

Reducing the Vulnerability of Digital Protective Relays to Intentional Remote Destructive Impacts: Technical-and-Economic Aspects

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Abstract

In the article answers are given on the most important questions asked by experts regarding a new way for protecting digital protective relays from cyber attacks and intentional destructive electromagnetic impact, described by author in previous publication.

Index terms— digital protective relays, intentional destructive electromagnetic impacts, cyber security.

1 Introduction

Some of my previous publications [1][2][3] illustrated the vulnerability of digital protective relays (DPR) to intentional remote destructive impacts (IRDI) such as electromagnetic and cybernetic attacks. In [4][5][6] rationalizes the necessity of DPR protection and [6] explains a specific method of protection based on an inseries combination of DPR and reed switch-based starting element, which unlocks the DPR only if at least one of the controlled parameters (current, voltage, angle between them, etc.) approaches the DPR operating threshold, Fig. 1. The statement itself and the proposed method of DPR protection against IRDI is so unusual and so different from anything that has been known before, that experts inevitably have raised a barrage of questions and a tornado of emotions (alas, they are not always positive). Lack of the answers to many of the emerging

2 Answers on most Important Expert Questions

Question 1. According to the diagram the reed switches are hung on DPR all-around like fairy lights on the Christmas tree. It is clear that the reed switches are not hung on the inputs and outputs of DPR like "fairy lights", rather they are located inside the single shielded enclosure together with all other elements of the proposed protection device, and the design of the enclosure is similar to that of the DPR with the only difference being that there is no need for a screen but there is an access to the operating threshold control units of the threshold element reed relays. This separate module has the same terminal blocks for connection to external circuits, as the DPR. Question 2. There is a common perception that reed switches are not reliable (they "stick"). Is it reasonable to use them in devices which should be characterized with enhanced reliability? Reed switches, or rather reed relays used in the starting unit (SU) of protection devices, have a wide range of benefits compared to conventional electromagnetic relays. First, the contact points of dry reed switches are enclosed in a sealed cylinder filled with a mixture of pressurized inert gases or vacuum and so they are not exposed to adverse environmental factors (moisture, dust, gases). These contacts require no adjustment or cleaning during the whole lifetime.

Second, the reed relay is 3-5 times, or more, faster than the conventional electromechanical relays. Third, under alternating current such a relay has a reset ratio of 0.9 -0.95, which is much higher than for conventional relays. Fourth, the reed relay allows for easy approach to the galvanic isolation level between input and output (between coils and contacts) of tens of kilovolts, which is unattainable for conventional electromechanical relays [7]. Fifth, unlike the conventional relays, the reed relays have clear and stable pick-up thresholds under gradual increase of control coil current/voltage, thereby enabling the development of sensitive reed-based measuring units for protection purposes. In addition to the above, it should be noted that the dry reed switches are insensitive to the position in space and can be easily combined with electronic, electromagnetic and magnetic components to develop a number of different functional modules and devices on their basis [8].

High-quality vacuum and gas-filled reed switches manufactured by leading companies specializing in this industry (such as proposed for use in the device [9]) are not cheap (\$15 -\$30 each), but they are highly reliable and widely used not only in industry and communications, but also in military and aerospace. Thanks to a number of advantageous options, the reed switches occupy an intermediate position between semiconductors and electromechanical switching elements. Therefore, the automatic telephone exchanges, such as reed-based ATX ("Quant", etc.) are called "quasi-electronic". According to the specifications the lifetime of such ATX is 40 years and the number of failed reeds should not exceed 0.3 % within the period. So the figures speak for themselves.

However, the reed relays have one fundamental difference from the conventional electromechanical relays: their magnetic system is not isolated from the contacts, rather, it is formed by them. This difference causes low overcurrent capacity of the reed switches. Unlike the conventional relays, the reed switches do not withstand even the short-term contact overcurrent. This is due to fact that the magnetic field of the current flowing through the closed contacts of the reed switch is directed opposite to that of the coil magnetic field, holding the contacts closed, and weakens it, thus decreasing the contact force up to the appearance of the gap. This leads to the increased erosion and sometimes to welding of the reed contacts even under the short-term currents exceeding the maximum allowable value for particular type of the unit. Poor awareness of this aspect and ignorance of the reed differences from the conventional relays (with regard to the overload capacity) often leads to the equipment failures and, as a consequence, to the distrust of the reed switches. Under properly selected operating mode the reed switches provide reliable circuit switching throughout millions of operation cycles.

When using reed switches for switching external circuits with a wide variation of the current, no one wants to monitor the reed current operating mode. It is much easier not to use them at all, which often happens in practice. In the proposed construction some reed switches are included only in the device's internal circuits, where the current load is tenfold less than the maximum allowable reed current. Other reed switches turn off the digital input circuits with the maximum current of several milliamps, which is two orders less than the limit. And the current of several Amperes can flow only though the reed switch connected in-series with the output terminals of the DPR intended to switch on the circuit breaker trip coil. However, 1) these reed switches do not switch these currents directly (they only assemble the circuit under no-current condition), and 2) their type (Bestact R15U, produced by the Japanese company Yaskawa) provides high current margin. elements for current, voltage and angle between them. Thresholds of pick-up of all these elements must be less than the minimum values selected as the DPR set points. Question 4. Why do we need to use expensive DPRs together with some new and also expensive protection devices, if we can just go back to the cheap and resistant to IRDI electromechanical relays? Indeed, the electromechanical protection relays (EPR) have been operated for over a hundred years and still provide reliable protection against emergency operation for all types of electrical equipment. Suffice it to say that some large and diversified national power systems (for example, in Russian) are even today nearly 70-90% equipped with EPRs. However, despite the fact that EPRs have proven their high reliability, about 30-40 years ago all the world's leading manufacturers of protective relays stopped developing and improving EPRs and began to intensively develop first the solid state relays completely duplicating the functions and characteristics of EPRs, and then the microprocessorbased relays with advanced features and improved performance. About 20-25 years ago, most of the world's leading manufacturers of protective relays stopped producing EPRs and concentrated all their efforts on the DPRs. The main reason for this phenomenon was that it was much more profitable to produce and test printed circuit boards with electronic components on the automatic equipment, than to produce miniature mechanical elements on highprecision turning and milling machines and manually assemble them into the rather complex mechanical design, make manual tests and customization.

Due to the large difference in production costs between the EPR and the DPR, the consumer stands to gain too as today the cost of DPRs produced by world's leading relay producers is much less than the cost of EPRs with similar characteristics. The statement that today the EPRs are much cheaper than MPDs is not correct and is not supported by the analysis of world market prices. For example, if electromechanical relay for three-stage line distance protection type LZ31 (made by ABB) could cost about 30-35 thousand USD (according to current prices), its microprocessor-based analogue with improved characteristics, such as the relay type D30 (made by General Electric) costs only 7,500 USD and Chinese analogue of the relay (type GTL-823 made by Guatong Electric) costs even less only 5,000 USD today.

In addition, a powerful advertising campaign pursued by the developers of DPRs, universities and research organizations interested in financing of new projects did the trick. Today, to raise the question about returning to EPRs means to become an outcast in the community of experts and to gain a character of retrograde who is trying to stop technological progress. None of the experts or decision-making officials would take such a responsibility. And even if they take it, it is safe to say that they will be inundated with charges of obscurantism and incompetence. In addition, for the sake of objectivity, it should be noted that DPRs do have some features and functionalities unattainable by EPRs.

With all of these factors in mind it can be stated that the question of returning to the EPR is not relevant. Question 5. Suppose that the return to EPRs is really not possible today. But why not to use DPRs completed with these EPRs instead of inventing some new reed switch-based devices?

In fact, the combination of EPR and DPR has long been used in practice, Fig. 2. However, they are not connected in-series (as suggested) -they are connected in-parallel to duplicate each other in order to increase the reliability. As explained previously [5], such a method of DPR and EPR combination (i.e., in-parallel) is

essentially not correct. In parallel connections the EPR really must completely duplicate the DPR functions and have the same set points. In any combination of multifunction DPRs and EPRs the whole set of expensive EPRs should be used, thus making this project very doubtful because of its high cost and availability of large areas for installation of a large number of different EPRs. The suggested protective reed-based device should be much more simple, smaller and cheaper than a set of EPRs necessary to protect one DPR. And this is the only way to make its use promising. Question 6. To provide the versatility and full functionality the functional capabilities of the suggested protective device should be the same as of the set of EPRs. Hence, its cost should be about the same. Why will it be cheaper? Let's look how the EPR works. For example, let's consider current-dependent time delay relay -Inverse Definite Minimum Time (IDMT). It is an electromechanical induction disc type relay where an aluminum disk begins to turn slowly and the movable contact associated with this disk starts to approach the fixed contact under the certain threshold current. After some time determined by the speed of disk rotation (based on the current flowing through the relay coil) the contact closes (via the intermediate relay) the circuit of the circuit breaker trip coil.

The starting element of the proposed DPR protection device requires no current-dependent time delay. This starting element should trip only under the certain current, somewhat smaller than the disk pickup current. That's all. Other functions are not required, since all other functions will be done by the activated DPR. That is, in this case, instead of a complex and expensive IDMT relay we need only the simplest relay consisting of a coil and a reed switch. As another example, let's consider several types of Line Distance Protection relays. The electromechanical alternative of this relay (for example, type LZ31, Fig. 3) contains many complex and interconnected electromechanical assemblies providing three or four stages of line impedance measurement to the short circuit point corresponding to these delay stages, special form of characteristics, etc. As noted above, the cost of such relays is 30-35 thousand USD. However, the whole complex is actuated by the simplest starting element controlling the balance between line current and voltage, Fig. ???. The element is actuated by an imbalance between preset current and voltage values.

Large and complex distance protection relay types RYZKB, RYZOE, RYZFB, manufactured by ASEA in the 70s, Fig. ???, implement several protection features. However, all these relays are equipped with very simple starting element (see the diagram in Fig. ???). These starting elements were an integral part of complex structures and were not sold separately. The exceptions were some types of relays, which were produced in Russia, for example, relay type KPC -112, Fig. 6, containing special chokes and four-pole inductors with rotor. In essence, this relay is a separate starting element of distance protection. However, it is too complex, expensive and large. Anyway, the combination of such obsolete designs with the up-to-date DPR technology is hardly a good idea. This is a very simple device comprising of T-shaped core with swinging rocker (upper part of the letter "T") and two coils: voltage coil and current coil acting on the ends of the rocker. The position of the rocker with attached contact depends on the balance of the magnetic fields generated by the current and voltage coils. This assembly is an internal part of HZM relay design and has never been sold separately. The reed relay, built on the same principle of balance between current and voltage (Fig. 8), is much simpler and more reliable [9]. This relay responds to the difference between the magnetic fields generated by the current and voltage coils and its threshold can be adjusted within a wide range by turning the reed capsule. Such a starting element can be successfully used in the SU.

Thus, the proposed device with a small number of reed-based elements of current, voltage and the difference between them is much simpler and cheaper than a full-featured set of EPRs. In addition, reed-based starting elements do not require maintenance during operation, have significantly less delay within the overall relay response time and provide a high level of insulation between input and output unattainable for old EPRs.

Question 7. In some cases, the circuit breaker trip command is issued directly by the protective relays (such as transformer gas protection relay) and is simultaneously duplicated by the signals sent to the logical inputs of DPR, thus triggering the fault recorder. How then will the proposed device (which blocks logical inputs of DPR) work? This is easy to resolve: it is only necessary to send a signal from trigger relay contacts (in this case, gas relay) also to one of the inputs of SU of protection device. In this case the DPR is unblocked and the fault recorder starts operation and records gas relay trip information.

Question 8. There is a requirement of inadmissibility to include any additional locking elements into the circuit of breaker trip coil, and in the proposed device this circuit is switched by the contact of the addition auxiliary relay. Is this acceptable?

In fact, normally the open contact of an auxiliary relay is not connected into the trip coil circuit breaker. It is connected into the circuit connecting the output DPR relay contact to the trip coil of the circuit breaker. That is, this additional contact does not block the control circuit of the circuit breaker trip coil; it only blocks the output circuit of DPR. The control circuit of the breaker trip coil remains free to connect any external contacts or manually operated keys. Question 9. How to deal with complex protection units, for example, with the protection units providing the offset from the transformer excitation current inrush and containing filters of 2 and 5 harmonics? Should the proposed device also contain such filters? Or another example: the differential protection. How to ensure the device operation if the emergency mode exists only in the protected area?

No, the SU does not need such filters or excitation current inrush offset for operation. The tripping of the SU under the transformer excitation current inrush only unblocks the DPR for about 10 seconds and nothing else. The DPR will block against unnecessary pick-ups with its own algorithm. After 10 seconds the SU reverts

to the original state and blocks the DPR again. The same applies to the differential protection. The SU device does not care where the fault is, within or outside the protected area. The only important thing is the presence of short circuit current, while the damage zone will be determined by the DPR after the SU unlocks it. The SU response time is about 6 ms and almost does not affect the total response time of relay protection since the DPR proper time is 30-40 ms. Question 10. If the DPR and the EPR are connected in-series, the capabilities of relay protection will actually be limited by the capabilities of the EPR, as it has reduced capabilities and characteristics. Is this good?

No, it is not. The proposed device in no way defines any properties or characteristics of relay protection. It only unblocks the DPR at the moment when at least one parameter of the entire set of monitored parameters approaches the DPR set point. The subsequent behavior of the relay protection and its response to emergency mode will be completely determined by the properties and characteristics of the DPR.

It is obviously that in practice there are more complex modes of DPR operation, which are not discussed in the article, and such modes will require special starting elements to be developed. This is possible. However, even if this will require the development of such a special starting element, then based on a combination of reed switches and magnetic circuits it is possible to create simpler, cheaper and faster units compared to the traditional electromechanical relays. For example, the device between the current and the voltage or as power measuring element.

Figure ?? : Variants of quasi-electronic starting elements of differential protection

The combination of magnetic, reed switchbased and high-voltage discrete semiconductor elements provides additional opportunities. For example, Fig. ??a illustrates the simplest device responding to the current difference, and Fig. ??b illustrates the device with differential current. Thus, the above analysis clearly shows that the practical implementation of the proposed method of DPR protection is quite feasible from the technical and economic point of view. Certainly, such an implementation should be done by the manufacturers of DPRs, which can offer consumers a quasi-electronic SU as an option for improving the safety and reliability of the relay protection for critical objects.

3 III.

Interest in the Proposed DPR Protection Device and the Experts Opinion

Naturally, the production may be interesting for manufacturers of DPRs, while the question of interest in application of this device is much more complicated. Some relay experts believe that their professional duties are limited only to the operation of relay protection. They openly declare that they absolutely don't care about the problems of relay protection against IRDI. In their opinion, these issues must be resolved by "special services" (Intelligence).

These experts believe that they have enough problems with relay protection, so they are totally against any additional remedies that may complicate their already difficult lives.

Many experts enthusiastically accept any newfangled ideas and trends in relay protection, no matter what these innovations may lead to. Whether it is "proactive relay protection", "artificial intelligence" relaying, digital substation or smart grid, they accept " " anything? to get the money for development and implementation. Why not? Why not to make some money, as long as the money is green?! Moreover, such projects are well paid and even covered by special national programs. So why not come up with some other "smart" toys for relay protection? The main thing is to provide attractive groundings and use scientific words for designation.

There are experts who believe that if the computational capabilities of modern microprocessors used in the DPR allow providing relay protection and a lot of other options and functions, such options should be fully used. Why not to connect the set of different sensors to the DPR and use it to monitor the status of electrical equipment? Why not to use the same DPR as an information-measurement system or ACS substation controller in addition to its basic functions? That is, they support the principle: the more the better and you always "need" if you "can". Some officials responsible for making strategic decisions on directions of relay protection development act on the principle: if any developed nation began to work in a certain direction, we cannot keep up, let's catch up and overtake! This policy reminds me an anecdote narrated by the Englishman, a good specialist in relay protection:

A large tribe of Indians lived near one of the big American cities. They were dissatisfied with their weather predictor, who made too many mistakes. So their forward-minded chief decided to call the Weather Forecast Office, as the weather played a very important role in the life of the Indians. He was told that an accurate forecast was not available yet, but it was assumed that the coming winter should be cold. So, the Indians began to gather firewood just in case. After some time, the chief decided to check the forecast and called the Weather Forecast Office again. The answer was not long in coming: "Yes, of course, the winter will be very cold, now we know it! Look how actively the Indians are gathering firewood for the winter; they never make a mistake!" shown in Fig. ?? may be well used to control the angle desensitization by the passing current value (offset).

Many experts think: we want to move forward in the direction of technological progress, so you must provide us with protection against all these IRDI! But it is time to realize that the current trends of relay protection development in the direction of "digital substations", "smart grids", relay protection with artificial intelligence and so on, where the DPRs are not only used as a protection relays, but also receive commands and communicate with many external objects across multiple communication channels, do not enable providing reliable protection

of the DPR against existing dangers . Some apologists of the DPR perceive the above statement as rejection of everything new and progressive. One prominent and important functionary in the field of relay protection wrote "the author is trying to slow down the technological progress" in the review on the article devoted to hazards of modern tendencies in relay protection development. Such guardians of technological progress either mistakenly or deliberately garble my position, since I don't advocate abandoning new technologies in the field of diagnosis of electrical equipment or information-measuring systems, but only separating their relaying.

4 Summing Up

I firmly believe that we can ensure effective protection of the DPR against IRDI, as well as improve the reliability of its operation under normal operating conditions, only if the microprocessor-based relay protection will be used solely to meet the challenges of relay protection. I also believe that after the stormy period of euphoria associated with the new opportunities in relay protection provided by microprocessor technology, it is the time to come down to earth and re-evaluate the situation.

However, I have to say with much regret that the majority of experts and officials engaged in resolving the pressing problems of today have little interest in the potential problems and hazards associated with current trends in relay protection development. This is understandable, because none of them will take the responsibility for the collapse of the power system under the IRDI, since no instructions or regulations on this subject exist yet. On the other hand, the implementation of new techniques and new technologies brings honors and awards.

Probably, the developers of electromagnetic and cybernetic weapons give today's tendencies in protective relaying an ovation, like the snake who is satisfyingly watching a frog trying to jump into its mouth.

We can only trust that the wisdom of experts and officials will take precedence over the short-term mercantile interests and hope that as expressed in the well known proverb (a peasant needs thunder to cross himself and wonder) the "peasant" will not wait for the "thunder".¹



Figure 1: Figure 1 :

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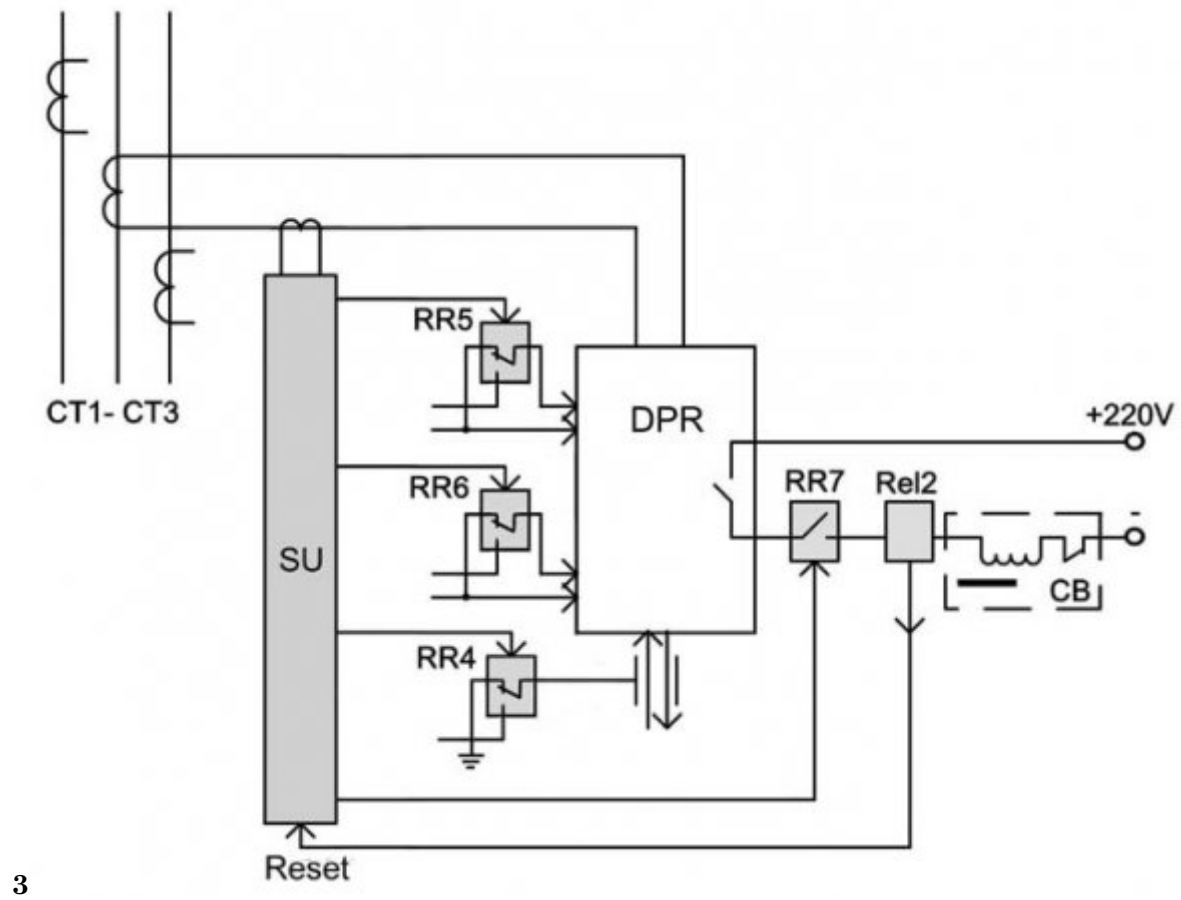
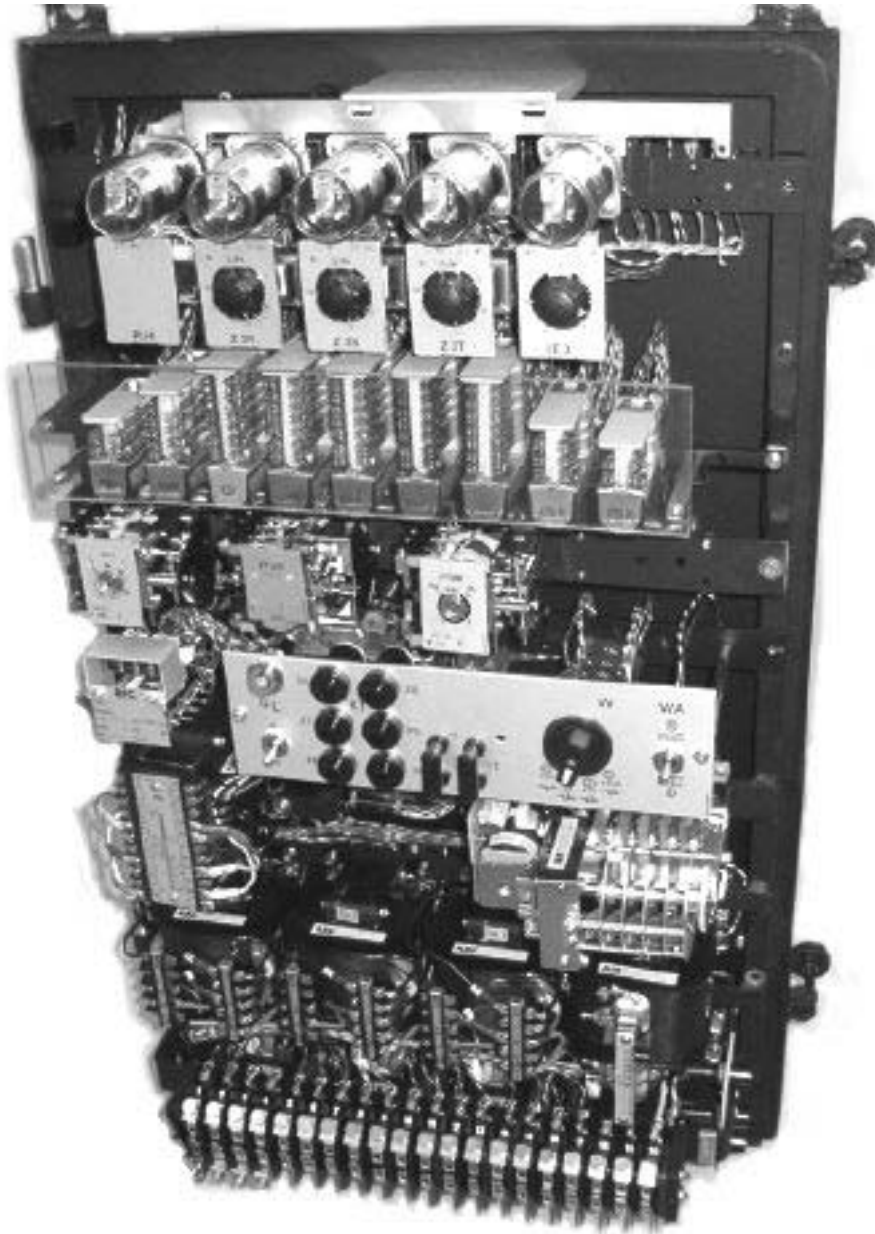


Figure 2: Question 3 .

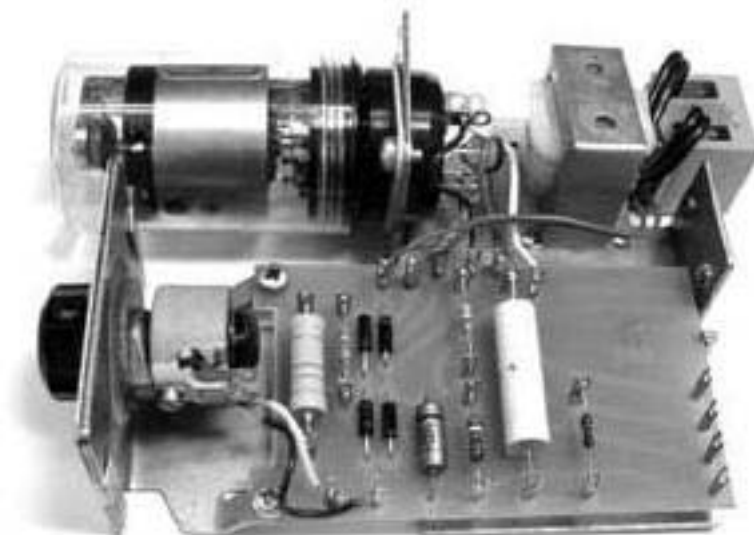
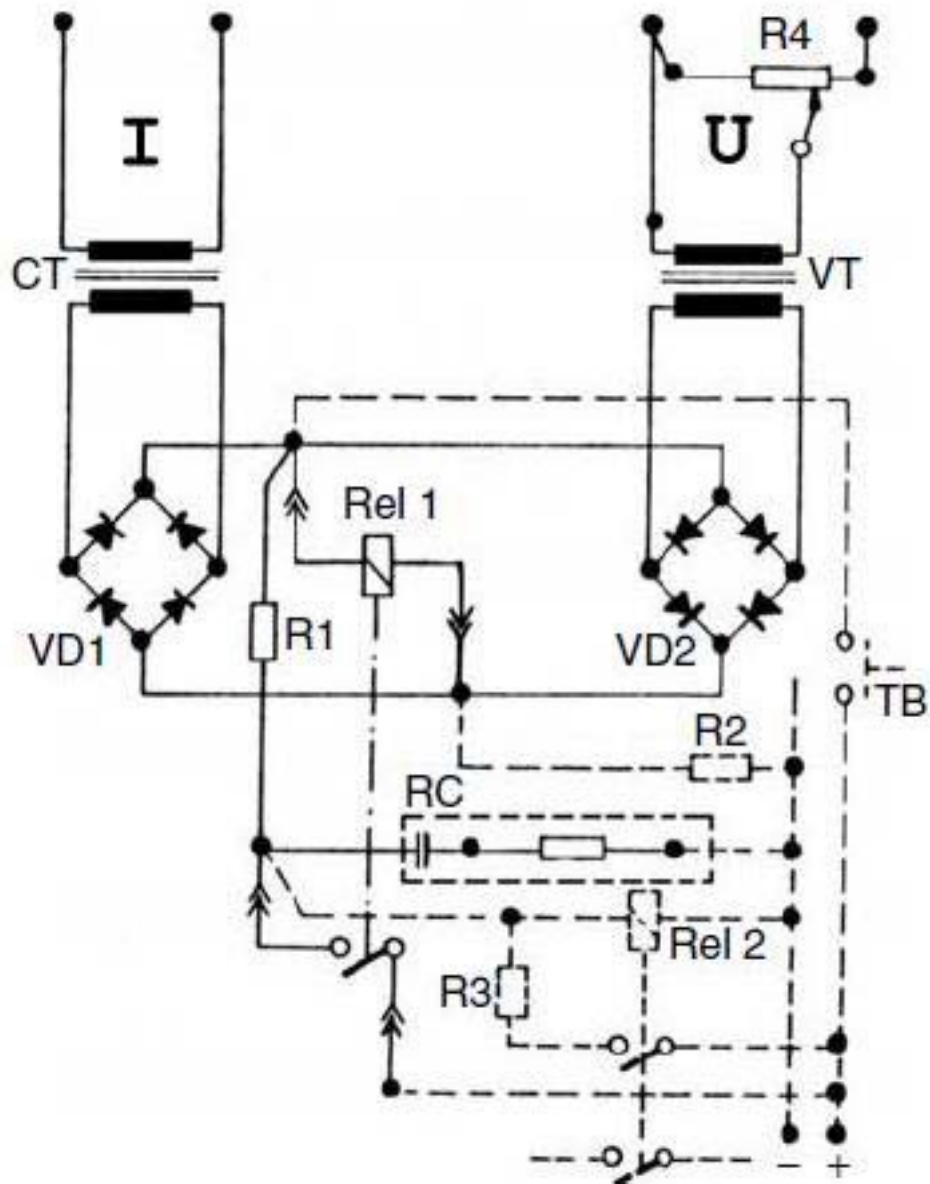


Figure 3: Figure 2 :



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Figure 4: Figure 3 :



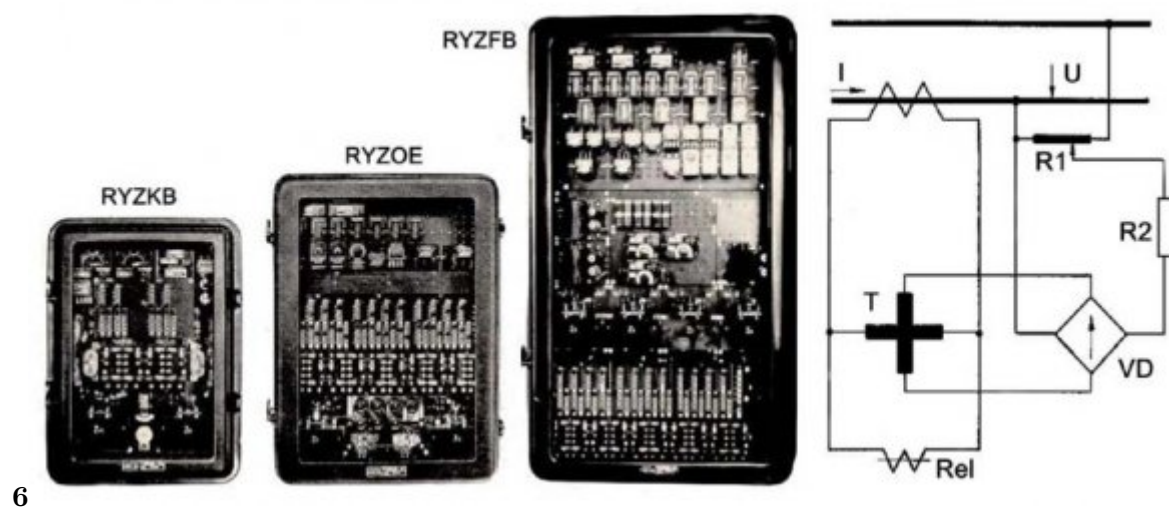


Figure 6: Figure 6 :

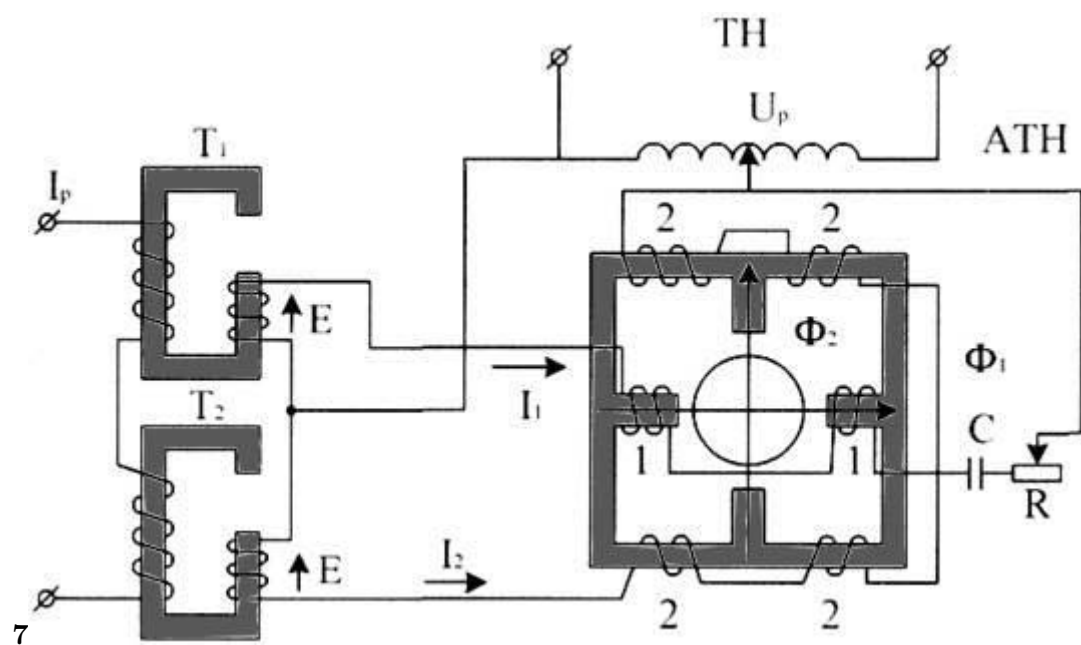
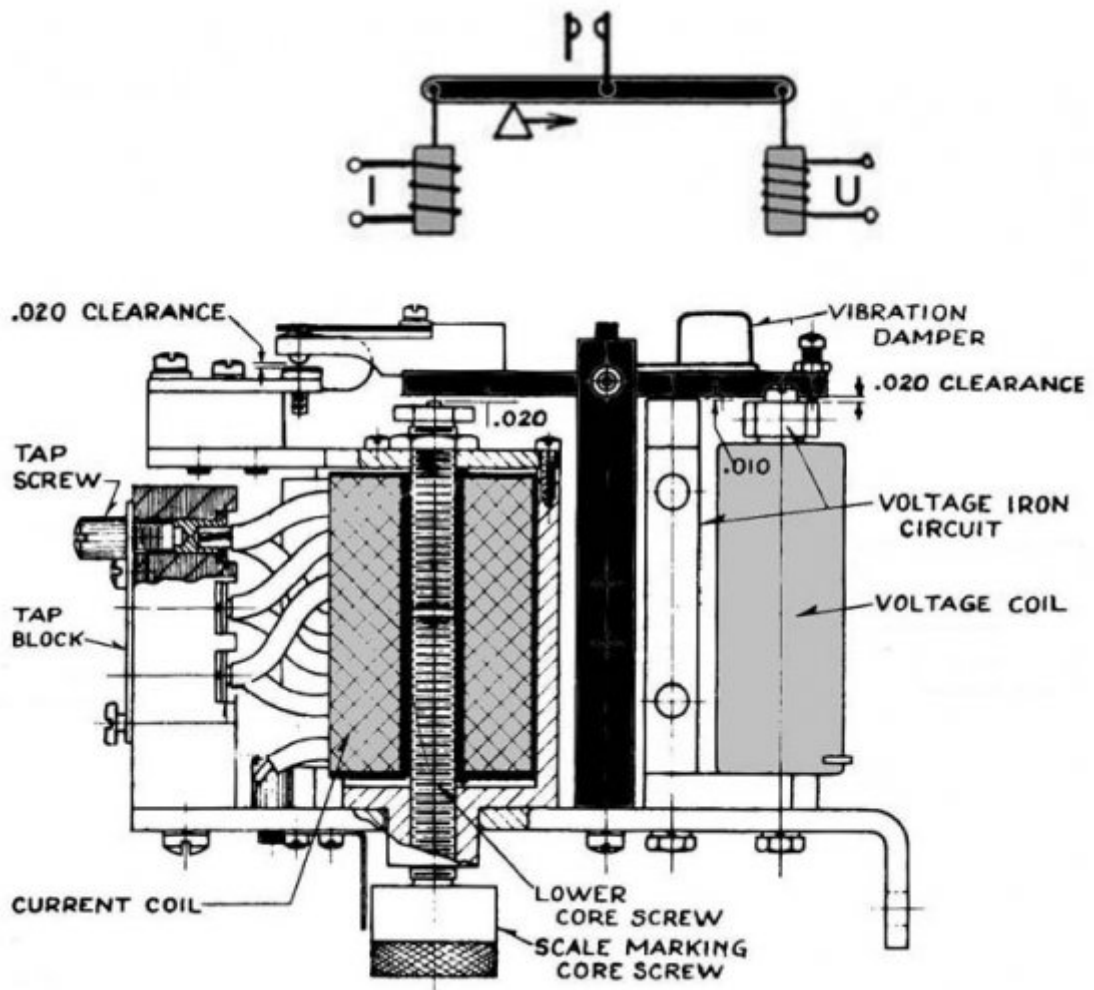


Figure 7: Figure 7 :



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Figure 8: Figure 8 :

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