Effect of Distributed Photovoltaic Generation on the Voltage Magnitude in a Self-Contained Power Supply System

B V Lukutin[1], E B Shandarova[1], A F Makarova[1] and I B Shvartsman[2]

[1]National Research Tomsk Polytechnic University, 30 Lenin Avenue,Tomsk, 634050, Russia
[2]Tallinn University of Technology, Ehitajate tee 5, Tallinn ,19086, Estonia

E-mail: shandarovaelena@mail.ru

Abstract. A promising way to increase the technical and economic characteristics of stand-alone power supply systems is to incorporate renewable energy installations in their structure. This saves fuel and extends the operational life of diesel power stations. The most common option is a hybrid system with photovoltaic power stations incorporated into the local network of the diesel power station. This paper deals with the dependence of the deflection voltage and power losses in the electric power transmission line on the graphs of electrical loads, the parameters of elements of the power supply system, connection points and the capacity of distributed photovoltaic power stations. Research has been carried out on the common low-voltage power supply systems of the radial type (0.4 kV) with an installed capacity of up to 100 kW. The studies have been conducted by simulating the operating modes of hybrid power systems of various configurations. As a result of these studies recommendations to reduce losses and voltage variations in the network by selecting the power and photovoltaic power connection points have been put forward.

Introduction

Consumers' electrification is implemented by connecting them to the central power grid or by creating their own power station. In areas with a high density of electrical loads a centralized energysupply has both technical and economic advantages. It is more expedient to provide electricity to remote sparsely populated areas that have low power consumption from their own autonomous power stations.

Russia can serve as an example of the parallel development of centralized and decentralized energy. The centralized power system covers only 30% of Russian territory, mainly in its European part and southern regions of Siberia. For the rest of the territory autonomous power sources are used to generate power, the vast majority of which (98%) is generated by diesel power stations (DPS). The average fixed capacity of DPS is around 340 kW.

The remoteness of decentralized electrification facilities, the harsh climate and complex transport logistics account for the major share of the tariff for electricity - costs for the purchase and delivery of fuel. This part of the operating cost amounts to 50-60% of the produced electricity cost. The tariff on DPS electricity in certain regions of Siberia reaches 100 rubles / kWh and can be higher.

One method to improve the technical and economic characteristics of the autonomous power supply systems (APSS) is to use renewable energy units in their structure [1,2,3,4].

The most universal of natural energy sources are wind energy and solar radiation [5,6]. The reduced cost of photovoltaic panels combined with their ease of installation and operation has sparked interest in photo diesel autonomous power in Russia.

The integration of the photoelectric station (PES) into the autonomous power supply system with DPS requires solutions to many problems related to the unbalance of load graphs of the electrification object and solar radiation during the day, and the power ratio of the diesel station and photovoltaic units and the autonomous power supply system configuration among others.

A study of autonomous power systems with renewable sources including photovoltaic power stations is deemed to be essential. The works [7,8,9,10] have all contributed to the development of thisproposition.

However, the complexity and diversity of the research problems as well as the intent to improve the technical and economic characteristics of the photo diesel energy sector require new research.

Research objectives

In previous studies, the issues of quality and the loss of electricity in an autonomous power system with photovoltaic distributed generation were not reflected. Of particular interest is the stability of the voltage and losses in power transmission lines depending on the power ratio of DPS and PES, daily schedules of insolation and electricity consumption, photoelectric stations' connection points to the autonomous electrical network and the type of inverter PES.

Object of study

Research was carried out on the geographical conditions in the middle latitudes of Russia. We considered an autonomous power supply system of the radial type 0.4 kV characteristic of that used for the electrification of small settlements.

Figure 1 shows the computational equivalent circuit. The letter C on the circuit designates the source DPS, equivalent to the diesel power station, and the inductive x_{ln} and active resistance r_{ln} of the circuit sections up to the consumers' connection points to the total power throughput in a complex form $\dot{S}_n$. Consumers are connected via the sections of lead-in lines with the parametersx_{nn},r_{nn}. Photoelectric stations are equivalent to the power source $\dot{J}_{ph}$ that can be connected to various points of the network the voltage of which is indicated as$\dot{U}_n$.
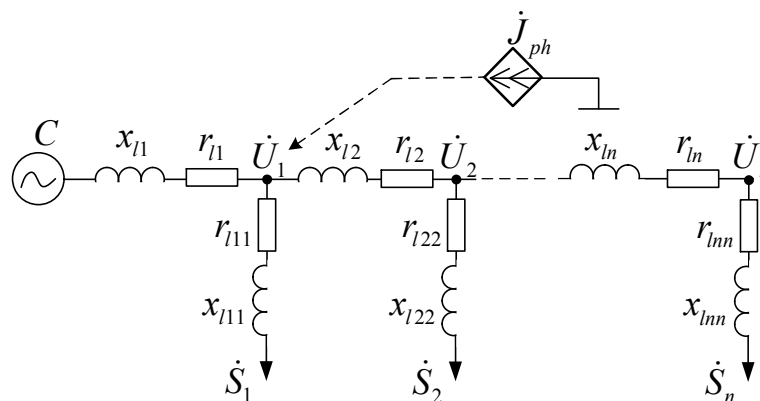
**Figure 1.**Computational equivalent circuit.

Photo panels transmit DC generated power via the network invertor. Modern invertors with MPPT functions in their output characteristics can be equated to the source of current [9]. DPS with control of excitation of synchronic generators is equated to the voltage source. The State Standard specifies a limit value toany deviation of not more than 10%. Thus, the line length will depend upon known factors: the specific linear resistance wires and power loads.

Taking into account the need for a large number of calculations related to the daily changes in insolation and electricity as well as an analysis of circuit configurations with different connecting points of PES with varying power, in this environment Matlab modelling is used as a method of study.

Results of the Study

Initial data for modelling are the daily schedules of electricity and insolation. Consumers of electricity in decentralized areas are mostly small towns with a population of up to several hundred people. The volume of electricity consumption in settlements is determined mainly by the communal household load as well as by small enterprises processing local natural resources and agricultural products.

For modelling we used typical daily schedules for the communal household load for conditions in Russia shown in Figure 2 and Figure3, where P, Q – active and reactive load power; w_s – total energy of the solar radiation on a horizontal surface within 24 hours at the latitude 55-56° (in summer).

active power P (p.u.),
reactive power Q (p.u.)
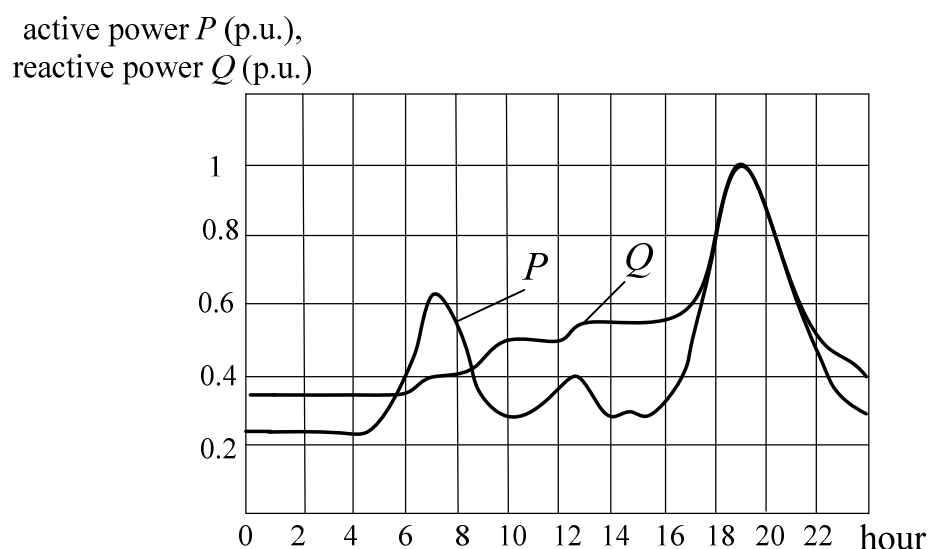
Figure 2. Winter consumer diurnal load graph.

For a seasonal factor of the summer load peak P_{maxs} against the winter $P_{maxw}$the value 0.7 is recommended. In the graphs of power consumption in named units it is convenient to use the maximum coefficient $k_{max}=P_{max}/P_{av}$ for a typical graph. Average power consumption P_{av} is determined by reporting data on monthly electricity generation by DES of the settlement.

The distribution of electricity consumers' power connected to the points of the power line along its entire length is important to the goal of this study. The main consumers are private houses and social facilities: schools, libraries, clubs, kindergartens, etc. For small and medium-sized towns with a population of 50-1000 people the established norms of the annual electricity consumption are 760-855 kWh / person (in the absence of stationary electric stoves). If we assume that the number of family members living in the house ranges from two to five people, the annual rate of power consumption will be 1710-4275 kWh. The average power consumption of the house is within $0.2 \div 0.5$ kW. At peak hours it increases in proportion to the maximal coefficient. Social facilities are more powerful electrical energy consumers. The maximum amount of power used by a school or a club for the considered settlements is 7-10 kW.

This paper investigates the power supply system for summer season conditions which is expedient as winter insolation in central Russia (55-56° N) is 15 times less than for summer. It defines the creation of PES that will only be effective for the summer season. In winter, with an increase in power consumption and a decrease in insolation, the role of PES is significantly reduced and it has virtually no effect on the electrical mode of the power supply system. Full power of the electricity transmission line in terms of voltage loss does not exceed 30 kVA.

active power P (p.u.),
reactive power Q (p.u.),
solar radiation w_s, (p.u.)
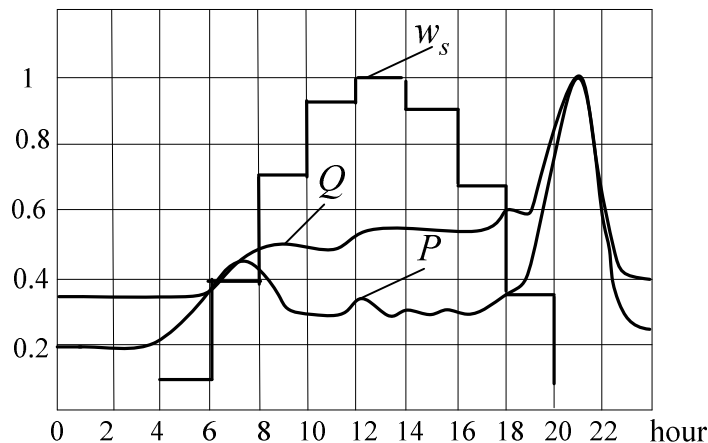
Figure 3. Summer consumer diurnal load graph and insolation.

Comparing a graph of the relative magnitudes of the total solar radiation w_s on a horizontal surface within 24 hours and a graph of power loads (Figure 3) shows that a morning load peak corresponds to only 40-50% of possible generation in relation to the midday solar insolation. The evening load peak corresponds to a reduction in insolation of 10% or less.

Thus, the question of a rational installed capacity of networked PES in the autonomous power supply system without an energy storage system arises. Similar schemes with power invertors are also spreading across the autonomous power supply systems due to their simplicity and low-cost implementation [11,12].

It is known that the network invertor can operate in parallel only with a sufficiently powerful electrical supply network. In autonomous objects such a power system is created by a diesel power station. Leading manufacturers of "solar invertors" do not recommend reducing the current capacity of DESin photo-diesel engines to less than 40-50% relative to the power of total generation. PES does not practically add its power during the morning and evening peak loads.

Thus, when taking into consideration the geographical conditions, the nature of electrical consumption of the object and restrictions on the mode work of the network invertor, it is recommended thatthe available electric power of the PES be limitedduring the summer period to a level of no more than half of the average daily consumed power without taking load peaks into consideration. In the course of modelling this recommendation is depictedby the corresponding current value $\dot{J}_{ph}$.

PESs with energy storage have more opportunityto match the graphs of electricity consumption and insolation. The power of storage batteries can be redistributed at specific times,for example, participating in ensuring the evening peak.

The matter of the connection point of the PES to an autonomous electrical system is critical. The PES is often connected in parallel to the DPS on the general switchgear. This practice is more economical on the switchgear and relay protection. Such a connection does not cause the electric mode of the distributed electrical network to change. Rather, it is the value of the transmitted current and resistance of the wires that determine the loss of power and voltage in the power line.

Connection of the current source, equal to PES, to other points on the electrical transmission line leads to redistribution of the currents in the electrical circuit diagram and, accordingly, to changes in levels of power loss and voltage at the connecting points of the loads.

In the nominal work mode of the DPS the voltage at the end of a simulated power line is reduced by 9.75% relative to the nominal. The amount of lost electricity is 8% of the transmitted power.

When an additional power source $\dot{J}_{ph}$ is connectedpower loads can be reallocatedbetween DPS and PES. The result is a change in the current valueat various parts of the network whichreduces power losses in the conductors and provides greater voltage stability at the connection points of consumers of electric power.

The modelling results showed that using power fromthe PES with the energy storage system at the rate of one half of the nominal load of the power supply system will reducevoltage loss at the end of the line by up to 2-3%. This is achieved by connecting the PES at a distance from DES that isnot less than half of the total length of the electrical transmission line. By sodoing the loss value is reduced to lessthan 1%. Under substantially uneven load power of the distributing power transmission lines, it is advisable to connect the PESat the connection point of the most powerful electro-consumer.

At low power supply system loads in the summer period when, consequently, thereis a need to reduce the PES power, the voltage stability over the transmission line is significantly higher and the level of energy loss is significantly lower. Implementation of the recommendations at the connection point of the PES improves the parameters of the electric mode butthese changes are not as noticeable as in the rated load of the system.

Conclusions

1. The effectiveness of using the PES inautonomous power systems without energy storage systems is significantly limited by the operating conditions of the network invertors.

2. For the geographical areas in the northern mid-latitudes the big difference between thevalues of insolation in summer and winter determines expediency of the maximum use of PES in the summer, which is contraryto reducing the summer electricity consumption.

3.To stabilize the voltage in the power system and reduce electricity losses it is advisable to use PES with energy storage systems and connect them closer to the end of the distribution line or to the connection point of the most powerful consumer. The generation power of the PES is limited to halfof the maximum capacity of electricity consumption.

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