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LABORATORY SET-UP FOR INVESTIGATION THE CHARACTERISTICS OF THE POWER TRANSISTORS' KEYS WHICH WORKS AS A PART OF SEMICONDUCTOR ENERGY TRANSFORMERS

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Modern system of adjustable electric drive are characterized by using in their construction semiconductor energy transformers based on full-controlled power keys, because their usage opens wide range of possibilities for creating high-efficient energy- and resource-saving devices. The process of designing the semiconductor energy transformer, or the process of improving existent devices, determines well-grounded selection of their constituent elements and circuit decisions. Herewith, special attention should be paid to accepted power losses in power keys and highly efficient methods for their cooling. Carried-out analysis of the power loss components in power keys has showed, that while designing the converters it is possible to assure minimum losses because of the ensuring such switching speeds, which would ensure optimal trajectory of the key turning-offs and turning-ons. Energy losses are also highly dependent on the passive safety system, which decreases possibility of turning transistor key to one of the breakdown modes. As the loss energy in the power transistors is extracted from semiconductor crystal and dispersed as a heat, important question is selection of the heat sink method. In this work it was presented the laboratory set-up, which allows one to conduct the number of experimental researches, namely: evaluation of the influence of additional fields used for formation the turning-on and turning-off trajectory of the power key on the dynamic energy losses; evaluation of the influence of the transistor passive safety system on dynamic energy losses; investigation of transistors' surge-protection methods effectiveness; investigation of the effectiveness of most popular t cooling systems used for ransistor keys. The developed laboratory complex allows students to conduct experimental evaluation the operating modes of the power IGBT's which works as a part of semiconductor energy transformers.

Key words: semiconductor key, laboratory set-up, dynamic losses, switching speed, safety circuits, cooling system.

ЛАБОРАТОРНИЙ КОМПЛЕКС ДЛЯ ДОСЛІДЖЕННЯ ХАРАКТЕРИСТИК СИЛОВИХ ТРАНЗИСТОРНИХ КЛЮЧІВ У СКЛАДІ НАПІВПРОВІДНИКОВИХ ПЕРЕТВОРЮВАЧІВ ЕНЕРГІЇ

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Сучасні системи регульованого електропривода характеризуються застосуванням напівпровідникових перетворювачів енергії на повністю керованих силових ключах, оскільки їх застосування відкриває широкі можливості при створенні високоефективних енерго- та ресурсозберігаючих пристроїв. Процес проектування напівпровідникового перетворювача енергії чи доопрацювання існуючого вимагає обґрунтованого вибору складових його елементів і схемотехнічних рішень, причому особливу увагу необхідно приділити забезпеченню прийнятних потужностей втрат у силових ключах та високоефективних методів їх охолодження. Проведений аналіз складових втрат потужності силових ключів показав, що при проектуванні перетворюючих пристроїв забезпечення мінімальних втрат можливе за рахунок формування швидкостей перемикання, які будуть забезпечувати оптимальну траєкторію ввімкнення та вимкнення ключа. Втрати енергії також суттєво залежать від системи пасивного захисту, яка зменшує ймовірність попадання транзисторного ключа в один із режимів пробою. Оскільки енергія втрат силових транзисторів виділяється в напівпровідниковому кристалі та розсіюється у вигляді тепла, важливим питанням є вибір способу його відведення. У роботі зображено лабораторний комплекс, що дозволяє проводити низку експериментальних досліджень, а саме: оцінку впливу додаткових кіл формування траєкторії ввімкнення та вимкнення силового ключа на динамічні втрати енергії; оцінку впливу систем пасивного захисту транзисторів на динамічні втрати енергії; дослідження ефективності застосування методів захисту транзисторів від перенапруг; дослідження ефективності застосування найбільш розповсюджених систем охолодження транзисторних ключів. Розроблений лабораторний комплекс дозволить студентам проводити експериментальну оцінку режимів роботи силових IGBT у складі напівпровідникових перетворювачів енергії.

Ключові слова: напівпровідниковий ключ, лабораторний стенд, динамічні втрати, швидкість перемикання, захисні кола, система охолодження.

PROBLEM STATEMENT. One of the most effective world-recognized techniques for energy- and resource-saving is commissioning of controlled electric-drive (ED) systems into all branches of industry. These systems are characterized by implementation in their construction the power electronic devices, main part of which are semiconductor keys. The transformation of electric energy and control of its parameters in power electronics are carried out using rectifying diodes, thyristors, transistors and hybrid power circuits. With the creation of bipolar transistors with isolated gate (IGBT modules) and integrated control circuits for them (drivers) the application area of the ED systems with transistor converters became practically unbounded. So, in early 90th a lot of companies made commercial transistor electric drives with power rate up to 350 kW (0.4 kV), and in 1995–96 it appeared commercial prototypes of the systems with rated power up to 1..1.5 MW. Nowadays it is commonly used transistor electric drives with the power rate of some megawatts and up to 10 kV voltages [1].

The fully controlled power semiconductor keys provide high values of such features as switching power, efficiency, dimensions and weight and also reliability. Their usage in converters allows one to provide economically efficient energy conversion and opens a wide range of possibilities for creation the modern converters.

The designing and creation of converters assumes variable variants of optimality criterions [2]. Most typical criterions are minimum cost price along with high technical parameters; or ensuring high technical parameters, as a rule, high efficiency; or ensuring converter miniaturization. These requirements often are interrelated, because huge losses are hard to be eliminated in small-sized equipment. According to this, depending on desired optimization criterion, the tolerable power losses in power transistor keys (PTK) could be determined basing on the following assumptions [2, 3]:

– limiting capability of transistor cooling system with appropriate technical and economical parameters (size, weight, cost) and taking into account maximum estimated environment temperature and maximum allowed PTK temperature;

– minimum possible losses to ensure high efficiency or small size of the converter.

Designing according to the second variant allows one to ensure significantly lower power losses in PTK comparing to the first variant. This could be possible because as the maximum calculated semiconductor temperature under its hardest rated operating mode it is recommended to take the value 25 °C lower than maximum allowed transient temperature. This leads to increase PTK lifetime, and ensure safety factor in case of converter overload.

Also it should be mentioned, that, besides designing new converter it also could appear more local task to improve existing device without cardinal change of its scheme or construction (for example, in case of change the type of power transistor key).

Thus, both designing and improving of the semiconductor energy converter demands grounded choice of the power keys. Basing on previously said, it is clear that it is necessary to pay special attention to such questions, as ensuring acceptable power losses in power keys and ensuring high-efficient cooling methods.

The aim of the work is to develop laboratory set-up for investigation transistor keys parameters, which allows students experimentally estimate operating modes of power IGBT's which works as a part of semiconductor energy converters.

EXPERIMENTAL PART AND RESULTS OBTAINED. As it is known [2, 4], the work of power semiconductor keys is characterized by the presence of losses, which could be separated to the losses under transients during switching (dynamic losses), the losses under switched-on or switched-off mode (static losses) and the losses in input control circuit.

Static losses are related to the fact, that under switched-on mode transistor direct voltage is minimal and current is defined by load parameters. Under switched-off mode transistor current is minimal and it's defined by its inner resistance, and voltage is controlled by power source. According to this, this kind of losses depends only on chosen semiconductor key type and do not contribute significantly in the total power losses.

Losses in output control circuit are related to the value of charge, which is accumulated in input switch capacity, and the value of control voltage, which is determined for key switching. As the power IGBT control current is relatively small, thus, by analogy to static losses, the amount of these losses depends on chosen transistor type and also do not contribute significantly in the total power losses.

In its turn, dynamic key losses are related to the fact that during transient processes transistor appears for definite time under high voltage and significant direct current state [5]. If the switching time is not limited, a part of power losses in total losses during switching could became significant. Usually, control of IGBT switching speed is derived by serial connection of limiting (breachblock) transistor between output driver node and key input circuit. At that, for keys with high switching speed, among which are MIS- and IGBT-transistors, the use of breachlock resistors under high load current amplitudes is requirement for safe work. Usually, minimal value of this resistor is shown in reference information from manufacturer for each type of power transistor.

The use of limiting resistor is a classical solution for effective control of switching speed. However, in some cases, for example, for limiting current and voltage surge under commutation of resistive-inductive load, the additional unidirectional circuits are used [2], which provide speed limit separately for switching-on or switching-off, or simultaneously under switching-on and switching-off. Besides brenchclock resistors the problem of the limiting the switching speed could be solved using drivers with separate control circuits for switching-on and switching-off signals [6]. However, in any case, limiting the switching speed leads to significant increase of dynamic losses, which is especially visible on the high frequencies of transistors switching. Thereby, the analysis of the losses components of power transistor keys has showed that during designing the converters, ensuring minimal losses could be derived by formation switching speeds, which will ensure optimal trajectory of the key working point. According to this, in order to provide experiments for investigation the influence of IGBT control circuit on dynamic losses, it was developed laboratory set-up, with scheme shown in Fig. 1.

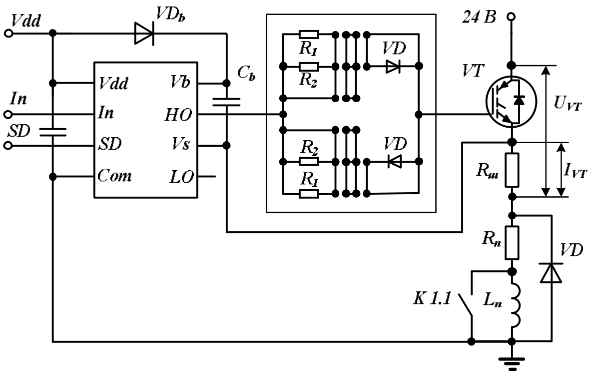
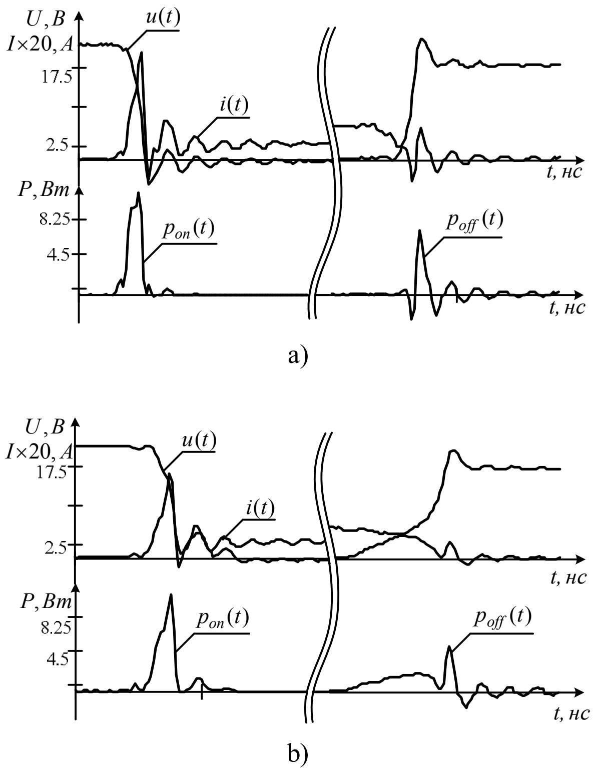


Figure 1 – The scheme of laboratory set-up for investigation the IGBT control circuit influence on energy dynamic losses

The shown laboratory set-up contains transistor control driver (*IR 2104*), scheme for connecting output driver circuit to input transistor circuit (formation of the determined scheme is ensured by connecting the elements of jumper control circuits, power transistor key *VT* (*IRG4BC10UD*), and reverse gate *VD* (*VS-15ETH06PBF*). The voltage of power bus line of the laboratory set-up is 24 volts. Laboratory set-up also allows one to conduct investigation of the working modes of power transistor with resistive-inductive and active load, which is assured using contactor *K 1.1*, which eliminates the load inductance L_n.

In order to estimate the influence of IGBT circuit on dynamical losses it may be used the proposed structural scheme for connecting driver output circuit to transistor input circuit. The use of this scheme allows one to investigate different circuits used for formation the transistor working point with different values of its components ($R_1 = 24\,\text{Ohm}$, $R_2 = 400$ Ohm), which aimed to limit the switching speed. In order to conduct experimental research it should be done measuring of voltage on the key (U_{VT}) and current flows thru the key (I_{VT}). Latter could be done using shunt (R_{sh}).

Currents and voltages, which were derived experimentally, and computed power losses signals, for conditions of switching transistor power key for the case of switching-on gate resistance of 24 Ohms are shown in Fig. 2,a, and for the case of switching-on gate resistance of 400 Ohms are shown in Fig. 2,b.



a)

b)

Figure 2 – Currents, voltages and power losses signals for the case of IGBT switching with gate resistances of 24 Ohms (a) and 400 Ohms (b)

According to experimental signals, shown in Fig. 2, the energy of losses for one transistor key switching during switching-on (e_{on}) and switching-off (e_{off}) could be calculates as following [7]:

$$e_{on} = \int p_{on}(t)dt;\; e_{off} = \int p_{off}(t)dt, \qquad (1)$$

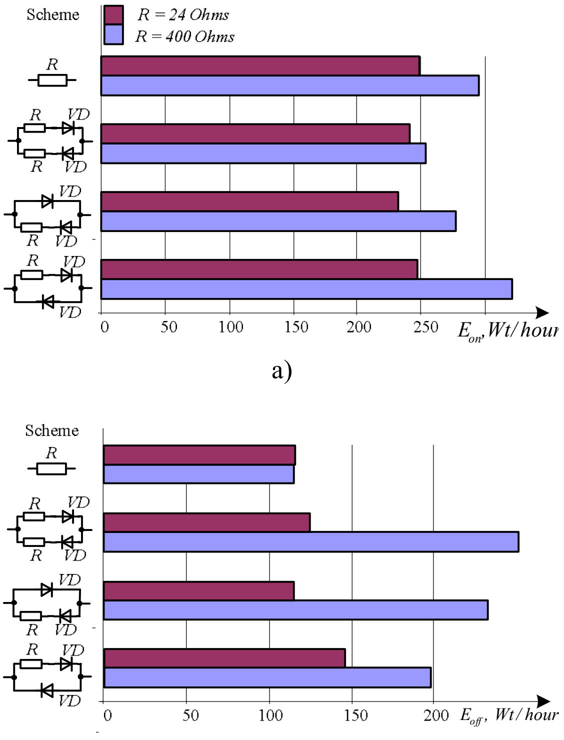
where $p(t)$ is loss power, which is determined as $i(t) \cdot u(t)$ (during calculation of e_{on} integrating limits are specified by direct current rise time, and during calculation e_{off} – by direct current fall time).

A calculation of an average loss power in a key structure during switching-on (E_{on}) and switching-off (E_{off}) during one working hour of transistor could be done using following expression:

$$E_{on} = e_{on} f 3600;\; E_{off} = e_{off} f 3600, \qquad (2)$$

where f is IGBT switching frequency, Hz.

The dependencies of dynamical energy losses for different cases of additional circuit construction for IGBT working with resistive-inductive load are shown in Fig. 3, where it is shown the losses for switching-on and switching-off for case of transistor one hour work with limiting resistances of 24 and 400 Ohms.



a)

b)

Figure 3 – The influence of additional circuits for IGBT working point formation on dynamic energy losses during switching-on (a) and switching-off (b)

Thus, developed laboratory set-up allows one to provide estimation of dynamic power losses during the work of transistor power keys. However, additional circuits, connected to IGBT, also significantly influence on its switching trajectory [7]. As an example of such circuits it could be named transistor safety circuits, because, as it's commonly known, power semiconductor keys are subject to possible breakdown (electrical, as a result of high voltage, or thermal, as a result of overheating because of high current) and if input voltage which supplies key could be easily calculated, then over-voltages which appears on a circuit's stray inductances, could be hardly predicted. According to this, in order to decrease probability of appearing transistor key in one of breakdown states, the necessary requirements for designing the semiconductor energy transformers are detailed design study, compact placing of power elements and minimization of electrical connection between them [8, 9].

In order to determine the influence of safety circuits on IGBT dynamic losses lets analyze the methods for over-voltage abatement in power energy converters. As a rule, transistor key breakage mechanism could be divided into breakage of transition “gate-emitter” and breakage of transition “collector-emitter” [2, 8].

Over-voltage at transition “gate-emitter” could appear as a result of driver breakage or breakthroughs on communication line between driver and transistor. To avoid such problem it's enough to insert over-voltage limiter between gate and emitter (as a rule, for the value of 18 V); the gate capacity itself would decrease dU/dt down to values, which are suitable for limiter, moreover, for most transistors the breakage of the gate could appear under voltage not less than 35..45 V, which means that there is significant reserve for over-voltage pulse suppression. The only mandatory requirement is that limiter should be installed as close to transistor as it possible. Thus, the use of safety system for transient “gate-emitter” do not influence significantly on dynamic losses value.

In its turn, to protect transient “collector-emitter” there are two main ways: active and passive. Active way requires such kind of transistor control, when voltage surges minimizes; to this way it belong the active protection and the gradual switching-off. The easiest way to ensure active protection is gradual switching-off of the transistor. As a rule, in order to generate gradual switching-off it should be installed resistor of high nominal value between driver input circuit and transistor gate. As result, the long-term gate capacity discharge mode takes place, and, as result, the switching-off speed is lower. In this case dynamic losses would be significantly dependent on the nominal value of gate resistor, which was described previously.

The active protection principle itself has more complicated schematic solutions for the case of protection power key from over-voltage [9]. Under active protection (active clamping) it should be assumed such circuit, where redundant voltage from collector-emitter circuit transfers to the gate, and, as a consequence, transistor opens. Active protection, as a rule, connects when it is needed, and, as a result, do not lead to increase of dynamic losses in rated operating mode, however, it inferior to passive protection because of its speed and simplicity of implementation.

Passive protection, in difference to active, is always connected, independent on its need at the moment. This type of protection could be represented in two ways [8]: decrease of dU/dt and over-voltage limiting. To the first way it belongs different types of snubbers, and to the second way – varistors and limiters. As this type of protection is always powered, it influences significantly on switching, and, as a result, leads to significant power losses.

Basing on conducted analysis of power transistors protection methods, we may conclude, that the passive protection methods influence most significantly on dynamic losses. According to this, it was developed laboratory set-up basing on scheme presented in Fig. 4, aimed to conduct experiments for investigation the influence of passive protection methods on IGBT dynamic losses. The presented laboratory set-up contains transistor control driver (*IR 2104*), power transistor key *VT* (*IRG4BC10UD*) and wheeling diode *VD* (*VS-15ETH06PBF*), physical models of stray inductances (L_{s1}, L_{s2}) and transistors safety circuits scheme, connected to collector and emitter of semiconductor key (formation of necessary scheme is provided by connection the elements of safety circuits using jumpers). Power bus of the laboratory set-up is powered by 24 V.

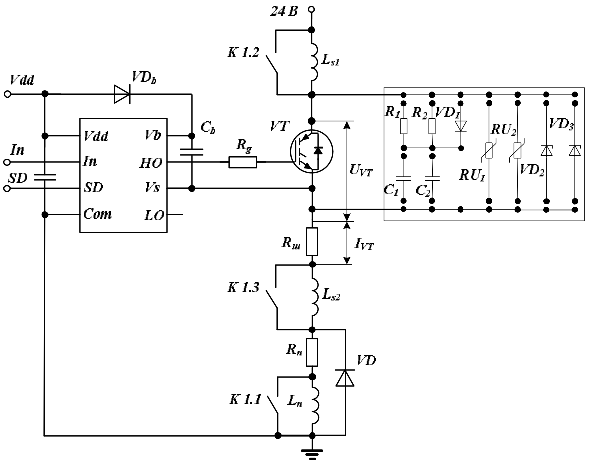


Figure 4 – The scheme of laboratory set-up for investigation the IGBT passive protection methods

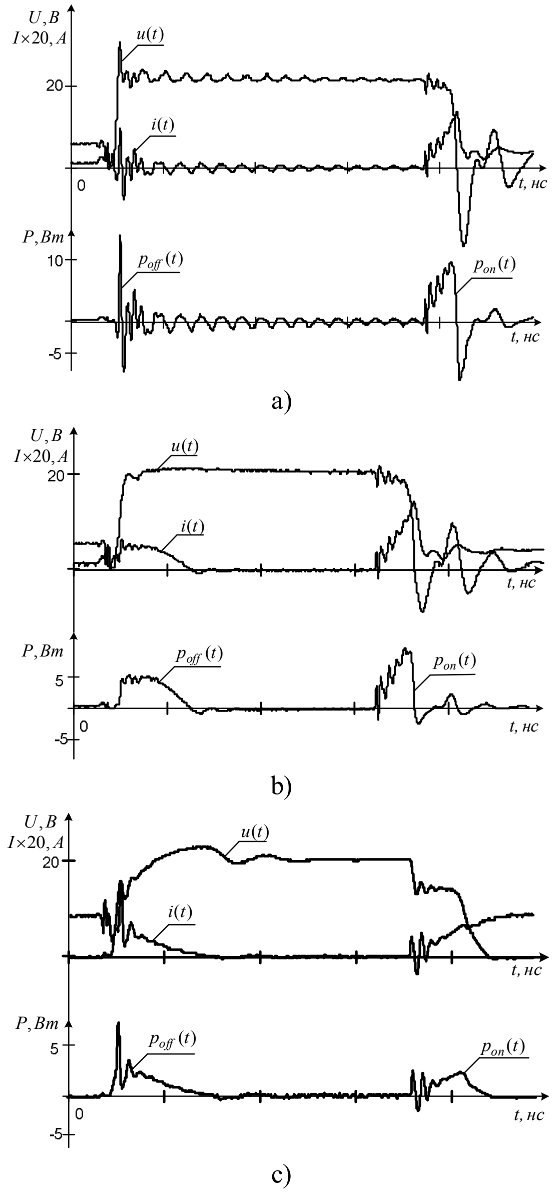
The presented laboratory set-up, besides investigation the influence of protection circuits on dynamic losses, allows one to conduct research on the effectiveness of the power transistor protection from over-voltage while working with resistive-inductive and inductive load, which is provides by use of contact *K 1.1*, which is used to eliminate load inductive component L_n.

In order to provide the possibility of investigation the protection from over-voltage methods for power transistors, in laboratory set-up it was installed physical models of stray inductances, which could be eliminated from the circuit using contacts *K 1.2* and *K 1.3*. As a passive protection method it is used the coupling scheme of snubber circuits, which allows one to conduct investigations of the effectiveness of the use of *RC*- and *RCD*-circuits, varistors ($RU1$, $RU2$) and TVS-diodes, also known as suppressors ($VD2$, $VD3$).

Thus, the presented structure of laboratory set-up allows one to provide the experimental investigations of the following working modes of the converter: stray inductance is absent (mode #1), stray inductance included before collector of the transistor (mode #2), stray inductance included after emitter of the transistor (mode #3), stray inductances are included before collector and after emitter of the transistor (mode #4).

Experimental investigations assumes measuring voltage signal on a key (U_{VT}) and current signal thru the key (I_{VT}). The latter could be done using shunt (R_{sh}). Evaluation of the effectiveness of presented over-voltage protection methods could be done on the basis of the following criterions: relative over-voltage value during IGBT switching-on and switching-off (Δu_{on}, Δu_{off}), time of switching-on and switching-off (t_{on}, t_{off}), dynamic energy losses per one hour of converter work (E_{on}, E_{off}).

The experimental signals of current, voltage and IGBT dynamic power losses under the presence of stray inductance before collector of transistor and when protection *RCD* circuit and TBS-diode are included in the circuit are shown in Fig. 5. The results are presented for the case of energy converter work with resistive-inductive load.



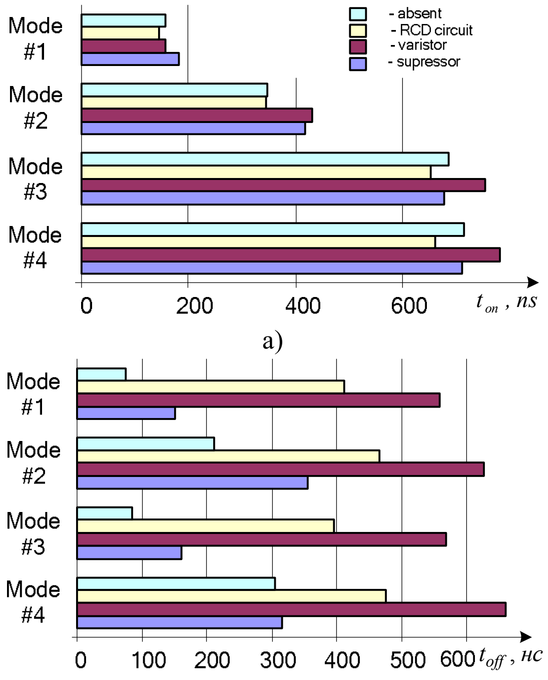
a)

b)

c)

Figure 5 – Current, voltage and IGBT power loss signals under stray inductance on the collector of the key (a) and while protection *RCD*-circuit (b) and TVS-diod (c) are included in the circuit

Analysis of derived results leads to conclusion, that the use of additional protection schemes for semiconductor keys allows one to solve the task of decreasing the voltage of the "collector–emitter" transition. However, along with this it could be observed significant deterioration of such commutating parameters, as switching-on and switching-off times (Fig. 6), which, in its turn, leads to increase the energy losses while transistor is in switching mode (Fig. 7).



a)

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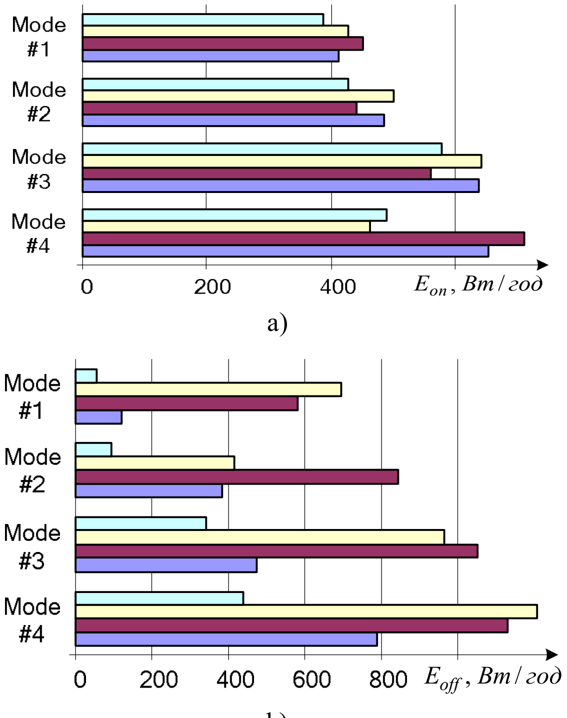
Figure 6 – Dependence of IGBT switching-on (a) and switching-off (b) times on the type of protection circuit



a)

b)

Figure 7 – Dependence of the losses under IGBT switching-on (a) and switching-off (b) on the type of protection circuit

The experiments aimed to investigate the effectiveness of IGBT circuits for over-voltage protection were conducted for energy converter work with resistive-inductive load (Fig. 8). It also should be mentioned, that over-voltage value under IGBT turning-on does not dependent on the protection scheme, and it is determined only by the placement of stray inductance.

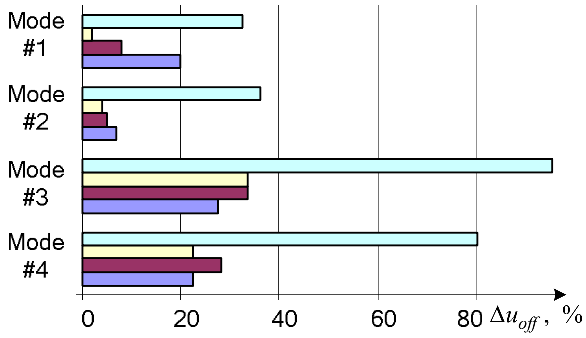


Figure 8 – The effectiveness of using the IGBT protection circuits

Thus, laboratory set-up allows one to conduct research both for investigation the influence of the most wide-spread methods for protection power transistor keys from over-voltage on IGBT dynamic energy loss, and for the effectiveness of their use.

Considering, that the energy of loss of power transistor key releases in semiconductor crystal and spreads as a heat, which should be abstracted from p–n barrier, another important question is the grounding the way for heat abstraction [2]. As it is known, the heat channel abstracts from a small volume of semiconductor crystal, in which it appears, penetrates thru number of layers of different materials used for manufacturing thermal compensators (tungsten, molybdenum), thru fillers (silver, tin), the basement (copper), cooler (aluminum, silumin), and abstracts to environment. Each from these layers has its own heat transfer parameters and resists to thermal flow penetration, which leads to temperature difference between semiconductor structure and each from these layers. Thermal calculation, taking into account thermal parameters of all layers types, is quite complicated multivariable problem. Thus, practically it used some simplifications, which allows one to conduct numeric evaluation of allowed working modes of PTK.

Usually, in order to increase output capability, with given maximum temperature of a structure, they try to decrease total heat resistance [3]. In semiconductor power devices the main part among total heat resistance is the resistance "cooler-environment", which could reach 70–80 %, resistance "structure-body" is 15–25 %, and the rest is resistance "body-cooler".

Resistance "body-cooler" is unstable and depends on the body type, contact area, application force between body and cooler, type of the heat-conducting interlaying between body and cooler. The use of heat-conducting material decreases resistance “body–cooler” to 3–5 times, and including electric isolating interlaying increases this resistance to 4–8 times [2].

The heat resistance “cooler–environment” depends on the type of a cooler and an environment. The most frequently used are air coolers (radiators). As cooling environment it usually used air, oil or water. Comparative heat-transfer of a system, where as an cooling environment used air, oil and water characterized by relation 1:10:100, which means, that the best heat abstraction while transferring from the cooler metal to cooling water.

Effective decrease of total heat resistance could be reached while blowing the construction. The most intensively resistance decreases under blowing speed of 6 m/s. Under blowing speed higher than 12 m/s the decrease of resistance is slight, and in order of general economy speeds higher than 12 m/s are not used.

To investigate the effectiveness of IGBT cooling systems it was developed laboratory set-up with the scheme, shown in Fig. 9.

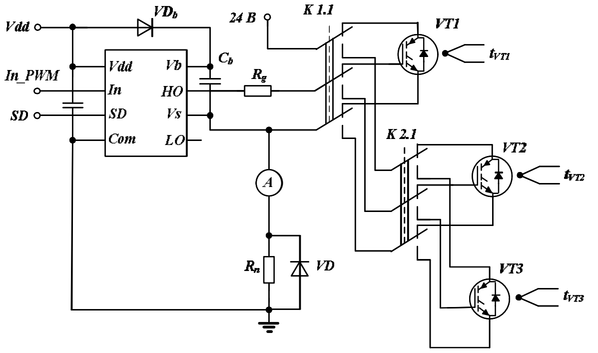


Figure 9 – Scheme of laboratory set-up for investigation the IGBT cooling systems

Presented set-up contains transistor control driver (*IR 2104*), three transistor power keys *VT1-VT3* (I*RG4BC10UD*) and wheeling diode *VD* (*VS-15ETH06PBF*), three thermoelectric temperature sensors t_{VT1}-t_{VT2}. The voltage of laboratory set-up power bus is 24 V.

The presented laboratory set-up allows one to investigate the heating of a power transistor key structure working without cooling system, with natural cooling system, and with forced cooling system. The natural cooling system determines installation on the transistor heatsink surface the radiator which is vertically oriented, including dielectric layout between them. In its turn, the forced cooling system, as well as natural cooling system, contains radiator installed on transistor heatsink surface, which is vertically oriented, including dielectric layout between them, and a fan, which provides direct blowing of the radiator surface. In order to control load current the laboratory set-up has possibility to install ammeter. The heat measurement could be done installing thermoelectric sensors.

Experiments for IGBT heating modes investigation were conducted for the case of the work of impulse energy converter with resistive load (Fig. 10).

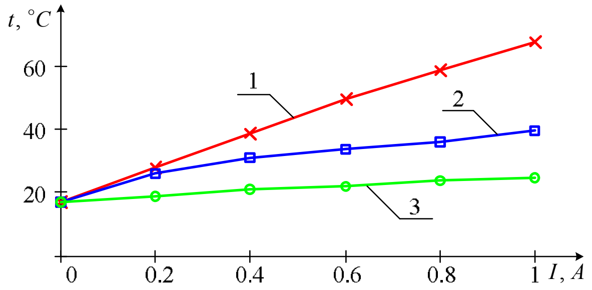


Figure 10 – Dependence of IGBT temperature on the load current: 1 – without cooling system; 2 – using natural cooling system; 3 – using forced cooling system

Thus, laboratory set-up allows one to investigate heating modes of power transistor keys which are part of energy transformers, and estimate the effectiveness of the most popular cooling systems.

It also should be mentioned, that presented laboratory set-ups meet requirements of the conception of small-sized laboratory set-ups [10]. According to this conception, laboratory equipments should meet the following requirements: safety, visualization of investigated objects and processes, small-size, compliance to modern requirements and maximum closeness to industrial equipment.

CONCLUSIONS. It was proposed the laboratory complex, which allows one to conduct a series of experimental investigations, namely: estimation the influence of additional circuits for power key working point formation on dynamic energy loss; estimation of the influence of transistors passive protection systems on dynamic energy loss; investigation of the efficiency of use the transistor protection methods against over-voltages; investigation of the efficiency of the most wide-spread cooling systems for transistor keys. Presented laboratory complex will allow students to conduct experimental estimation of power IGBT working modes which works as a part of semiconductor energy converters for the tasks of their further designing or improvement.

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ЛАБОРАТОРНЫЙ КОМПЛЕКС ДЛЯ ИССЛЕДОВАНИЯ ХАРАКТЕРИСТИК СИЛОВЫХ ТРАНЗИСТОРНЫХ КЛЮЧЕЙ В СОСТАВЕ ПОЛУПРОВОДНИКОВЫХ ПРЕОБРАЗОВАТЕЛЕЙ ЭНЕРГИИ

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Современные системы регулируемого электропривода характеризуются применением полупроводниковых преобразователей энергии на полностью управляемых силовых ключах, поскольку их применение открывает широкие возможности при создании высокоэффективных энерго- и ресурсосберегающих устройств. Процесс проектирования полупроводникового преобразователя энергии или доработки существующего требует обоснованного выбора составляющих его элементов и схемотехнических решений, причем особое внимание необходимо уделить обеспечению приемлемых мощностей потерь в силовых ключах и высокоэффективных методов их охлаждения. Проведенный анализ составляющих потерь мощности силовых ключей показал, что при проектировании преобразовательных устройств обеспечение минимальных потерь возможно за счет формирования скоростей переключения, которые будут обеспечивать оптимальную траекторию включения и выключения ключа. Потери энергии также существенно зависят от системы пассивной защиты, которая уменьшает вероятность попадания транзисторного ключа в один из режимов пробоя. Поскольку энергия потерь силовых транзисторов выделяется в полупроводниковом кристалле и рассеивается в виде тепла, важным вопросом является выбор способа отвода тепла. В работе представлен лабораторный комплекс, позволяющий проводить ряд экспериментальных исследований, а именно: оценку влияния дополнительных цепей формирования траектории включения и выключения силового ключа на динамические потери энергии; оценку воздействия систем пассивной защиты транзисторов на динамические потери энергии; исследования эффективности применения методов защиты транзисторов от перенапряжений; исследования эффективности применения наиболее распространенных систем охлаждения транзисторных ключей. Разработанный лабораторный комплекс позволит студентам проводить экспериментальную оценку режимов работы силовых IGBT в составе полупроводниковых преобразователей энергии.

Ключевые слова: полупроводниковый ключ, лабораторный стенд, динамические потери, скорость переключения, защитные цепи, система охлаждения.

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