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Control of Improved Hybrid Power Line Conditioner

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***Abstract*—Features of static and dynamic modes of the improved hybrid adjustable power line conditioner (APLC) in the autonomous electric power system (EPS) with powerful semiconductor converters (SC) are considered. The conditions for full compensation of the reactive power (RP) of the load are determined and the principles of constructing the structure of the corresponding automatic control system (ACS) of the APLC are proposed. The MATLAB-model of the system was created and investigated to optimize the regulator parameters to achieve the quality of transients and provide conditions for electromagnetic compatibility (EMC).**

Keywords*— *adjustable power line conditioner (APLC); inactive components of the total power; reactive power (RP); power quality (PQ); voltage and current harmonic distortion factors; pulse-width modulation (PWM); controlled reactor compensator (CRC); synchronous generator (SG)

I. Introduction

A. General Terms and Definitions

Ensuring a high level of energy efficiency is one of the main problems of modern electric power industry when all electricity produced is used with maximum benefit. Powerful semiconductor converters (SC) in the load lead to a distortion of the shape of the current consumed and phase shift of its fundamental harmonic. As a consequence, the power factor decreases, energy losses in sources and consumers increase, and emergency modes are also increased due to higher-harmonic emission. To reduce these negative effects, active and passive power line conditioners are used in power supply systems of limited power [1,2,3,4].

The development of improved adjustable power line conditioner (APLC) is a very urgent task concerning autonomous electric power systems (EPS) of sea vessels, stationary sea platforms and floating drilling rigs which have thyristor frequency converters based on the "controlled rectifier – load-driven current inverter" circuit, feeding propulsion synchronous motors with total power up to tens of MW.

Thus, controlled compensation of non-active components of full power, including reactive power (RP) and distortion power (DP), provides energy efficiency and power quality (PQ) in autonomous EPS with SC. The solution of such a double task requires taking into account that modern active or hybrid APLCs themselves are sources of higher harmonics [5,6,7,8,9].

APLC operation in the autonomous EPS with powerful SC is complicated by additional features [10]:

1. The presence of significant short-term deviations of the network voltage and frequency (± 20% within 1.5s and ± 10% within 5s respectively).

2. The requirement of accurate RP compensation in both static and dynamic modes. APLC should have a much higher performance than synchronous generator automatic exciters to avoid or reduce network voltage fluctuations.

3. Elimination of the possibility of a resonant increase in the harmonics of the network voltage under any EPS scheme and changing the mode parameters (at different variants of combination of generators and loads).

A new improved hybrid APLC structure (Fig. 1,a) was proposed in [11]. It consists of a resonant LC-filter (RF) (X_{C0}, X_{L0}) and a controlled reactor compensator (CRC), containing a reactor with impedance X_{LK} and a dual-operational semiconductor switch with pulse-width modulation (PWM) control. CRC is an adjustable equivalent resistance $X_{CRC} = X_{LK} / s^2$ at high switching frequency ($f_s = 10 \ldots 20$ kHz), where s – duty ratio of PWM. RF is simultaneously an impedance filter with respect to CRC with PWM due to CRC connection to the connection point of the inductance and capacitance of RF. This eliminates the need for an additional noise filter to reduce the harmonics generated by PWM CRC. In [12,13,14] for the system with APLC and SC, the voltage harmonic distortion factors were studied and the conditions for additional poles cancellation of the impedance frequency response of the system and the resonance possibility elimination at higher harmonics were specified.

B. Research Tasks and Objectives

The purpose of this work is to determine the condition for full RP compensation in the autonomous EPS using the advanced hybrid APLC, to design the structure of the

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corresponding ACS and optimize the regulator to achieve the desired or required quality of transients in dynamic modes and provide conditions for EMC.

II. Definition Of Reactive Power Compensation Condition

In the system equivalent circuit the synchronous generator (SG) is represented by a sinusoidal EMF source with a complex RMS value $\dot{E}_S$ and resistance X_S. A transformer or an input reactor of the SC is represented by resistance X_{SC}. Consider now the circuit as shown in Figure 1,a. The phasor diagram for the complex RMS values of the fundamental harmonics of SG voltage $\dot{U}_S$ and current $\dot{I}_S$ of the circuit is shown in Figure 2.

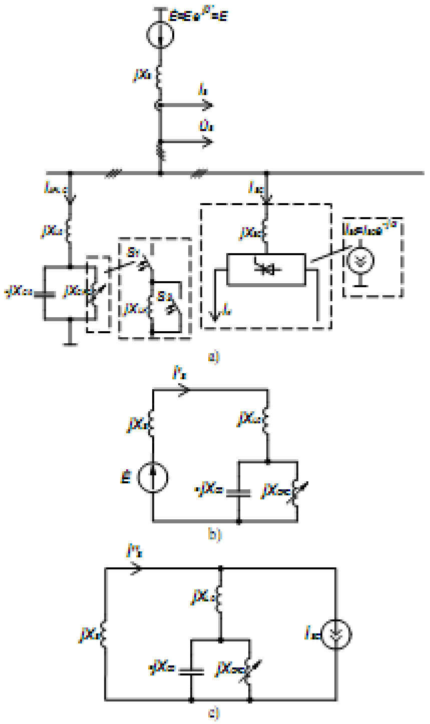

Fig. 1. The autonomous EPS with SC and APLC: single-line circuit (a), partial equivalent circuit (b, c)

The dependence of the simultaneous operation of the SG and the converter should be taken into account when analyzing the effect of APLC on the RP system. In accordance with the principle of superposition, the current $\dot{I}_S$ is a vector sum of the two components $\dot{I}'_S$ and $\dot{I}''_S$, and is determined by the voltage $\dot{E}_S$ and current consumed $\dot{I}_{SC}$ by the SC. $\dot{I}_{SC} = I_{SC} e^{-j\alpha}$ where $I_{SC} = \sqrt{6}\, I_d / \pi$, I_d and α are the rectified current and the control angle of the SC, respectively.

From the analysis of circuits Fig. 1,b,c:

$$\dot{I}'_S = jK_1(s)\dot{E}\,; \tag{1}$$

$$\dot{I}''_S = K_2(s)\dot{I}_{SC}\,; \tag{2}$$

where

$$K_1(s) = \frac{1}{X_{C0}/\left(1 - s^2 X_{C0}/X_{LK}\right) - \left(X_S + X_{L0}\right)}, \tag{3}$$

$$K_2(s) = \frac{X_{C0}/\left(1 - s^2 X_{C0}/X_{LK} - X_{L0}\right)}{X_{C0}/\left(1 - s^2 X_{C0}/X_{LK}\right) - \left(X_S + X_{L0}\right)} \tag{4}$$

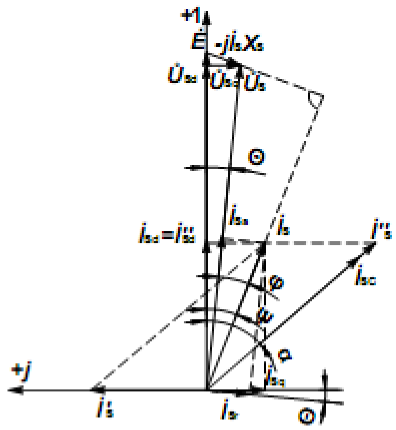

Fig. 2. The phasor diagram for the complex RMS values of the fundamental harmonics of the SG voltage $\dot{U}_S$ and current $\dot{I}_S$

These functions are real and positive. $K_1(s)$ is the conductivity function and varies from 0 to $1/\left[X_{C0} - \left(X_S + X_{L0}\right)\right]$. $K_2(s)$ is the dimensionless function that is rather weakly dependent on the duty ratio of PWM and slightly increases from 1 to $\left[X_{C0} - X_{L0}\right]/\left[X_{C0} - \left(X_S + X_{L0}\right)\right]$. The component $\dot{I}'_S$ has a capacitive character in relation to $\dot{E}_S$, and $\dot{I}''_S$ lags $\dot{E}_S$ by the angle α. $\dot{I}''_S$ is in phase with the SC consumed current $\dot{I}_{SC}$. The magnitude of component $\dot{I}''_S$ is slightly larger than magnitude of $\dot{I}_{SC}$.

The magnitude of the generator current I_S and the lag angle between $\dot{I}_S$ and $\dot{E}_S$ are determined from the expressions

$$I_S = \sqrt{I_{Sq}^2 + I_{Sd}^2}\ , \tag{5}$$

$$\psi = \operatorname{arctg}\left(I_{Sq} / I_{Sd}\right), \tag{6}$$

where I_{Sq} and I_{Sd} are the current components along the q- and d-axis respectively,

$$I_{Sq} = I_S'' \ \sin\alpha - I_S' , \tag{7}$$

$$I_{Sd} = I_S'' \ \cos\alpha . \tag{8}$$

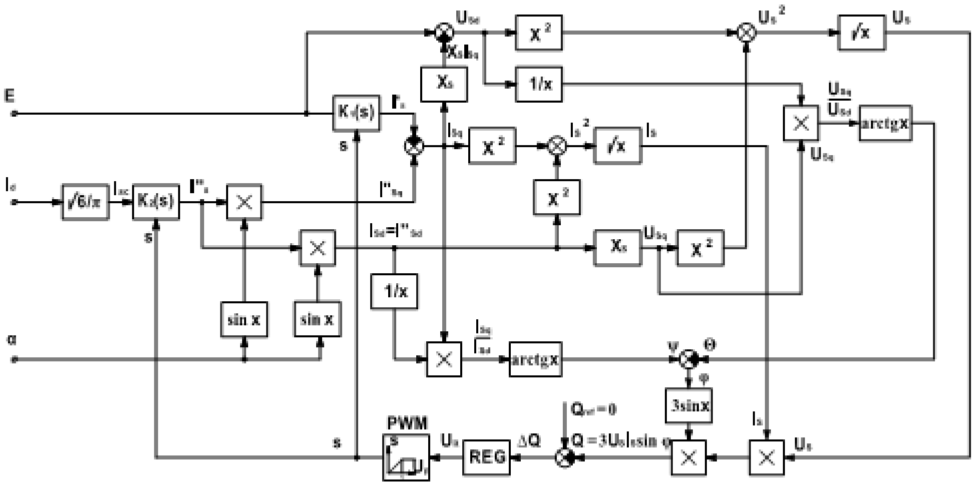

Fig. 3. The block diagram of the APLC ACS

Magnitude of generator voltage $\dot{U}_S$ and lag angle between $\dot{U}_S$ and $\dot{E}_S$

$$U_S = \sqrt{\left(E - X_S I_{Sq}\right)^2 + \left(X_S I_{Sd}\right)^2}\ , \tag{9}$$

$$\Theta = \operatorname{arctg}\left(E - X_S I_{Sq}\right) / \left(X_S I_{Sd}\right). \tag{10}$$

Reactive power consumption of CS-APLC system is

$$Q = 3\,U_S I_{Sr}\ , \tag{11}$$

where $I_{Sr} = I_S \sin\alpha$ is the reactive component of SG current; φ is the lag angle between $\dot{I}_S$ and $\dot{U}_S$.

The condition for RP full compensation in an autonomous EPS is determined by the expression

$$\varphi = \psi - \Theta = 0 \ \Rightarrow\ \psi = \Theta . \tag{12}$$

The block diagram of the APLC ACS, which implements the condition (12) taking into account the set of expressions (1-11) is presented in Fig. 3. The scheme operates using compensation principle and contains the sensors of the rectified current I_d and the control angle α of SC. To control the CRC semiconductor switches, ACS forms PWM impulses with variable duty ratio s. If the number of loads increases the structure in Fig. 3 is complicated by increase in the number of associated sensors and control channels.

These disadvantages are eliminated in the functional scheme of ACS shown in Fig. 4. The generator voltage and current sensors are used in digital program unit (DPU) to calculate the instantaneous RP as follows:

$$Q = \frac{1}{\sqrt{3}}\left(i_{SA} u_{SBC} + i_{SB} u_{SAC} + i_{SC} u_{SAB}\right) . \tag{13}$$

To obtain the dc component of instantaneous RP the DPU signal (13) is passed through low-pass filter.

In addition, the scheme provides greater accuracy of RP compensation by calculating RP directly.

III. Regulator Settings Optimization and Simulation

To study the system SG-SC-APLC, which is nonlinear and discrete, the MATLAB-Simulink model is used (Fig. 5). The simulated ACS structure is corresponds to the variant shown in Fig. 4.

The main purpose of the simulation is to study RP and the voltage of SG transients with a step change of the SC control angle or current load, and optimization of the regulator parameters according to the specified quality of these transients.

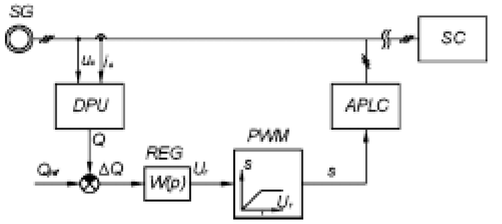

Fig. 4. The functional scheme of APLC ACS in the autonomous EPS with SC

The models with three regulator structures: I, PI and PID were studied in transients caused by the step changes in the SC control angle with constant load current and the step changes in the load current with constant control angles.

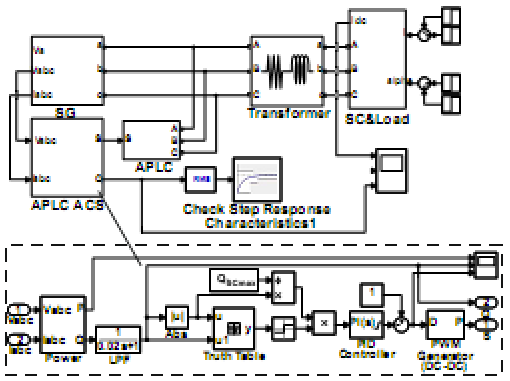

Fig. 5. MATLAB-model of autonomous EPS with SC and APLC

Optimization criteria for transient processes: transient time is $\leq 0{,}15$ s; overshoot – maximum relative magnitude of RP (as a fraction of the total rated power) is 20%; relative generator voltage dip (overshoot) is $\delta U = \pm 20\%$; the steady-state error is 5%.

To improve the transient process, the controller parameters are optimized using the built-in MATLAB tools including Simulink Design Optimization library with Check Step Response Characteristics block which provides functions and interactive tools for analysis and adjustment of any model parameters.

Parameters of the MATLAB model: $S_s = 1$ MVA, $U_S = 220$ V, $X_S = 0{,}02$ Ohm, $X_{SC} = 0{,}01$ Ohm, $I_{dnom} = 1400$ A, $U_{dnom} = 440$ V, $X_{C0} = 0{,}227$ Ohm, $X_{L0} = 9{,}07 \cdot 10^{-3}$ Ohm, $X_{LK} = 0{,}218$ Ohm, $f_s = 19800$ Hz.

Optimization of the regulator parameters was performed for PI and PID-regulators, which are more efficient than the I-regulator. Characteristics of both regulators are almost identical, however, when using the PID-regulator, the phase voltages have asymmetry and harmonics which are multiple of three with slow decay (within 1 s). Figure 6 shows transients of voltage dips and overshoots as well as transients of reactive power. Simulation was carried out for optimized PI-regulator and step changes in current I_d.

The experiment established the expediency of choosing a non-zero RP compensation error. Recommended error band is set to Q_{ref}=0.05$Q_{SC\max}$. This condition significantly reduces the time and oscillations of transients without noticeable deterioration of power characteristics of the system.

The results of the transients study with optimized regulators are given in Table 1 and 2. Table 1 shows the voltage maximum dips and overshoots with two control modes, the first mode uses a constant control angle α $(t_1 \Rightarrow I_d = 0 \rightarrow 1400$ A, $t_2 \Rightarrow I_d = 1400 \rightarrow 200$ A$)$ and the second one uses a constant load current I_d $(t_1 \Rightarrow \alpha = 10^\circ \rightarrow 90^\circ,\ t_2 \Rightarrow \alpha = 90^\circ \rightarrow 30^\circ)$. Table 2 shows RP transient time in similar modes with PI and PID-regulators.

TABLE I. The voltage Maximum Dips and Overshoots

α	I_d	δU, % (PI)	δU, % (PID)
30°	0 → 1400A	8,1	12,8
	1400 → 200A	12,9	17,6
60°	0 → 1400A	4	4,8
	1400 → 200A	12,8	4,5
10° → 90°	1400 A	8,1	12,8
90° → 30°		12,9	12,8
10° → 90°	500 A	12,8	3,2
90° → 30°		12,8	3,2

TABLE II. RP Transient Time

α	I_d	t, sec (PI)	t, sec (PID)
30°	0 → 1400A	0,06	0,12
	1400 → 200A	0,06	0,12
60°	0 → 1400A	0,16	0,12
	1400 → 200A	0,16	0,12
10° → 90°	1400 A	0,11	0,14
90° → 30°		0,11	0,14
10° → 90°	500 A	0,05	0,1
90° → 30°		0,05	0,1

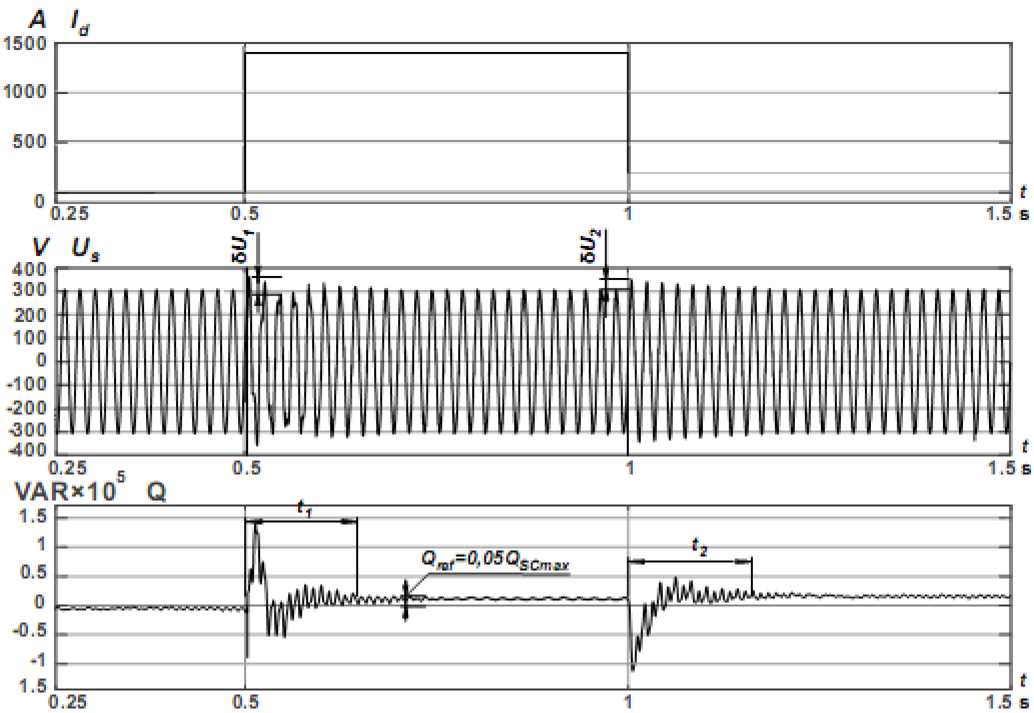

Fig. 6. Transients of voltage and reactive power in the autonomous EPS with SC and APLC during load rise and load drop. ACS uses optimized PI-regulator

Conclusions

This paper explores the features of static and dynamic modes of the improved hybrid adjustable power line conditioner (APLC) in the autonomous electric power system (EPS) with powerful semiconductor converters (SC) and allows drawing the following conclusions:

1. The main condition for full RP compensation in the autonomous EPS with SC and hybrid APLC is $\varphi = 0$ when EMF phasor $\dot{E}_S$ and generator current phasor $\dot{I}_S$ are in phase. It is achieved by controlling PWM duty ratio s of CRC regulator.

2. Implementation of ACS APLC is possible using rectifier current and SC control angle sensors (Fig. 3). With an increase in the number of loads, this structure becomes complicated. This drawback can be avoided using the scheme in Figure 4, which uses only the generator voltage and current sensors to calculate RP in DPU directly.

3. Since in transients three-phase voltages and currents of the generator are asymmetric and have high harmonics, calculated RP signal contains high-frequency distortions and needs to be passed through low-pass filter.

4. Autonomous EES with SC and APLC is nonlinear and discrete. To achieve the specified quality of the transients, the optimization of the regulators was performed using the MATLAB model. An analysis of the model experiment results shows that the PI-regulator is more efficient than the I- and PID-regulators. The specified quality criteria for transients, in particular, the reduction of transient time to 0,15 sec, are achieved by optimizing the parameters of controllers using the Simulink Design Optimization library with the Check Step Response Characteristics block.

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