrated in the series resistances (R_w, R_{w1}). The other contribution to R_w and $R_{w1/2}$ comes from the wire harness itself. The wire harness can be modelled as a series circuit of resistor and inductance ($L_w, L_{w1/2}$). Furthermore, something that can be found almost always is a voltage stabilizing capacitor in the ECUs. It is modelled with its capacity C and the equivalent series resistance R_{ESR}. The load itself can behave in various different ways. Typical behaviors can be constant resistance, such as various heating elements, or constant power, such as electrical machines or DC/DC-converters. The behavior is represented by a variable resistor R_L. The arc, in relative positions to the termination, is modelled as described in [11], as a voltage source that creates the characteristic arc voltage and a resistor for open or short circuits, and to perform transitions between various arc model states.

Basically, two important main types of simulation approaches can be identified regarding to arc events in power systems. On the one hand, static simulations can provide an estimation of the dissipated power and energy, which leads to an evaluation of the potential risk of damage or even fire in the car. In the static cases, the wire impedances are reduced to its ohmic behavior and the capacitor changes into an open circuit. On the other hand, transient simulation provides current and voltage signals, e.g. during the ignition or the extinguishing period.

III. Identification of worst-case situations

The main goal of safety research is to avoid dangerous situations for passengers and other traffic participants in any case. To ensure this, critical worst-case situations have to be considered. Arc events can happen in many different situations and the arc itself can be in various operation points. So, identifying the worst-case situations for arc events can be a highly relevant task, prior to specific simulations and prior to the development process of automotive power supply systems. Worst-case situations can last for a relatively long time, so static analysis is required.

A. Worst-case situations for series arcs

In many cases, the point of maximum power dissipation turns out to be the worst-case. Regarding to the maximum power transfer theorem, the operation point of maximum dissipation power is with $v_{arc} = V_s/2$. The arc can reach such a state in nearly any combination of surrounding components with an appropriate length d, which is shown in Fig. 4. Fig. 3 shows clearly the presence of a maximum in the length dependent arc power for a specific circuitry.

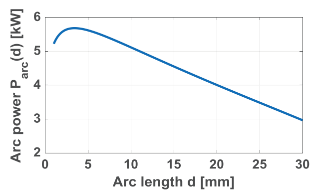

Fig. 3. Dissipated arc power varies with arc length; according to Fig. 1: $V_s = 50\,V, R_w = 10\,\text{m}\Omega$, $R_L = 100\,\text{m}\Omega$

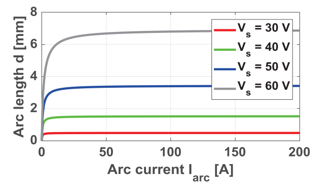

Fig. 4. Necessary arc lengths for the operation point of maximum dissipation power, so $v_{arc} = V_s/2$

Assuming this specific operation point, the dissipation power increases with decreasing load resistance according to:

$$P_{arc,max,ser} = \frac{1}{4 \cdot (R_L + R_w)} \cdot V_s^2 \quad (3)$$

This shows that the arc's operation point of maximum power dissipation is achieved in relatively short arcs, which makes this scenario much more possible and even more important. The main aspects regarding to worst-case situations of series arcs can be summarized as follows:

- The higher the supply voltage V_s, the higher the maximum dissipation power of the arc;

- The lower the termination resistance/load resistance R_L, the higher the maximum dissipation power of the arc;

B. *Worst-case situations for parallel arcs*

In the same way, parallel arcs can be analyzed. To give a formal relation between the maximum power and the circuitry (4) can be used:

$$P_{arc,max,par} = \frac{R_L + R_{w2}}{4 \cdot R_{w1} \cdot (R_{w1} + R_L + R_{w2})} \cdot V_s^2 \quad (4)$$

Assuming $R_L \to \infty$, (3) is also valid:

$$\lim_{(R_L+R_{w2})\to\infty} P_{arc,max,par} = P_{arc,max,ser} \quad (5)$$

In most cases R_{w1} is much smaller than R_L, as R_{w1} represents an internal source resistance or a wire resistance. Therefore, parallel arcs possess the potential for higher maximum power configurations, i.e. more damage to the surrounding material. Calculated values are shown in Fig. 5. The variation of R_{w1} can for example either represent the location of the parallel arcs regarding to the wire or the State of Health or State of Charge of a battery, as a source.

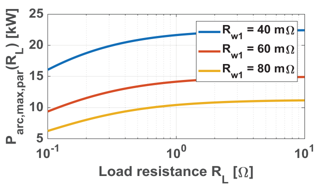

Fig. 5. Operation point for parallel arcs with maximum dissipation power varying with parallel load resistance R_L; $V_s = 60$ V, $R_{w1} = var.$, $R_{w2} = 0\ \Omega$

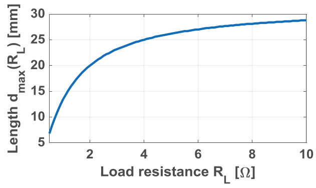

Fig. 6. Variation of maximum arc length depending on parallel load resistance R_L; $V_s = 50$ V, $R_{w1} = 260$ mΩ, $R_{w2} = 0\ \Omega$

Fig. 6 shows that by increasing the parallel load R_L, the maximum possible arc length increases [12], as well, and the whole setup converges to the series arc setup. As a conclusion, a series arc can be described as a special case of a general parallel arc setup. Additionally, with an increased maximum arc length, the possibility of the arc keeping any stable operation point in real applications increases, as well.

Another aspect that should be considered is that there are different detection methods of parallel arcs. Worst-case situations can also be defined in terms of detectability. So, a lack of sensors or low sensor resolution can make it hard to detect arcs, in various situations, especially if the arc current is similar to the normal load current. From this point of view, the point of minimum current of a parallel arc can also be seen as worst-case situation. As described in (1), low currents lead to high arc voltages. If the arc voltage crosses the maximum possible voltage operation point, respectively, the current decreases to zero, the arc expires. So, high arc lengths come along with low arc currents. The maximum length of an arc before it reaches an impossible operation point depends on the circuitry. This relationship is shown in Fig. 7. The corresponding currents are shown in Fig. 8.

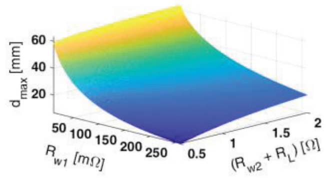

Fig. 7. Relationship between the maximum arc length d_{max} and the circuitry in a parallel arc situation; $V_s = 50$ V

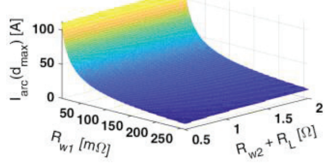

Fig. 8. Influence from the circuitry onto the arc current in the moment of expiration ($d = d_{max}$)

These values can be seen as worst-case currents with the assumption that the arc length increases very quickly after the ignition up to its maximum length. At this point, the arc has the least influence on the circuitry, hence this can be the point of most difficult detection.

The main aspects regarding to worst-case situations of series arcs can be summarized as follows:

- Worst-case situations may depend on detectability
- The higher the resistance $R_L + R_{w2}$,
    - the higher the possible maximum dissipation power
    - the higher the maximum arc length
- The higher the resistance R_{w1},
    - the lower the maximum arc length
    - the lower the arc current in the moment of extinction

IV. Application: Arc Suppression and Extinction for Special Cases

Some of the shown characteristics can be utilized in specific situations in order to suppress arcs in the moment of ignition or to force arcs into an unstable situation where no operating point is possible and the arc will have to extinguish. This potential is presented and discussed in the following section.

A. *Special expiration event in combination with parallel arcs and variable loads*

Some situations can be identified that force the arc into an unstable situation. Here, there is no operating point possible due to the courses of the provided operating points by the circuit, and the arc's characteristic V-I-curve. Especially, this can be achieved with variable loads.

In a test setup this has been utilized in order to delete a parallel arc. Important events are marked with *markers 1 - 5* in Fig. 9 and Fig. 10. The scenario is explained in detail in the following:

- Before *marker 1* there is the normal operation of the system without arcs and with $R_{L(1)}(+R_{w2}) \approx 730$ mΩ, $V_s \approx 48$ V, $R_{w1} \approx 260$ mΩ.
- At $t = 0.5$ s (*marker 1)* a parallel arc occurs and increases its length up to $d \approx 4$ mm. This length has been reached at *marker 2*.

- Between *marker 2* and *marker 3* the arc is in a stable operation point with $P_{arc} \approx 1.1$ kW. Due to limitations of the test bench, this is only a limited dissipation power caused by the high value of $R_{w1} \approx 260$ mΩ. In real setups, R_{w1} used to be smaller, so P_{arc} higher.
- At *marker 3* the load begins to linearly decrease its resistance from $R_{L(1)} \approx 730$ mΩ to $R_{L(end)} \approx 140$ mΩ. This value has been reached at *marker 5*.
- However, the reduced load resistance leads to a shifted load line, so that the operation point of the arc moves along its characteristic V-I-diagram. This can clearly be seen in Fig. 10. The shifted load lines are shown for three different values of $R_{L(x)}$.
- At *marker 4* the load line does not have any cross section with the characteristic V-I-diagram of the arc so that the arc expires.
- After *marker 5* the load returns into its initial operation point and the system is fault-free again.

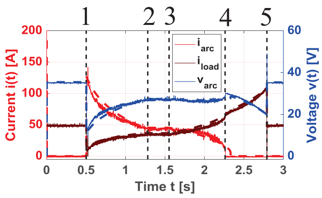

Fig. 9. Comparison of scenario between simulation and measurement. Arc deletion due to load control

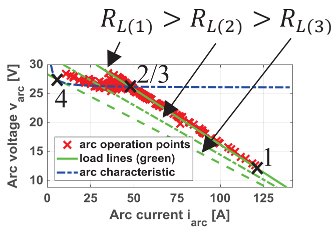

Fig. 10. Measured operation points of arc explained with the load line for $R_{L(1)} = 730$ mΩ and the characteristic arc V-I-diagram for $d = 4$ mm

The presented scenario and behavior may be expected by constant power loads. The voltage drop due to an arc event leads to an increased current in order to keep the power constant. This means the resistance is decreased.

B. *Series arc extinction directly after ignition due to oscillations*

In a wide range of investigations, the arc in combination with the whole power network can be assumed as a static system. In this case, all transient effects decay quickly, respectively changes in the network happen slowly or less rapid. However, especially the moment of ignition causes a strong transient response due to the very steep voltage step ($10^3 \ldots 5 \cdot 10^9\ V/s$) [13]. In this moment, the dynamic elements of the entire power network have a huge influence. The power supply system can form an oscillating circuit (compare Fig. 1), due to the available voltage stabilizing capacitors and the wire inductances. Then, the switching arc voltage in the moment of ignition is the system's excitation, which causes the oscillation. Once the oscillating arc current crosses zero, the arc expires. The degree of oscillation depends on the circuit parameters. The influence on the oscillation through a variation of the parameter C is shown in Fig. 11. The current oscillation for $C = 210$ µF crosses zero, so the arc would expire in this moment. The theoretical oscillation is shown with a dashed line. All combinations of components that lead to an arc extinction in the moment of ignition are depicted in Fig. 12. All points above the surface force the arc current to zero directly after its ignition.

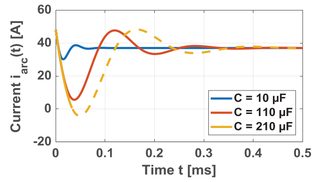

Fig. 11. Theoretical oscillations of the arc current for series arcs in the moment of ignition; $V_s = 48$ V, $L = 5$ µH, $R_L = 1$ Ω, $R_{ESR} = 100$ mΩ, $V_{arc} = 11$ V

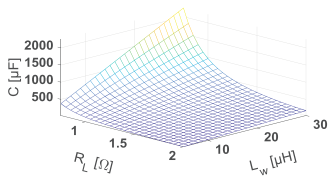

Fig. 12. Simulation of necessary capacitors depending on load resistance R_L and wire inductance L_w in order to gain a self-deleting arc; $V_{arc} = 11$ V; $R_{ESR} = 100$ mΩ

Calculating these boundaries requires the analysis of the differential equation of the oscillating circuit for $R_w = 0$:

$$\frac{d^2}{dt^2} i_{arc} + a_1 \cdot \frac{d}{dt} i_{arc} + a_0 \cdot i_{arc} = b_1 \cdot \frac{d}{dt} v + b_0 \cdot v \quad (6)$$

with:

$$\begin{aligned} a_1 &= \frac{R_L \cdot R_{ESR} \cdot C + L_w}{(R_L + R_{ESR}) \cdot C \cdot L_w} \\ a_0 &= \frac{R_L}{(R_L + R_{ESR}) \cdot C \cdot L_w} \\ b_1 &= \frac{1}{L_w} \\ b_0 &= \frac{1}{(R_L + R_{ESR}) \cdot C \cdot L_w} \end{aligned} \quad (7)$$

and v as the system input, respectively a source that is reduced from 48 V to 48 V $- V_{arc} = 37$ V, as an ideal step. The arc voltage in the moment of ignition can be assumed as a constant value, if assumed that all transient effects decay much quicker than the arc length varies.

Fig. 13 shows an arc that reaches a stable operation point despite of an oscillation in current and Fig. 14 shows an arc that expires in the moment of ignition because the oscillating current crosses zero. Both is depicted as simulation (dashed line) as well as measurement result (solid line).

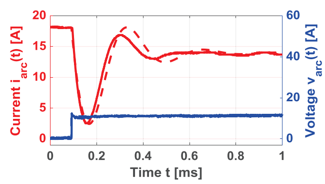

Fig. 13. Transient response due to a series arc ignition; $V_s = 48$ V, $L_w = 28$ µH, $C_L = 80$ µF, $R_{ESR} = 250$ mΩ, $R_L = 2.65$ Ω, $V_{arc} = 11$ V

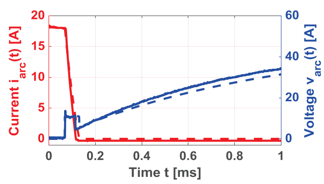

Fig. 14. Transient response due to a series arc ignition with zero-crossing current and arc extinction; Variation to Fig. 13: $C_L = 320$ µF

A more comprehensive representation is shown in Fig. 15 and Fig. 16. Here, the dashed line represents the calculated transition from an arc being able to reach a stable operation point and an arc expiring in the moment of ignition due to an oscillating current that is reduced to zero. The plotted points represent measurements that distinguish between those two classes. The figures vary in inductance L_w.

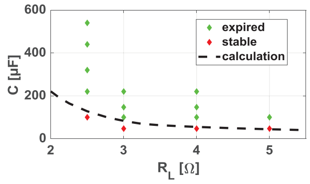

Fig. 15. Validation of calculation of arc expiration in the moment of ignition based on oscillating circuit theory; $L_w = 33$ µH, $R_{ESR} = 150$ mΩ

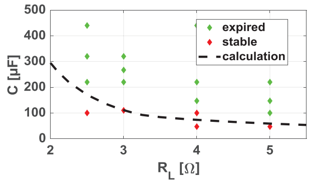

Fig. 16. Validation of calculation of arc expiration in the moment of ignition based on oscillating circuit theory; $L_w = 44$ µH, $R_{ESR} = 150$ mΩ

Also the quality of the capacitor's R_{ESR} can influence the extinguishing behavior, which is shown in Fig. 17.

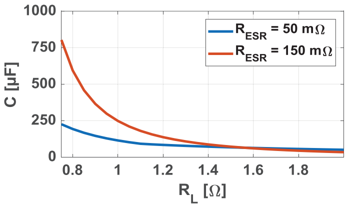

Fig. 17. Boundary shift due to variation of R_{ESR} of the capacitor; $L = 5$ µH, $V_{arc} = 11$ V, $V_s = 48$ V

During the discharge of the capacitor C, the discharge path is mainly through the source V_s. So, the internal resistance can be included in the variation of R_{ESR}. This assumption can be made if the load resistance R_L is much larger than the wire resistance R_w, which is almost always the case.

V. Conclusion

In 48 V automotive power supply systems, arc faults are important possible faults that have to be considered. The design and dimensioning of power networks have a huge influence on the worst-case situations of arc events. In consequence, arc scenarios should be considered during the design process for safety investigations.

Various worst-case situations for series and parallel arcs and varying power network components have been analyzed. The operating points of highest dissipation power have been calculated. Operating points where parallel arcs are hard to detect have been described and discussed. These points can also be influenced by specific behaviors of different ECUs. A low supply voltage may cause an ECU-shut-off, even before the worst-case operation point has been reached.

Arcs can be deleted by actively controlling its operating points via variations in power network components. In one specific setup with a parallel arc, the shift of a load line through a decreasing load resistance can force the arc to extinguish. Such a behavior may be expected by constant power loads.

Circuit oscillations can be used in order to limit the situations where arcs reach a stable operation point. Arc currents that cross zero due to oscillations, caused by the wire inductance and the ECU capacitors, extinguish very quickly. In these cases, the risk of damaging surrounding material or even fire is significantly reduced, or rather nearly disappears at all.

In order to create powerful and robust detection methods, the analyzed properties can be used. For specific 48 V power supply systems, worst-case situations can be identified and these situations can be used in order to find the limits of various given detection algorithms. Additionally, power network component's properties, such as wire lengths or capacitor values, may be chosen in order to create extinguishing conditions for arcs.

Finally, a comprehensive safety concept for arcs can be designed, based on the presented findings.

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