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CONTENTS

Section I. Modern Energy Systems & Power Electronics

Optimal Components Design for Modified Z-source Based IPT Approach <i>Bohdan Pakhaliuk, Oleksandr Husev, Ryszard Strzelecki and Kostiantyn Tytelmaier</i>	11
Influence of Direct Lightning Strikes and Lightning Strikes Near Power Lines with Protected and Non-Insulated Wires <i>Sergey Shevchenko, Dmytro Danylenko, Stanislav Dryvetskiy and Ksenia Minakova</i>	17
Design and Simulation Verification of Low Power Wireless Charging Battery System for Electric Bicycle <i>Viktor Shevchenko, Oleksandr Husev, Bohdan Pakhaliuk and Ihor Kondratenko</i>	22
The Efficient Power Supply Scheme of Alternating Current Electric Arc Furnaces <i>Anton Malinovskyi, Volodymyr Turkovskiy, Andrii Muzychak and Yurii Turkovskiy</i>	28
Voltage Harmonic Distortion In Autonomous Electric Power System With An Adjustable Power Line Conditioner <i>Oleksandr Zhuk, Dmytro Zhuk and Dmytro Kryvoruchko</i>	33
Intensification of Biogas Fermentation Processes in the Bioenergy System <i>Mykola M. Zablodskiy, Vitaliy Savchenko, Petr Klendiy and Vladyslav Pliuhin</i>	39
Maximum Permissible Value Correction for Dielectric Loss Tangent of 110 kV Air-Tight Bushing Basic Insulation Subject to Operational Factors Impact <i>Oleg Shutenko and Aleksandra Zagaynova</i>	45
Detection of Accident Causes on Turbine-Generator Sets by Means of Numerical Simulations <i>Andrey Rusanov, Gennadii Martynenko, Konstantin Avramov and Volodymyr Martynenko</i>	51
Modeling Of Electrical Supply Restoration In Local Electrical Systems After Loss Of Centralized Power <i>Petro Lezhnyuk, Serhii Kravchuk, Iryna Koylko, Iryna Hunko and Natalia Sobchuk</i>	55
About Electromagnetic Compatibility of Rail Circuits With the Traction Supply System of Railway <i>Tetiana Serdiuk, Vitaliy Kuznetsov and Yevhenia Kuznetsova</i>	59
An Error Estimation Of The Current Sensors Of The Automated Control System Of The Technological Process Of Graphitization <i>Dmytro Yarymbash, Mikhaylo Kotsur, Serhiy Yarymbash and Iryna Kylymnyk</i>	64
Electromagnetic Parameters Determination of Power Transformers <i>Dmytro Yarymbash, Tetyana Divchuk, Mikhaylo Kotsur and Serhiy Yarymbash</i>	70
Parameters Determination of the Trolley Busbars by Electromagnetic Field Simulation <i>Dmytro Yarymbash, Mikhaylo Kotsur, Yulia Bezverkhnia, Serhiy Yarymbash and Igor Kotsur</i>	76
Analysis of Three-Phase Parallel Active Power Filter Operation Mode With Arc Furnace Active Power's Fluctuations <i>Ruslan Vlasenko, Olexiy Bialobrzheskiy and Andrii Gladyr</i>	80
Synchronous Mode Analysis of an Asynchronized Generator in the Scheme of Power Bridge "Ukraine-EU" <i>Kostyantyn Pokrovskyy, Olherd Mavrin and Andrii Muzychak</i>	85
Mathematical Modelling of the Electric Field in Systems With Conductive Rods for Lightning Protection <i>Marina Rezinkina, Yevgen Sokol, Oleg Rezinkin and Svitlana Lytvynenko</i>	89
Determination of the Conditions of Inception of an Upward Leader From Grounded Objects in Thunderstorm Conditions <i>Marina Rezinkina, Oleg Rezinkin, Svitlana Lytvynenko, Boris Kubrik, Elena Svetlichnaya and Elena Sosina</i>	93
A Pulse-Width Regulation of a Compound Excitation System for a Synchronous Generator <i>Andriy Kutsyk, Mykola Semeniuk, Taras Galiytskyi and Vasyi Tutka</i>	97
Estimation of Energy Efficiency of the Frequency Converter Based on the Resonant Inverter with Pulse-Density Control <i>Gennadiy Pavlov, Irina Vinnichenko and Mikhail Pokrovskiy</i>	101

Modeling and Active Shielding of Magnetic Field in Residential Buildings Located near Group of High Voltage Power Lines	106
<i>Borys Kuznetsov, Tatyana Nikitina, Aleksandr Voloshko and Ihor Bovidul</i>	
The Formed Autonomous Source For Power Supply of Single-Phase Consumers on the Basis of the Three-Phase Asynchronous Generator	110
<i>Volodymyr Chenchevol, Iurii Zachepa, Oleksii Chornyi, Vita Ogar, Dmytro Shokarov and Nataliia Zachepa</i>	
The Increase in Efficiency of the Modes Power Resources Consumptions of the Processing Equipment of the Enterprises of Oil-processing Industry	116
<i>Dmytro Shokarov, Oleksandr Lazurenko, Halyna Cherkashyna and Viktoriia Chorna</i>	
Improvement of the Spectral Composition of the Input Currents of a Three-to-One-Phase Matrix Converter at Sector Boundaries	121
<i>Svetlana Podnebenaya, Vladimir Burlaka and Sergey Gulakov</i>	
Residential Uninterruptible Power Supply System with Renewable Energy Sources and Battery Pack	125
<i>Vladimir Burlaka, Svetlana Podnebenaya and Sergey Gulakov</i>	
Geomagnetic Induction Currents as the Factor of Automatic Disconnections in Trunk Transmission Lines 750 kV	129
<i>Valerii Kyryk and Bohdan Zhuk</i>	
Load Characteristics of the Serial-to-serial Resonant Converter with Pulse-number Regulation for Contactless Inductive Energy Transfer	133
<i>Pavlov Gennadiy, Mikhail Pokrovskiy and Irina Vinnichenko</i>	
Combination of Distributed MPPT and Distributed Supercapacitor Energy Storage Based on Cascaded Converter in Photovoltaic Installation	139
<i>Ihor Shehur, Daniel Kulwas and Robert Wielgosz</i>	
Cell Equalizer for Series-connected Lithium Batteries	145
<i>Bohdan Syslo, Vadym Makarov, Mykola Tymchenko, Viktoriia Varvianska, Serhii Kryvoshelev, Michael Shyshkin and Liudmyla Fetlukhina</i>	
Experimental Research of Effectiveness of Active Shielding System of Overhead Transmission Lines Magnetic Field with Various Control Algorithms	151
<i>Ihor Bovidul, Borys Kuznetsov, Aleksandr Voloshko and Tatjana Nikitina</i>	
Full Soft Switching Dual DC/DC Converter With Four-Quadrant Switch for Systems With Battery Energy Storage System	155
<i>Volodymyr Ivakhno, Volodymyr Zamarudev, Bohdan Syslo and Yevgen Sokol</i>	
The Incentive Scheme for Maintaining or Improving Power Supply Quality	161
<i>Oleksandr Miroshnyk, Oleksandr Savchenko and Irina Trunova</i>	

Section II. Renewable Energy Systems & Distributed Generation

Evaluation of the Small-Scale Wind Turbine Converter's Efficiency Built with Various Types of Semiconducting Devices	166
<i>Stanislav Pirlenko, Martin Neuburger, Po-Wen Cheng, Ulrich Ammann, Alexander Balakhontsev and Duleepa J. Thrimawithana</i>	
Investigation of the Supernominal Power Throws Factors on the Wind Turbine With Variable Speed	172
<i>Olga Pankova, Dmitry Alekseevskiy, Aleksandr Alyeksyeyev, Konstantin Turyshev and Sergey Shmalyt</i>	
High-speed Flywheel Energy Storage System (FESS) for Voltage and Frequency Support in Low Voltage Distribution Networks	176
<i>Shahab Karrari, Mathias Noe and Joern Geisbuesch</i>	
Topological Task of Distributed Generation Placement Using a Pareto Optimization	183
<i>Vadim Bodunov, Tetiana Kulko, Anatoliy Prystupa and Alexander Gai</i>	
Criteria Based Assessment of the Level of Ecological Safety of Exploitation of Electric Generating Power Plant That Consumes Biofuels	189
<i>Olexander Kondratenko, Yana Suchikova, Igor Mishchenko, Gennadiy Chernobay and Yuriy Derkach</i>	

Participation of Small Hydropower Plants in the Regulation of the Balance of Electric Energy in the Power System <i>Oksana Dovgalyuk, Alexander Lazurenko and Sherali Saidov</i>	195
Analysis of Modern Geoinformation Systems for Renewable Energy <i>Pavlo Bezkostnyi and Oksana Dovgalyuk</i>	201
Solving the Hydrodynamical Tasks Using CFD Programs <i>Kseniya Rezvaya, Evgeniy Krupa, Aleksandr Shudryk, Viktor Drankovskiy and Vadym Makarov</i>	205
Energy Co-ops as a Driver for Bio-energy Sector Growth in Ukraine <i>Tetiana Kurbatova and Yevgeniy Hyrchenko</i>	210
Selective Compensation of Current Harmonics in Grid-Connected Doubly-Fed Induction Generator based Wind Energy System <i>Ivan Shapoval, Valerii Mykhalskyi, Volodymyr Sobolev, Vasyl Chopyk and Serhii Polishchuk</i>	214
Forming of Current of the Single-Phase Grid Inverter of Local Combined Power Supply System with Photovoltaic Solar Battery <i>Olexandr Shavolkin and Iryna Shvedchykova</i>	219
The Development of Technology CdTe and CdS Layers for Thin-film Solar Cells Creation <i>Eugen Sokol, Alina Khrypunova, Dmitriy Kudii and Maksim Khrypunov</i>	224
The Optical and Electrical Properties ITO Thin Film <i>Alina Khrypunova, Dmytro Kudii and Irina Khrypunova</i>	229
Meteorological Parameters Analysis for Hourly Forecast of Electricity Generation by Photovoltaic Power Station on the Day Ahead <i>Petro Lezhnyuk, Vyacheslav Komar, Serhii Kravchuk, Vladislav Lesko and Volodymyr Netrebkiy</i>	235

Section III. Intelligent & Adaptive Systems in Smart Grid

Intelligent Locomotive Decision Support System Structure Development and Operation Quality Assessment <i>Oleksandr Gorobchenko, Oleksiy Fomin, Igor Gritsuk, Victoria Saravas, Yuriy Grytsuk, Mykola Bulgakov, Mykyta Volodarets and Dmitriy Zinchenko</i>	239
Analysis of Efficiency Of Primary Load-Frequency Control of Integrated Power System of Ukraine <i>Oleksandr Yandulskyi, Anatolii Marchenko and Volodymyr Hulyi</i>	244
On the Influence of Electromagnetic Processes of Power Transformer on Parameters of Normal Regime of Electric Network Operation <i>Igor Khomenko, Ivan Stasiuk and Sergey Iglin</i>	248
Active Voltage-Source Rectifiers With Interleaving. Analyses of Power Losses in Supply Grid Caused by Current Harmonics <i>Oleksandr Plahtii and Volodymyr Nerubatskyi</i>	253
Six-Phase Multi-Inverter System with Power Balancing and Voltage Waveform Symmetries <i>Valentin Oleschuk and Vladimir Ermuratskii</i>	259
Optimization of Reactive Energy Flows in the Electric Grid Taking Into Account Allowable Voltage Fluctuations <i>Volodymyr Kulyk, Oleksandr Burykin, Juliya Malogulko and Viktor Pirnyak</i>	265
Evaluating and Ensuring the Cybersecurity of Power Line Remote Monitoring Systems <i>Andrey Zuev, Oleg Gryb, Vadym Makarov and Sergey Shvets</i>	271
Energy Efficiency of Microgrid Implementation with Solar Photovoltaic Power Plants <i>Dmitry Tugay, George Zhemerov, Serhii Kotelevets and Serhii Korneliuk</i>	275

Section IV. Industrial Electronics & Electrical Drives

Adaptive Current Control for Shunt Active Power Filters Under Resistance and Inductance Uncertainty <i>Sergei Peresada, Yuriy Zaichenko, Dmytro Pushnitsyn and Viktor Reshetnik</i>	280
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Efficiency of Application of Electric Fields in Biogas Plants at Different Temperature Modes <i>Yuriy Kachan, Viktor Kovalenko and Olesia Lapkova</i>	286
18-Pulse Rectifier With Electronic Phases Shifting And Width-Pulse Modulation <i>Volodymyr Zamaruev, Yuriy Volovych, Olha Butova, Vadym Makarov, Eugene Sokol and Volodymyr Ivakhno</i>	290
Investigation of the Energy Consumption on Performance of Handling Operations Taking Into Account Parameters of the Grasping System <i>Roman Mykhailyskyi, Volodymyr Savkiv, Frantisek Duchon, Volodymyr Koloskov and Illia Diahovchenko</i>	295
Analysis of Frontal Resistance Force Influence During Manipulation of Dimensional Objects <i>Roman Mykhailyskyi, Volodymyr Savkiv, Frantisek Duchon, Volodymyr Koloskov and Illia Diahovchenko</i>	301
Parametric Synthesis of Electromechanical Servo Systems <i>Borys Kuznetsov, Ihor Bovdul, Aleksandr Voloshko and Tatjana Nikitina</i>	306
Robust Passivity-Based Controllers for Fast Output Voltage Regulated, Non-Ideal DC-DC Boost Converter in Hamiltonian Representation <i>Ihor Shchur and Yuriy Biletskyi</i>	310
A Model of the Assessment of an Induction Motor Condition and Operation Life, Based on the Measurement of the External Magnetic Field <i>Zagimiyak Mykhaylo, Bisikalo Oleg, Chorna Olga and Chornyi Olexii</i>	316
Modelling Distortions of an Optical Signal by a Recording Optoelectronic Device <i>Anton Bukariev, Viktor Liesnoi and Olexsandr Kyslytsyn</i>	322
Accounting for an Interconnection of Electrical, Magnetic and Mechanical Processes in Modeling the Dynamics of Turbomachines Rotors in Passive and Controlled Active Magnetic Bearings <i>Gennadii Martynenko</i>	326
Efficiency of a Linear Pulse Electromechanical Converter of Induction Type with a Two-section Power Capacitor of Energy <i>Vladimir F. Bolyukh, Alexander I. Kocherga and Igor S. Schukin</i>	332
Mathematical Model, Research and Improvement of the Switched Reluctance Generator Voltage Stabilization Methods <i>Maksym Shykhnenko, Leonid Mazurenko, Olexsandr Dzhura and Olexsandr Bilyk</i>	338
Adaptive Filter of Input Information Signal for Discharge Pulse Installation Control System <i>Sergey Kozyrev, Dmitriy Vinnichenko and Natalia Nazarova</i>	343

Section V. Special Power Electronics Systems & Applications

Analysis of Gas Content in High Voltage Equipment With Partial Discharges <i>Oleg Shutenko and Ivan Yakovenko</i>	347
Axial Flux Permanent Magnet Controlled Generator <i>Mykola Ostroverkhov, Vadim Chumack and Eugene Monakhov</i>	353
The Ways of Stabilization of High-Current Glow Discharge in Welding <i>Gennady Bolotov, Maksym Bolotov and Serhii Stepenko</i>	358
Research of the Influence of Input Voltage Deviations on the Pulse-Width Converter With Microprocessor Control System <i>Ievgen Korol and Andrii Kipenskiy</i>	363
Research of the Electromagnetic Method for the Control Rolled Steel of the Same Grade of Various Manufacturer <i>Boris Gorkunov, Anna Tyshchenko, Sergey Lvov and Abbasi Jabbar</i>	385
Perfection of Methods for Constructing Remote Monitoring Systems for Patients in Emergency Situations <i>Kolisnyk Kostyantyn and Zamiatin Petro</i>	389
Automatic Implantable Insulin Pump, adapted to Normal Activity of the Pancreas <i>Yevgen Sokol, Stanislav Lapta, Iurii Karachntsev, Nona Kravchun, Olga Solovyova, Nikolay Mustetsov, Natalya Pichko, Yana Zubova and Olga Goncharova</i>	395

Voltage Harmonic Distortion in Autonomous Electric Power System with an Adjustable Power Line Conditioner

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Abstract— An improved analytical method for estimating of voltage harmonic distortions in autonomous electric power system (AEPS) with powerful semiconductor converter (SC) and hybrid adjustable power line conditioner (APLC) had been proposed. APPLC consists an uncontrolled resonant filter and PWM controlled reactor compensator. An analysis of piecewise function of voltage in steady state regime of the system is fulfilled. The analysis is taking into account the influence of its elements and their parameters. Analytical expressions for the voltage harmonic distortion factor were obtained taking into account the entire voltage harmonics spectrum in a closed finite form. The comparison of analytical calculations and computer simulation results had been executed.

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)

I. INTRODUCTION

A. General Terms and Definitions

The resulting distorted form of grid voltage from higher harmonic emissions and the consumption of reactive power (RP) on the main harmonic is accompanied by the operation of powerful installations with semiconductor converters (SC). To reduce these negative effects and to ensure the conditions of electromagnetic compatibility active and hybrid adjustable power line conditioners (APLC) are used [1,2,3,4]. The safety of the operation of modern seagoing vessels and structures with powerful SC depends on the successful solution of the actual tasks of APPLC improvement and methods of assessing their effectiveness. Some autonomous electric power systems (AEPS) of these objects contain frequency converters according to the scheme "controlled rectifier – load-driven current inverter". Rowing and technological synchronous motors with a total capacity oftens of MW are such load.

Total harmonic distortion (THD) factor of voltage is one of the main conditions of the electricity quality deterioration. Sometimes it results in an AEPS accident. Its integral index is determined by the distortion coefficient of sinusoidality, which is normalized by territorial and international standards [4].

$$K_U = \left(\sqrt{\sum_{v=2}^{v_{\max}} U_{S(v)}^2} / U_{S(1)} \right) \cdot 100\%, \quad (1)$$

where $U_{S(1)}$, $U_{S(v)}$ is RMS primary and v-th harmonic voltage respectively, $v_{\max}$ is the highest harmonic order that is taken into account. The values of $v_{\max}$ adopted in different normative documents differ significantly. For example, [5] and [6] take into account 40 and 200 in respectively.

To prevent unacceptable errors in determining K_U , the following factors should be taken into account [7]:

- mutual influence of power sources, SC, APPLC on real electromagnetic processes in AEPS at finite (non-zero) switching angles;
- commensurability voltage harmonics in a very wide range of frequencies and therefore need to consider the whole range of harmonics.

B. Research Tasks and Objectives

The purpose of this work is to obtain analytical expressions of determination of K_U in a finite closed form by analysis of electromagnetic processes in AEPS with SC and APPLC; comparison of analytical calculations with the results of computer simulation.

II. DEFINITION OF TOTAL HARMONIC DISTORTION FACTOR

The single-line equivalent scheme of AEPS with SC and hybrid APPLC for phase A is depicted in Fig. 1. The generator (power grid) is represented by a sinusoidal EMF $e_A = E_m \sin \theta$ and a short-circuit resistance X_S , SC is the source of the periodic nonsinusoidal current i_{SCA} of the primary winding and the short-circuit resistance X_{SC} of transformer. The hybrid APPLC includes a resonant LC filter (RF) (X_{C0} , X_{L0}) and a controlled reactor compensator (CRC), which contains a reactor with impedance X_{LK} and a dual-operational semiconductor switch keys with pulse-width modulation (PWM). CRC is an adjustable equivalent

impedance $X_{RC} = X_{LC} / s^2$ at high switching frequency ($f_s = 10 \dots 20$ kHz), where s is duty ratio of PWM. Simultaneously RF is an impedance filter for CRC with PWM by connecting the CRC to the point of connection of the inductance and capacitance of RF [8].

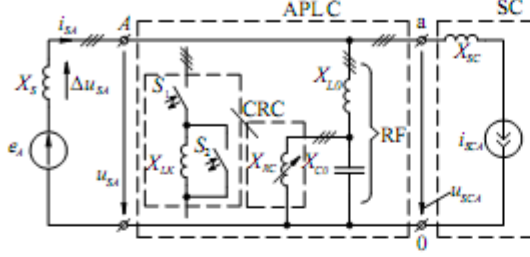


Fig. 1. The single-line equivalent scheme of autonomous AEPS with SC and APLC

The setting of frequency order of RF $\nu_0 = \sqrt{X_{C0} / X_{L0}} \leq m - 1$ (m is pulse of SC). The frequency response characteristic of the system relative to the nodes a and 0 has a zero of order $\xi = \sqrt{X_{C0}(X_{L0} + X_{RC}) / (X_{L0} \cdot X_{RC})}$ and a pole of order $\mu = \sqrt{X_{C0}(X_s + X_{L0} + X_{RC}) / ((X_s + X_{L0})X_{RC})}$.

If SC is made on a three-phase bridge circuit with single type transformer windings the current shape i_{SCA} can be considered as blocks of equal trapezoid (Fig. 2). The bases $2\pi/3 \pm \gamma$ and height $I_{ASC} = I_d / k_T$ of trapezoid (I_d is rectified current, k_T is transformation ratio, α and γ is control angle and switching angle).

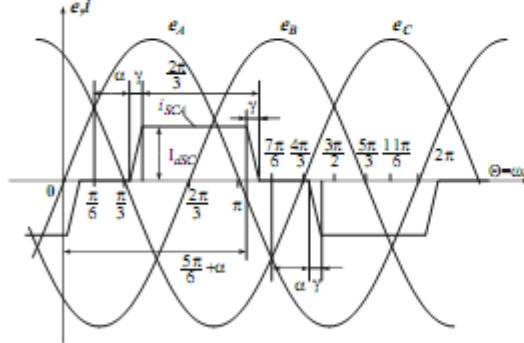


Fig. 2. Diagram of instantaneous values of the generator phase voltages and load current i_{SCA}

The assumption of the linear nature of switching current does not cause significant errors and allows to apply the operator method of separate components to determine the instantaneous value of the grid voltage u_{SA} considering

current i_{SCA} as the known perturbation [7]. Based on the principle of imposing u_{SA} is defined as the difference between two components. The first (sinusoidal) is the source of EMF e_A and the second (distorting) is the source of current Δu_{SCA}

$$u_{SA} = K_E E_m \sin \Theta - \Delta u_{SA}, \quad (2)$$

where $K_E = X_{L0}(\xi^2 + 1) / ((X_{L0} + X_s)(\mu^2 + 1))$.

In steady state the value Δu_{SA} on each N continuous interval of current i_{SCA} is determined by the method of separate components [9]

$$\Delta u_{SA}^{(N)} = \sum_{p \neq p^*} \text{Res}[Z_{a0}(p) I_{SCA}^{(N)}(p) e^{pt}] - \sum_{p^*} \text{Res}[Z_{a0}(p) I_{SCA}^{(N)}(p) e^{pt}], \quad (3)$$

where $I_{SCA}^{(N)}(p)$, $I_{SCAT}^{(N)}(p)$ is operator image of the current i_{SCA} in this interval as an analytic and as a periodic function, respectively; $Z_{a0}(p)$ is operator resistance of the system defined through the inductance and capacity of its elements relative to the nodes a and 0 :

$$Z_{a0}(p) = \frac{pL_s[p^2L_0C_0L_{RC} + (L_0 + L_{RC})]}{p^2C_0L_{RC}(L_0 + L_s) + (L_0 + L_s + L_{RC})}. \quad (4)$$

The first component of (3) is the sum of residues at all poles of both functions $I_{SCA}^{(N)}(p)$ and $Z_{a0}(p)$. Only the poles of function $Z_{a0}(p)$ take into account the residuals of the second component. The operator images of current i_{SCA} is given in Table 1. There are the beginning of the count coincides with the beginning of each interval. Expressions for the instantaneous values of Δu_{SA} on the intervals of continuity in accordance with (3) are presented in Table 2.

Following designations is accepted:

$$a = (X_{L0} + X_{RC}) / (X_s + X_{L0} + X_{RC}); \quad M = 1 - \mu^2 / \xi^2; \\ N_1 = \sin(\mu\gamma/2) \cdot \sin(\mu\pi/3) / \cos(\mu\pi/2); \\ N_2 = \sin(\mu\gamma/2) \cdot \cos(\mu\pi/6) / \cos(\mu\pi/2).$$

At the switching interval $\pi/6 + \alpha \leq \Theta \leq \pi/6 + \alpha + \gamma$ the ratio for the phases A and C is executed

$$u_{SA} - u_{SC} = 2X_{SC} di_{SCA} / d\Theta. \quad (5)$$

The equation for determining the switching angle γ is obtained by integration (5):

$$\sqrt{3}K_E E_m \sin\left(\alpha + \frac{\gamma}{2}\right) \sin \frac{\gamma}{2} + \frac{aX_s I_{ASC}}{\mu\gamma} M \sin \mu\gamma = \\ = (X_{SC} + aX_s) I_{ASC}. \quad (6)$$

TABLE I. THE OPERATOR IMAGES OF CURRENT I_{SCA}

Interval	Θ	$I_{SCA}^{(N)}(p)$	$I_{SCAT}^{(N)}(p)$
I	$\frac{\pi}{6} + \alpha \leq \Theta \leq \frac{\pi}{6} + \alpha + \gamma$	$\frac{I_{dSC} \omega}{\gamma p^2}$	$\frac{I_{dSC} \omega}{\gamma p^2} \left(1 - e^{-\frac{\gamma p}{\omega}} \right) \left(1 - e^{-\frac{2\pi p}{3\omega}} \right) / \left(1 + e^{-\frac{\pi p}{\omega}} \right)$
II	$\frac{\pi}{6} + \alpha + \gamma \leq \Theta \leq \frac{5\pi}{6} + \alpha$	$\frac{I_{dSC}}{p}$	$\frac{I_{dSC}}{p} - \frac{I_{dSC} \omega}{\gamma p^2} \left(e^{\frac{\gamma p}{\omega}} - 1 \right) \left(e^{-\frac{\pi p}{3\omega}} + 1 \right) e^{-\frac{2\pi p}{3\omega}} / \left(1 + e^{-\frac{\pi p}{\omega}} \right)$
III	$\frac{5\pi}{6} + \alpha \leq \Theta \leq \frac{5\pi}{6} + \alpha + \gamma$	$\frac{I_{dSC}}{p} - \frac{I_{dSC} \omega}{\gamma p^2}$	$\frac{I_{dSC}}{p} + \frac{I_{dSC} \omega}{\gamma p^2} \left(e^{-\frac{\gamma p}{\omega}} - 1 \right) \left(e^{-\frac{\pi p}{3\omega}} + 1 \right) / \left(1 + e^{-\frac{\pi p}{\omega}} \right)$
IV	$\frac{5\pi}{6} + \alpha + \gamma \leq \Theta \leq \frac{7\pi}{6} + \alpha$	0	$\frac{I_{dSC} \omega}{\gamma p^2} \left(1 - e^{-\frac{\gamma p}{\omega}} \right) \left(1 - e^{-\frac{2\pi p}{3\omega}} \right) e^{-\frac{\pi p}{3\omega}} / \left(1 + e^{-\frac{\pi p}{\omega}} \right)$

TABLE II. THE INSTANTANEOUS VALUES OF Δu_{SA}

Interval	Θ	Δu_{SA}
I	$\frac{\pi}{6} + \alpha \leq \Theta \leq \frac{\pi}{6} + \alpha + \gamma$	$\frac{I_{dSC} X_S}{\gamma} a \left\{ 1 - M \left[\cos \mu \left(\Theta - \alpha - \frac{\pi}{6} \right) - 2N_1 \cos \mu \left(\Theta - \alpha - \frac{\gamma}{2} \right) \right] \right\}$
II	$\frac{\pi}{6} + \alpha + \gamma \leq \Theta \leq \frac{5\pi}{6} + \alpha$	$\frac{2I_{dSC} X_S}{\gamma} a M N_2 \sin \mu \left(\Theta - \alpha - \frac{\gamma}{2} - \frac{\pi}{2} \right)$
III	$\frac{5\pi}{6} + \alpha \leq \Theta \leq \frac{5\pi}{6} + \alpha + \gamma$	$-\frac{I_{dSC} X_S}{\gamma} a \left\{ 1 - M \left[\cos \mu \left(\Theta - \alpha - \frac{5\pi}{6} \right) - 2N_2 \sin \mu \left(\Theta - \alpha - \frac{\gamma}{2} - \frac{\pi}{2} \right) \right] \right\}$
IV	$\frac{5\pi}{6} + \alpha + \gamma \leq \Theta \leq \frac{7\pi}{6} + \alpha$	$\frac{2I_{dSC} X_S}{\gamma} a M N_1 \cos \mu \left(\Theta - \alpha - \frac{\gamma}{2} - \pi \right)$

The angle γ can't be found explicitly directly from the transcendental equation (6).

Taking into account the smallness of angle γ in real modes ($\gamma \leq 20^\circ$) and replacing the sinus and cosine functions by the first definition terms of the corresponding power series the equation (6) is reduced to square equation. The solution of (6) is

$$\gamma = \left(-B + \sqrt{B^2 - 4AC} \right) / 2A, \quad (7)$$

where $A = (\sqrt{3}/4) K_E E_m \cos \alpha$; $B = (\sqrt{3}/2) K_E E_m \sin \alpha$; $C = -(X_{SC} + a X_S \mu^2 / \xi^2) I_{dSC}$.

Expression (1) can be depicted in a finite form based on the Parseval's equality. It allows to determine the THD of voltage taking into account the entire harmonic spectrum:

$$K_U = \left(\sqrt{\Delta U_S^2 - \Delta U_{S(1)}^2} / U_{S(1)} \right) \cdot 100\%, \quad (8)$$

where ΔU_S is full RMS value of the fundamental harmonic and $\Delta U_{S(1)}$ is the RMS value of the fundamental harmonic of the phase voltage distorting component Δu_S .

As a piecewise-continuous function in half of the period of component Δu_{SA} is defined for phase A (Table 2), then

$$\Delta U_S^2 = \frac{1}{\pi} \int_{\pi/6+\alpha}^{\pi/6+\alpha+\gamma} \Delta u_{SA}^2 d\Theta. \quad (9)$$

Taking into account Table 2 expression (9) is reduced to

$$\Delta U_S^2 = \frac{X_S^2 I_{dSC}^2}{\pi \gamma^2} a^2 \left[2\gamma - 4 \frac{M}{\mu} \sin \mu \gamma + M^2 \left[\gamma + \frac{1}{2\mu} \sin 2\mu \gamma - \right. \right.$$

$$-2N_2 \left(\gamma - \frac{1}{\mu} \sin \mu \gamma \right) \sin \mu \frac{\gamma}{2} + 2 \left[\frac{\pi}{3} (N_1^2 + 2N_2^2) + \frac{1}{\mu} \cos \mu \gamma \left(N_1^2 \sin \mu \frac{\pi}{3} - N_2^2 \sin \frac{2\pi}{3} \right) \right] \right] \quad (10)$$

The RMS values of the grid voltage main harmonics and its distorting component are determined as follows

$$U_{S(i)} = K_E \left[\left[E - X_S I_{SC(i)} \sin \left(\alpha + \frac{\gamma}{2} \right) \right]^2 + \left[X_S I_{SC(i)} \cos \left(\alpha + \frac{\gamma}{2} \right) \right]^2 \right]^{1/2}, \quad (11)$$

$$\Delta U_{S(i)} = K_E X_S I_{SC(i)}, \quad (12)$$

where $I_{SC(i)} = (\sqrt{6}/\pi) I_{dSC} \sin(\gamma/2) / (\gamma/2)$ is the RMS value of the main harmonic of SC consumed current; $E = E_m / \sqrt{2}$ is the RMS value of the main harmonic of source EMF.

Expressions (2-12) are also valid for AEPS without APLC. In this case follow parameters is: $X_{L0} \rightarrow \infty$; $X_{C0} \rightarrow \infty$; $X_{RC} \rightarrow \infty$ and in the above expressions $a=1$, $K_E=1$, $\mu/\xi=1$, $M=0$.

III. ANALYTICAL CALCULATION AND SIMULATION MODELLING. SELECTING THE SYSTEM PARAMETERS

The values of K_U are found by described analytical calculations method and by simulation in MATLAB (Simulink). Its are compared in Table. 3. AEPS and APLC parameters is: $S_S = 1 \text{ MVA}$, $U_S = 220 \text{ V}$, $X_S = 0,02 \text{ Ohm}$, $X_{SC} = 0,01 \text{ Ohm}$, $I_{dnom} = 1400 \text{ A}$, $U_{dnom} = 440 \text{ V}$, $k_T = 1$, $X_{C0} = 0,227 \text{ Ohm}$, $X_{L0} = 9,07 \cdot 10^{-3} \text{ Ohm}$, $X_{RC} = 0,218 \text{ Ohm}$, $f_s = 19800 \text{ Hz}$.

Two modes of SC were investigated:

Mode 1: $\alpha = 30^\circ$, $I_{dSC} = 1400 \text{ A}$;

Mode 2: $\alpha = 60^\circ$, $I_{dSC} = 1400 \text{ A}$

TABLE III. THDFACTOR K_U IN APS

Mode	$K_U, \%$			
	APS without APLC		APS with APLC	
	Analytical calculation	Modeling	Analytical calculation	Modeling
1	16,93	17,84	5,97	5,93
2	22,56	23,47	8,61	8,68

The graphs of voltage u_S and current i_S are obtained by mode 2 in the system with the absence and with the presence of APLC. The comparison of the results of calculation the graph of u_S that is built by simulation modelling and analytical calculations in fig. 3 are given.

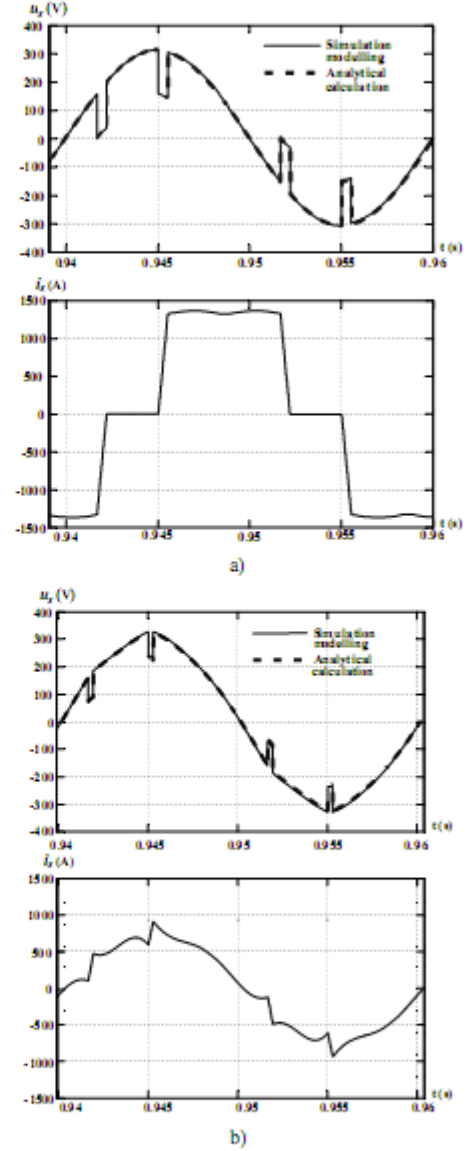


Fig. 3. The diagram of voltage u_S and current i_S in AEPS without (a) and with (b) APLC

The calculation of K_U by commonly used simplified technique based on the assumption of instant switching [10] leads to almost twice the overestimation of the result compared to the real value. The error is caused by the assumption that the voltage harmonics are determined by expression

$$U_{S(v)} = v^{-1} \left[(vX_S)^{-1} + (vX_{L0} - (vX_{RC})^{-1} - v/X_{C0})^{-1} \right]^{-1} \cdot \sqrt{6} I_{dsc} / \pi \quad (13)$$

and it form a divergent series.

The above results shows that the proposed analytical method is sufficiently accurate and general. It is very convenient for solving the problems of estimating the power quality indicators (voltage distortions) depending on the circuit and mode parameters of the AEPS with SC and APLC.

The choice of APLC parameters is performed under two conditions. The first is the compensation of RP Q_{SC} and the second is the necessary limitation of THD voltage factor K_U . The condition of full RP compensation for any mode of the system is

$$Q_{RFmax} = Q_{RCmax} = Q_{SCmax},$$

where Q_{SCmax} is the maximum RP of SC; Q_{RFmax} and Q_{RCmax} is required maximum capacities of the RF and CRC; $N \geq 1$ is the required multiplicity of the compensation reserve.

Full RP compensation is already possible at $N=1$. Sometimes an increase in this value is needed to achieve the required limit of THD K_U .

If in the whole range of regulation DC current is equal to nominal ($I_{dsc} = I_{dscnom}$), then

$$Q_{SCmax} = I_{dscnom} \sqrt{U_{d0}^2 - U_{dmin}^2} \quad (14)$$

where U_{d0} and U_{dmin} is the maximum and minimum value of the rectified voltage at the control angles $\alpha_{min} = 0$ and α_{max} respectively.

Thus, the parameters of the elements of the RF can be found in the expression

$$X_{L0} = 3U_S^2 / (v_0^2 - 1) N Q_{SCmax}, \quad (15)$$

$$X_{C0} = X_{L0} v_0^2, \quad (16)$$

The required inductance of CRC

$$X_{LK} = 3s^2 U_S^2 / N Q_{SCmax} \quad (17)$$

if duty ratio of PWM $s=1$.

The results of voltage distortion studies in Table. 3 and Fig. 3 corresponds to the APLC parameters according to the multiplicity of the compensation reserve $N=1$.

Fig. 4 constructed dependences K_U from N for regimes 1 and 2. Dependences indicate an effective reduction of 1 with increasing N .

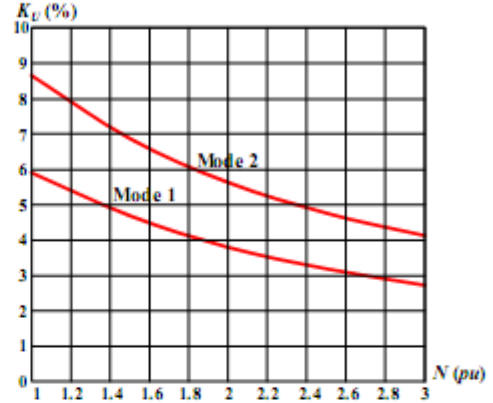


Fig. 4. The dependences voltage THD K_U from N in the AEPS with APLC

The graphs show that if the APLC has a 3-fold compensation reserve of reactive power, then K_U is reduced more than twice.

The proposed analytical method allows estimating the effect of the technological spread of the RF parameters on the voltage THD.

The surfaces that illustrates the dependence of K_U on the parameters of the resonant branch (C_0, L_{L0}), when the deviation of these parameters from exactly calculated values in the range of $\pm 10\%$ is shown in Fig. 5 and Fig. 6. The surfaces correspond to the considered example of the system with APLC in mode 1 and mode 2 in respectively.

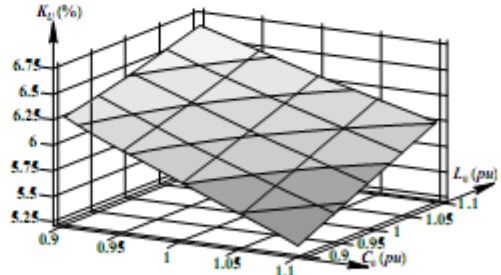


Fig. 5. The dependence of K_U on the parameters L_0 and C_0 of the resonant filter in mode 1

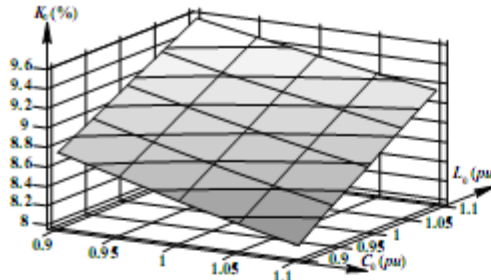


Fig. 6. The dependence of K_U on the parameters L_0 and C_0 of the resonant filter in mode 2

The form of the surfaces is explained as follows. Deviations in the parameters of RF elements (L_0 and C_0) cause changes in the frequency response characteristic of the system's resistance. It is the zero position and the angle of asymptote of this characteristic, which in turn affect the grid voltage distortions.

At constant values of C_0 and change the values of L_0 the main influence is exerted by the position of the asymptote. If L_0 decreases the angular coefficient decreases also. Therefore, all harmonics and the total harmonic distortion factor decreases. The opposite deviation of L_0 causes an increase in K_U .

If L_0 and the position of the asymptote is unchanged, the shift in the zero of the frequency response characteristic of the system's resistance has a determining effect on the harmonic distortion. If C_0 increases the order of the zero frequency shifts to the left with respect to the order $v_0 = m - 1$ of the lowest-frequency of the higher harmonics (in our case $v_0 = 5$). With the opposite deviation of C_0 the zero shift occurs to the right. In both cases, a non-zero harmonic of the order of v_0 appears in the spectrum. However, in the first case, the value of this harmonic is somewhat less than in the second. Correspondingly, K_U decreases with increasing C_0 and increases with decreasing C_0 .

CONCLUSIONS

This paper explores the features of the change in total harmonic distortion (THD) factor of voltage in the autonomous electric power system (AEPS) with powerful semiconductor converters (SC) and hybrid adjustable power line conditioner (APLC). The work allows drawing the following conclusions:

1. Based on the Laplace transform the analysis of electromagnetic processes in AEPS with SC and APLC is performed. The analysis takes into account the mutual influence of the system elements. Expressions for the harmonic distortion coefficient of voltage in the final form are obtained taking into account the entire spectrum of harmonics.

2. The proposed method is sufficiently general and acceptable for AEPS with APLC and without APLC. The use of the method also allows further theoretical analysis of the voltage quality when the parameters of the scheme and operating conditions of the system is changed.

3. Testing on the MATLAB model confirms the reliability of the obtained analytical expressions and the efficiency of APLC. K_U is reduced by almost three times with full compensation of the reactive component of the current K_U .

4. A significant decrease in K_U can be achieved by increasing the reactive power of the APLC relative to its sufficient value.

5. The changes in K_U due to the permissible technological dispersion of the RF parameters in the APLC structure is well correlated with this spread and does not exceed $\pm 10\%$. The smallest value of K_U reaches at simultaneous maximum deviations L_0 in the decreasing direction and C_0 in the increasing direction. The largest value of K_U reaches in opposite deviations of these parameters.

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