Hybrid harmonic compensation device adapted for variable speed drive system

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Abstract. The structure of the hybrid harmonic compensation device adapted for variable speed drive system is proposed in the paper. The main feature of the proposed device is the usage of common direct current link both for inverter of power frequency converter and for inverter of active part of the hybrid device. This decision allows to decrease the cost of active part of the proposed hybrid device. The proposed hybrid device is firstly intended for voltage and current harmonic determination and elimination. A mathematical model of generalized industrial power supply system with nonlinear load and the proposed hybrid device was developed by means of Matlab Simulink software. During simulation the proper efficiency of the proposed hybrid device is shown in different modes of voltage and current harmonic compensation.

1. Introduction

The main feature of modern power supply systems of industrial enterprises, including all industrial areas, is the intensive spread of nonlinear and highly variable loads [1]. The main type of nonlinear load in conditions of any industrial enterprise is the power frequency converters of different processing installations with variable speed drive systems. A nonlinear load is the main source of voltage and current harmonics, which negatively influences on power quality and electromagnetic compatibility level [2]. The power quality and electromagnetic compatibility level is presented by set of factors, including total harmonic distortion and individual harmonic distortion factors for voltage (k_U, %) and current (k_I, %). These factors are regulated by National and International standards and rules.

The exceeding of harmonics permitted value leads to life time decreasing of electric equipment such as power transformers and capacitors, incorrect functioning of digital relay protection systems, electrical and technological automation, conductive and inductive disturbances in connection, control and automatic systems. For example the exceeding of k_U factor by more than 8 % for low voltage networks leads to life time decreasing of power transformers 8 times, of capacitor banks – 6.5 times [3]. The mentioned set of negative influences is the main reason of breakdowns and long time power supply interruptions in electric networks [4]. Hereby the power quality and electromagnetic compatibility levels are key factors of continuity and stability of any responsible process in different industrial areas. The electric networks failures caused by poor power quality and electromagnetic compatibility are also the reason of process irregularity and significant economical damage.

2. Existing harmonic elimination methods and technologies

The existing methods and technologies of passive filtration and network impedance change, in case of power factor, current and voltage harmonic correction have a number of considerable disadvantages, which not allow to apply them in modern industrial electrical networks with required level of technical and economic efficiency [5]. Passive harmonic compensation by means of resonant shunt filters and damped filters has a limited efficiency. They are capable to eliminate one or several character harmonics, which order is defined by resonance circuits settings. Such technology can be effectively applied in networks, where the total harmonic distortion value is defined by one or several character harmonics, for example 5th, 7th, 11th and 13th harmonics of power frequency converters, based on three phase bridge topology. The installation of dumping reactors leads to additional voltage looses and opportunity of resonance in networks with large capacitor banks for power factor correction. The limitation of nonlinear load rated power to 15-20% of supplying transformer rated power, which is used in power supply systems of oil production enterprises, is not always technically realizable and enough economically effective [6].

Nowadays the most effective, flexible and multifunctional devices for power quality and electromagnetic compatibility level increasing by means of voltage and current harmonic elimination are shunt and series active filters, which don't possess mentioned disadvantages [7]. That's why any active correction system, such as STATCOM device, switched var compensator (SVC) and dynamic voltage restorer, is based on a shunt or series active filter. Also shunt and series active filters may be a part of hybrid filters and hybrid correction systems.

3. Existing hybrid correction systems

Hybrid correction systems are based on different hybrid filters topologies, which are defined by the way of active and passive part connection among themselves and with network. Therefore hybrid correction systems can be classified according to the following key factors [8]: the way of active and passive part connection to each other, the way of hybrid system connection with network, the type of power converter in active part.

According to the first factor hybrid correction systems may have "parallel active/series passive", "series active/parallel passive", "parallel active/parallel passive", "series active/series passive" configurations [9]. According to the second factor hybrid systems may be series and parallel types. According to the third factor hybrid systems may function in controllable current and voltage source modes. Also for hybrid systems it is necessary to use more difficult control algorithms and methods of distortion detection and elimination [10].

In most cases hybrid correction systems, based on series active filters, are intended for voltage dips and deviations compensation. Also such systems can be used for network voltage unbalance compensation in case of parallel functioning centralized and distributed power supply systems. In conditions of electric networks with great number of variable speed drive systems as main type of current harmonics source it is reasonable to use the hybrid correction systems, based on shunt active filter, which is the main part of most existing active correction systems [10].

Any shunt active filter consists of three main elements: power converter, control system and storage element. The power converter is often realized on the basis of IGBT voltage source inverter and output passive resistive, inductive and capacitive filter. The control system consists of voltage and current primary sensors and programmable controller, realizing the algorithm of voltage and current harmonic detection and elimination. The storage element is realized on the basis of capacitor, connected in direct current side of IGBT inverter [11].

The control pulses for IGBT inverter elements are formed by control system on the basis of information processing from voltage and current primary sensors and according to correction algorithm. Consequently there is the generation of correction current to network through IGBT inverter. The value and spectral content of this current is similar to spectral content of nonlinear load current in each harmonic magnitude, but is opposite in phase. The control system also maintains the specified level of storage capacitor voltage, forming the correction current reference value according to nonlinear current value and eliminated reactive power variations.

Also the necessity of high-pass passive filter installation on the shunt active filter output was detected according to the results of experimental researches and mathematical modeling. The mentioned output passive filter may contains of resistors, inductances and capacitors. Such filter can be used for increasing efficiency of harmonic correction by shunt active filter and for resonance elimination on high harmonic frequencies in point of shunt active filter connection. Hereby shunt active filter with output passive filter may be considered as the kind of hybrid correction system, which is connected in parallel with compensated network and includes parallel connection of active and passive part.

The common structure of shunt active filter control system often includes phase conversation blocks, phase-locked loop (PLL) system, and control pulse former on the basis of hysteresis current regulators. Shunt active filter in hybrid correction system can implement two main functions. The first one is the voltage and current harmonic compensation, the second one is the power factor correction [3, 4]. In terms of this the control algorithm can include additional functioning blocks, intended only for harmonic compensation or reactive power elimination, or both power factor and current and voltage waveforms correction [7].

The rated correction current is the main parameter of shunt active filter. The value of this current is defined firstly by rated power of nonlinear load. According to researches results it was detected that rated current of shunt active filter should be 0.5-0.7 from nonlinear load current. In case of installation one or two passive filters, which are tuned to eliminate character harmonics, before the point of shunt active filter connection, the rated compensation current of shunt active filter can be significantly decreased. Also in case of one powerful variable speed drive system it is reasonable to unify direct current link capacitor of power converter with storage capacitor of shunt active filter. Such decisions help to decrease the cost of shunt active filter [10] and whole hybrid correction system.

4. Proposed structure of hybrid harmonic compensation device

The basic structure of proposed hybrid harmonic compensation device is presented in Figure 1a. The proposed structure includes shunt active filter with output inductive-capacitive filter and two passive filters, tuned for elimination of the 5th and 7th character current harmonics.

In Figure 1a: SAF – shunt active filter, OPF – output passive filter, HF – hybrid filter on the basis of SAF and PF, PF5 and PF7 – passive filters, tuned for the 5th and 7th harmonic elimination correspondingly, VSD – variable speed drive system as nonlinear load.
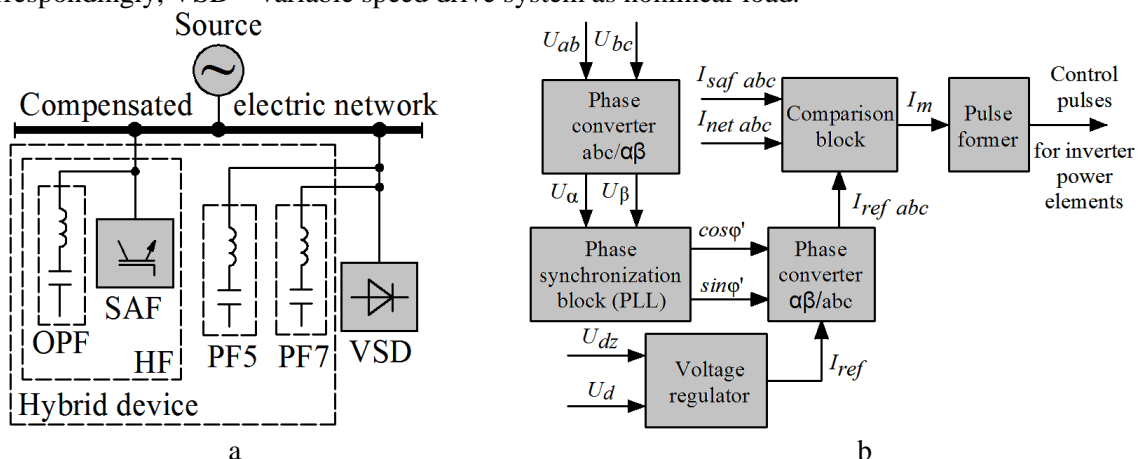

Figure 1. Proposed hybrid harmonic compensation device: a - basic structure; b - control system of active part

In Figure 1b the functional diagram of developed control system for shunt active filter in proposed hybrid device is presented. In Figure 1b: U_{ab}, U_{bc} - the measured line network voltages, U_α, U_β - the converted line voltages in $\alpha\beta$ reference frame, $cos\varphi'$, $sin\varphi'$ - unit cosine and sine voltage signals of

angle between representing voltage vector and its α and β axis projections correspondingly, U_{dz} - the required level of storage capacitor voltage, U_d - the actual level of storage capacitor voltage, I_{ref} - the reference sinusoidal current, $I_{saf\ abc}$ - the actual shunt active filter compensation phase current, $I_{net\ abc}$ - the actual network phase current, $I_{ref\ abc}$ - the reference sinusoidal phase current, I_m - the currents mismatch.

When forming the reference current signal ($I_{ref\ abc}$), control system of shunt active filter uses the well-known Clark transformations from three phase system a, b, c to two phase system α, β. According to the diagram on Figure 1b mentioned calculations are provided by means of phase converter abc/αβ.

The control system of shunt active filter in any hybrid device must contain special block for extraction of first (fundamental) network voltage harmonic. This function is relized by PLL, which forms unit voltage signals $\cos\varphi'$ and $\sin\varphi'$. Angle φ is adjusted by means of PLL to value φ', which corresponds to sinusoidal waveforms of network voltage and current. With usage of these unit signals the sinusoidal reference current is formed.

The value of storage capacitor voltage is maintained on the required level by means of proportional-integral regulator. On the basis of comparision of actual U_d and required U_{dz} voltage of storage capacitor regulator forms the reference for compensation current I_{ref}, generated by IGBT inverter. The obtained reference phase currents $I_{ref\ abc}$ are compared with nonlinear load currents $I_{net\ abc}$ and actual shunt active filter currents of $I_{saf\ abc}$, using comparison block. The current mismatch signals on the comparison block output come to the pulses former input, which is realized on the basis of hysteresis current regulators with variable width of hysteresis zone. Pulses former generates control pulses for IGBT inverter [7].

The PF5 and PF7 installation in proposed structure helps to decrease the rated current of shunt active filter. Also for optimization of storage elements quantity it is reasonable to combine the storage element of shunt active filter with direct current link of frequency converter of variable speed drive system. Hereby the presented decision allows to improve the economic indicators of proposed hybrid harmonic compensation device and to adapt them to variable speed drive system, which is the main nonlinear load type in industrial enterprises networks [6].

The detailed structure of proposed hybrid harmonic compensation device adapted for variable speed drive system with common direct current link is presented on the Figure 2.

On the Figure 2: DR – diode rectifier of power frequency converter, C – storage capacitor of the direct current link of power frequency converter, VSD INV – inverter of frequency converter, VSD – variable speed drive system on the basis of power frequency converter with vector control system, VSD CS – control system of VSD, SAF INV – inverter of shunt active filter, SAF CS – control system of SAF, L – output SAF inductance, OF – output capacitive passive filter, PF5 and PF7 – passive filters, tuned for 5th and 7th harmonic elimination correspondingly, M – electric motor, HHCD – the proposed hybrid harmonic compensation device.
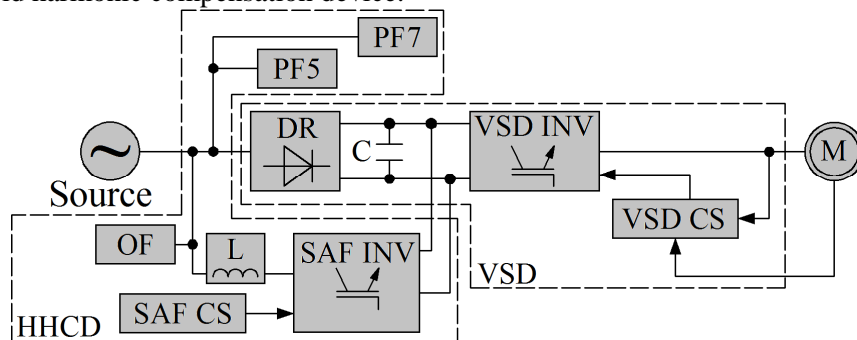

Figure 2. Detailed structure of hybrid harmonic compensation device adapted for variable speed drive system with common direct current link

5. Simulation results

The mathematical model of proposed hybrid harmonic compensation device in 0.4 kV industrial electric network was designed for the evaluation of harmonic elimination efficiency.

The developed model includes power source, long power lines, variable speed drive system as a nonlinear load and proposed hybrid device. In this model the control system of shunt active filter is realized on the basis of algorithm of harmonic determination and compensation with usage of phase Clark transformations according to functional diagram on Figure 1b. The model of variable speed drive system includes the following main parts: the three-phase bridge rectifier, storage capacitor, voltage source inverter, asynchronous squirrel cage motor, and vector control system on the basis of Clark transformations. Such type of variable speed drive system has the wide application in technological equipment of industrial enterprises. The simulation was carried out by Simulink subsystem of MatLab software.

A simulation process includes the following modes of proposed hybrid device functioning: harmonic elimination only by means of passive filters (mode no.1), harmonic elimination only by means of shunt active filter without output capacitive filter (mode no.2), harmonic elimination only by means of shunt active filter with output capacitive filter (mode no.3), harmonic elimination by means of whole hybrid device (mode no.4).

The received results about efficiency of decreasing voltage total harmonic distortion factor k_U and current total harmonic distortion factor k_I in mentioned functioning modes of proposed hybrid device are presented in Table 1. Before application of proposed hybrid device the values of k_I and k_U were 19.6 % and 17.3 % correspondingly.

Table 1. The efficiency of decreasing voltage and current total harmonic distortion in different modes of proposed hybrid device functioning

	Functioning mode no.			
	1	2	3	4
k_U, %	7.78	4.4	3.77	3.02
k_I, %	5.78	4.2	3.69	1.68

The oscillograms of network voltage U_c and current I_c waveforms are presented in Figure 3 before (mode no.1) and after (mode no.4) harmonic elimination by means of proposed hybrid device as the results of computer simulation of developed mathematical model.
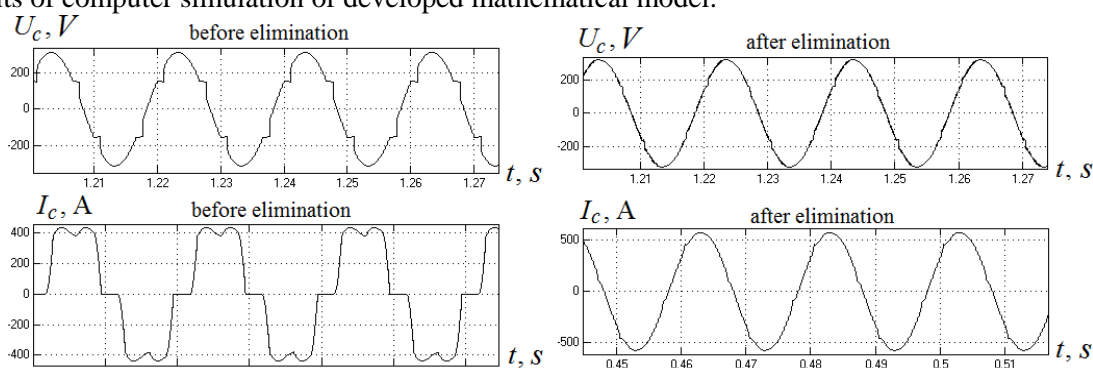

Figure 3. Oscillograms of network voltage U_c and current I_c waveforms before and after harmonic elimination by means of proposed hybrid device

The information of Table 1 shows the proper efficiency of voltage and current waveform correction by means of proposed hybrid harmonic compensation device adapted for variable speed drive system. The current total harmonic distortion factor k_I decreases more then in 10 times from 19.6 % to 1.68 %, the voltage total harmonic distortion factor k_U decreases from 17.3 % to 3.02 %.

Hereby the results of mathematical modeling prove the efficiency of voltage and current harmonic compensation, using the proposed hybrid device with common direct current link. The results also

show a compliance of voltage and current harmonic level after elimination with requirements of Russian and International standards in power quality area for low voltage networks. Also the proposed device provides reactive power compensation, improves power recuperation of drive system, and provides supply voltage stability in case of network failures. According to modeling results power factor improves from 0.75 to 0.98. Also, during short circuit simulation in network, the proposed device ensures voltage dip compensation for variable speed drive trouble proof stop.

6. Discussion
Nowadays there are a number of hybrid correction systems with different topology and functional set. The main advantages of proposed hybrid device are the compactness of technical realization, satisfactory efficiency in conditions of territorially dispersed nonlinear consumers with long power lines, low cost of active part due to common storage element. The functioning algorithm of proposed hybrid device is protected by the Russian patents no. 2354025, 2413350 and 2446536.

7. Conclusion
The results of mathematical modeling by the example of the industrial enterprise network show the application efficiency of the proposed hybrid device on the basis of the shunt active filter, the output passive capacitive filter, two passive filters and the common storage element with the variable speed drive system. The main singularities of the proposed hybrid device are the harmonic and reactive power compensation, voltage dip elimination, power recuperation of variable speed drive improving. The proposed hybrid device can be considered as the basic technical device for power quality increasing and electromagnetic compatibility ensuring in industrial enterprises networks. Also the application of the proposed hybrid device helps to ensure the continuity and stability of the responsible process of any complexity and any industrial area.

8. Acknowledgments

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