Reactive power balancing transformers in control systems for electric drives of direct and alternating current

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Abstract. The features of the application of the balancing transformers with artificial switching as regulated power sources of the process plants are considered. The proposed approach makes it possible to convert AC to DC to supply the load and simultaneously generate reactive power of a capacitive nature, which is aimed at meeting the current Russian and foreign standards for electromagnetic compatibility of the consumer with the supply network. The characteristics obtained as a result of computer simulation in the MATLAB Simulink environment and its SimPowerSystems application confirmed the main positive features of compensation converters. It is shown that the main advantage of controlled compensation converters is the possibility of creating a frequency-controlled asynchronous electric drive with separate frequency and voltage control, which will significantly improve the energy characteristics of an asynchronous motor by reducing losses, increasing the service life of insulation, and significantly improving electromagnetic compatibility.

1. Introduction
To minimize the electricity losses in power lines (ETL) is one of the most important tasks of energy conservation.

Most of the energy losses in power lines can be divided into two main types by the mechanisms of origin [1]:

- losses due to active resistance of current-carrying components of the power system;
- losses associated with reactive power in the network.

At the same time, the production of reactive energy can be carried out by compensating installations at the place of its consumption. Nowadays, the main means of reactive power compensation in the companies is a power capacitor batteries connected in parallel to the power grid (shunt compensation). They have a number of significant drawbacks that complicate their operation and reduce the reliability of the power system:

- lack of smooth automatic regulation of reactive power delivered to the network;
- negative effects of overvoltage and higher harmonics;
- probable resonant and self-sustained oscillation processes to occur in certain combinations with the inductance of the components of the power supply system.
As a result of the analysis of the shortcomings of the existing means of reactive power compensation, taking into account the need to regulate the productivity of process units, the main qualities were determined [2], the combination of which in one device will improve efficiency of electric power conversion in relation to a controlled electric drive:

- none movable mechanical elements;
- ease of installation and installation on site;
- no restrictions on the application of the minimum working power;
- low intrinsic loss of active power;
- high response;
- protection against resonant phenomena, or the complete elimination of their occurrence;
- smooth adjustment of reactive power compensation of both characters;
- the ability, in addition to reactive power compensation, to perform the task of regulating the voltage (current) to power the electric drive of the process units;
- to be integrated easily into external automated process control systems (Process I&C) and power supply of the company [3];
- ability for long-term unmanned operation.

2. Balancing transformer

As a result of the analysis of the possibility of implementing each of the indicated qualities, using a systematic approach [4] and taking into account their integration into a single device, a static semiconductor balancing transformer was developed [5] – AC conversion device that combines the functions of reactive power compensation and power control of process units. The schematic diagram of the idealized power unit of the BT is shown in figure 1.

![Figure 1. Schematic diagram of an ideal power part of the balancing transformer.](image)

The basis of the balancing transformer is a three-phase power bridge, consisting of fully controllable keys which are IGBT or IGCT, depending on the operation of the converter, respectively, as a voltage or current source. Components and switches (IGBT) are auxiliary, forming two identical nodes of Surge Protection Device (SPD). The energy source (mains) is represented in the diagram by a three-phase EMF system \( e_a \), \( e_b \), \( e_c \) with internal inductance \( L \) and DCR \( R \) respectively. The load is represented by an active-inductive component \( R_a \), \( L_a \), typical for most consumers [6].

The principle of operation of the converter is the phase control of power rectifiers relative to the point of their natural switching. The use of fully controllable rectifiers makes it possible to implement
a mode of operation in the balancing transformer at leading angles of control. Balancing transformer simultaneously performs two functions in this mode: control of the output voltage (current) and generation of capacitive reactive power into the power network, compensating an inductive reactive power in the network.

Evident positive features of the balancing transformer are as follows:

- the ability to convert AC to DC to power the load and at the same time generate capacitive reactive power;
- a small number of switching power rectifiers on the repeatability interval of processes, that allows to apply balancing transformer in high power installations;
- the ability to direct the energy stored in the inductances of the phases of the supply network (or input transformer) to the load) [7];
- higher stability of the output characteristics of the converter relative to existing analogues;
- compliance with current national and international standards for electromagnetic compatibility with the mains;
- at all control angles, capacitive reactive power is generated;
- the value of the generated reactive power smoothly varies;
- the possibility to exclude 5.7.9 and other higher harmonics from the current consumed from the mains;
- the compensating ability of the converter increases when the matching transformer is rejected;
- in case of parallel operation of the converter with reactive power consumers of an inductive nature in the load node, the supply network is unloaded by reactive power.

3. Computerised modelling of the balancing transformer
MATLAB Simulink and its application SimPowerSystems were used for a computer study of the characteristics of balancing transformer as an element of the energy system. The processes in the valves of the balancing transformer are similar to the processes in the existing circuits of valve devices and do not have fundamental differences, therefore, the accuracy of the approximation of the CVC of the valves in Simulink can be considered quite sufficient for the selected level of analysis [8].

The model consists of a power unit, a control system and a set of measuring and visualization parameters of the converter. The developed computer model of the balancing transformer allows us to study stationary and transient (figure 2) modes of its operation, and also evaluate the effect of various parameters on input and output characteristics.

Figure 2. The oscillogram of the average \( \bar{I}_t(t) \) and instantaneous amplitude \( i_t(t) \) of the output current of the balancing transformer when operating at RL–load and abrupt change in control angle from \(-45 \) up to \(0\) el.degrees, current axis scale \(-100 \) A/units, along the time axis \(-0.01\) s/units.
The most important characteristics obtained as a result of the study of the balancing transformer by computer simulation are shown in figures 3–6.

**Figure 3.** Dependence of the voltage on the capacitor $U_c(\gamma_1, C)$ from the capacitance $C$ of the capacitor SPD and the angle of the first stage of switching $\gamma_1$ when balancing transformer operates with SPD.

**Figure 4.** Dependence of the THD of the input voltage of the balancing transformer $K_{THD}(\gamma_1, C)$ from the capacitance $C$ of the capacitor SPD and the angle of the first stage of switching $\gamma_1$ when balancing transformer operates with SPD.

**Figure 5.** External characteristics of balancing transformer ($U_{0s}(I_a), U_{45s}(I_a)$ – with SPD; $U_{0s}^2(I_a), U_{45s}^2(I_a)$ – with none SPD).

These characteristics confirm the main positive features of the balancing transformer, namely:

- the quality of the SPD operation is determined by the value of the capacitor capacitance and the angle of the first switching stage (figure 3);
• the charged capacitor of the SPD serves as a potential barrier, eliminating the flow of short circuit current in the switching circuit and thereby contributing to the transfer of switching energy to the load (figure 4);
• SPD significantly reduces switching overvoltages in the conditions of anticipatory switching (figure 4);

SPD enhances the rigidity of the external characteristics of balancing transformer, as was obtained as a result of theoretical analysis [2] (figure 5).

Also, computer simulation of balancing transformer has confirmed the theoretical conclusions [9] that at leading control angles, the input and output parameters of the balancing transformer are determined by the control angle and change similarly to the parameters of rectifiers on single-operation thyristors with a difference in the nature of the reactive power.

4. Scope of application of the balancing transformer

The scope of compensation converters has two directions: distribution circuit and load centers.

Distribution circuits:

• Controlled sources of reactive power (capacitive and inductive nature) for distribution networks, load nodes and local installations;
• filter compensating devices to compensate higher harmonics of current and voltage;
• phase load balancing in three-phase circuits;
• redistribution of active and reactive power flows in parallel power lines;
• transfer of 6-10kV AC to DC circuits with installation of voltage inverters with reactive power generation at substations (especially rural) for consumers.

Load centers:

• controlled converters for powering regulated DC electric drives, adjustable DC sources for electrolysis, electric welding, electric transport, etc.:
• adjustable AC electric drives in all industries, agriculture, housing and communal services, induction heating, arc furnaces, electrical technologies, etc.;
• adjustable converters for supplying exciters of direct and alternating current machines;
• substation voltage stabilizers of 6-10/0.38 kV;
• devices for connecting secondary power supplies and local units to the power system with the implementation of two-way power exchange [10].

The main application of the balancing transformer in distribution networks are regulated sources of reactive power of capacitive or inductive nature, in load centers – adjustable electric drive and technological installations of direct and alternating current.

5. Performance of the balancing transformer

The efficiency of the balancing transformer increases with increasing current consumed by the load in the entire In the case of a large number of consumers of small and medium power, the most effective will be the installation of balancing transformer on a certain part of them in this way, so that for this load center the production and consumption of reactive power is balanced (cluster of consumers with balancing transformer).

One of the main advantages of controlled balancing transformer is the ability to create a frequency-controlled asynchronous electric drive with separate control in frequency and voltage level, which will significantly improve the energy characteristics of an induction motor by reducing losses, increasing the life of the insulation, and significantly improving electromagnetic compatibility (specially in the segment «frequency rectifier - motor»).
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