Optimization of the vacuum insulator stack of the MIG pulsed power generator

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Abstract. The MIG multi-purpose pulsed power machine is intended to generate voltage pulses of amplitude up to 6 MV with electron-beam loads and current pulses of amplitude up to 2.5 MA and rise time 100 ns with inductive loads like Z pinches. The MIG generator is capable of producing a peak power of 2.5 TW. Its water transmission line is separated from the vacuum line by an insulator stack. In the existing design of the insulator, some malfunctions have been detected. The most serious problems revealed are the vacuum surface flashover occurring before the current peaks and the deep discharge traces on the water–polyethylene interface of the two rings placed closer to the ground. A comprehensive numerical simulation of the electric field distribution in the insulator of the MIG generator has been performed. It has been found that the chief drawbacks are nonuniform voltage grading across the insulator rings and significant enhancement of the electric field at anode triple junctions. An improved design of the insulator stack has been developed. It is expected that the proposed modification that requires no rearrangement of either the water line or the load-containing vacuum chamber will provide higher electric strength of the insulator.

1. Introduction
Terawatt-class pulsed power generators are of great interest for use in basic research and applications dealing with extreme states of matter. In 1996, at the Institute of High Current Electronics (Tomsk, Russia), the MIG pulsed power machine [1] was built. The generator is designed to produce voltage pulses of amplitude up to 6 MV and current pulses of amplitude up to 2.5 MA with a peak pulse power of 2.5 TW. The generator currently operates by the following scheme: linear pulse transformer – water pulse-forming lines – vacuum transmission line – load. A capacitor bank capable of storing 400 kJ of energy is used as the primary energy store. The linear pulse transformer transfers the energy stored in the capacitor bank into the first pulse-forming line whose electrical length and impedance are, respectively, 75 ns and 1.3 Ω. When a single-channel water spark gap operates, part of the energy is transferred to the second pulse-forming line (26 ns, 0.65 Ω). On the operation of a nine-channel water spark gap switch, up to 120 kJ of energy is supplied, a power of 1.2–1.4 TW, through the 0.65-Ω transmission line to the (cone-shaped) vacuum transmission line and then to the load. The water-filled transmission line is separated from the vacuum line by an insulator stack of external diameter ~90 cm.
The MIG generator is relatively compact among the machines of this power level. The dimensions (length, width, and height) of the pulse transformer with the primary energy store are $5.5 \times 3.2 \times 2.7$ m$^3$. The length and diameter of the transmission lines are, respectively, 6 m and 2.3 m. The generator is located in a bunker-type premise of area $11 \times 16$ m$^2$. Using the MIG generator, various experiments have been performed to study intense electron beams [2–6], imploding Z-pinch plasmas [7–9], metal surfaces explosions in megagauss magnetic fields [10–12], and phase transformations of matter under high pulsed pressures [13]. When the generator operates into a load of inductance $\sim 20$ nH, the current amplitude reaches $2.5$ MA within a rise time $\tau_{0.1-0.9} \approx 70$ ns.

The water-vacuum insulator stack is a key part of the MIG generator. The insulator provides the delivery of an electromagnetic pulse from the water transmission line to the load placed in a vacuum chamber. The insulator stack consists of five polyethylene rings of outer diameter 89.6 cm separated by stainless steel grading rings. A standard (+45$^\circ$) configuration is used for the vacuum interface. The thickness of each polyethylene ring is 2.5 cm.

![Figure 1](image1.png) ![Figure 2](image2.png)

**Figure 1.** Load current and insulator voltage waveforms for shots without (a) and with (b) insulator flashover.

**Figure 2.** Top view of the insulator rings. The cathode is on the left.

The operation of the insulator stack is complicated at least by two adverse factors, which are possibly interrelated. The first one is illustrated by Fig. 1, which presents load current and insulator voltage traces recorded at different peak voltages. It can be seen that for the lower peak voltage (750 kV), the current trace has the typical $(1 - \cos)$ waveform until the time the reverse voltage peaks (see Fig. 1a). This time corresponds to the insulator flashover, as evidenced by abrupt flattening of the current waveform due to the crowbar effect. For the higher peak voltage (950 kV), the flashover time is closer to the time at which the current peaks. This indicates that the peak load current decreases due to the insulator flashover (Fig. 1b). The second adverse factor shows up as well-defined discharge traces on the water-facing surfaces of the polyethylene rings (Fig. 2). As can be seen in Fig. 2 (the insulator stack centerline is horizontal), only the two polyethylene rings nearest to the anode were damaged. Besides, these traces appeared only in the upper part of the insulator stack.
To estimate the flashover electric field, well-known relations can be used. The peak electric field at which the water-facing surface of the insulator is expected to flash, $E_w$, can be estimated by the formula [14]

$$E_w = K \cdot t_{0.63}^{-0.25} \cdot d^{-1/3} \text{ [MV/cm].}$$

(1)

Here $K = 0.2$ for polyethylene, $d$ is the insulator thickness [cm], and $t_{0.63}$ is the effective voltage pulse width [μs] defined as the full width of the applied voltage pulse at 63% of the peak voltage. Strictly speaking, this formula is valid only for a flashover in a uniform field. Therefore, to estimate the electric strength of an actual insulator, it is reasonable to compare $E_w$ with an average electric field $E_{av} = U/d$, where $U$ is the peak voltage across the insulator. Setting $U = 1$ MV, $t_{0.63} = 0.03$ μs, and $d = 12.5$ cm characteristic of the MIG insulator stack, we obtain $E_w \approx 210$ kV/cm, which is about 2.5 times the average electric field of 80 kV/cm typical of the MIG machine.

The vacuum flashover electric field can be estimated by the formula proposed by J. C. Martin (see, e.g., Ref. 15):

$$E_v = 175 \cdot t_{0.89}^{-1/6} \cdot A^{-1/10} \text{ [kV/cm],}$$

(2)

where $A$ is the insulator area [cm$^2$], $t_{0.89}$ is the effective voltage pulse width [μs] defined as the full width of the applied voltage pulse at 89% of the peak voltage. For our case, we have $A = 4959$ cm$^2$ and $t_{0.89} = 0.013$ μs, and formula (2) yields $E_v \approx 155$ kV/cm.

Thus, for both cases, the estimated flashover electric field is considerably greater than the average electric field, suggesting low flashover probability for the MIG insulator stack. Nevertheless, the existing insulator has often been observed to flash. The work presented in this paper was aimed at finding the reasons for the insulator flashovers and seeking ways to mitigate them.
2. Numerical simulation of the electric field distribution at the insulator surface

We supposed that there are at least three possible reasons for the flashover: nonuniform voltage grading among the insulator rings, significant enhancement of the electric field at the anode triple junctions, and contaminants present on the insulator surfaces.

To check these suppositions, a two-dimensional electrostatic model was developed and corresponding numerical simulations were performed using the Elecut 5.1 software.

Figure 3 gives the equipotential curves calculated for the existing design of the insulator. The polyethylene rings are marked with numbers. The cathode (C) is situated on the left; it is at a potential of 1 MV, whereas the anode is grounded. The potential distribution along the vacuum surface of each ring is shown in Fig. 4a. It can be seen that ring 1 is at the highest voltage. The average electric field \( E_{av} = U/d \) reaches 110 kV/cm. In contrast, the field \( E_{av} \) at ring 5 is not over 40 kV/cm. The calculated distribution of the tangential electric field \( E_t \) at the vacuum surface of each ring is shown in Fig. 4b. The cathode triple junction corresponds to \( L = 0 \), where \( L \) is the distance along the vacuum surface. The \( E_t \) distribution is evidently nonuniform. It is well known that the analytical solution of the Laplace equation for a 45° configuration gives an electric field infinitely increasing on approaching an anode triple junction. For our case, the electric field strength in the regions located about 2 mm away from the triple junctions should be considered not well defined because of the limitation on the computational spatial grid. The respective points were not included in the plots. It can be seen that \( E_t \) increases almost linearly, showing some enhancement near the anode triple junction. The maximum tangential electric field (120 kV/cm) near the anode triple junction has been predicted for ring 1. This is at least 1.5 times higher than the average electric field 80 kV/cm.

3. Numerical simulation of the electric field distribution for successive flashovers of the rings

Preliminary estimates have shown that the electric fields in the insulator are evidently insufficient for a total flashover to occur, but the flashover of ring 1 seems to be most probable. We have performed a numerical simulation assuming successive flashovers of the insulator rings. At the first step, ring 1 is considered to flash. This implies that the whole of the initial voltage will be applied to the other rings. At the next step, rings 1 and 2 are considered to flash. (The reason for the flashover of ring 2 is that when ring 1 flashes, the highest voltage appears to be applied to ring 2.) Thus, the whole of the voltage is switched to rings 3–5. So, the highest-voltage ring is considered to flash at each step. The results of this simulation are presented in Table 1.

| Number of flashing rings | Normalized voltage grading among the rings | Maximum tangential electric field \( E_{vac} \) at the vacuum surface, kV/cm | Maximum tangential electric field \( E_{wp} \) at the water-facing surface, kV/cm | Maximum average electric field \( E_{av} \), kV/cm |
|--------------------------|------------------------------------------|---------------------------------|---------------------------------|------------------|
| 0                        | 3/2.2/2.1/2.3/1                          | 120                             | 180                             | 108              |
| 1                        | 3.6/2.4/2.4/1                            | 180                             | 210                             | 148              |
| 1–2                      | 3.5/2.5/1                                | 220                             | 320                             | 194              |
| 1–2–3                    | 3.3/1                                    | 330                             | 750                             | 304              |
| 1–2–3–4                  | –                                        | 420                             | 1000                            | 400              |

It can be seen that successive flashovers of the rings make the voltage grading among the rings more and more nonuniform. As a result, even when only the first ring flashes, the maximum average electric field \( E_{av} \) increases by a factor of 1.4, reaching 148 kV/cm. Estimation of the flashover strength of the insulator stack for this situation seems to be complicated as the effective voltage pulse width is
not well-defined. Nevertheless, it should be noted that the predicted average electric field is quite close to the vacuum surface flashover strength $E_v \approx 155 \text{ kV/cm}$ for the insulator stack. Therefore, it should be expected that the flashover of one ring will significantly increase the flashover probability for the whole of the insulator stack.

The data given in Table 1 also show that the maximum tangential electric field at the water-facing surface, $E_{wp}$, increases more sharply than the tangential electric field at the vacuum surface, $E_{vac}$. For rings 1–3 supposed to flash, the field $E_{wp}$ is more than twice the field $E_{vac}$. This result can possibly explain the observed flashover traces along the water-facing surfaces of rings 4 and 5 (see Fig. 2).

4. Improved design of the water–vacuum insulator of the MIG generator

Comprehensive numerical simulations have been performed to find out the optimal design of the MIG water–vacuum insulator. In the course of the numerical optimization, the only requirement was set to be fulfilled. Namely, the modification of the design should not concern the water line and the vacuum chamber containing a load because of the high cost of these units. In the modified design, metal plugs were inserted in the polyethylene rings to reduce the electric field at anode triple junctions [16]. In addition, the insulator was shifted by several millimetres toward the cathode to provide a more uniform electric field distribution among the rings. A few minor changes have also been made. The results of the numerical modelling of the optimal insulator design are presented in Figs. 5 and 6.

![Figure 5](image1.png)

**Figure 5.** Calculated equipotential curves for the modified design of the insulator.

![Figure 6](image2.png)

**Figure 6.** Calculated potential distribution along the vacuum surface of each ring (a) and distribution of the tangential electric field $E_t$ at the vacuum surface of each ring (b) for the modified design of the insulator.

The improved design of the insulator provides a more uniform potential distribution along the insulator rings. The tangential electric field reaches the highest value ($85 \text{ kV/cm}$) at rings 2 and 3, and it is only a little greater than the average electric field ($80 \text{ kV/cm}$). A significant reduction in electric field is observed near the anode triple junctions. Therefore, the highest electric field for the modified
design is no less than 1.4 times lower than the highest fields at the anode triple junctions calculated for
the existing design. The proposed modification requires no rearrangement of either the water line or
the load-containing vacuum chamber and should provide higher electric strength of the insulator stock.

5. Summary
A comprehensive numerical simulation of the electric field distribution has been performed for the
water–vacuum insulator of the MIG pulsed power generator. The principal disadvantages of the
existing design have been revealed. The simulations have confirmed that the nonuniform voltage
grading among the insulator rings and significant enhancement of the electric field at anode triple
junctions could be responsible for the low electric strength of the insulator. A numerical modelling of
successive flashovers of the insulator rings has revealed a more pronounced voltage grading among
the rings. Also, it has been found that the tangential electric field at the water-facing surface increases
sharper than the electric field at the vacuum surface. This seems to account for the observed flashover
along the water–polyethylene interface of the two rings located closer to the anode. An improved
design of the insulator stack has been developed. The proposed modification requires no
rearrangement of either the water line or the load-containing vacuum chamber and should provide
higher electric strength of the insulator stack.

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