Electrical Device Protection from Overvoltage in a DC Power Supply Network

Fast-acting Protection, Realized by an "Artificial" Short Circuit in the Input of the Protected Device

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Abstract—**In the present paper a protective device based on the so-called "artificial" short circuit in the input of the network, is proposed. To ensure the necessary time for switching on the protection, the increased power supply voltage is delayed to reach in the input of the protected device by additional inductance L, which is connected in series to the power supply. As a result of this forced short circuit, the DC-power supply is switched off by a standard protective circuit-breaker. The short circuit is realized by a fast-acting semi-conductor device (e.g. diac + thyristor, etc.). The controlling signal is formed as a voltage across a capacitor that is a part of RC-circuits connected in parallel to the DC-power supply network. An analytical expression for this voltage, using a classical method for transient analysis, is obtained. The main aim is to determine the exact time of switching on the protection. The research is confirmed with simulations by OrCAD PSpice under the exact values of the elements in the RC-circuits considered. Two rapid increase cases in the power supply voltage are considered: positive jump and linear increase. The suggested solution is applicable for overvoltage protection of different electrical devices. The electrical scheme, based on the electronic components, ensures a fast-acting breaking, which guarantees secure protection. Based on the analytical expressions, the synthesis of the circuit for control and protection is made and the respective values of its elements are calculated.**

Keywords—electrical engineering; electronics; overvoltages; short circuit's protection by electronic unit; transients analysis by classical method

I. INTRODUCTION

Many electrical devices have one DC-power supply (either from a current rectifier or from a special network) [1]. During normal operation they are subjected to variations of power supply network parameters. This can lead to exceeding the maximum admissible values guarantying the normal operation of these devices. Overvoltage in the DC-power supply network occurs due to different atmospheric influences, switching on and off of large consumers, etc. The normal operation of a number of electrical devices deteriorates and sometimes overvoltage is the cause of damage or breakdown. So, the purpose of this work is to suggest a simple electrical scheme for overvoltage protection. It only consists of *RC*-groups (Figure 1). It guarantees greater reliability than similar protection solutions that use additional electronic elements or controllers [2-5]. The main disadvantage of most of the existing solutions is that they are designed to protect low power and low voltage consumers [6-8]. An additional advantage of the proposed solution is that it can be applied to form the level of the control signal activating the protection at both low and high voltages only by an elementary change in the values and parameters of the elements in the RC groups. There are also simple solutions designed for specialized protection with a specific form of voltage (e.g. DC + triangle voltage form [9]). Authors in [10] discuss a variety of protection schemes to ensure protection from faults causing overvoltage supplying some electronic elements working in low voltages. A simple method for protecting the analog channel from overvoltage is resistive input attenuation ahead of a precision operational amplifier. IC device junctions, such as base-collector and JFET gate-source junctions, don't exhibit the same degradation in performance upon breakdown and the input current should be 5mA. Overvoltage protection can be achieved using CMOS channel protectors. It is possible to break ground loops by using digital isolation techniques. To eliminate a possible damage, a protection based on the so-called "artificial" short circuit in the power supply input of the convertor with semi-conductor device *S* (Figure 1) is used. The convertor discharges both from voltage and current which is the main advantage of this method. It is also faster than the protections realized by switching off from the power supply with standard commutation apparatus [11].

In Figure 1, a fast-acting commutation apparatus *S* (e. g. diac + thyristor) that carries out a short circuit in the input of the protected electrical device is shown. A protecting breaker *K* connected in series with the power supply [11-13] is also shown in this figure. *RC*-circuits are connected in parallel to *S*. They form the time and the parameters of the switching off

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signal realizing the short circuit. The protected device is marked with “El. Device”.

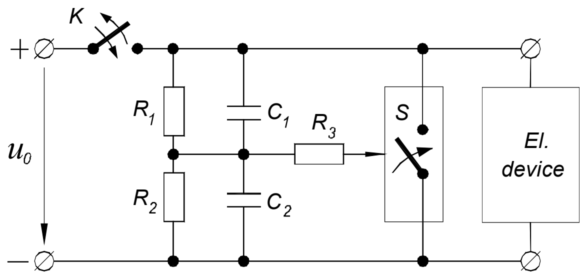

Fig. 1. A short circuit protection on the input of the convertor

The proposed protection is analyzed below. The parameters of the control signal and its variation in order to ensure effective protection are determined. The necessary parameters for different input signals of the circuit can be realized with the variation of the elements’ values. Afterwards, an analytical solution for the voltage across the common node of the two discussed *RC*-circuits during an unexpected change of the power supply voltage is suggested. This change determines both the time dependence of the processes and the parameters of the control signal intended for the commutation apparatus *S* that carries out a short circuit in the input of the protected device. The classical method for transient analysis is applied [14, 15]. The results from the solution are confirmed with illustrative examples by computer OrCAD PSpice simulations. The paper concludes with remarks about the advantages and disadvantages of the proposed protection and with some perspectives for a future research.

II. PROBLEM STATEMENT

The principal scheme of the proposed protection from overvoltage in DC-power supplying network is shown in Figure 2. The processes in the circuits that form both the parameters of the signals and the moments of switching on the protection are very significant. It is necessary to determine the connection between the times and the parameters of the scheme’s elements in order to make a correct choice of their values in each specific case of power supply overvoltage. The fact is that different devices have different parameters, different power supply voltages, etc. In an emergency, the power supply voltage of a given electrical device can rapidly increase. To limit this increase a protective system is necessary to be applied. In the considered case the system is an electric scheme that generates a switching off protective signal applying to a fast commutation apparatus *S*. In the control circuit of *S* the device (e.g. diac – not shown in Figure 2) is included. It actuates when the voltage in the main node of C_1 and C_2 exceeds the definite value. The parameters of both the signal and the reaction time of the protection depend on the specific scheme solution and the ratio of the values of the elements. The control signal is proportional to the voltage across the R_2C_2-group. It is essential to have a capacitor in which a sufficient amount of energy is accumulated to activate the protection. When the necessary parameters of the control pulse are reached, the apparatus *S* switches on and the power supply of the protected electrical device acts as a short circuit. As a result, the input current increases and reaches a value that causes the opening of the breaker *K* and the power supply voltage is switched off. An additional inductance *L* can improve the effectiveness of the protection (Figure 2(b)). The inductance delays the moment when the increased supply power voltage is switched on at the input of the device. In this way an extra time is ensured for switching on the apparatus *S* and switching off the breaker *K* due to the increase of the input current.

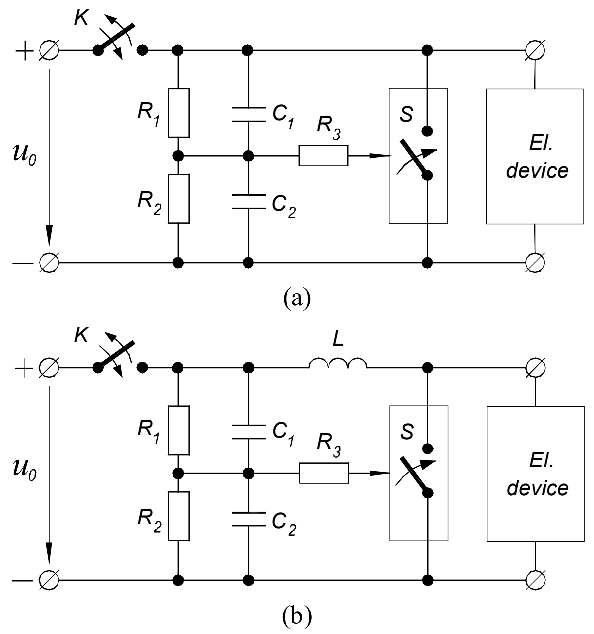

Fig. 2. Protective circuit from overvoltages in DC-power supply network: (a) default, (b) with additional inductance *L* for overvoltage protection

This method is better than the Laplace transform [16] because on each step of the solution the physical interpretation of the result can be visualized.

III. ANALYTICAL SOLUTION TO THE TRANSIENTS VIA CLASSICAL METHOD

In the present paper, an analytical solution based on the classical method (using a set of ordinary differential equations) for determining the transient of the voltage $u_{C_2}(t)$ (Figure 3) is proposed. This transient appears when the power supply voltage increases rapidly and the electrical device should be protected. Two cases of power supply overvoltage are considered:

- Positive jump of the power supply voltage (Figure 4(a)) $u(t) = u_1 > u_0 \ (\mathrm{V})$.
- Linear increasing the power supply voltage (Figure 4(b)) $u(t) = u_0 + k.t \ (\mathrm{V})$

Since the studied electric circuit consists of two parallel *RC*-groups connected in series, then the transients are of the 1st order. So, in both cases mentioned above, the transient $u_{C_2}(t)$ satisfies the aperiodic law:

$$u_{C_{2\ trans}}(t) = A.e^{-\frac{t}{T}}\ (\mathrm{V}) \quad (1)$$

where the time constant is: $T = \frac{R_1 R_2.(C_1 + C_2)}{(R_1 + R_2)},\ (\mathrm{s})$. The initial conditions also are the same for both cases:

$$u_{C_2}(0_+) = u_{C_2}(0_-) = \frac{u_0.R_2}{(R_1 + R_2)}\ (\mathrm{V}) \quad (2)$$

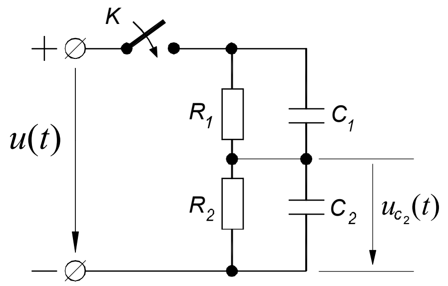

Fig. 3. Input protection *RC*-circuit

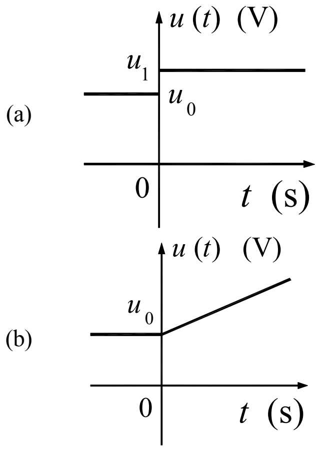

Fig. 4. (a) Positive jump of the power supply voltage, (b) linear increase of the power supply voltage

However, the new steady states are different:

- If $u(t) = u_1 > u_0\ (\mathrm{V})$, then

$$u_{C_{2\ steady\ state}}(t) = \frac{u_1.R_2}{(R_1 + R_2)}\ (\mathrm{V}) \quad (3a)$$

- If $u(t) = u_0 + k.t\ (\mathrm{V})$, then:

$$u_{C_{2\ steady\ state}}(t) = \frac{u_0.R_2.k}{(R_1 + R_2)}.t + \frac{u_0.R_2.k}{(R_1 + R_2)^2}.\left[R_1 + R_2 + R_1.(R_1C_1 - R_2C_2).k\right]\ (\mathrm{V}) \quad (3b)$$

The final solution about the transient is:

$$u_{C_2}(t) = u_{C_{2\ trans}}(t) + u_{C_{2\ steady\ state}}(t) = A.e^{-\frac{t}{T}} + u_{C_{2\ steady\ state}}(t)\ (\mathrm{V}) \quad (4)$$

For each of the analyzed cases the following results are obtained:

- When $u(t) = u_1 > u_0\ (\mathrm{V}) \Rightarrow$

$$u_{C_{2\ steady\ state}}(t) = \frac{u_1.R_2}{(R_1 + R_2)}\ (\mathrm{V})$$
$$A = \frac{(u_0 - u_1).R_2}{(R_1 + R_2)} \quad (4a)$$
$$T = \frac{R_1 R_2.(C_1 + C_2)}{(R_1 + R_2)}\ (\mathrm{s})$$

- When $u(t) = u_0 + k.t\ (\mathrm{V}) \Rightarrow$

$$u_{C_{2\ steady\ state}}(t) = \frac{u_0.R_2.k}{(R_1 + R_2)}.t + \frac{u_0.R_2}{(R_1 + R_2)^2}.\left[R_1 + R_2 + R_1.(R_1C_1 - R_2C_2).k\right]\ (\mathrm{V})$$
$$A = \frac{u_0.R_2R_1.(R_2C_2 - R_1C_1).k}{(R_1 + R_2)^2} \quad (4b)$$
$$T = \frac{R_1 R_2.(C_1 + C_2)}{(R_1 + R_2)}\ (\mathrm{s})$$

In the present paper the proposed power supply overvoltage protection will switch on (the commutation apparatus *S* will be a short circuit in the input of the protected device) when the threshold value of the capacitor voltage has been reached, i.e. $u_{C_{2\ trans}}(t) = u_{threshold}$.

IV. ILLUSTRATIVE EXAMPLE

A scheme for power supply overvoltage protection is considered (Figure 2). Without some special considerations the power supply voltage of u_0=300V is chosen. Note that in normal operation the power supply voltage can deviate up to 20% from the nominal one, i. e.:

$$u_0 = 300\ (V)\ \pm\ 20\ \% = [240,\ \ 360]\ (\mathrm{V}).$$

The protection has to be set in such a way that it switches on only when the upper bound of the power supply voltage is exceeded.The commutation apparatus *S* has to switch on when the threshold voltage $u_{threshold}$=20V according to the chosen semi-conductor element (e.g. diac), which watches on the value of the control signal (in the common point of the *RC*-groups.

$$\eta = \frac{u_0}{u_{threshold}} = 15 \quad (5)$$

The relation between the resistors R_1 and R_2 is given by:

$$15 = \eta \le \frac{R_1 + R_2}{R_2} \quad (6)$$

To ensure a normal exploitation, the voltage across the capacitor C_2 has to be smaller than the threshold voltage of switching on the commutation apparatus *S*, i.e.:

$$u_{C_2}(0_+) = u_{C_2}(0_-) = \frac{u_0 . R_2}{R_1 + R_2} \le u_{threshold} \quad (7)$$

$$10.424\,\text{V} < 20\text{V} \quad (7a)$$

On the base of (6) and (7), (7a), the values of the resistors R_1=100kΩ and R_2=3.6kΩ are determined. The capacitances of the capacitors C_1 and C_2 determine the speed of variation and the time of the transients. The latter fade away faster when these values are smaller, because in this case the time constants are also smaller. The specific values are determined based on the following condition: The energy stored in the capacitor C_2 has to be enough to activate the apparatus *S*. The switching time depends on the thyristor and it is up to tens of microseconds. As an illustration of the process, the following values are chosen: C_1=2nF and C_2=200nF. The analysis of the two considered cases follows.

- Positive jump of the power supply overvoltage (Figure 4(a)), when $u(t)=u_1$=600V
- Linear increasing of the power supply overvoltage (Figure 4(b)), when $u(t)=u_0+kt$=300+50000t (V).

Simulations with OrCAD PSpice were conducted. The scheme and the results are shown in Figures 5-7.

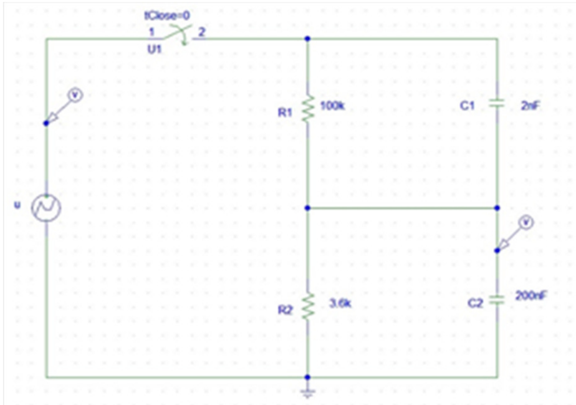

Fig. 5. Simulation of the overvoltage protective circuit in a DC-power supply voltage

The time for switching on the proposed protection for both cases of overvoltage in the power supply network is analytically calculated by (4), (4a) and (4b) and it is determined by the simulations' graphs. The results are shown in Table I. The relative errors from the analytical solution and from the simulations for both cases are 12.99% and 0.33% respectively.

TABLE I. TIME FOR SWITCHING ON THE PROTECTION

Input power supply voltage	Analytical solution	Simulation solution
$u(t)=u_1$=600V	1.77 (ms)	1.54 (ms)
$u(t)=u_0+kt$=300+50000t	6.02 (ms)	6 (ms)

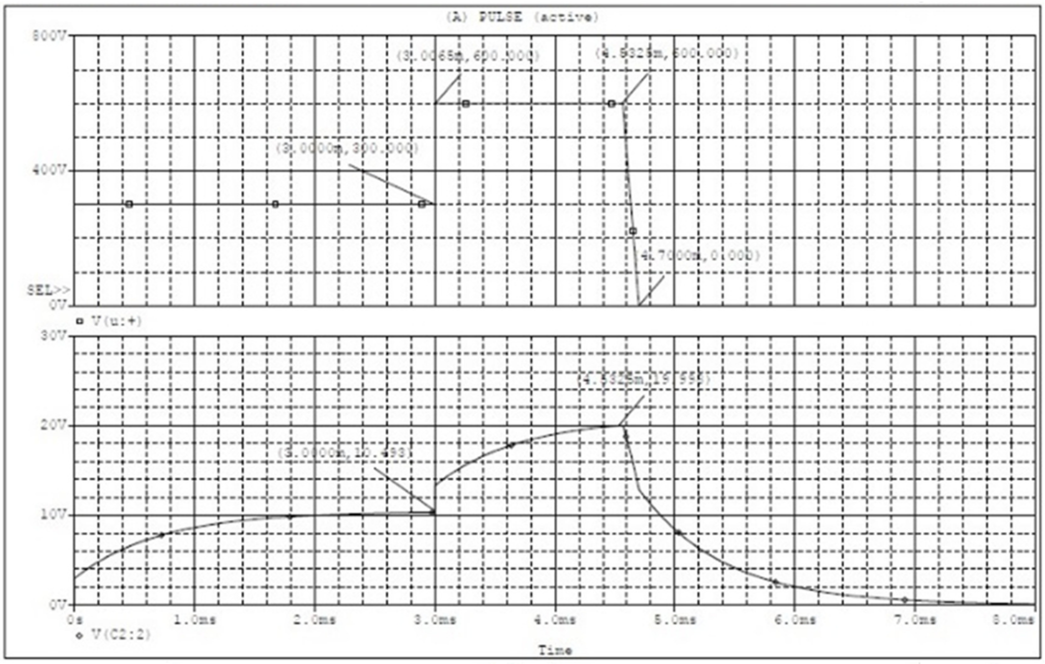

Fig. 6. Voltage $u_{C_2}(t)$ in a positive jump of the DC-power supply voltage

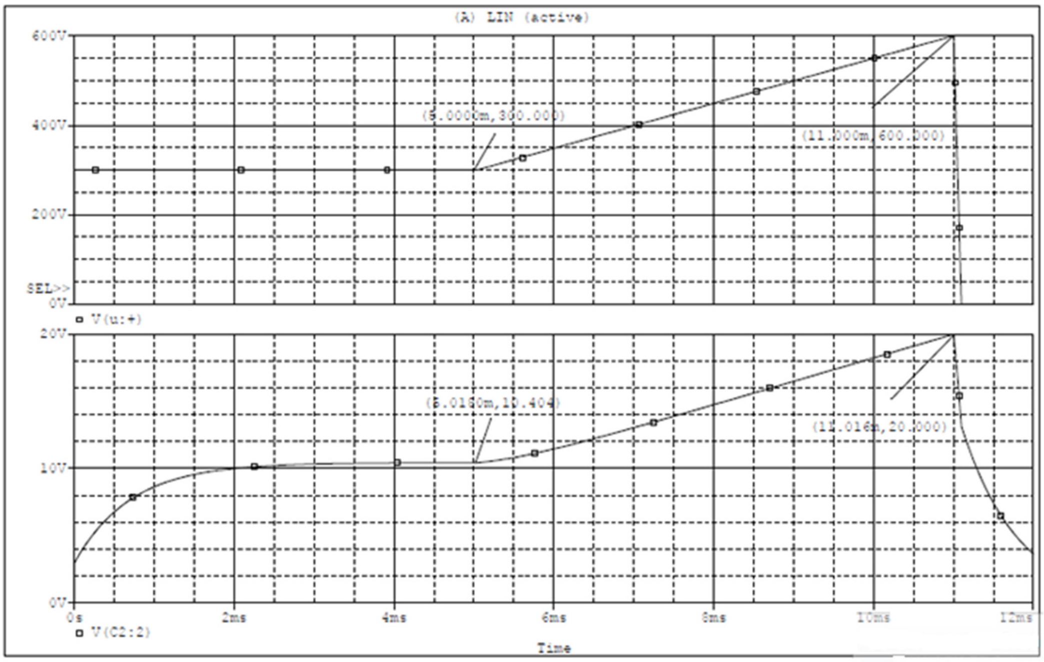

Fig. 7. Voltage $u_{C_2}(t)$ in a linear increasing DC-power supply voltage

V. CONCLUSION

In the present paper, a method of control and protection of the electrical devices (usually electronic) from overvoltage in power supply network is suggested. It is realized by a short circuit in the input of the protected device. The proposed approach for DC surge protection is based on basic theoretical knowledge. Its innovation is the simple calculation of the time for activating the protection by using the classical transient analysis method without the need for mathematical processing using Matlab or other similar software. Another major advantage is that this scheme is applicable to arbitrary values of the supply voltage and its form: DC-jump, linear, saw, etc. Unlike other schemes (with a resistive divider only), the use of RC-groups in this work increases the sensitivity of the offered protection. It can also be used to form control and protection signals at both low and high voltages in low and high power consumers. To ensure the necessary time for switching on the protection, the increased power supply voltage is delayed to reach the input of the protected device by an additional inductance L, which is connected in series to the power supply. Two cases of rapid increase of the power supply voltage are considered: positive jump and linear increase. Analytical expressions for the voltage $u_{C_2}(t)$ which determine the moment of switching on the protection are given for each case. The expressions are obtained using the classical method for transient analysis.

The main advantage of the classical method for transient analysis is that in each step of the solution, one should take in mind the physical interpretation of the processes considered while it is not necessary when using other known methods such as Laplace transform, Duhamel's integral, state space method, Fourier transform, etc. One disadvantage of the classical method for transient analysis is the tedious and long description during the solution. Based on the analytical expressions, the synthesis of the circuit for control and protection is made and the respective values of its elements are calculated. The respective moments for switching on the protection are determined analytically and by simulations. The resulting relative errors are 12.99% and 0.33%, respectively. This shows that the simulations confirm the final analytical solution. The differences are due to the different rounding methods applied during the calculations.

A possible perspective for future research of the problem considered in this paper is to obtain the analytical expression for the control signal to the commutation apparatus S, using Duhamel's integral.

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