Modular aggregation functions performed by static inverters in autonomous power supply systems

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Abstract. Static power inverters (SPI) are important functional elements to provide efficiency and reliability for autonomous power supply systems (APSS). The paper proposes to improve technical and economic characteristics of APSS through modular aggregation functions and reduced number of power electronic devices constituting SPIs. The paper provides a generalized SPC topology and insights into its performance. It deals with some electric schematic diagrams for a controlled rectifier and a three-phase modular inverter, a three-phase voltage inverter based on two single-phase inverters and a single-phase-three-phase rotating-field transformer, as well as a chain diagram for a universal modular static power inverter. It is shown that modular aggregation functions of APSS static power inverters will improve reliability through back-up operations performed by the main functional units and assemblies, and reduce time intervals for their maintenance and repair. The efficiency of autonomous systems will be advanced due to a decrease in the total number of power electronic devices constituting SPIs. In addition, the level of electromagnetic interference generated by these devices will decrease. A significant technical and economic effect will be achieved by using universal modular static inverters in the APS systems, capable of passing energy flows back and forth in both directions and operating in various modes.

1. Introduction
Nowadays, autonomous power supply (APS) systems are widely used as backup, to ensure uninterruptible power supply to consumers, and main sources of electricity in remote areas. Moreover, they can be stationary and transport. Recently, to improve energy efficiency in APS system, renewable energy sources (RES) have been applied, mainly wind turbines and photovoltaic arrays [1–3].

APSs feature static power inverters (SPI) – inverters, frequency converters, rectifiers and converters that, besides converting electricity, can serve as electric power stabilizers. As a rule, the efficiency and reliability of APSs depend on static power inverters.

It is possible to improve operational and technical characteristics, including reliability of APS systems, through modular aggregation functions performed by their main components, and a reduced number of power electronic devices constituting SPIs [4, 5].

The paper discusses the methods for SPI modular aggregation and ways to improve their reliability and efficiency by reducing the number of power electronic devices.

2. Methods
A study was based on theoretical and empirical methods related to the analysis and synthesis of different approaches to SPI topology with improved operational and technical capabilities, as well as a
comparison of the main characteristics of well-known technical solutions with those developed on a modular basis.

3. Results
In order to proceed to the consideration of methods for SPI modular aggregation, it is advisable to deal with their structure and performance features. Figure 1 shows a generalized SPI topology. It comprises a power unit 1 containing input and output filters 4.1 and 4.2, respectively; a converter 5; a control system 6 containing input and output devices for monitoring electric power parameters 7.1 and 7.2, respectively; a signal correction device 8; a signal amplifier 9. Figure 1 also shows an output 1 for connecting a power source and an output 2 for electricity consumers.

The input filter 4.1 protects the power source from switching overvoltages arising from the power electronic devices of the converter 5, and the output filter 4.2 ensures the required quality of electric power parameters. The converter 5 generally converts that type of current required for electricity consumers and, in addition, coordinates a source voltage level with electricity consumers. To do this, a matching transformer is provided as part of the converter 5.

The monitoring device 7.1 also functions as a power source of the control system 6. In the signal correction device 8, control pulses of power electronic devices of the converter 5 are formed, which make them open and close at a specified time.

SPIs are proved to malfunction most commonly due to faulty power electronic devices [6, 7]. To avoid the replacement of a three-phase rectifier containing a transformer and six semiconductors, one of which is inoperative, with a similar three-phase rectifier, it is advisable to structurally separate the transformer from the rectifier and each of the power electronic devices, by connecting them to one module. In case one power electronic device fails, it is excluded from a rectifier circuit by automatic or manual replacement with a working device.

Figure 1. Generalized SPI diagram

Figure 2 shows a schematic diagram for a controlled rectifier, designed using transistor and diode modules. Figure 2 does not show the input and output filters and the converter control system. The transformer in this diagram, in addition to voltage conversion, is responsible for galvanic separation of the source and consumers. What is more, its windings act as an impedance bond.

Figure 3 shows a schematic electric diagram for a three-phase voltage inverter, designed for single-phase inverters A, B and C. The power single-phase designs contain two transistors. The control system synchronizes the single-phase inverters to obtain a three-phase symmetrical voltage system, is such a way that when the transistors 1 are open, the transistors 2 of the inverter are closed. There are time intervals when transistors 1 and 2 in single-phase inverter designs are closed. By changing the time length the transistors are closed, the control system provides voltage stabilization at the inverter output. In this case, the voltage is stabilized independently in each phase, i.e. the control system provides voltage stabilization in asymmetric operating modes.
The combined alternating operation of transistors and a transformer with a midpoint enables to reduce the number of power semiconductors of single-phase inverters and a three-phase inverter. A voltage regulation range also increases, as compared to conventional three-phase inverter designs for six power electronic devices. The proposed diagram for a three-phase inverter (Figure 3) has advanced reliability and efficiency. Its main disadvantage, though, is relatively large weight and dimensions [4].

A three-phase symmetrical voltage system is possible provided that a single-phase-three-phase rotating-field transformer (RFT) is added to a single-phase inverter design. In this case, the total number of DC to AC power devices will decrease, with reliability and efficiency to improve [4].

Structurally, RFT can be based either on a toroidal transformer (a closed core has a ring shape, while a cross-sectional profile differs from a round one) or on a wound-rotor electric machine. In the latter case, a wound rotor is fixed and there is almost no stator-to-rotor gap, which increases the efficiency of the transformer. In addition, electric-related manufacturing technology is easier since windings are dropped in slots, unlike magnetic toroidal system where coils are wound around a toroidal ring.

Figure 4 shows a simplified power diagram for a three-phase voltage inverter. A magnetic system of a 1-phase-3-phase RF transformer is based on an electric machine. Two primary windings of the transformer containing midpoints are evenly distributed along the slots in a toroidal part (stator), while
one coil is structurally shifted relative to the other at an angle of 90°. Transformer secondaries placed on the core (rotor) at an angle of 120° from each other have a star network connection [1].

When a DC voltage source is connected to the inputs 1 and 2, current flows pass in different directions along the primary RFT windings 3 (Figure 4). Alternating current is flowing due to alternating operations of transistors in single-phase inverters. Alternating current causes alternating magnetic fluxes that create a rotating magnetic field in RFT magnetic system. A symmetric 3-phase alternating electromotive force is induced in the secondary windings. By changing time intervals when transistors 1 and 2 of single-phase inverters are open, the control system, when destabilizing factors occur, provides voltage stabilization at the secondary terminals, including unbalanced operation modes.

Technical and economic indicators of APS systems can be significantly improved by using universal modular static inverters (UMSI) in their configuration.

Figure 4. Schematic diagram for a single-phase-three-phase rotating-field transformer

Figure 5 shows one of the UMSI designs. It includes modular units: a switchgear 1; a control and protection system 2; filters 3.1 and 3.2 respectively; single-phase transformers 5.1–5.4; transistor switches 6.1–6.4. The figure also shows contacts 4.1–4.4, buses 7.1 and 7.2, respectively.

The switchgear 1 connects UMSI with sources and power consumers through the control and protection system 2. The control and protection system is a microprocessor comprising several programs to ensure that UMSI can operate in different modes, as well as programs that process information from monitoring sensors and, if need be, give a command to replace faulty modular links consisting of single-phase transformers and transistor switches.

In a rectifier mode, the control system 2 connects an AC power source to the buses 7.1 via the switchgear 1. The filter module 3.1 in this mode is idled. The AC voltage is applied via the buses 7.1 and contacts 4.1–4.3 to the output buses 7.2 through the modular blocks 5.1–5.3 and transistor switches 6.1–6.3. The transformers lower the voltage, and transistor switches convert it to DC voltage. The modular filter block 3.2 smoothes the ripples, thus providing the required quality for power consumers that are connected to the switchgear 1. AC voltage sources of single-phase and three-phase systems can be connected to the buses 7.1.

In an inverter mode, a DC power source is connected to the buses 7.2 through the filter module 3.2. In this mode, the modular blocks of transistor switches 6.1–6.3 convert DC voltage to AC voltage. Due to the reversibility of single-phase transformers 5.1–5.3 (the ability to let energy flows pass in both directions), their inputs and outputs change places and perform the functions of step-up transformers. Thus, a single-phase, and if need be, a three-phase symmetrical voltage system is connected to the buses 7.1.

The modular blocks 5.4 and 6.4 for the above modes are redundant. They kick in for a corresponding phase of the power source, in the event of a malfunction of one of their single-phase transformers or block of transistor switches.
To operate in a frequency converter mode, additional modular blocks of transistor switches are required. In this mode, modular blocks of matched single-phase transformers as well as filter 3.1 are idled. A high-frequency voltage of the power source is connected via the switchgear 1 to the buses 7.1. The transistor switches operate in a direct frequency converter mode, i.e., convert high-frequency voltage to low-frequency that is connected to power consumers through the filter 3.2.

**Figure 5.** Functional diagram for a universal modular static inverter

In a converter mode, two UMSIs are connected in series, with the first operating in inverter mode and the other – in rectifier mode. In this mode, voltage can be stabilized both by changing the control angle of the high-frequency inverter transistors, and by changing the control angle of the rectifier transistors.

4. Conclusion

Operational and technical characteristics of APS systems based on modular static power inverters can be significantly improved through modern mathematical methods for electromagnetic compatibility of the main functional elements of the system [8, 9].

All in all, modular aggregation functions of static power inverters in APS systems will improve the reliability of the system through back-up operations performed by the main functional units and assemblies, and reduce time intervals for their maintenance and repair. The efficiency of autonomous systems will increase due to a decrease in the total number of power electronic devices constituting SPIs.

In addition, the level of electromagnetic interference generated by these devices will decrease. A significant technical and economic effect will be achieved by using universal modular static inverters in APS systems, capable of passing energy flows back and forth in both directions and operating in various modes.
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