Electrical Complex for Autonomous Power Supply of Oil Leakage Detection Systems in Pipelines

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Abstract. The authors proposed a scheme of autonomous power supply for oil leakage detection systems in pipelines by applying the photovoltaic modules and thermoelectric generators as a power source. Laboratory experimental studies were carried out, the operating energy characteristics of the complex were obtained. A sufficient number of generating units has been determined for uninterrupted power supply to the data collection point of the oil leakage detection system.

1. Introduction

In Russia, the length of the main pipeline is more than 50 thousand km. The pipelines freight turnover exceeded the railway transportation in 2016. However, oil transportation may cause oil leakage (Figure 1) leading to severe environmental and economic consequences [1].

According to the report of the Russian Federal Agency for Oversight of Natural Resource, there had already been more than 8.5 thousand cases of such accidents at oil pipelines in 2017 [2–4]. Oil spills lead not only to financial damage including fines, but also to damage to the reputation of the company that caused the accident.

To prevent such accidents, oil leakage detection systems (LDSs), based on permanent monitoring methods [5–8], are installed on the pipeline. However, there is a problem with its uninterruptible power supply due to the frequent location of oil pipelines in inaccessible areas. Thus, the task of providing uninterruptible power supply to the LDS of liquid hydrocarbons seems relevant and significant for oil companies.

Figure 1. Consequences of oil leaks from pipelines

2. The structure of the complex

The existing methods of power supply for data collection points of oil and liquid hydrocarbon LDSs are:

– 0.4/6/10/35/110 kV laid along the road route overhead or cable power lines supplied by a centralized power system;

– 0.4/6/10 kV local networks powered by autonomous diesel generators (ADG);

– renewable energy sources (RES) complexes.

The way to ensure uninterruptible power supply using power lines is high cost in terms of investment (from 1 million rubles per km of line). The use of ADG has a resource limit (from 4 to 20 thousand service meter hours) and leads to the need for mandatory service that in many cases is also costly due to the location of the pipeline in inaccessible areas [9–11].

The method of providing uninterruptible power supply using RES can be divided into two main types. In the first case, the power is supplied from a wind-driven generator (WDG) that is autonomous but poorly predictable and there is a significant unevenness in generation of electricity. Accordingly, it is problematic to provide LDS with uninterruptible power supply. Secondly, the power supply from the photovoltaic module (PV module) in the complex under consideration requires the use of a high-capacity battery since there is no power generation at night and due to the stochastic nature of weather [12, 13].

Therefore, authors propose the method to provide LDS with a hybrid power supply based on units of thermoelectric generators (UTEG) and PV modules. Based on the Seeback effect, UTEG generates electricity continuously because of the temperature difference between the hot and cold sides of the unit. One side of UTEG will be attached to the pipeline (the temperature of the transported oil is about 40°C), the other side through the radiator will be cooled by the environment. Continuity of power generation will reduce the capacity of the backup power source. In the summer, the use of PV modules compensates for the reduction in electricity production when the difference between the ambient temperature and the pipeline is minimal and UTEG produces much less electricity. For these reasons, the development of the electrical complex for autonomous power supply of LDS based on UTEG and PV modules is relevant.

The block diagram of the developed complex is presented in Figure 2.

This scheme includes:

– power supply (UTEG and PV module);

– a controller of micropower sources (it switches between energy sources or ensures their parallel operation);

– the backup power supply (the battery);

– the low-resistance load switch;

– the wireless controller;

– sensors.

One or both of the studied generators can be used as a power source. $LiFePO_4$ or $Li_4Ti_5O_{12}$ batteries may be a backup source. Such types will not lose their properties in bad weather conditions, including the extreme north.

When using PV modules, it is necessary to include a capacitor with a nominal value of several mF, as shown in the diagram. This is because solar cells have high output impedance and a low output voltage that does not allow them to be used for direct supply of sensors.

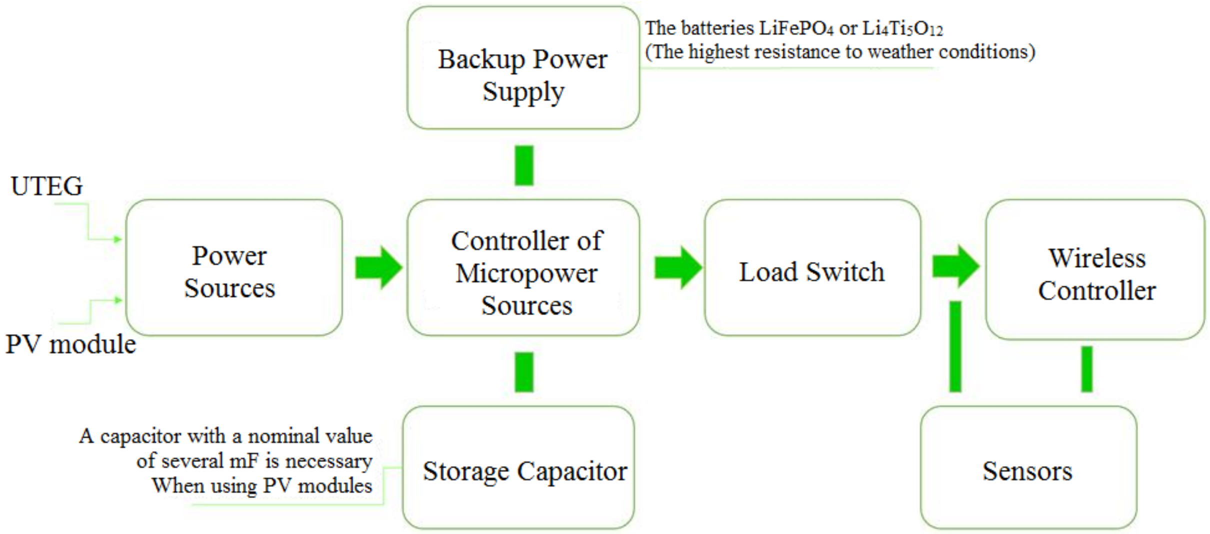


Figure 2. Block diagram of the complex.

3. Experimental studies of UTEG based on a physical model

In order to determine the characteristics of UTEG and calculate the required number of modules for supplying LDS in wide ranges of temperature difference, an experimental setup was developed (Figure 3). The initial LDS controller power consumption was accepted 5 W [14]. The thermoelectric module of the Krioterm company (TGM-199-1.4-0.8) was used in this installation.

Stand composition includes (Figure 3):

1. Laboratory autotransformer.
2. Resistance in the UTEG circuit (not shown).
3. A radiator located on the cold side.
4. Thermoelectric module.
5. Heat distribution plate.
6. Heating resistors.
7. Cold and hot side temperature sensors.

The heat flux was created by energy released from two resistors placed on a heat distribution plate. The plate was in contact with one of the sides of UTEG. The other side was cooled by a radiator. The value and temperature change of the hot and cold sides were recorded using electronic sensors. Under these conditions, the no-load voltage created by the generator and the operating current were determined when a load module with different resistance was included in the circuit. To simulate operating conditions at negative temperatures, the side with the radiator was placed in a box with dry ice, which allowed to simulate negative temperatures up to minus 40°C.

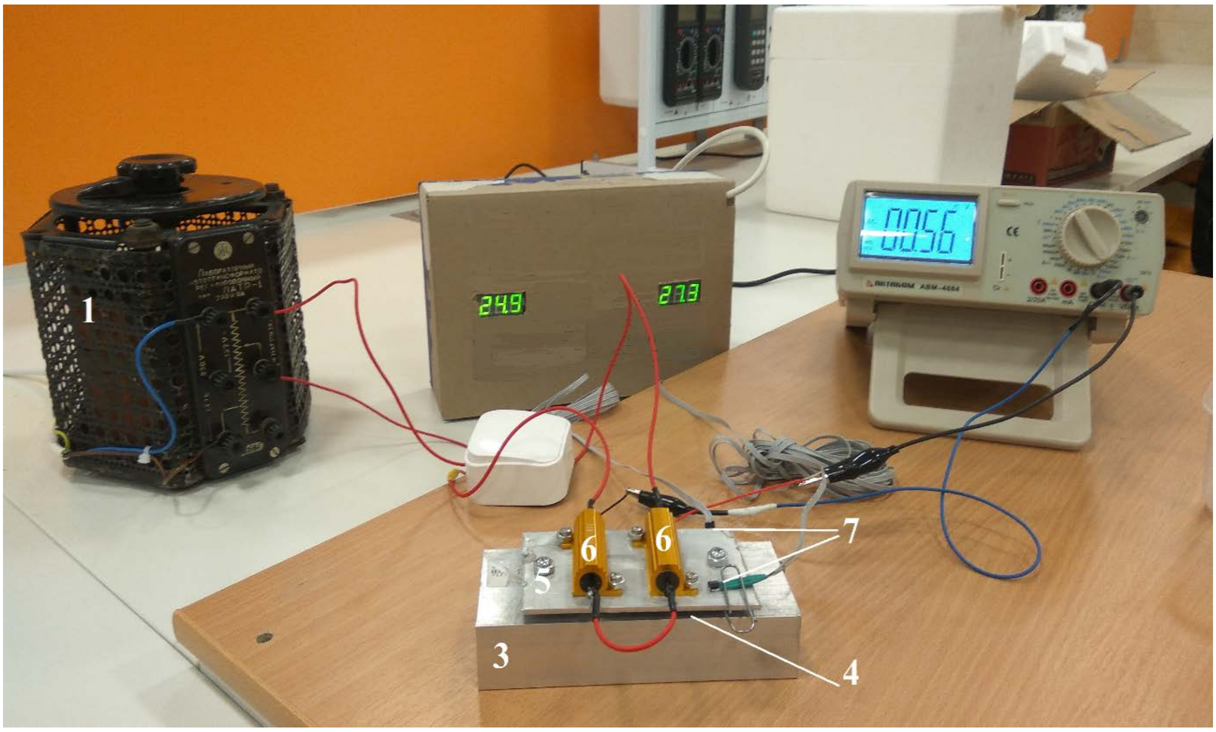


Figure 3. Photo of a laboratory bench with UTEG.

4. Computer simulation of PV module

To calculate the parameters of the PV module and the capacity of the backup source for LDS, it is necessary to know the distribution of solar radiation for the selected area. The method used for calculating solar radiation is described in [15, 16]. The applied technique can be used to obtain the necessary daily solar radiation schedules for any latitude, any tilt of the solar panel and any day of the year. For the calculation example, two latitudes were used, related to Nizhnevartovsk (60°N) and Astrakhan (46°N). These cities are one of the key nodes of oil transportation. The climate of Astrakhan is arid, lukewarm and the climate of Nizhnevartovsk is boreal. The choice of these cities belonging to different climatic zones is also determined by the definition of a universal approach to the selection of parameters of LDS's autonomous power supply complexes.

PV module generation of 5 W average daily power per day with a minimum of solar radiation will allow us to prove the possibility of uninterruptible power supply to LDS on other days of the year that have more solar radiation. Therefore, the calculation of daily solar radiation on the day of the winter solstice (December 22) was performed for latitudes 60°N and 46°N.

The solar radiation scattering coefficient was calculated based on NASA empirical data for 2018 and 2019 that allowed determining the dependence of solar scattering on the geographical location of the object.

In order to determine the required area of the PV module for LDS power supply, simulation was carried out in the Matlab/Simulink system using the model shown in Figure 4. The model consists of several main blocks: PV array – a solar panel simulation block, with parameters correspond to Delta SM 30-12M (P_{nom}=30 W, V_{noload}=22.64 V, $I_{short\text{-}circuit}$=1.73 A, V_{max_power}=18.57 V, I_{max_power}=1.65 A, N_{cells}=36), I_{rr} – irradiance (W/m^2), T – panel temperature (^{0}C), DC/DC converter with MPPT (maximum power point tracking) control algorithm.

Load is active resistance (Ohm). The choice of panel is based on the minimum possible nameplate power of this type of device. Using the Irr block, the daily illumination was set that corresponded to the graphs presented in Figure 4. Using the recording blocks, PV module power and energy generation graphs were obtained.

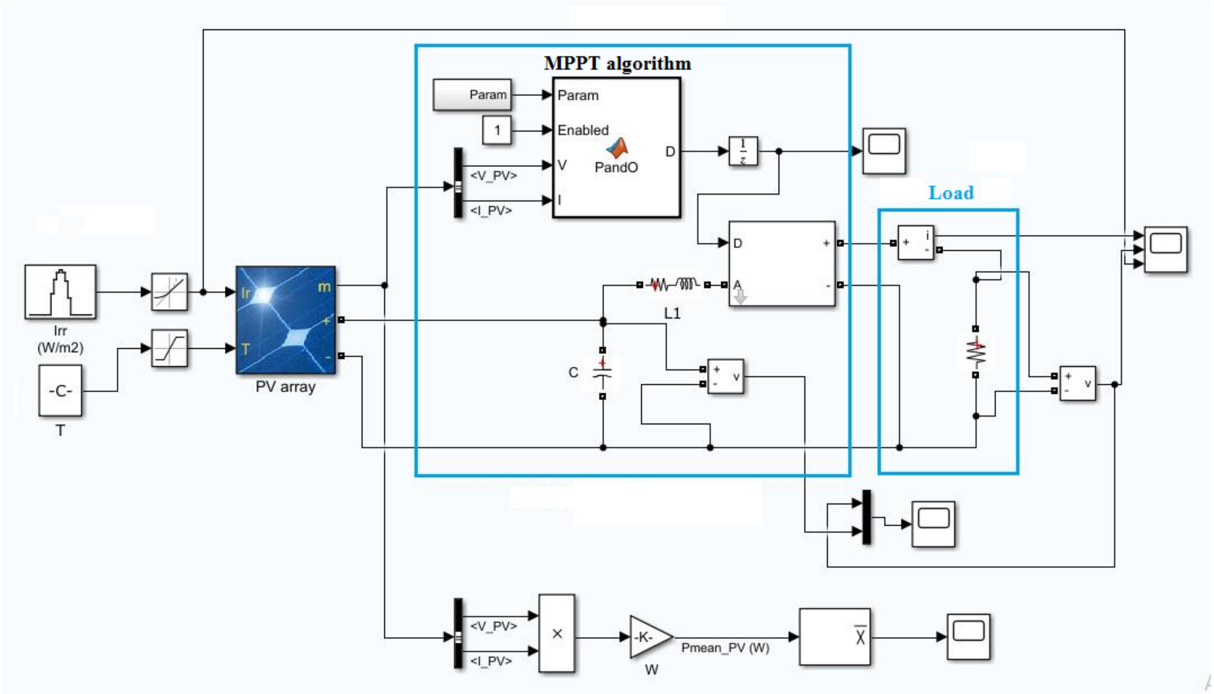


Figure 4. PV module simulation model.

5. The results of an experimental research of UTEG

As a result of the first experiment, the current-voltage characteristic of UTEG was obtained. It showed the linearity of the internal resistance of the UTEG element in a wide range of operating temperatures. The average value of internal resistance was R_{int}≈12 Ohm. The characteristics shown in Figure 5 are the result of further experiments. The two graphs on the left refer to the mode when both the cold and hot side of UTEG had an above zero temperature. Two dependencies on the right relate to the mode in which a negative ambient temperature is simulated using a box with dry ice.

Analyzing of the obtained data, one module generates P = 0.65 W when average temperature range between the hot and cold sides of UTEG is 40°C that means 8 UTEGs will be sufficient to generate 5 W of required power.

However, the temperature difference over 40°C between the hot and cold sides of the UTEG is achievable in the autumn, winter and spring months for Nizhnevartovsk (average temperature: minus 1.9°C in October, minus 3°C in November, minus 19°C in December, minus 21.8°C in January, minus 25.9°C in February, minus 11.9°C in March, minus 3.1°C in April). In other months, the temperature difference will be lower. At the same time, the temperature difference about 40°C will be reached only in the winter months for Astrakhan (average temperature: minus 1.9°C in December, minus 5.6°C in January, minus 4.9°C in February).

These circumstances necessitate the additional use of the PV module.

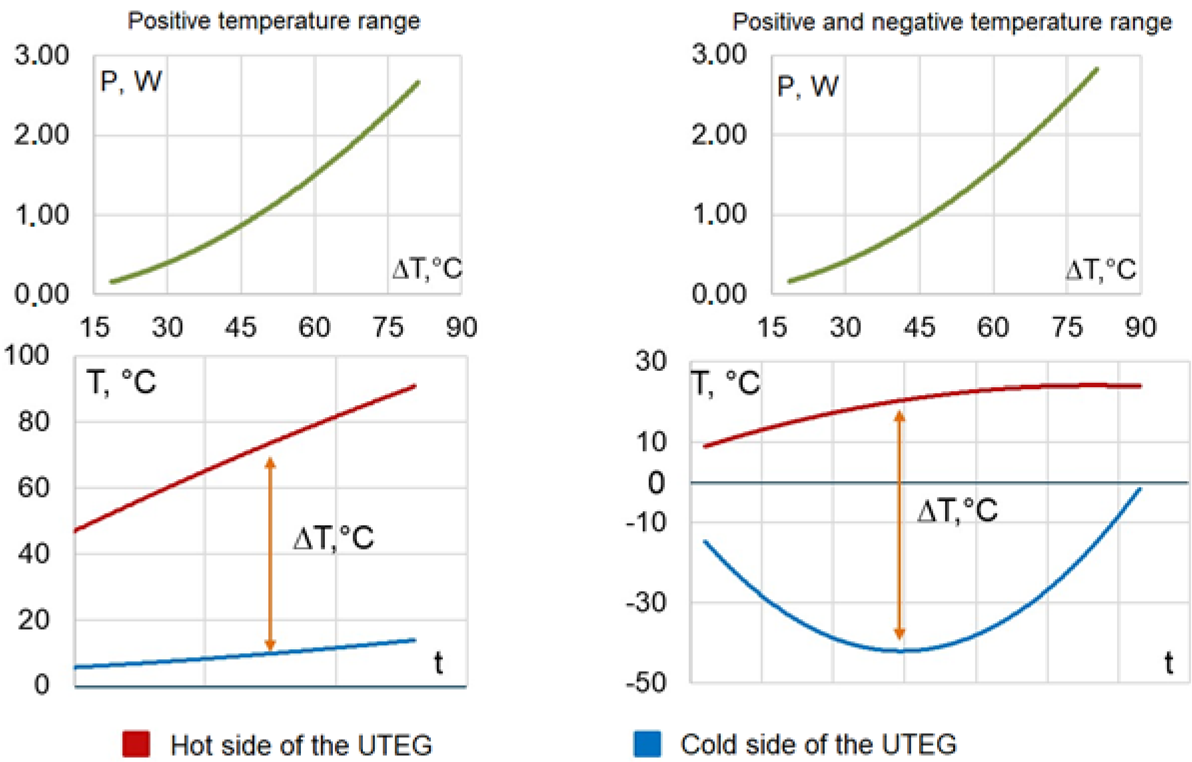


Figure 5. The results of processing the data obtained during the experiments.

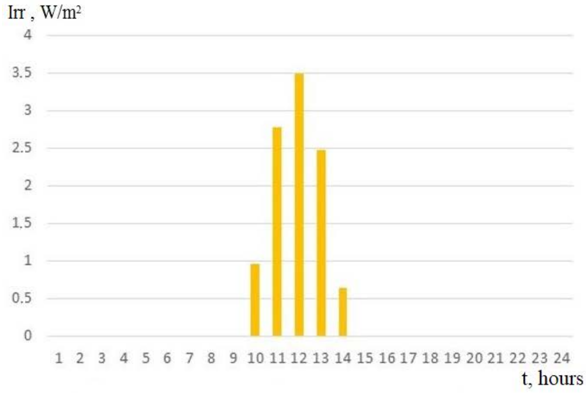
6. Results of PV module computer simulation

Based on the obtained daily distribution graphs, minimum solar radiation on the day of the winter solstice is not enough (Figure 6) to generate energy for LDS for the latitude corresponding to Nizhnevartovsk (60°N). However, the average temperature for Nizhnevartovsk in months with a minimum of solar radiation (7 months) is sufficient for UTEG power generation.

On the other hand, according to the results of the model (Figure 4) for latitude 46°N of Astrakhan (Figure 6) and 7 hours daylight duration, the total daily energy on the day of the winter solstice for the selected solar panel was 78.4 Wh and the average daily power generated by the PV module was 3.26 W. This is not enough to provide an average power of 5 W but with the addition of another panel of the same type (6.53 W) the required power will be achieved.

Thus, to provide autonomous power supply of LDS only from photovoltaic panels, two single-crystal panels with a total nominal power of 60 W for latitude corresponding to Astrakhan will be required. However, in this case, a battery is required that will be the main source of power within 17 hours. The energy stored by the battery should be 85 Wh with an average power of 5 W. Since the average voltage of a lithium battery cell is 3.7 V, the capacity of the required battery is about 23.000 mAh or 12 cells with an average cell capacity of 2.000 mAh.

The need to use high-capacity batteries with the parameters that significantly depend on temperature and on the number of discharge-charge cycles reduces the reliability and autonomy of the complex in general. Therefore, the need for additional utilization of UTEG for latitude 46°N of Astrakhan also exists. Based on previous calculations, the average power of 8 UTEGs will be 5.2 W in the winter months. Therefore, the energy additionally generated by UTEG in 17 hours will be 88.4 Wh that is higher than the required 85 Wh. Thus, a lithium battery when using UTEG is necessary only to compensate for the stochastic nature of the weather.



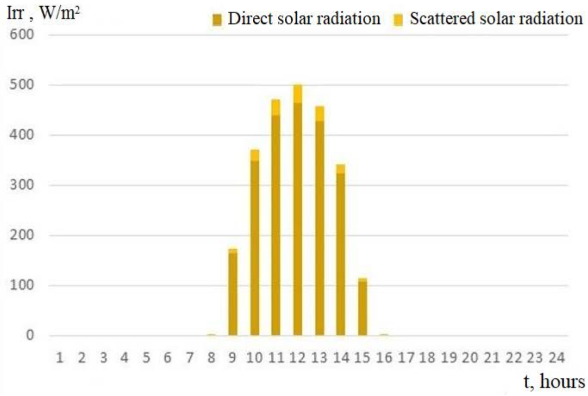


Figure 6. Direct and scattered solar radiation for latitudes 60°N (left) and 46°N (right) on the day of the winter solstice.

7. Conclusions

As a result of the studies, a block diagram of the electrical complex for autonomous power supply of LDS has been developed, the UTEG and PV module parameters necessary for LDS uninterruptible power supply have been determined. The need to share UTEGs and PV modules for LDS uninterruptible power supply has been proven depending on the location of the pipeline. The applied method for determining the parameters of PV modules is generalized and can be used taking into account the location of the object.

The developed electric generation complex using thermoelectric generating and photoelectric elements for autonomous supply to liquid hydrocarbons LDS with electric energy can be installed on trunk and field pipelines of any diameter when will be technically implemented. Such a product solves not only the problem of energy-efficient power supply to leak detection systems but also reduces the time to search for accidents at oil pipelines owing to the possibility of more frequent installation of these systems and their installation in inaccessible areas. This reduces both the negative impact on the environment and the financial costs of enterprises to eliminate accidents.

With the further implementation of this project, it is possible to install a prototype on an existing pipeline for pilot and further field trials. This will make it possible to create a technology for using the associated heat of the transported liquid in pipelines for autonomous power supply to low-power consumers, automation and telemechanics systems, to ensure increased reliability of oil transportation.

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