Electromagnetic phenomena with an impact on IT operations

In the current security situation, the issues of possible attacks on energy and industrial infrastructure are being discussed. These attacks can take the form of cyberterrorism or military operations (diversion into the territory of a foreign state). An electromagnetic pulse attack has been popularized through films such as "Ocean Eleven." But what is the level of risk? And is this the only method of influencing the functioning of electronics?

First, it is necessary to realize how the electromagnetic phenomena in question actually take place. In the case of electronics, this is the incoming voltage peak, which can be followed by a current shock. Alternatively, resonance frequencies are used, which allow the circuit to vibrate beyond its operating characteristics. Whether in the case of one or repeated peak, we are talking about an electromagnetic pulse, because it takes place in a limited time and usually in a limited location. But if this situation occurs globally and for several hours to days, we are talking about an electromagnetic storm.

If we want to get enough energy to our destination, several physical obstacles prevent it. Apart from the decrease in power with distance, this is of course also the wavelength. We need the shortest possible (the highest frequency) to be able to pass as much energy as possible to the target. For these reasons, microwave radiation is often used. On the other hand, the higher the frequency, the smaller the device must be (resonance cavities correspond to the wavelength or its multiples) and the harder it will be to cool. These weapons are often called non-lethal, although under certain conditions microwave radiation can cause health damage or even death.

On the side of involuntary reception, it is necessary to use the dimensions of individual metal components, which can substitute the function of the receiving antenna (for inductive binding). From the point of view of the attacker, it is therefore necessary to "tune" the frequency range accordingly. The received energy can then cause the following phenomena on different parts of the system. On the power side, these are voltage peaks, or harmonic oscillations capable of overloading defined ranges of the power supply. On the low-voltage parts (motherboard, memories and other components) then metal elements replace antennas, and because these components are extremely sensitive to voltage pulses and resonances, it is again possible to get voltage outside defined working ranges. In these cases, it is therefore mainly inductive and to some extent galvanic binding.

Similar phenomena manifest, for example, in a known lightning strike. Here, it is mainly inductive and capacitive binding, and to some extent galvanic. Fortunately, the probability of something like this is low - approximately 1:300,000 (the probability of a car accident is roughly 1:90, the probability of winning the EuroJackpot is 1:139,838,160), which can be translated into roughly one strike at the headquarters in 500 years. But the effects of such a strike are devastating for electronics. The question is, is it possible to create such a lightning or something resembling it artificially? And is it the only threat?

Electromagnetic pulse

Energy sources

Many nations and industries are involved in the development of weapons capable of influencing electromagnetic pulse behavior or computer technology. For both scientific and military reasons. But these weapons typically require high voltage input. Due to certain properties, power circuits can serve to some extent as a simple pulse generator. The simplest example is the so-called "Marx ladder," which can be created by any enthusiastic amateur. Its principle is used in various ionizers, often interfering with electronics, and in the case of a more powerful type at a distance of units of meters, it can disrupt its operation or lead to permanent damage to some components. In this case, it is nothing more than a cascade of capacitors and resistors, which is terminated by a spark gap. The voltage at the output can reach tens or hundreds of kV, so these are not toys for children. Yet the interference is not the aim of these devices, but they can be used for high voltage power supply.

In scientific centres, for high pulse power, they use mainly PFN (Pulse Forming Network) or Blumhein, where a cascade of capacitors and coils is used. Such a system can be discharged very quickly, which can be used to power pulse lasers in physical experiments. But discharging, and especially discharging coils, has certain effects on the environment. Each coil acts as an antenna, which sends a part of the power to the surroundings. Although PFNs achieve power up to the order of MW, higher energies are also discussed. But the emitted electromagnetic field is a side effect, not a primary one, but the goal is to pass the maximum energy to the output. These devices can interfere with electronics over a distance of several tens of meters, but it is also not their purpose. Their purpose, as in the first case, is to create an extremely high voltage and corresponding current.

The last device, able to act as a source for these generators and at the same time, to some extent, as an electromagnetic weapon, is the so-called MHD generator (magnetohydrodynamic generator). Its principle uses the division of the ionized gas, that is, the plasma, in the electromagnetic field into a positively and negatively charged part. This can then either be captured and converted into energy by means of electrodes, or, conversely, energy can be used to create a plasma and create a stream of gases. It should also be possible to use this as a rocket motor. In a similar way, it is possible to use salt water instead of gases. This procedure was mentioned as a theoretical "caterpillar drive" in the famous movie "Hunt for the Red October submarine." In a real environment, however, such a drive would need a huge amount of energy, therefore its operation would be impractical. On the other hand, as a power generator it is efficient, but it needs a flame temperature in excess of 3700˚C (usually gas combustion or fluid coal combustion). At the output it is able to provide power in the order of MW.

Electrical equipment generating electromagnetic pulse

Among the devices capable of generating an electromagnetic pulse is the so-called Flux generator (EPFCG, Explosively Pumped Flux Compression Generator) or otherwise HMCG (Helical Magneto Cumulative Generator). It is a primitive and inexpensive device that can still achieve remarkable outputs. It is a hollow metal tube filled with fast explosive (detonation velocity must be higher than 8 km. s^{-1}). The tube is inside the coil, which is connected to the radiating antenna at one end. If a high voltage and corresponding current is introduced into the coil, detonation of the explosive causes a short circuit on the winding. This compresses the magnetic field and most of the energy is subsequently radiated by the antenna [1]. The output is directed and efficient according to the power in the order of tens to hundreds of meters.

The design of such a device is extremely simple and inexpensive. According to available data, this principle was used both in the first electromagnetic bombs and is to be used in the Chinese DF-17. Such a construction is also likely in the case of terrorism. Unfortunately, due to the use of explosives in this case, it is not possible to speak of a non-lethal weapon, at the moment of initialization the surrounding area is threatened by debris.

Another device, capable of generating microwave radiation with a specific frequency, is a magnetron [3][4] (used in "microwaves" for heating food). It is an oscillator tuned by the size of the cavity, there is a regular signal at the output. Apart from high conversion efficiency, around 70%, it has the advantage of being able to automatically synchronize the output frequency. If there are more magnetrons connected to the same waveguide, their output frequency is aligned and the output energy is thus added up. The waveguide can be terminated by a directional antenna and depending on power it is possible to threaten electronics at a distance of tens to hundreds of meters. On the other hand, the first of these oscillators requires a vacuum chamber, albeit only with a low vacuum. For a long time it was used, for example, in radar for generating microwave signal. In the case of this generator, it is necessary to use frequencies that correspond to the dimensions of the conductors in order to make the most of the induction in these "antennas." From the point of view of the attacker, the frequencies used, for example, by a kitchen magnetron are not ideal, its frequency is relatively low and the microwave radiation of some frequencies is heavily absorbed by the wet material. Nevertheless, it is another of the risky technologies, available even for attackers with a low level of knowledge. The price of these devices is usually low and starts at around 50 euros, but with powerful devices there is no problem with the price of around 50,000 euros.

The Klystron [5] is another tool capable of producing a strong, usually oscillating output. It is a microwave oscillator and a signal amplifier, so there must be another oscillator on the input. It is sometimes called by other names that reflect the way it is constructed. It is a reflex or reflective electron, two-cavity/two-cavity, multicavity/multi-cavity electron, planotron, gyroclystron or relativistic klystron. In all cases it is a device where there is a source of electrons that is simultaneously connected to a high voltage. The electrons are therefore attracted to the collector inside the tube. The incoming microwave signal affects the current of the electrons, which then oscillate inside the tube. This leads to a huge amplification, but the amplifier has to be tuned to a specific frequency by design. More recently, relativistic klystrons are mainly studied, which achieve extreme amplification values and significant output values. Klystron requires an extremely high vacuum, with pressure values of at least $1.3*10^{-7}$ Pa, the best results are achieved around $7*10^{-11}$ Pa. The efficiency of energy conversion is about 42%, the value of amplification is above 50 dB for conventional klystrons. The record output described in the experimental data so far reaches 180MW. Again - the effective range is in the order of tens to hundreds of meters, the output can be routed, but the price of powerful klystrons can start at 100,000 euros and above. Besides klystrons it is possible to use klystrons, which are significantly smaller and have higher efficiency (they use voltage instead of the speed of electrons).

The last interesting device is the vircator [1] (vircator, abbreviation from VIRtual CAThode OscilatoR, microwave oscillator). This is a cavity where the source of electrons is again connected to one pole of high voltage, the other is the collecting grid. The electrons are accelerated and their momentum is affected by this voltage. If their momentum exceeds a certain limit, they pass by the collecting electrode. This creates a "cloud" of electrons that oscillates in a certain area, from one of the edges of this area comes the name (virtual cathode). These movements of the electrons then emit so-called braking, in this case microwave radiation. The maximum efficiency of this device reaches 30% and peak power around 80MW, the effective range in tens to hundreds of meters. For basic abilities, the cavity needs at least a low vacuum below 1kPa, but it starts reaching optimum performance only at a pressure below 0.1Pa. The price of powerful vircators starts at €100,000. Another development stage of vircators is reditron (Reflected Electron DIscrimination microwave generator), which achieves significantly higher efficiency, almost comparable to magnetrons.

Although it would be ideal to use masers (microwave laser), their use is disadvantageous. It achieves efficiency of about 3%, which at 10MW requires a huge resource. Therefore, I will not pursue the topic of masers further. On the other hand, it is advisable to monitor this area, in case of advancement of technology, this device could become a dreaded weapon.

These devices are never used separately. For their effective use, a primary source of energy is needed, which can be pulse capacitors, supercapacitors, MHD generators or even under specific conditions explosives. Their energy is subsequently converted by multipliers (Marx ladder, EPFCG) and usually charges PFN/Blumlein. This converts a certain amount of energy spread over time into a high pulse of energy in an extremely short time. This is the condensation of energy, the transformation, its formation and conversion to a short pulse. This energy is then provided to systems such as electromagnetic emitters (klystrons, reditrons). This makes it ideally possible to perform a pulse in repeatable pulses, which can be destructive to unprotected electronics.

Electromagnetic pulse produced by a nuclear explosion

A separate chapter for creating electromagnetic pulses is the explosion of a nuclear bomb. In this case, however, there are three separate pulses named E_1, E_2 and E_3, which have an impact on electronics. In addition to these pulses, a phenomenon known as System Inducted EMP (SIEMP) occurs for certain distances. Should a nuclear explosion occur, we will have other worries than how to revive computers.

Nevertheless, it is interesting to understand what phenomena occur, what their effects are and how to protect against them.
The first pulse is called E_1, which lasts for several ns during the course of a nuclear explosion. It occurs at a time when a ball of plasma is just beginning to form at the site of the original nuclear bomb. It is generated by a stream of gamma radiation from decay, possibly even by the fusion of the materials used, which knocks out electrons most often from oxygen and nitrogen atoms. The inconvenience is the possibility of a change of direction (dispersion) on these atoms, so there is no shadow as a result. Of course, if electrons are knocked out of the atoms, this creates an electrical charge, which then has to be discharged somewhere. For the idea, it is as if a huge spherical antenna is being created, which spreads from the point of the explosion. On the surface of this antenna there is a high voltage (it reaches tens to hundreds of kV/m).
Around the same time, the E_2 pulse begins. It lasts considerably longer, but its intensity is lower. It is caused by the material used for the nuclear bomb. The power limit, the so-called Taylor limit, is about 6kT TNT/1kg bomb, but the equivalent of 6kT TNT is just less than half a gram of matter converted into energy. The rest is activated by neutrons and possibly ionized. Some of these materials are unstable radioisotopes, which transform almost immediately and emit additional gamma radiation during this transformation. The pulse lasts up to tenths of a second, but its intensity reaches hundreds of V/m.
The last part is the E_3 pulse. It resembles, to some extent, the phenomena generated by solar storms. The point is that all ionized material (ionized air, bomb material, part of the material absorbed by the explosion) begins to orient itself through the Earth's magnetic field and is directed towards the poles according to the charge. This causes subsequent discharging, which starts a few seconds after the explosion and can last up to units of hours. The voltage produced is low, it is tenths of V/m, but harmonic oscillations can cause damage to some components.
Outside of the actual pulse (induced voltage), component damage occurs in several ways. First, there is the mentioned SIEMP, where an intense stream of neutrons can cause the activation of some atoms with all possible impacts. Starting with the EMP pulse generated locally, e.g. inside chips, after a change in chemical properties and subsequent change in properties of PN transitions. These phenomena can cause degradation or destruction of electronics. Then there is the passage of charged particles, which can short out e.g. electrolytic capacitors, break through resistors ... This leads in a better case, e.g. to discharge of memory cells, in a worse case to irreversible damage of circuits.
If there is an explosion high in the atmosphere (100-200 km), electronics are affected in a large area [6]. An explosion of a warhead equivalent to 2 MT TNT over the Czech Republic would ensure complete "extinction" of most systems throughout Europe. The layer of the atmosphere is strong enough to dampen most of the dangerous radiation. But all critical infrastructure, traffic control, communications, but also cars and other means of transport, would stop.

Solar storm

In the rank of induced electric fields, it is necessary to include a completely natural phenomenon, which is associated with the most massive body of the local planetary system, the Sun. The Sun not only controls the movements of planets and other bodies in the Solar System, but it is also a source of charged particles flooding interplanetary space. Our planet Earth is not fundamentally affected by the resting solar wind, as it is protected from the penetration of charged particles by its own magnetic field. This magnetic field acts as a certain form of shield, and in the equilibrium resting state, it is permeable for solar wind particles only in the polar regions, where the induction lines of the field sink into the Earth's atmosphere.

Our Sun, however, is a body equipped with a very complicated magnetic field. Therefore, we can observe phenomena on it, which we call phenomena of solar activity, solar activity. Among the most famous are undoubtedly so-called sunspots, dark places observable even in amateur conditions. Sunspots are evidence for the presence of very strong and complex localized magnetic fields, in which the magnetic induction reaches up to 0.6 T, while dimensionally such spots are comparable to planet Earth, i.e. with dimensions in the order of tens of thousands of kilometres.

While a complex magnetic field may be stable in the long term, in certain situations it can be violently disrupted. The process, which is referred to in the scientific literature as reconnection, leads to a sudden (even explosive) change in the configuration of the field to another, simpler form, in which process the accumulated energy of the complex field is released. The so-called solar flare occurs. Sudden bursts lasting minutes to tens of minutes are associated with the release of the order of 10^{25} J of energy[1)]. This energy is released in the form of electromagnetic radiation mainly in hard regions of the spectrum (X-ray regions, extreme ultraviolet regions) and in the form of directional beams of charged particles (mainly electrons and protons). Under certain circumstances, a solar flare may be accompanied by the ejection of hot solar plasma into interplanetary space. These phenomena are known as coronal mass ejections (CMEs) and can penetrate the entire Solar System. Because the flare has switched magnetic fields, a CME is usually accompanied by its own magnetic field, which has been "ripped off" from the Sun.

The eruptions take place in an extremely localized area of the Sun's surface and their manifestations are directed to an imaginary cone with a relatively sharp top angle. However, the distance between the Sun and Earth is large (150 million kilometres) and therefore a solar plasma cloud with an original size in the tens of thousands of kilometres becomes a large formation at this distance due to expansion, whose probability of collision with the bodies of the Solar System, including Earth, is not zero.

If such a collision occurs, the Earth's magnetospheric umbrella receives a violent shock of dense hot solar plasma, which also brings with it its own magnetic field. The magnetosphere reacts to arrival by shrinking on the windward side. If it brings with it a cloud of magnetic field of opposite orientation, the Earth's magnetic field on the windward side weakens. Both effects, shrinkage and possible weakening, lead to considerable changes in the whole magnetosphere of the Earth, not only on the most affected windward side. Measuring stations register temporal changes in the geomagnetic field, we are talking about an ongoing geomagnetic storm [7]. Charged particles are thrown from the tail parts of the Earth's magnetosphere along the lines of the geomagnetic field into the Earth's atmosphere, where they light up the auroras in the northern regions.

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1) This amount roughly corresponds to the energy produced by a 1 GWe reactor of a nuclear power plant over a period of about 300 million years.

In the ionosphere, a whole system of flat electric currents is induced and amplified, generating large electric fields with intensities of up to 1 V/km, which penetrate from the ionosphere into the lower atmosphere and further into the layers of the Earth's body. Electric currents are induced on conductive structures, which are called geomagnetically induced currents (GICs). GICs flow through the conductive structures of the globe (water-saturated rocks, the ocean), but also through technological elements of critical infrastructure, such as electricity distribution lines, metallic signal networks or pipelines.

Like the effects of CMEs, numerous instability and fluctuations in solar wind currents behave. They can also be the cause of geomagnetic storms, but usually their magnitude is smaller, although storms caused by irregularities in the solar wind can last longer than those caused by CMEs.

Geomagnetic storms are a relatively common phenomenon and are closely linked to the level of solar activity. Solar activity goes through a cycle of around 11 years, and geomagnetic activity shows a similar trend. Geomagnetic storms are rare during the period of low solar activity, when there are hardly any sunspots on its surface. Conversely, during the period of high, when the sun is literally "dotted" with spots, geomagnetic storms are almost a daily occurrence. However, the really strong ones, which can be counted on to have measurable effects on human technological elements, occur at a much lower frequency. Strong G4-class geomagnetic storms are counted at a hundred per cycle, and extremely strong G5-class storms at less than ten during the same period.

Historically, the so-called Carrington event of September 1859 is considered to be the archetype of a destructive geomagnetic storm. A technological fad of the time was the telegraph, which suffered a global blackout. Eyewitnesses describe how sparks were emitted from the telegraph poles, operators were electrocuted when contacting the telegraph key. On short routes, messages could be sent without connected batteries. On long routes, communication was impossible. Northern lights were observed in the Caribbean and Mumbai.

Such a massive event has not been recorded in subsequent history until now. It is estimated that it occurs statistically once every hundred to four hundred years. A more accurate estimate is not possible, as our observation series are too short. A careful analysis of the concentration of so-called cosmogenic elements shows that Earth seems to remember stronger events than Carrington's. Only none occurred in the modern era. Their estimated frequency is one to two times every thousand years. After their discovery, they are referred to as Myake events, and the expert public agrees that such an episode would pose a real problem for both terrestrial and space infrastructure.

The most beloved issue in connection with extreme geomagnetic storms is the presence of GICs in power distribution [8][9]. These currents, whose value is at best several hundred amperes, have a long time scale of changes in the order of a few minutes. GICs represent a DC contribution for equipment of 50 Hz AC distribution. Although its value is much smaller compared to working AC currents, it is enough, for example, to saturate the transformer core with one polarity and shift the working hysteresis curve. The core radiates a magnetic field, a reactive component grows, the core overheats. The oil bath can undergo pyrolysis, the transformer oil releases e.g.

hydrogen, methane and other flammable gases, the transformer gases. In extreme cases, the transformer may fail or even melt.
The presence of GICs generally disrupts the wave area of the working current, and these changes can be evaluated as dangerous by the securing elements. This leads to a sudden disconnection of network elements, or even entire network segments. This situation can then recur in the same network with a missing segment. In extreme cases, the network cascades.
On March 13, 1989, on a deep Canadian night, the CME arrived on Earth as a result of a series of eruptions that had been registered on the Sun in the preceding days. The phenomenon lasted only 90 seconds, and the James Bay area of Quebec province was without power. The 735kV Hydroquébec network line cascaded and was without voltage for nine hours. The sudden collapse of the network over a large area led to mechanical failures in a number of power turbines.
Large-scale GICs also flowed through three nuclear power plants in the Delaware estuary in New Jersey. Operators tried to regulate fluctuations in reactive power, noting the frequent formation of the reverse system (incorrect order of phases in the line). A week later they took samples from the output transformer of a gigawatt unit Salem I. The amount of gas in the oil was enormous, the transformer had to be shut down and disassembled. Engineers watched in disbelief the melted and heat-deformed plates of the primary winding. The transformer could not be repaired.

In the following two years, twelve key power grid installations crashed in Canada and the United States. Such an error rate had never been recorded before. Although the Quebec blackout is perhaps the best historically recorded event with effects of geomagnetic activity on the power grid, it was by no means the first or the last. Experts then began to ask themselves in the first decade of the 21st century whether, in the case of geomagnetic storms, there is a boundary above which problems occur and below which the installations are safe. Instead of studying individual events, statistics [10][11][12] came to the fore. And they showed very surprising results. Even the much weaker events are counted. All 4% of the operational anomalies recorded on the North American power grid can be attributed to the effects of solar activity. Statistically speaking. It is not possible to identify specific operational anomalies that would be caused solely by solar activity, but the trend of the increase is well established. The anomalies follow the trend of the 11-year cycle and are visibly concentrated in days with strong geomagnetic storms. This percentage was subsequently confirmed by reports from insurance companies dealing with insurance claims related to anomalies on the electricity supply.

Surprisingly, the statistical study showed that the increase depends little on the distance of the assessed point from the equator. In absolute terms, the effects are of course greater in areas closer to the poles, but the relative increase is similar even in states seemingly unaffected, e.g. Nevada or California. The increase in abnormalities does not only affect the high-voltage backbone network, but practically equally affects the low-voltage distribution network, leading directly to end customers. A similar statistical study was subsequently carried out for the Czech Republic, with basically comparable results. The number of anomalies on the Czech grid increased by 5 to 10% in the five days following the strong spike in geomagnetic activity. Other studies confirm these conclusions for Slovakia, Poland and other countries, for which these effects were not expected at all.

GIC amplitudes are not measured in the Czech Republic. Mathematical models show that it could be tens of amperes of DC current flowing through the neutral of the transformer station. It is not the hundreds of amperes that led to the destruction of the Salem I unit, but the longer-term repetitive load has its effects as a result. Some engineering studies have shown that one minute of exposure to DC current with an amplitude of one ampere leads to saturation of the transformer core with one polarity with all negative effects.

We must not forget the other negative consequences of stormy solar activity. During a geomagnetic storm, the disturbed atmosphere complicates radio communication and blinds navigation systems based on the propagation of electromagnetic signals, including the GPS system and similar. A significant part of the infrastructure depends on the presence of artificial satellites in Earth's orbit. Apparatus outside the Earth's atmosphere is much more sensitive to the vagaries of space weather, there are now twelve known cases of artificial satellites whose destruction was contributed to by solar activity. This does not include the recent loss of nearly four dozen Starlink satellites, of which solar activity also played an important role. There is no protection from the effects of events like Carrington's or Myake's, nor can it be arranged. The only conceivable defence is a fleet of spare satellites stored on Earth ready for launch.

Military technology is not spared from the effects of the sun. On August 4, 1972, a geomagnetic storm detonated a dozen sea mines, laid near the town of Hon La as part of the naval blockade of North Vietnam during the Vietnam War. The British patrol submarine Acheron was left without radio contact on February 24, 1956, while carrying out a patrol mission in the Arctic region. Before radio contact could be established after many hours, the British Navy announced a huge rescue operation. Recently, archives also revealed that at least once mankind was close to nuclear war, because of the sun. When the US Air Force lost radar signal and radio communication over the northern regions on May 23, 1967, the command was convinced that the instruments were being interfered with by the Soviets, who were preparing for a military strike. Fortunately, it quickly became apparent that the interference was caused by the sun, and the planes with nuclear warheads were able to remain on Earth. It was because of the interference of radio signals that the US Air Force and other world military organisations had been interested in solar activity since the 1950s and were heavily involved in the creation of worldwide observation networks.

Thus, there are a number of solar influences on technology. In this context, however, it should be stressed that the discussion of the direct consequences of the associated (electro)magnetic pulse is irrelevant. The changes in the Earth's magnetic field during a geomagnetic storm are at worst in the hundreds of nanoteslas, which roughly corresponds to the "EMP" caused by a subway train passing at a distance of a few dozen meters. Thus, ordinary electronics are not immediately threatened by the Sun, at least not by the equivalent of an electromagnetic pulse. However, this is no longer the case for globally functioning interconnected systems [13][14].

Electromagnetic pulse protection

This information is intended to draw attention to some of the neglected risks. The probability of a terrorist attack with an electromagnetic weapon is low for the time being and may remain so for a long time. So is a nuclear attack. Moreover, here, in a nuclear explosion, there is no protection against the E_1 pulse at the moment. But against solar storms and, to some extent, electromagnetic pulse attacks, there is a possibility to defend ourselves [15].

Protecting infrastructure technologies from the potential effects of a powerful geomagnetic storm is difficult. As has been said before, for example, for technologies located in Earth's orbit (telecommunications satellites or global navigation systems) it is completely impossible and there would be no choice but to replace the destroyed satellites with others.

In the case of ground elements, we are in a somewhat different situation. Experience from real-life situations that have already occurred in the past shows that the protection of key equipment of the electricity grid is quite critical. In the case of other natural disasters, such as earthquakes, there are widespread outages of entire large segments of the grid. After the major damage has been removed, traffic is usually restored by bringing voltage from a neighbouring segment that has not been affected by the disaster. However, in the case of a catastrophic geomagnetic storm, there is a risk of grid failure on the scale of entire continents. At best, the globalised grid would break up into island systems, at worst, a global collapse. Normal recovery scenarios would then be out of the question. It is therefore important not to let the situation come to this.

It has already become standard for high-voltage lines to include filters (basically capacitor banks) that aim to stabilise the working voltage and current wave area close to the expected working frequency (50 or 60 Hz depending on the continent). These filters aim, among other things, to suppress almost DC geomagnetically induced currents. However, history has repeatedly shown that the higher harmonic frequencies of GICs penetrate these filters. For the best protection, a capacitive filter would have to be installed on every stage of each key transformer. The current state is far from ideal.

Another approach (implemented in Finland, for example) is to include additional ZN resistance between the ground and neutral conductor, which both limits the penetration of GIC into the transformer node from the conductive substrate and reduces the asymmetry of the phases. However, the choice of the optimum ZN value is quite delicate and tests show that it could even change depending on the operational mode of the transformer.

A more reliable way is to develop high-voltage transformers immune to the presence of GICs. This marks a significant departure from the classic post-war design, when the high-voltage transformer was merely an enlargement of low-voltage transformers. However, these designs are still in operation in the world and their sensitivity to the presence of GICs is enormous. The design of GICs immune transformers is currently a patented technology. It is based on the presence of compensating windings and DC current diverters, which very effectively eliminate the presence of GICs in the transformer core [16], [17].

The cheapest countermeasure, however, is elaborated operational procedures clearly instructing operators of the surveillance centre how to act in case of an imminent danger. The basis is cooperation with the appropriate scientific organisations (this is standard in the USA, for example, where the Space Weather Prediction Center operates in Boulder with 24-hour service, a similar unit is also operated by the British MET Office and other countries such as Sweden, Finland, etc., the Space Weather Office is also operated by the European Space Agency ESA, to which the Solar Department of the Astronomical Institute of the AVCR contributes), which is able to inform in advance about the level of an imminent danger. For example, reduction of network load and increased monitoring of key nodes in real time are suitable preventive measures.

The situation is significantly simpler on low voltage distribution systems. The reason is that the connection, which is not part of the grid infrastructure, is only a sampling point. Its availability is therefore not critical for other components, although it may be critical from other perspectives. Current technologies allow the following components to be used for protection design:

- Varistor, a semiconductor element with variable resistance, dependent on voltage. Reaction speed around hundreds of ms.
- LC filters (Inductor-Capacitor) are used to filter high-frequency noise and overvoltage. They can be used as a supplement to protect against induced frequencies caused by EMF or geomagnetic anomalies.
- Chokes can limit rapid current changes and thus protect the device from current peaks. They can be used as a supplement to protect against current shocks in EMF pulses.
- Suppresors, transils or transnorbs are overvoltage diodes (TVS). They are actually classic Zener diodes. They allow very fast reactions to overvoltage in the order of ps to ns. They are the only ones that allow to create protection against direct lightning or EMP pulse.
- Gas Discharge Tubes (GDT) is used for protection against high overvoltages, reaction time ranges from ns to ms. It is suitable as protection against direct lightning strike. The disadvantage is the penetration of some power into the line (the reason is the power required to ignite the internal arc for the leak).
- Circuit breakers are used for repeatable protection against overcurrents. Thermal-magnetic circuit breakers have reaction of magnetic part in the order of ms, for thermal protection in the order of seconds to minutes. An alternative is electronic circuit breakers with reaction time in the order of ms.
- Circuit breakers are used for one-time protection against overcurrents. Fast fuses can react in the order of tens of ms, slow fuses in the order of seconds to tens of seconds.

Based on this information, it is clear that no protection is perfect. This is also the reason for layered protection, usually three-level [18]. At such a moment peak surges occur and then due to power and communication network outages the organisation practically switches to the island mode of operation, i.e. it is completely cut off from the surroundings. What needs to be ensured?

- It is necessary to have high-quality filtering and separation of energy inputs into the organization. At least three-level protection should be used. This includes surge and power peak protection, frequency filters, inverters, or other

components. Electromechanical galvanic separation can be used under certain conditions, but due to transmission losses it is operationally expensive.
- Protect critical power distribution from voltage induction by metal sheathing or coaxial lines and their grounding.
- Backup power sources that are regularly tested. These sources should be capable of up to 24 hours of operation based on fuel reserves, battery capacity, etc. Another option is to use renewable sources to provide emergency supply (all of which fall under the island power regime).
- Internal communications must be galvanically separated from external ones. Firewalls will not help here, interruption of conductive routes is necessary. Optoplanes or lines of communication routes with optical cables are ideal. Any metallic cable is vulnerable, fortunately for radio links this is only true at certain frequencies. Similarly, similar separation between buildings should occur to limit the impact of differences in ground potentials and lead currents.
- In case of use of cloud technologies, it is necessary to have a local copy of the data and ensure the possibility of activating a local copy of the data at least for critical operations.

The advice may sound exaggerated. But it will not only help in the event of an electromagnetic weapon attack. It has a chance to mitigate the effects in the event of solar storms, a nearby lightning strike, or, most importantly, operational failures in power distribution.

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