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HYBRID VAR COMPENSATOR WITH IMPROVED EFFICIENCY

In modern electrical networks thyristor-switched capacitors (TSC) are most used devices for VAR compensation. These devices don't contain rotating parts and mechanical contacts, provide a stepwise control of reactive power and no generation of harmonics to the network. However, with the help of TSC it's not possible to ensure smooth control of reactive power and capacitor banks (CB) are exposed to the negative impact of higher harmonic components of the network voltage. Hybrid VAR compensator don't have such drawbacks. It consists of active filter (AF) and capacitor bank with discrete regulation. The main drawback of such systems is the necessity of accessing all six terminals of CB, while most of them are manufactured with three terminals, internally delta-connected. In the article, the topology and control system of hybrid VAR compensator free from beforementioned drawback, is proposed. The control system provides operating modes of overcompensation or undercompensation reactive power. VAR distribution regulator performs redistribution of reactive power between active filter and capacitor banks with the condition to minimize active filter's power. Scheme of the hybrid VAR compensator, which includes a three-phase three-terminal delta-connected capacitor banks, is shown. Proposed approach allows to provide smooth control of reactive power, isolate the capacitor bank from harmonic currents and use a more effective low-voltage power components.
Keywords: *VAR compensator, capacitor, active filter, thyristor switching capacitors, voltage source inverter (VSI).*

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Бурлака В.В., Гулаков С.В., Поднебенная С.К., Савенко О.С. Гибридный компенсатор реактивной мощности с повышенной эффективностью. *Предложены схемные решения гибридного компенсатора реактивной мощности, состоящего из последовательного активного фильтра и батареи конденсаторов с тиристорным переключением ступеней. Рассмотрена работа системы управления гибридным компенсатором. Предложенное решение позволяет «изолировать» БК от токов высших гармоник и обеспечить плавное регулирование реактивной мощности.*
Ключевые слова: *компенсатор реактивной мощности, конденсатор, активный фильтр, конденсатор с тиристорным переключением, автономный инвертор напряжения.*

Бурлака В.В., Гулаков С.В., Поднебенна С.К., Савенко О.С. Гібридний компенсатор реактивної потужності з підвищеною ефективністю. *Запропоновані схемні рішення гібридного компенсатора реактивної потужності, що складається з послідовного активного фільтру і батареї конденсаторів з тиристорним перемиканням ступенів. Розглянуто роботу системи управління гібридним компенсатором. Запропоновані рішення дозволяють «ізолювати» батерею конденсаторів від струмів вищих гармонік і забезпечити плавне регулювання реактивної потужності.*
Ключові слова: *компенсатор реактивної потужності, конденсатор, активний фільтр, конденсатор з тиристорним перемиканням, автономний інвертор напруги.*

Description of the problem. Reactive power (RP) flowing in the network reduce the lifetime of the equipment, increase power losses and decrease the network capacity. The conventional methods of reactive power compensation have several disadvantages: synchronous condensers require installation of a large number of additional equipment, fixed capacitor banks are not regulated, and mechanically switched capacitors don't provide continuity of control and have relatively large response time. Therefore, in modern electrical networks with the 0.4 kV voltage level advanced VAR compensators, which don't contain rotating parts and mechanical relays, are widely used.

Analysis of the last researches and publications. Application of thyristor-controlled compensators, static compensators and active filters is the actual solution of the problem of reactive power compensation. Among these devices, thyristor-switched capacitors are most commonly used in modern power networks.

TSC (Fig. 1) consists of the capacitor banks with thyristor-switched stages and inductors, which serve to limit the rate of change of thyristor current and / or to change the reactance of the network to prevent resonances. To ensure a "soft" thyristor switching its firing is performed at the moment, when the capacitor voltage and the network voltage have the same value.

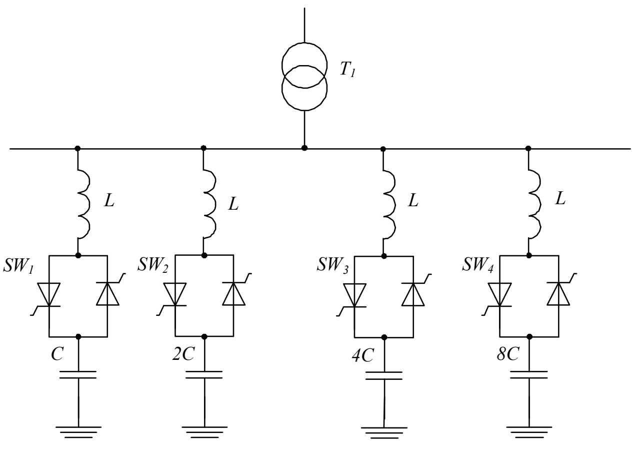

Fig. 1 – The circuit configuration based on the TSC device

Compensators of the TSC type allow to regulate the reactive power stepwisely, have high response time and no generation of harmonics to the network.

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In such devices effective solution is to install a capacity of CB stages proportionally to the power of two (Fig. 1) [1]. It makes possible to get 2^n regulation steps for n CB stages. For example, for the circuit that includes 4 capacitors with the reactive power – 1, 2, 4 and 8 kVAr, you can get 16 steps of regulation – from 0 to 15 kVAr with the 1 kVAr steps.

A significant disadvantage of the TSC is also the fact that the capacitor banks are exposed to the negative impact of higher harmonic components which present in the network voltage. Working under the conditions of non-sinusoidal CB current waveform could lead to resonance overvoltage, over-current, and as a result, overheating of the banks and their failure.

Stepless control of reactive power can be achieved by connection of the CB and controlled impedance in series (Fig. 2). Moreover, by performing this resistance with high impedance at the frequencies of the higher harmonics, it's possible to achieve a significant reduction of the harmonic's level in the CB current. Herewith, the frequency response of the network in the point of the hybrid compensator's connection isn't changed, thus risk of resonance on the frequencies of higher harmonics doesn't appear.

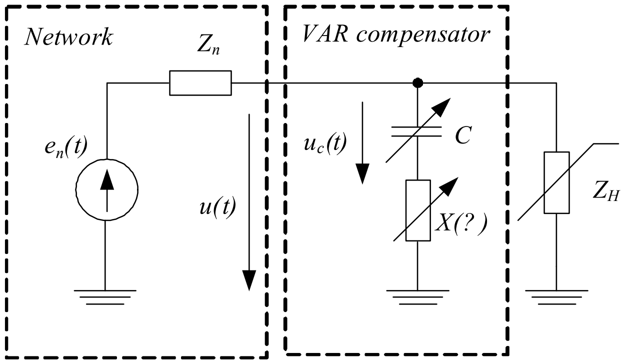

Fig. 2 – The equivalent circuit of the hybrid VAR compensator

It's possible to implement such reactance by applying the serial active filter [2, 3]. Generally AF is implemented as voltage source inverter with high-capacity storage capacitor in the DC link and LC low pass filter in the AC link. The resulting scheme of hybrid VAR compensator is shown in Fig. 3.

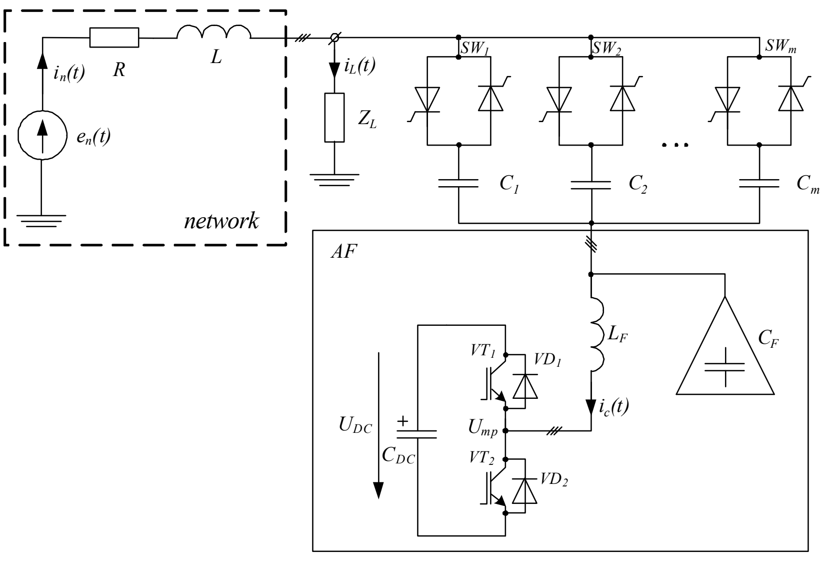

Fig. 3 – The single-phase circuit of the hybrid VAR compensator

The disadvantage of this hybrid VAR compensator is the need to use six terminals of the three-phase capacitor bank, while in practice the majority of three-phase CB are produced with internal connection "delta". In this case, the capacitor bank has only three terminals.

The objective of the article is to propose a hybrid VAR compensator topology suitable for using with three-terminal delta-connected capacitor banks while maintaining all advantages of hybrid approach – smooth VAR control and harmonic current suppression.

Basic material. To control the gates of transistors VT1 and VT2 a control system is to be used the schematic diagram of which is shown in Fig. 4. Hysteresis control of inverter with current feedback was applied (the current loop, Fig. 4). The reference current $i_{REF}(t)$ is determined as the sum of the in-phase $i_P(t)$ and quadrature $i_q(t)$ components.

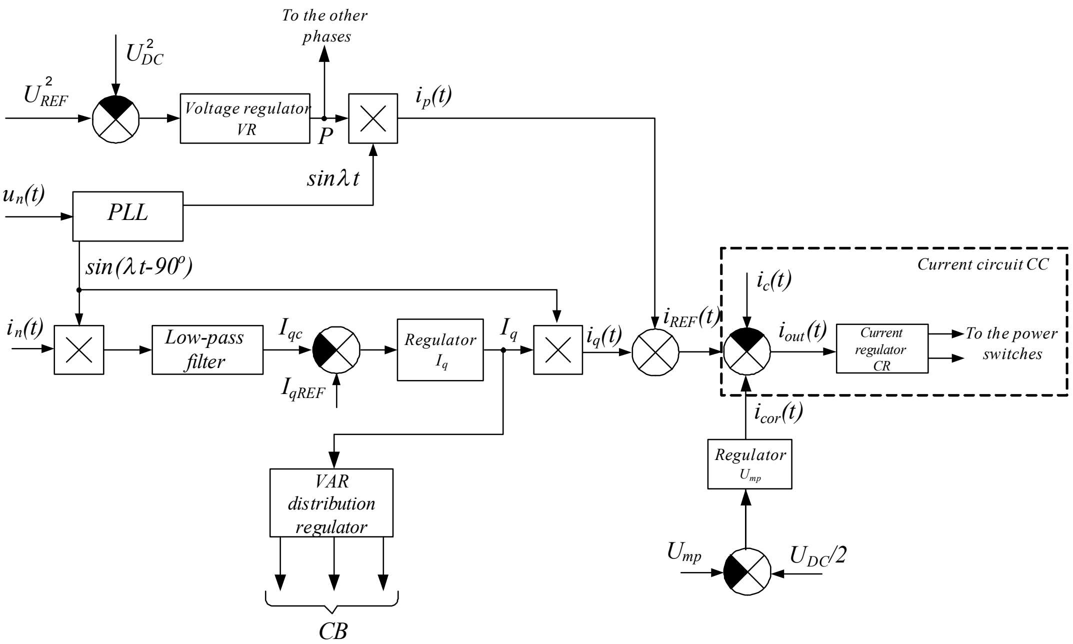

Fig. 4 – Block diagram of the VAR compensator control system

Formation of the in-phase current component is implemented by the regulator of DC link voltage U_{DC}. This current has a small value since the active power consumed by the AF is spent only for losses therein. For this reason, in further analysis of the hybrid VAR compensator's properties this current will be ignored.

PLL (Phase Locked Loop) block is used for the eduction of the in-phase and quadrature components of the fundamental frequency from the network voltage. These signals are used for the formation of in-phase and quadrature components of the reference current.

Eduction of the quadrature component from the network current is carried out by multiplying with the reference signal from the PLL and the subsequent low-pass filtering. As a low-pass filter, first-order sinc-filter with an interval of integration equal to the network period is used. The obtained signal I_{qc} with the reference current I_{qREF} is supplied to the adder. Using a non-zero current I_{qREF} allows to perform overcompensation or under-compensation of reactive power. The difference signal is input signal for the regulator of the reactive current amplitude I_q, the output signal of this regulator is used for formation of $i_q(t)$.

VAR distribution regulator performs redistribution of power between CB and AF with the condition to minimize the AF power, i.e. it's chosen such CB capacity, at which output voltage AF will be minimal for a given reactive power.

Maintaining average voltage at the midpoint of the half-bridge on the level $0{,}5U_{DC}$ relative to the negative bus of the AF DC-link is performed by the regulator U_{mp}, the output of which is the correction current $i_{cor}(t)$. In this case it's sufficient to use P-regulator with a small gain. Without this regulator uncontrolled constant voltage component will be present on the CB, the correct control of the current of VAR compensator will be impossible.

Fig. 5 shows the equivalent circuit of the hybrid VAR compensator, which includes a three-phase CB with three terminals. In the equivalent circuit active filters are represented as current sources.

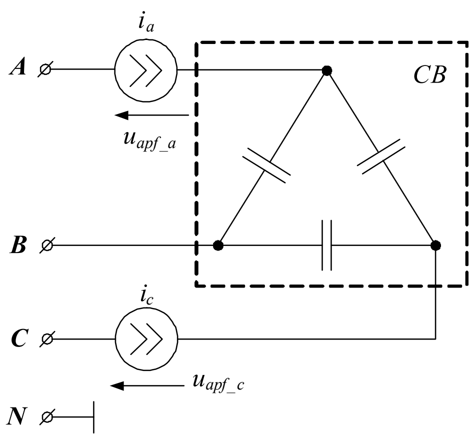

Fig. 5 – The equivalent circuit of the hybrid VAR compensator

Figure 6 shows a generalized diagram of a hybrid VAR compensator topology which includes three-phase CB with the three terminals, and its control system. One phase (on the fig. 6 - phase B) is connected directly to the network, and the other two - through the secondary windings of transformers. The primary transformer windings are "open-delta" connected and connected to the VSI.

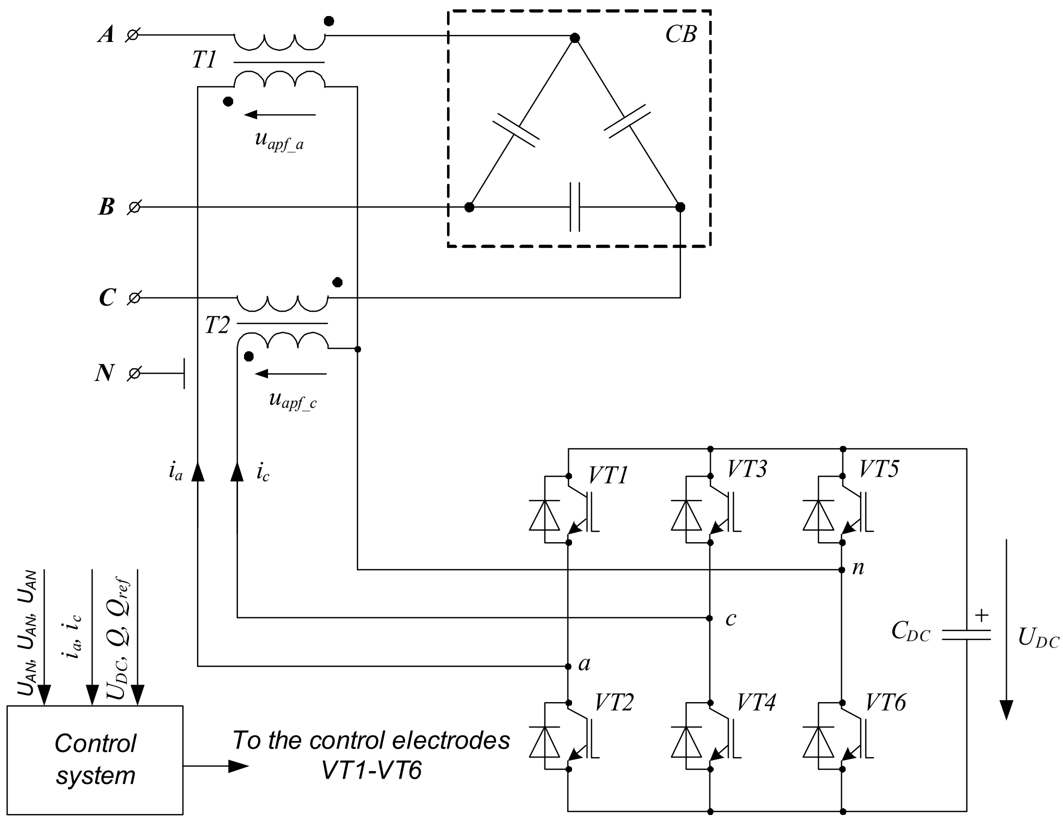

Fig. 6 – Scheme of the hybrid VAR compensator

Block diagram of the control system is shown in Figure 7.

The control system similar to scheme in Figure 4: low-pass filtering of the network voltage is performed, the received signal is shifted by 90° with the help of PLL block. To obtain a reference value of in-phase and quadrature current components multiplication by the scaling coefficients G_{REF}

and B_{REF} is performed. Low-pass filters LPF_2 are introduced to exclude the transformer magnetizing by the direct current - it's provided a zero mean value of output inverter voltage u_{apf_a}, u_{apf_c} with the help of negative feedback. P-controller with the gain 1/3 is used for the formation of zero-sequence voltage, which is then subtracted from the signal of phase voltage.

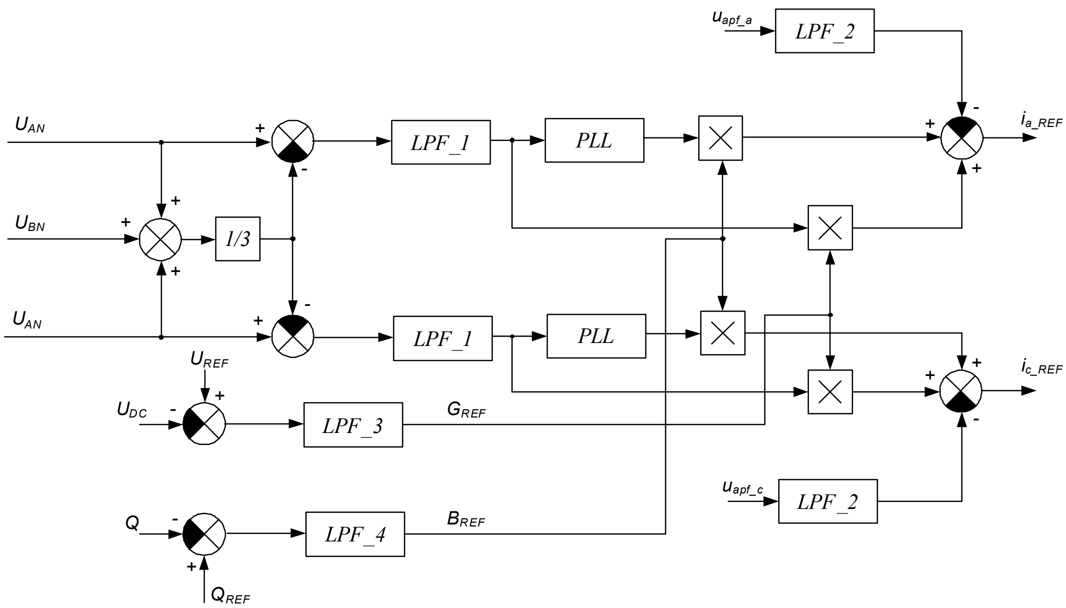

Fig. 7 – Block diagram of the hybrid VAR compensator control system

Such approach to the control of the hybrid VAR compensator can be applied not only in the case of two single-phase transformers in two phases, but in the case of a three-phase transformer. The utilized wiring diagram of the transformer is shown in Figure 8.

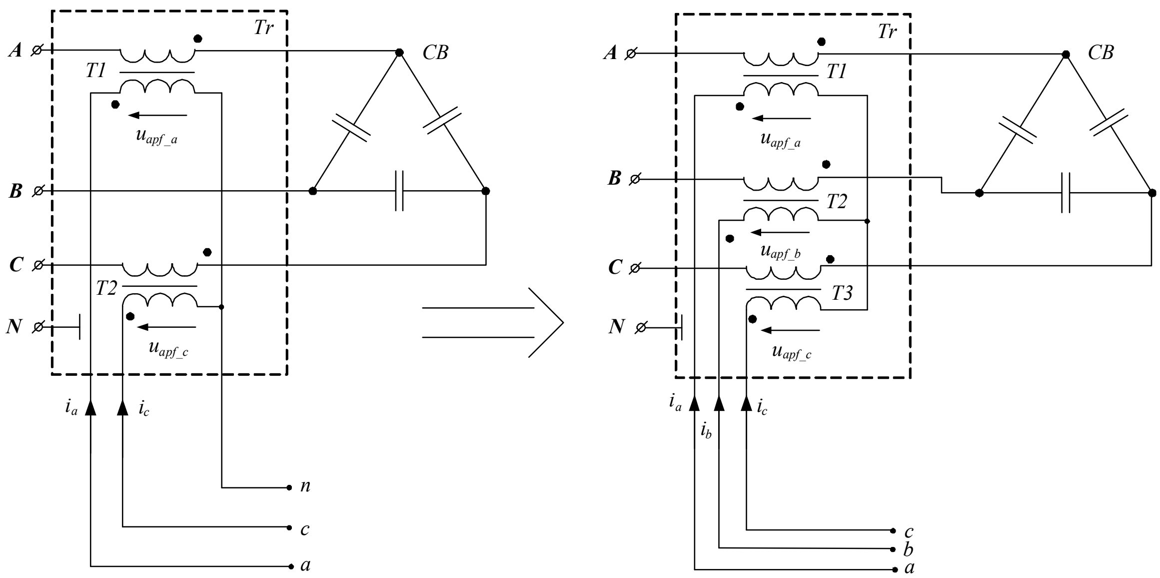

Fig. 8 – Wiring diagram of the single-phase and three-phase transformers

The authors also proposed an original method of selection the value of CB capacity and AF rated power [4].

When selecting the maximum output AF voltage, it should be taken into consideration that:

1) the spectrum of the output AF voltage contains all high order harmonics of the network voltage – it's a condition for ensuring of sinusoidal CB current;

2) the first harmonic of the output AF voltage determines the value of the hybrid compensator's RP.

According to [5] in 0.4 kV networks normally permissible value of harmonic distortion is 8%, the maximum allowable value - 12%. Selecting the maximum output AF voltage of the active filter at 10% of network voltage, it is possible to regulate the value of hybrid compensator's reactive power in the range $(0,9\div1,1)\cdot Q_{rated}$.

It's economically advisable for hybrid VAR compensator to decrease the output AF voltage, which allows to use a more effective low-voltage power components.

Conclusions

1. Hybrid VAR compensator, which is consisting of series-connected TSC and AF, is proposed. It allows to "isolate" TSC from harmonic currents and to provide smooth control of the RP.

2. Proposed is an improved hybrid VAR compensator, which allows to use standard capacitor banks delta-connected. It simplifies the practical implementation of the device, provides smooth control of the RP and protection of the CB from harmonic currents.

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ПРЕДПОСЫЛКИ СОЗДАНИЯ АВТОМАТИЗИРОВАННОЙ СИСТЕМЫ МОНИТОРИНГА И РАННЕГО ДИАГНОСТИРОВАНИЯ СОСТОЯНИЯ ВЫСОКОВОЛЬТНЫХ ЛИНИЙ ЭЛЕКТРОПЕРЕДАЧ

В статье рассмотрены основные предпосылки необходимости создания автоматизированной системы мониторинга и раннего диагностирования состояния высоковольтных контактных соединений, приведены основные аппаратные и алгоритмические решения.

Ключевые слова: *контактные соединения, системы мониторинга, системы диагностирования, сенсорные сети, самоорганизующаяся сеть.*

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