High-performance converters with the high-frequency section for systems of energy influence upon geology objects

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Abstract — The approach of developing systems of acoustic influence upon geological objects is described in the article. In such systems a sound emitting device is often located within a considerable distance from the energy source. Energy is transmitted between them through a long cable which structure causes limitations in the levels of voltage being used, brings additional active and reactive elements into the system. The system's peculiarities' influence on circuit solutions of semiconducting converters that match an sound emitting device system's peculiarities' influence on circuit solutions of additional active and reactive elements into the system. The causes limitations in the levels of voltage being used, brings transmitted between them through a long cable which structure such systems a sound emitting device is often located within a influence upon geological objects is described in the article. In

I. INTRODUCTION

Under engineering geophysical research and intensive hydrocarbon production the technologies of energy (power) influence upon an object are widespread. For example, influencing upon the seabed by acoustic impulses; the bottom rock features could be determined according to the characteristics of the reflected signal. Various converters that convert electric power into acoustic energy could serve as acoustic energy sources in such cases: electrodynamical (EDE) or piezoelectric (PZE) emitters, electric spark gaps (ESG) etc. Apparently, the effectiveness of acoustic influence upon an object and the response signal's information fullness are increasing as acoustic converter is getting closer to an object: it is recommended to locate an acoustic radiation source close to an object. When researching the seabed an emitter on an armored cable, which transmits energy for a radiator, is put down the ship's side. This is similar to the technology of acoustic stimulating of the oil or gas wells (the acoustic processing of stratum's areas close to the bottomhole); an ultrasonic emitter (PZE, for example) is put into a well down to a perforation area; energy for PZE supply is transmitted through the cable. The cable length in both cases could vary from several hundred meters up to 5-6 km. The initial source of energy which is converted into acoustic one later on is, as a rule, a self-contained generator with the standard output voltage - three-phase 3x380 V 50 Hz or single-phase 220 V 50 Hz.

The system's of acoustic influence structure and technical indicators are effected by the emitter's power supply characteristics. Thus, the principle of operation of the systems with EDR and ESG consists in periodic discharge of the preliminarily charged energy storage capacitor through a key to an emitter. As the discharge current equals to thousands of Amperes under the voltage of 3-5 kV, it is clear that an emitter, a capacitor and a discharge switch must form a compact structure located in a submarine device (Fig. 1), a high-voltage stage of the device for charging the energy storage capacitor should also be located there. It is reasonable to provide the optimal charging process by the means of a semiconductor power converter.

In the systems with PZE it is necessary to convert ship's side or surface autonomous source's energy into energy with the required for PZE working parameters - sinusoidal high-frequency voltage (Fig. 2).

The common feature of the described systems is: firstly - a considerable distance between an energy source and a receiver, and, therefore, the necessity of electric power transmitting through a cable; secondly - the necessity of matching the parameters of the initial energy source's electric power and the emitters' parameters by the means of semiconductor converters. This article is devoted to the description of the ways of developing such systems that were created at the Department of Industrial and Biomedical Electronics of National Technical University «Kharkov Polytechnic Institute» from 1986 till 2012.
II. CONVERTER FOR SUPPLYING A SUBMARINE EDE

A converter is meant for working as a part of seismic-acoustic complex for seabed hydro-geological prospecting. As pointed above, the required characteristics of EDE electric supply have a significant influence on the system parameters: nominal supplying capacitor voltage is 3200 V, energy of EDE is 500 J, converter’s input voltage is 3x380 V, cable’s length 900 m, resistance of cable is 20 Ohm.

At the beginning of the development the thyristors were used in the converters with the power of several-dozens of kilowatts. "Power" bipolar transistors had collector-emitter voltage limitations - 700 V with the collector current - several Amperes and insufficient reliability.

When developing the power supply system the following conceptual points were accepted:

1) The storage energy capacitor is charged under the regime of constant current source which allows to obtain the high efficiency of charge opposite to the constant voltage source regime.

2) The constant current source is realized by a high-frequency series resonant inverter (SRI), with the following transformation by the means of a step-up transformer and rectification by a diode rectifier (Fig. 3). High frequency allows to use a relatively small transformer.

3) The SRI input constant voltage is formed on the ship side by the rectification of 3x380 V input voltage; the rectifier output is connected with the SRI input through a cable-rope. Thus, energy to SRI is transmitted by the constant current.

For thyristors control the method which allows effective regulation and stabilization mean volume of current of half of period was developed. This current is proportional of the storage capacitor charge current. At the same time this method ensures absolute SRI commutation stability, including the conditions of suddenly changing voltage of SRI load [1]. The method's essence is in the following: by the means of an SRI output current sensor the moments of changing of sign of current is defined, a waiting impulse generator is turned on. The generator's impulse time is not less than the thyristor's turning off time $t_q$. After the impulse is ended the modulator's linear form rising voltage is begun to be formed. When this voltage is equal to regulator's voltage the thyristor, which current direction is the same as the direction of SRI current, is turned on (for example, proportional-integral regulator of mean current) (Fig. 4). It is clear, that the following thyristor turning on signal could not be given before the end of time interval from the time point of zero current till the end of time of direct recovery of thyristor. This control method is characterized by a free frequency of commutation. The load is characterized as voltage source. The regulation of amount of transmitted to load energy is achieved by the angle shift between rectangular form voltage on the commutator's output and its output SRI voltage (phase-frequency method).

Comparing to energy transmitting by sinusoidal alternative voltage the use of constant voltage allows to increase the energy transmission efficiency up to two times, to decrease the requirements to the maximum insulation voltage of cable. Really, under the same voltage amplitude, which defines the maximum insulation voltage of cable, the $\sqrt{2}$ times increase of effective voltage is obtained, and under the same current density of cable the $\sqrt{2}$ times increase of power dissipation in cable is obtained too. When transmitting energy by constant current possible power supply line's (PSL) as an object with distributed parameters and, therefore, with resonance features, influence on energy transmission process is absent.

The rise of converting frequency $f_c$ and of own frequency $f_0$ of commutation loop is reasonable, because with the rise of frequency the sizes of SRI reactive power components are decreased. In the case of $2f_c>f_0>f_c$ the regime zero current switching (ZCS) of control SRI power switches turning off takes place. This excludes the switching commutation losses, allows using the thyristors, but requires the inductive turning on snubbers. The "T4"-type of thyristors by Tallinn Electrotechnical Plant were used in the device. The conversion frequency is around 10 kHz.

When the storage capacitor's voltage reaches the certain numbers the energy transmitting to capacitor is stopped by short connecting of primary winding of transformer. This short connecting is provided by special power switch to direction and parallel connected thyristors VS3, VS4. In order to improve transition process this short connecting moments are synchronized with zero current time moments. At the moments of short connecting sudden changes of SRI output voltage occur.

Fig. 5 shows a simplified power schematic of high voltage stage of a converter [2]. When the discharging thyristor VS2 is turned on the current impulse in EDE L3 is formed. Under the given load and storage capacitor parameters the shape of load current is almost sinusoidal. As Q-factor of equivalent LC-tank of EDE with the storage capacitor is near 1.5, after the end of discharge significant energy is storage in the capacitor. Thyristor VS1 and inductor L2 form a schema which partially returns load energy to the storage capacitor. The part of this energy is about 25%. Inductor L1 protects the diodes from current under-load under negative voltage of storage capacitor.
The supply of SRI control system (CS), of drivers of discharge switch thyristors, and of control-measuring devices which are located in submarine block is provided by additional winding of SRI power inductor voltage. Such a solution along with the uninterruptible SRI work allows to refuse from a special high voltage supply device.

When sudden SRI perturbation from load (under regular primary winding short circuit at the moment of capacitor charge ending and at charging renewal), aside from SRI commutation stability, it is necessary to pay special attention to ensuring high quality of SRI transient processes. Incorrect regulator’s tuning may lead to mean output current overcorrection and, therefore, to the corresponding voltage amplitude increasing at the commutating capacitor. For the needs of phase-frequency method being used an original method of modulator’s control signal forming that ensures SRI complete controlling (the absence of amplitude overcorrection at the commutating capacitor or mean SRI output current) under certain conditions was developed [3]. The essence of the method is in the following. At the interval from zero SRI output current moment to turning on a following thyristor the possible commutating capacitor voltage which will take place at the following zero current moment is calculated. If the calculated and the required voltages are equal, the following thyristor is turned on. This method is one of the predictive control methods because future values of one of the LC-tank conditional variables are calculated. This is being done because in order to define conditional variable (commutating capacitor voltage) it is necessary to find out the value of another conditional variable (inductor current), i.e. LC-tank energy, this method could be described as the energy one.

The precise method implementation requires providing functional conversions such as vector’s rotations and their relative value calculation. Although it was found out that almost the same results (meaning the quality of regulation) could be obtained by adding to the traditional regulating structure with PI-regulator a perturbation regulating section. In this case the PI-regulator’s output signal is added to the signal which is proportional to the value of perturbation (the voltage which is proportional to the SRI load). Such a system implements mean SRI current invariance from SRI load voltage during regular perturbations and finite quantity of time during irregular perturbations, for example, sudden short circuit of load after the moments of following thyristor’s turning on.

III. CONVERTER FOR SUPPLYING SUBMARINE ESG

The functional purpose and the characteristics of this converter are similar to the ones described above. Just like in the previous case, the essence of its work is in the periodic discharge of the previously charged storage capacitor onto ESG. The storage capacitor voltage is 5000 V, the discharge energy is 1250 J. The ESG features are such that the discharging process is aperiodic.

While elaborating the converter the concepts of the previous system were developed and its shortcomings were taken into account. System’s main features were saved - transmitting energy through a cable by constant current, high-frequency SRI which works in the regime of constant mean output current usage, high-frequency power transformer usage.

The control system is gradually simplified; converter’s high-voltage stage is overworked, high-frequency power transformer’s construction and rectifier’s construction are simplified; supply system is overworked because of changes in submarine block packaging arrangement; additional power thyristors are excluded.

In converter for supplying submarine ESG resonant converter is in the discontinuous current mode with the frequency which is 2 times lower than the LC-tank own frequency 2f_o>f_f, (Fig. 6). Under this mode, as it is known [4], when working on counter-emf the value of mean half converter period output SRI current does not depend on SRI load voltage, but proportionally depends on the input SRI voltage. Certain inaccuracy of current source mode due to voltage dissipation in cable and primary power source voltage variations is paid over by the control system’s simplicity: the system does not require any special current regulator. Thyristors are turned on and off at the zero current moments, and inductive turn-on snubbers are not required (but there is still a necessity in thyristor voltage increasing speed limiting snubbers).

In order to simplify transformer’s construction, to increase its reliability by decreasing its output voltage it was suggested to use a voltage multiplier at the secondary side (Fig. 7).
the given capacitance ripple voltage coefficient [5]. It is shown that the required capacitance of a capacitor is proportional to the third power of multiplying coefficient and is inversely to the relative current source voltage increase, its frequency and equivalent resistance load.

Another advantage of the converter comparing to the described above is the converter frequency constancy. While the shortcoming is the necessity to limit voltage load value relatively to the input voltage at the rate of 0.7-0.85 because of the danger of commuting capacitor discharge by the magnetizing transformer's current and, therefore, of free willing diode current time decreasing. The last one may lead to thyristor not being turned off.

Discharge switch thyristors turning on impulses are formed around zero current moments of free willing diodes (this does not require a special current sensor, because this moments are inflexibly connected to inductor current half-wave length and are known in advance) when capacitor's voltage reaches the given value (synchronous relay regulation). This way, sudden inverter's perturbation from its load side occurs at the zero current moment and under the same value of another state variable - commuting capacitor voltage. As a result mean output SRI current invariance from voltage load is realized, i.e. mean load current and power switches overregulation is absent.

IV. CONVERTER FOR SUPPLYING SUBMARINE PZE

This converter is used for supplying submarine PZE which works in the seismic-acoustic complex of groundwater seabed prospecting according to the structure Fig. 2a. The converter is a parallel half-bridge resonance source voltage inverter (PRI) in which output loop there is an alternative current power switch (Fig. 8).

![Fig. 8 Proposed converter for supplying submarine PZE](image)

Frequency modulated voltage impulses with 50 ms to PZE which has mechanical resonance frequency 5 kHz - in the middle of linear converter output frequency deviation diapason. PZE power drive is 2000 W (Fig. 9).

![Fig. 9 Current and voltage waveforms of PRI](image)

In the converter's control system there are two channels for output voltage parameters regulation: a channel for frequency regulation by linear method (it is realized by alternative current thyristor switch) and a channel for regulating load voltage (it is realized by modified phase-frequency switch control method of PRI itself).

The difference between phase-frequency modulator realization and the one described in chapter II is in the first place in the following: a one-shot impulse generator which forms time interval for thyristor direct recovery (and synchronized by the impulse ending moment generator of linear increasing modulator voltage) is not synchronized by the zero current thyristor moment, but is synchronized by the moment of alternative current thyristor switch turning on. The presence of two generators - conversion frequency and one-shot impulse generator - allows to provide converting frequency regulation (in phase-frequency method itself it is free) while saving PRI absolute commutation stability.

Another difference is regulating the value of output voltage by the means of PI-regulator of voltage, but not of current. The detailed analysis of the dynamic system properties with such a regulator (as well as with the two power commutators) was carried out and its parameters that ensure practical amplitude constancy of output voltage at the interval of output frequency deviation were found.

V. CONVERTER FOR SUPPLYING PZE COMPLEX FOR ACOUSTIC WELLS' STIMULATION

This work was completed over the past two years and aimed to increase hydrocarbon production from the wells. The work was carried out together with Institute of informatics and management of National Academy of Sciences and of Ministry of Education and Science of Ukraine.

For hydrocarbon production at the bottom part of a well (bottomhole) punched holes are made which are located in front of the oil or gas bearing zone. Hydrocarbons are moved to the well because of the difference between pressure in the formation and in the well.

Well's productivity decreases with time because of the following (aside from the formation lowering):
- technological liquids' solid stage (damping, budding, sludge, etc.) and other solid depositions' sedimentation in the bottomhole formation area;
- appearance of plugs in punched holes due to moving of reservoir rock from the formation, reaction products falling out because of widely used bottomhole treatment with chemical reagents;
- kolmatation (falling out onto surface and micropores smaller particles) of bottomhole area capillary system because of pore channels plugging, etc. [6].

Powerful ultrasonic acoustic waves could reduce the kolmatation in the bottomhole area of the productive formation, increase its penetrability by changing the structure of its pore space, provide acoustic degassing and remove gas plugs in capillaries. Ultrasonic influence reduces oil's viscosity which also increases well's yield. Along with the increase of acoustic power the useful effect increases.

In order to provide ultrasonic influence upon the bottomhole area PZE is put down into punch hole area by armored cable Fig 2b. The diameter of immersible system section is limited by the corresponding sizes of used tubing (for example, 44 mm). One well is processes during 2 to 20 hours, the effect duration is from 6 to 18 months. The economic effect from well acoustic processing is universally recognized [6].
PZE electric supply is provided by a special generator (converter) which forms sinusoidal voltage with the frequency that coincides with the emitter’s mechanical resonance frequency. In the converter’s control system frequency self-tuning is used in order to ensure maximum PZE output acoustic power. The standard that is accepted in Commonwealth of Independent States [7] sets the required value and allowed diapason of frequency changes: 22±1.65 kHz.

The PZE could be presented as an equivalent circuit that consists of series LC-tank and parallel capacitor which considers the piezoelectric cell own capacitance (Fig. 10). In the resonance regime the equivalent schema is degenerated to parallel connected capacitor and resistor. Q-factor of the resonance regime the equivalent schema is degenerated to consists of series LC-tank and parallel capacitor which applied voltage.

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\text{Q-factor} = \frac{\text{energy stored in resonant circuit}}{\text{power dissipated in resistor}}
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PZE output power increases along with the increase of PZE output acoustic power. The standard that is accepted in standard 0,75-60-200 type cable with values and allowed diapason of frequency changes: 22±1,65 kHz.

As a result, the use of ground PZE electric supply system becomes inefficient when the formations’ depth of occurrence is more than 1.5 km.

In Ukraine most oil and gas fields’ depth of occurrence is more than 3-5 km. At such depths the pressure is more than 50 MPa, and the temperature may reach 130 °C.

In the elaborated PZE power supply system the concept of energy transmission through a cable on constant current was implemented (Fig. 11).

![Fig. 11 Block diagram of energy transmission through a DC cable](image)

The PZE power supply system of 500 W nominal output electric power includes an autonomous 220 V 50 Hz power source which supplies a secondary power source with a high-frequency transformer galvanic separator, the last one gradually decreases the size and the weight of the device's ground-based part. Ground-based part including next blocks: input rectifier R1, high-frequency autonomous inverter I1, separating transformer Т1, high-frequency rectifier R2. This power source forms a controllable constant voltage 100-400 V, and is connected to a load bearing cable. The cable’s output is connected to converter’s (autonomous inverter I2) input. The autonomous voltage source's load is a transformer T2, which secondary winding is connected to PZE. The PZE’s case has a galvanic connection with the environment, i.e. with the ground (the peculiarity of the PZE being used).

Such a structure of the power supply system has essential advantages when compared to the traditional ground option. Aside from obvious ones – around 2 times increase in efficiency of energy transmission by constant current through a long current supply line compared to energy transmission by sinusoidal current, absence of additional losses in conductors and cable insulation at conversion frequency, and insulation load decrease due to the absence of wave-type energy transmitting processes – there are also some additional advantages:

1) Transmitting energy by constant current with the use of dual galvanic isolation allows using steel cable armature as a reverse conductor for energy transmission. For the mentioned above cable running cable armature’s resistance is 5 Ohm/km. If parallel connected three conducting cable strands are used as a direct conductor, then around four times decrease of conducting cables ohm resistance (to 13 Ohm/km) could be achieved. The use of such connection schema allows to gain in cable voltage drop and, therefore, to ensure input voltage decrease with corresponding reliability and durability increase.

2) The presence of the transformer in the structure which connects I2 output and PZE input allows to provide approximate equality of cable resistance and I2 equivalent input resistance on direct current. Resistances' matching corresponds to ensuring the regime of maximum possible transmitting power value.

The implementation on this PZE power supply system faces certain difficulties, mainly of technological kind. The main one of them is – the necessity to place the converter well part (matching output transformer T2, power switches' control system which provides frequency self-tuning to PZE...
mechanical resonance frequency, control system's and power switch drivers' secondary power supply) into the gage which allows to put this construction into the well. System's well part is a leak-tight and pressurized construction made of stainless steel 2000-3000 mm long depending on modification (Fig. 12).

System's components are located within the space which axial section's diameter is 32 mm. Modern power electronic components were used in the system: power MOSFET with small $R_{ds(on)}$, ferrite cores with small hysteresis losses. The control system is based on TMS320F2801PZS-60 microprocessor. Schematic design ensures critically small losses in $I_2$ power switches, the special construction of power magnetic elements is applied. The well part of the device could function under the temperature of 120 ºC.

The use of converter for supplying PZE complex for acoustic wells' stimulation with the 5 km cable in real-life conditions for more than 50 hours has shown the high efficiency of the system. The speed of processing was up to 0.7 m/hour. According to state official acts the discharge of processed wells has increased up to 100%.

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