Electric Power Converter with a Wide Input Voltage Range

K.O. Khokhlov[1], G.K. Khokhlov[2], A.V. Ishchenko[3], A.N. Cherepanov[4], A.S. Naronov[5]
[1,2,3,4] Department of Experimental Physics, Ural Federal University
[5] Scientific and Production Association of Automatics Named after Academician N.A. Semikhatov

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ABSTRACT

The electric power converter for downhole telemetry systems of oil-well pumps include a downhole block connected to the pump that contains electronic circuits required for the operation of the motor pump sensors and transmission of data about their condition to the surface are described. A few methods of electric power conversion for this purpose are considered. The circuit contained two steps of voltage converting are proposed. The electrical scheme of this method is considered in the article. Proposed decisions are simulated and verified experimentally. The input high supply voltage range (200-4200 V) without loss of efficiency (even temporary) was obtained.The results of simulation and experimental studies have shown very close results.

Corresponding Author:

Aleksey Ishchenko,
Departement of Experimental Physics,
Ural Federal University named after the first President of Russia B.N.Yeltsin,
620002, 19Mira Street, Ekaterinburg, Russia.
Email: a-v-i@mail.ru

1. INTODUCTION

In spite of the large volumes of mining operations in the world the many problems are still remains unsolved in the field of oil extracting. Particularly the high-quality hardware condition monitoring of submersible borehole pumps and drives is a serious problem for the continuation of the oil and gas industry progress. The main technique for data transmission from the borehole is power-line communication technique which is to carry communication signals over power-transmission conductors. Generally, the motivation using this technique is to utilize existing conductor infrastructures rather than dedicated data lines to minimize expenditure [1-2]. As a rule, the downhole telemetry systems (DHTS) of oil-well pumps include a downhole block connected to the pump that contains electronic circuits required for the operation of the motor pump sensors and transmission of data about their condition to the surface [3-5]. For resource-saving in the development of downhole telemetry systems and downhole equipment for power supply of power units and transmission of data about the system condition from the hole depth to the surface, designers often have to use a single power cable. In this case, the typical downhole telemetry system looks as illustrated in Figure 1.

Power supply (Power Supply block is situated in Down hole block, Figure 1) of this equipment should be provided by low voltage 12 … 15 V, which is converted in the downhole block from direct voltage 200-300 V supplied from the surface. Three-phase supply voltage of the motor which is transmitted through power cable (KIFBP-250, Figure 1) has acting voltage about 3000 V and frequency 50±10 Hz which is mass-produced by three-phase transformer located on the surface. Windings of the transformer and three-phase motor are brought into the circuit with the star connection. The transformer on the surface and the pump motor in the hole are connected with a three-phase cable protected by a metal armor. Since the system does not provide for any other cables except for the three-phase motor cable, positive supply voltage of the downhole block (approximately 200–300 V) is connected to the neutral point of the transformer windings connection (Figure 1).

In ideal case in condition of symmetric three-phase system the neutral points of the transformer and the motor are equipotential. Therefore, the same voltage (200–300 V) is formed at the neutral point of motor windings relative to the well-grounded metal armor which is connected with the negative side of the 200-300 V voltage source. However, in real case may occur a voltage unbalance, for example due to a mechanical overload on the motor shaft. Because of this the potential of the neutral point of the pump motor may reach 1200 V during long-time, and short-time voltage surges can get phase amplitude value up to 4200 V.

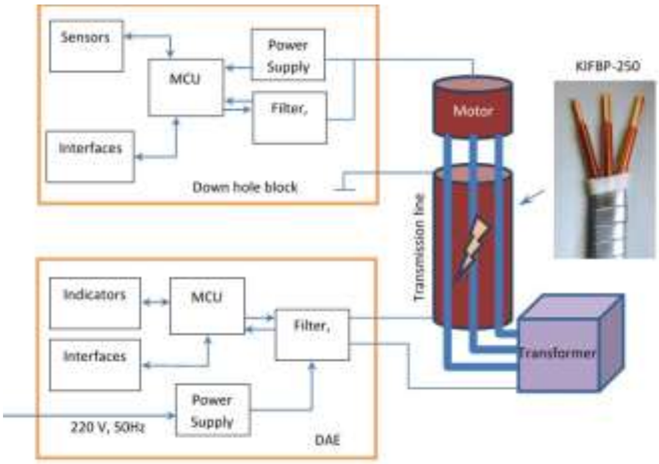

Figure 1. The block diagram of a typical DHTS with KIFBP-250 cable (right)

Thus, downhole telemetry systems require a converter with low output stabilized voltage (about 15 V±5%), which is powered by the input voltage in the range 200-1200 V and can resist to short-time surges of input voltage up to 4200 V without losing (even temporarily) function during a long time (at least two-three years). It is also necessary to provide for voltage supply of the internal blocks of the converter. Taking into account that the downhole temperature ambient is usually above 100 °C, the converter should have high efficiency so that it would not add additional heat to the electronic circuits and have high reliability.

This paper is aimed at development of an electric converter with high range of input voltage with stabilized low output voltage (approximately 12–15 V), which is powered by input voltage in the range 200–1200 V, and can function at short-time input voltage surges up to 4200 V. The additional condition is high efficiency requirement.The proposed method is to use a two-stage converter. The first stage-the line input limiter which cuts short high surges of input voltage. The second stage the high-frequency pulse transformer inverter with the stabilization of the output voltage by pulse width modulator. The proposed method is described below.

2. CRITICAL ANALYSIS OF SIMILAR SOLUTIONS

There are a lot of technical solutions in the field of DC-DC power supply, for example [6-10]. Therefore, a search and a critical analysis of existing similar solutions in this area were performed before the development of the above problem. This section also gives consideration to some general applicability issues of different structures of DC-DC converters for downhole systems. The analysis included patent applications in the area of design of pulse voltage converters.

Patent [11] describes a flyback voltage converter with protective disconnection in cases of input surges. The peculiarity of the converter is as follows. Input voltage of the converter is supplied to the inputs of the control unit. With the increase of this voltage above the permitted level, the control unit generates a signal disabling the flyback converter, which is sent to the input of the PWM controller, which determines the end of formation of the power transistor control pulses, and turns off the converter. Voltage of the transistor in the switched off condition is considerably (about twice) lower than the pulse voltage that appears during the circuit operation with the same value of the supply voltage at the inputs of the converter. The drawback of this converter is that the shutdown lasts until voltage is restored to the acceptable level. The second drawback is that the surge value is no more than double nominal input voltage, while downhole telemetry systems require a minimum of 20 times exceeding of the input voltage without losing function. Moreover, voltage amplitude in the operating mode of single-cycle inverters at key elements may exceed value of input voltage more than twice (due to self-induction and resonant surges). This property of single-cycle inverters complicates their use in voltage converters with high input voltage.

Patent [12] unlike patent [11] uses a push-pull half-bridge inverter for high-frequency converting and input voltage rectification using a transformer in order to obtain a constant output voltage. Advantage of bridge and half-bridge inverters over single-cycle converters is that the voltage amplitude at key elements does not exceed the input voltage. However, the device [12] and similar devices lack stabilization of output voltage which would vary in proportion to the change in input voltage, which is a significant drawback.

Development of the considered device is covered by the invention patent "DC Transformer" [13]. The proposed device additionally includes a signal winding of the transformer, an additional rectifier, a capacitive filter, a differential signal amplifier and a frequency-controlled oscillator connected with its control input to the output of the differential signal amplifier, wherein the first input is connected to the reference voltage, and the second input is connected via the capacitive filter and the additional rectifier to the signal winding of the transformer. The feedback allowed one to stabilize the output voltage using frequency modulation. However, stabilization is performed not by the output voltage but by the magnetic flux in the magnetic core of the transformer that prevents high values of stabilization factor. Changing frequency conversion is another disadvantage. This is a common knowledge that the overall power of the transformer is inversely proportional to the operating frequency, hence, the transformer should have dimensions corresponding to minimum frequency which would have a negative impact on its dimensions and weight. In addition, frequency modulation does not provide sufficient depth of adjustment in case of large range of input voltage changing. In this case, it is more effective to apply the PWM principle of the output voltage to stabilize is at fluctuations of the input voltage. The device [13] also has a more complex structure of the transformer.

Patent case [14] described a "Transformerless voltage converter" where circuits are powered from the input AC circuit using a capacitive coupling. Summary of the invention consists in that the device includes ballast capacitors to reduce high input alternating voltage to supply voltage of the control circuit. In fact, active power losses in service chains are minimized, which is required for conversion of the downhole block. However, this device only works with AC, whereas the downhole block is powered by DC voltage.

Analyzed above circuit solutions allow you to implement function of voltage converters only in the specified rather narrow range of voltages and do not allow application of the device at voltages exceeding the allowed operating values for electronic components. Some of them include devices interrupting supply of high voltage to elements either for a short time or completely which is not acceptable for DTS whose operation should be provided at all working conditions.

3. CICRUIT DESCRIPTION

Based on the results of the critical analysis presented above, the problem was solved as follows.Thecircuitof the developed device which is an input voltage converter is presented in Figure 2. As was mentioned above the proposed method is to use a two-stage converter. The first stage-the line input limiter which cuts short high surges of input voltage. The second stage-the high-frequency pulse transformer inverter with the stabilization of the output voltage by pulse width modulator.

Input voltage converter contains the first resistor block 1 whose upper output is connected to the drain of the field effect transistor with insulated gate 3 forming positive input of the device. Lower output is connected to the upper output of the block of Zener diodes 2 and transistor gate 3 whose source is connected to the output of high-voltage power supply of the half-bridge inverter 10 and higher output of the second resistor block 4 whose lower output is connected to the capacitor 5, diode cathode output 6 and outputs of the positive power of the feedback unit 7, pulse-width modulation units 8 and half-bridge inverter driver 9, feedback circuit output 7 is connected to the input of the pulse-width modulation circuit with a two-cycle output 8, whose outputs are connected to the inputs of the driver of the half-bridge inverter 9, whose outputs are connected to inputs of the half-bridge inverter 10, whose outputs are connected to the primary winding of the transformer 11, secondary winding is connected to inputs of the rectifier 12, whose outputs are connected to inputs of the inductive-capacitive filter 13, whose positive output is connected to diode anode 6 and input of the feedback unit 7 forming positive output of the transformer, where in lower outputs of the negative power supply of units 7, 8, 9, 10, and 13, anode of the block of Zener diodes 2 and lower output of the capacitor 5 are connected to form negative output and input of the converter.

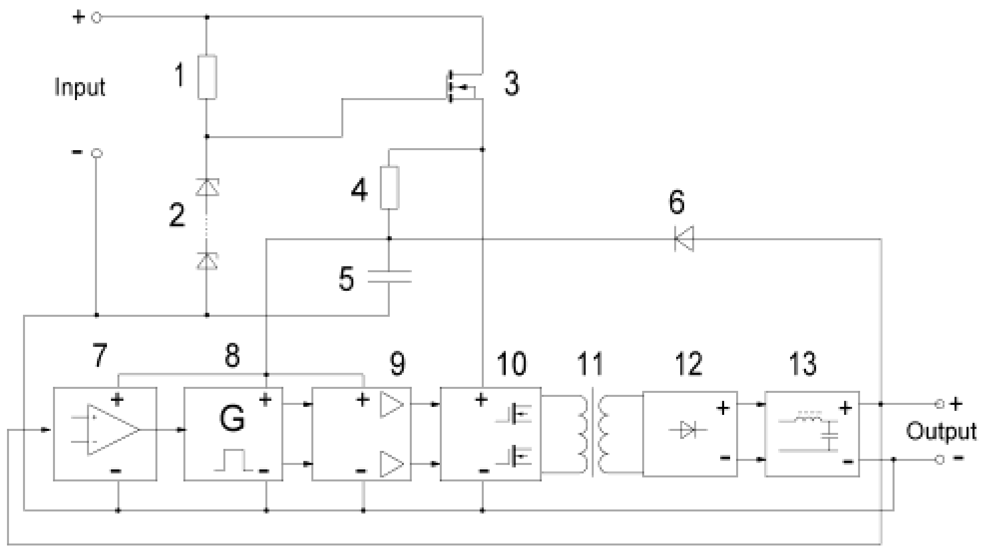

Figure 2. Electrical energy converter with high input voltage range. 1-first resistor block, 2-zener diode block, 3-MOSFET transistor, 4-second resistor block, 5-capacitor, 6-diode, 7-bias circuit, 8-PWM, 9-driver, 10-half-bridge inverter, 11-transformer, 12-rectifier, 13-filter.

4. CIRCUIT OPERATION

Electrical energy converter with a wide input voltage range whose circuit is shown in Figure 1 operates as follows. Input voltage is supplied to the first resistor unit 1 and drain of the FET with an insulated gate 3. When input voltage is less than the breakdown voltage of the Zener block 2, transistor gate 3 is connected to the drain through the resistor unit 1 to the source. Transistor 3 is almost fully open, has low channel resistance, does not dissipate power and transfers input voltage from the drain to the source virtually unchanged. When input voltage exceeds the breakdown voltage, current starts flowing through it, and voltage does not increase above the breakdown voltage. Transistor 3 in this case operates in the mode of a source-follower amplifier and maintains voltage at the source on the level of breakdown voltage at Zener units 2 which does not change significantly with the increase of input voltage. Since the transistor gate current value of this type is not more than 0.1 microampere, total resistance of the resistor unit 1 can be selected in the range of tens of megohms, preventing their heating at high input voltages. Units 1, 2 and 3 form the first control stage which is designed to limit voltage at the source of transistor 3, on the level of breakdown voltage at Zener block 2 (Figure 2). This voltage is determined by the breakdown voltage and the number of Zener diodes connected in series, constituting Zener unit 2. In this case, value is set to 1200 V, as this is maximum voltage of the existing drivers of half-bridge inverters (e.g., IR2213 microcircuits). Here you can set requirements to the operating voltage of the transistor 3, which is the difference between maximum input voltage (4200 V) and limiting voltage (1200 V). Hence, it should have low channel resistance the operating drain-source voltage at least 3000 V (e.g., IXTL2N450). A bipolar transistor with an insulated gate (e.g. IXGF30N400) can also be used as transistor 3.

It should be noted that excess voltage is applied to the transistor 3 when current flows through it, therefore, the transistor operates in the active mode, which leads to release of useless power on it. However, this mode emerges only at short-term overloads of electric motors and it is not permanent. Therefore surges of increased power consumption do not affect the reduction of efficiency of the device as a whole. As the result, voltage is formed at the first control stage and it can vary from 200 to 1200 V with fluctuations of input voltage from 200 to 4200 V.

This voltage charges the capacitor 5 through the resistor unit 4. Total consumption current of the feedback unit 7, PWM unit 8 (e.g., microcircuits UCC3808-1 or UCC38083, which has both the above units - 120 μA) and driver of the half-bridge inverter 9 (e.g., microcircuit IR2213 - 300 μA) switched off, is negligible and does not impede the charge of the capacitor 5. Diode 6 cuts possible discharge of the capacitor 5 through the load connected to the converter. Therefore, resistance of the resistor unit 4 can be high in order to reduce power dissipation on it. When voltage at the capacitor 5 reaches the operating threshold (by the supply voltage) of the PWM circuit 8, it gets switched on and a series of pulses supplied to the inputs of the half-bridge inverter driver 9 which controls the half-bridge inverter 10 is formed. Capacitor 5 begins to discharge current, consumed by the specified microcircuits. At the same time, alternating rectangular voltage starts forming at the primary winding of the transformer 11, then it transforms to the secondary winding, and gets rectified by rectifier 12 and converted by filter 13 into direct output current which is supplied through diode 6 to the capacitor 5 and maintains voltage required for operation of units 7, 8, and 9. Capacitor 5 should have sufficient capacity not to discharge until it is charged through the diode 6. Then output voltage is supplied to the input of the feedback unit 7 which controls the PWM unit 8 for stabilizing of the output voltage. Filter 13 should be inductive and capacitive (LC) in order to maintain constant output voltage at the desired level using pulse-width modulation at high voltage oscillations from the source of transistor 3. Thus, units 7, 8, 9, 10, 11, 12, and 13 form the second control stage (Figure 2). Here you can set requirements to the operating voltage of transistors of the half-bridge inverter 10, which shall be no less than 1200 V (e.g., IXFR16N120P or IXFR20N120P-field-effect transistors with an insulated channel, as well as IXA4IF1200UC or IXGY2N120, which are bipolar transistors with an insulated gate). Resistor units are a chain of resistors connected in series to improve total resistance and operating voltage.

5. CIRCUIT SIMULATION

The second control stage is a PWM inverter performed according to the classical circuit which changes in its wide input voltage range from 200 V to 1200 V. Therefore, the first control stage is interesting for simulation, which limits voltage at the second control stage. The basic circuit (Figure 2) includes a single-cycle version of the limiting circuit. On the other hand, several transistors connected in series can be applied instead of a single transistor using "Beanstalk" circuit, which is widely used in high-voltage transistor amplifiers. Such incorporation will allow even distribution of applicable voltage and, corresponding distribution of power at transistors and will allow application of transistors with significantly lower operating voltage.

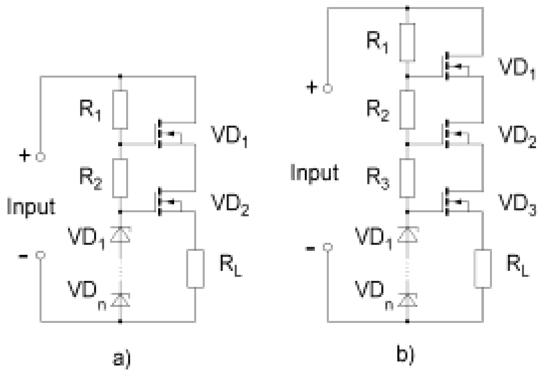

Figure 3. Two-transistor (a) and (b) three-transistor circuits of input voltage limiters

Figure 3 shows versions of the first control stage comprising 2 and 3 transistors connected in series. These circuits were simulated in LT spice software package. Input voltage was used as input parameters, output voltage from the first control stage was used as output parameter. Total voltage of the zener diode unit was 1200 V. However, taking into account that they operate with micro-currents, actual breakdown voltage was lower and amounted to the value of about 1100 V. The simulation used available transistors IRFDE20 with allowed operating voltage 900 V. Thus, the twin-transistor circuit allowed simulation in the range of input voltage up to 2800 V, and three-transistor-up to 3600 V. Small voltage margin was also taken into account (about 100–150 V). Value of the load resistor R_L during simulation ranged from 100 kOhm to 10 MOhm. At lower values of the converted power and maximum voltage of 1100 V, this value was equal to 12 watts, more than enough to power the electronic circuitry of the downhole block. Resistance of the resistor R_L in this range did not affect the simulation results (affected slightly).

Simulation results are presented graphically in Figure 4. For clarity of the operation of the limiters, intermediate values of voltages at sources of all transistors are specified in the diagrams to give the idea of voltage distribution.The graphs show that when the input voltage is up to the limit value, the voltage is passed without change, and in surplus - excess voltage distributed evenly on transistors regardless of their number. This confirms the assumption made above about the correctness of proposed method.

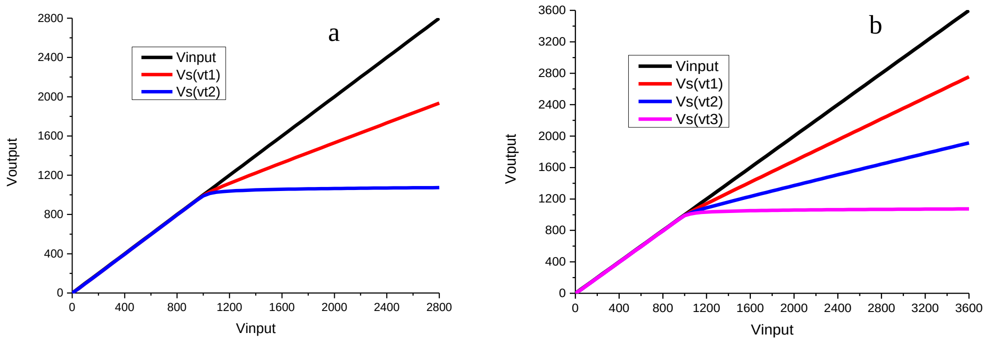

Figure 4. Output voltage distribution diagrams for two-transistor (a) and three-transistor (b) limiters

Simulation results, in addition to their graphical representation, are provided in the table which shows the results for the twin-transistor circuit. The table shows both absolute voltage values at transistor sources and voltage drops at every transistor for comparing of their operation modes. It is easy to see that the estimated operation modes are practically identical with the theoretical assumptions. The simulation results showed good results, but the authors decided to carry out experimental studies to confirm theoretical and simulation results.

6. EXPERIMENTAL RESULTS

The circuit shown in Figure 3a was mounted on the circuit board and was verified experimentally. Voltage in the range from 200 to 2600 V was used at the input parameter. This range is caused by the available laboratory power supply unit BNV2-90. Output parameter - limit voltage which is determined by the Zener block breakdown voltage. Limit voltage in the experimental study was about 1100 V, which is slightly less than theoretical value. This was the first sign of confirmation of the simulation results. Intermediate value from the source of transistor VT1 was also provided. Experimental values are also shown in Table 1. It is easy to see that they are also close to the calculated values, although they differ more than the simulation results. However, experimental results confirm theoretical assumptions and the ability of the considered circuits of suppressors to carry out their functions.

Table 1. Simulation results and experimental study results for a two-cycle suppressor

U_{in}, V	U_{s1}, V		U_{s2}, V		U_{ds1}, V		U_{ds2}, V	
	Theor.	Exp.	Theor.	Exp.	Theor.	Exp.	Theor.	Exp.
200.0	195.5	195.4	195.5	195.4	4.5	4.6	0.0	0.0
1000.0	992.7	991.5	989.8	987.7	7.3	8.5	2.8	3.8
1100.0	1061.0	1038.0	1026.5	978.0	39.0	62.0	34.5	60.0
1200.0	1117.1	1089.0	1038.6	980.0	82.9	111.0	78.4	109.0
2000.0	1530.2	1550.0	1064.8	1095.0	469.8	450.0	465.3	455.0
2600.0	1833.8	1856.0	1072.2	1099.0	766.2	744.0	761.7	757.0

V_{s1}-VT1 source voltage, U_{ds1}-drain-source voltage VT1, V_{s1}-VT2 source voltage, U_{ds2}-drain-source voltage VT2 or voltage on the load $R_L$of PWM converter simulator.

7. CONCLUSION

The considered version of high input voltage suppression which is used to supply power of electronic circuits of the DTS downhole block is one of the possible solutions to the problem of uncontrolled voltage surges transmitted by the "neutral" power supply of pump motors of the downhole unit. The main conclusions that can be drawn from the results of the considered solution.

1. High supply voltage range of 200-4200 V without loss of efficiency (even temporary) was obtained.
2. High efficiency due to the application of pulse energy conversion was achieved, provided that voltage surges exceeding 1200 V and reaching 4200 V are short-time and do not last longer than 30-40 seconds.

An important factor is that the considered electric circuit diagram was simulated in a specialized software package and was tested experimentally. Simulation and experiment results were practically the same. Some deviations of values can be explained by a slight mismatch of the breakdown voltage of zener diode blocks in simulation and experimental studies. A similar solution was applied by the authors in the upgrading of the radiation control system at Kursk NPP.

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