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Conversion of Fixed-Parameters Compensator in Four-Wire System with Nonsinusoidal Voltage Into Adaptive Compensator

Abstract. *The paper shows how fixed-parameters reactive compensators in four-wire systems with a nonsinusoidal voltage can be converted into controlled-parameters compensators. Such compensators can serve as adaptive balancing compensators of reactive power of unbalanced loads. Thyristor switch inductors (TSIs) are used for such conversion. The fixed-parameters balancing reactive compensators are synthesized using the Currents' Physical Components (CPC) – based power theory. The adaptive compensator is composed of two sub-compensators, one in the Δ structure and the other in the Y structure. The method is illustrated with a numerical example and results of computer modeling of the load with a fixed-parameters and with an adaptive compensator.*

Streszczenie. *Artykuł pokazuje jak równoważący kompensator reaktancyjny prądu biernego, o stałych parametrach, w systemach cztero-przewodowych, może być przekształcony w kompensator o parametrach kontrolowalnych. Kompensator taki może być użyty jako kompensator adaptacyjny. Przekształcenie takie umożliwiają włączane tyrystorami induktory (TSI). Parametry równoważącego kompensator prądu biernego mogą być obliczone z pomocą teorii mocy opartej na Składowych Fizycznych Prądu (CPC). Kompensator jest zbudowany z dwóch sub-kompensatorów, z którch jeden ma strukturę Δ a drugi strukturę Y. Przedstawiona w artykule metoda syntezy jest ilustrowana przykładami liczbowymi i rezultatami kompensacji. (**Przekształcenie kompensatora o stałych parametrach, odbiorników zasilanych cztero-przewodowo napięciem niesinusoidalnym, w kompensator adaptacyjny**)*

Keywords: Asymmetrical systems, CPC, Currents' Physical Components, unbalanced loads.
Słowa kluczowe: Systemy asymetryczne, CPC, Składowe Fizyczne Prądów, odbiorniki niezrównoważone.

Introduction

Three-phase loads of very high power, at the level of hundreds MVA, such as manufacturing plants, especially the metallurgic ones, coal or copper mines, due to the omnipre-sence of single-phase loads in their structure, are supplied from four-wire lines, meaning three-phase lines with a neutral conductor. Single-phase loads in three-phase systems are the main cause of three-phase loads imbalance which causes an increase of energy loss at its delivery. Therefore, methods of load balancing are the subject of continuous studies [1, 4, 7, 6, 8, 13].

Load balancing could be associated with compensation of the reactive power and just this is usually regarded as the primary objective of the compensator. The reactive power is compensated because there is a common opinion in the power engineering community that the reactive power causes energy oscillations, which degrade the effectiveness of the energy transfer. As it was demonstrated in [15], energy oscil-lations do not degrade this effectiveness and should not be associated with the reactive power. When the reduction of energy oscillations becomes the goal of compensation, as it is in the case of switching compensators controlled by algo-

rithms founded on the Instantaneous Reactive Power p-q Theory, the compensator instead of improving the power factor, can degrade it [9, 10]. Therefore, this paper does not apply to switching compensators but to reactive ones which compensate the load by modification of the admittance as seen from the supply terminals.

The first compensator for three-phase load balancing was developed in 1917 by Steinmetz [1]. This compensator is known as the Steinmetz circuit [6]. It was developed for loads supplied from a three-phase line with a sinusoidal voltage. Its generalization to loads supplied by a nonsinusoidal voltage was done in [4]. A sort of the Steinmetz circuit, but for load supplied with sinusoidal voltage from a four-wire line was developed in [11], and supplied in the same system with a nonsinusoidal voltage was developed in [13].

The reactive, unbalanced, and the load-generated har-monic currents are not only the main causes of increased energy losses at its delivery but also degraded supply quality (SQ) inside of the plant. The SQ declines because the supply voltage in the plane's distribution system is affected by the reactive, unbalanced, and harmonic currents, due to the voltage drop by these currents on the supply system impe-dance.

The energy loss and SQ degradation occur mainly in the impedance of the supply transformer of the plant because this impedance is usually a dominating component of the supply impedance.

Thus, to reduce the harmful components of the supply current, the compensator should be installed on the secon-dary side of the transformer. The compensator has to be able of compensating loads supplied by four-wire lines.

Although in some cases a fixed-parameters compensator can provide a satisfactory reduction of energy loss and degra-dation of the supply quality, an adaptive compensator is rather needed for that.

When the load power is in the range up to a few MVA, the load can be compensated by a switching compensator. Such a compensator is built of power transistors, used as controlled switches, which shape the compensating current. Adaptability is the intrinsic property of such compensators. They cannot operate without instantaneous control.

Adaptive balancing compensators of very high power loads, of the order of hundreds MVA, cannot be built as switching compensators, however. The switching power of transistors is not sufficient for that. Thyristors, which are switched only once a period, have to be used instead. Their switching power can be several times higher than that of transistors. Their ON/OFF switching time is too long, however, for using thyristors for shaping the compensating current needed in switching compensators. They can be used only for a slow control of reactive compensator parameters. It can be done by thyristor-switched inductors (TSI) as intro-duced in [2].

With the switching capability of thyristors now on the level of 50 kA, there are technical tools needed for the development of adaptive balancing reactive compensators of very high power. Unfortunately, such TSIs are sources of harmonic currents, which can substantially disturb the distribution sys-tem performance.

Originally, a TSI connected in parallel with a capacitor, as shown in Fig. 1, has enabled the construction of adaptive compensators of the reactive power [2, 3].

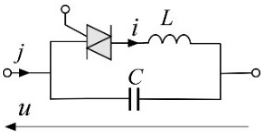

Fig. 1. A thyristor-switched inductor with a shunt capacitor.

When the compensator branches are configured in Δ, then the dominating current harmonic of the 3rd order, gene-rated by inductor's switching in particular compensator bran-ches are mutually in-phase, so that they do not leave the com-pensator. Balancing compensators are unbalanced devices, however. Thyristors in particular branches are switched at different angles and consequently, the compensator could be a source of the 3rd order harmonic.

This paper will present the conversion of a reactive com-pensator with fixed parameters into a TSI-based adaptive compensator with a reduced level of the current distortion.

A procedure of reactive compensator synthesis

The method of compensator synthesis as presented in this paper is rooted in the concept of the Currents' Physical Components (CPC) which has paved the route for interpre-tation of power-related phenomena in electrical circuits and causes of the power factor degradation, as well as for fun-damentals of a reactive compensation. Papers [4] and [14] are key references for these issues.

The presented method has a few distinctive steps. In the first of them (i), the load power properties are clarified in terms of the Currents' Physical Components [13]. This means that the load current is decomposed into orthogonal components, which are associated with distinctive physical phenomena or structural properties of the load. It reveals components res-ponsible for the power factor degradation.

In the next step (ii), the possibility of compensation of individual current components is investigated and the struc-ture of a reactive compensator is determined.

In the third step (iii) the susceptances of compensator branches for harmonic frequencies are calculated. The com-pensator branches with such susceptances are not synthe-sized, however, because this can require branches with such a high complexity, that a compensator would not have any technical merits. Instead of that, calculated previously sus-ceptances are used in an optimization procedure (step iv) to calculate LC parameters of branches with the complexity reduced to branches with no more than two reactive elements by the compensator branch.

Finally, the branches with optimized susceptance of a fixed-parameters compensator are superseded by branches with a TSI. The structure and parameters of these branches should enable the reduction of the thyristor-generated current harmonics and be insensitive to the supply voltage harmo-nics.

The steps (i), (ii), and (iii) are explained in very detail and presented in [13]. This paper is focussed on the conversion of the balancing compensator with fixed parameters obtained in these three steps, into the adaptive compensator.

Example of a load and its compensator

Steps (ii), (iii), and (iv) of the balancing compensator synthesis was illustrated in [13] by developing it for the load shown in Fig. 2.

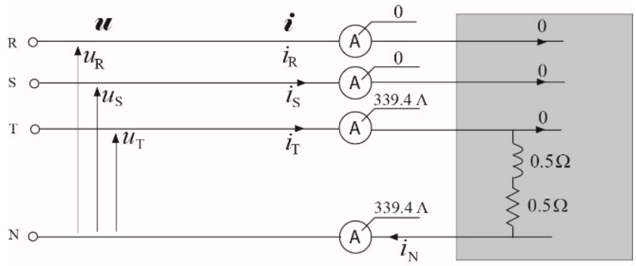

Fig. 2. An example of an unbalanced load.

The load in that example was supplied with a symmetrical voltage of the fundamental harmonic rms value U_1 = 240 V, distorted by the 3rd, 5th, and 7th order harmonics of relative rms value U_3 = 2%U_1, U_5 =3%U_1 and U_7 = 1.5%U_1. The supply source with such a load has the power factor $\lambda = P/S$ = 0.408. The three-phase rms values $\|.\|$ of the load current phy-sical components are equal to, respectively

Active current: $\|\boldsymbol{i}_{\rm a}\|$ = 138.5 A

Scattered current: $\|\boldsymbol{i}_{\rm s}\|$ = 4.9 A

Reactive current: $\|\boldsymbol{i}_{\rm s}\|$ = 138.6 A

Unbalanced current: $\|\boldsymbol{i}_{\rm u}\|$ = 277.1 A

while the symmetrical components of the positive, negative, and zero sequences of the unbalanced current have the following three-phase rms values:

Positive sequence component: $\|\boldsymbol{i}_{\rm u}^{\rm p}\| = 2.4$ A

Negative sequence component: $\|\boldsymbol{i}_{\rm u}^{\rm n}\| = 196.0$ A

Zero sequence component: $\|\boldsymbol{i}_{\rm u}^{\rm z}\| = 196.0$ A

As demonstrated in [13], the reactive current and only two of three symmetrical components of the unbalanced current can be compensated entirely by a reactive compensator. The number of reactive components needed to build such a com-pensator is very high, however, which, unfortunately, reduces its technical value.

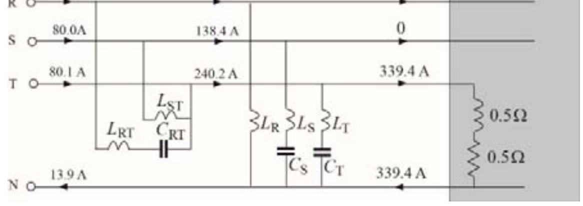

Fig. 3. The load with a compensator of reduced complexity.

The complexity of the compensator can be reduced on the condition that instead of the total compensation of these currents, their three-phase rms value is only minimized. Assuming that the compensator branches cannot have more than two reactive elements, the reduced complexity compen-sator, shown in Fig. 3, was synthesized in [13].

The reduced complexity compensator parameters are compi-led in Table 1.

Table 1. LC parameters of a reduced complexity compensator.

Line:	R	S	T	RS	ST	TR
H	1.730	0.770	0.444	0	2.600	1.155
F	0	0.399	0.691	0	0	0.266

It reduces the three-phase rms value of the supply current physical components to

Reactive current: $||\boldsymbol{i}_{\mathrm{s}}||$ = 11.9 A

Unbalanced current: $||\boldsymbol{i}_{\mathrm{u}}||$ = 8.0 A

while the three-phase rms values of the unbalanced current symmetrical components were reduced to, respectively

Positive sequence component: $||\boldsymbol{i}_{\mathrm{u}}^{\mathrm{p}}|| = 5.9$ A

Negative sequence component: $||\boldsymbol{i}_{\mathrm{u}}^{\mathrm{n}}|| = 4.4$ A

Zero sequence component: $||\boldsymbol{i}_{\mathrm{u}}^{\mathrm{z}}|| = 3.1$ A

Such a compensator reduces the supply current three-phase rms value from $||\boldsymbol{i}||$ = 339.4 A to $||\boldsymbol{i}||$ = 139.3 A and improves the power factor to $\lambda = P/S = 0.994$.

With such effectiveness of compensation, it seems that the complexity of the compensator, reduced as assumed, to no more than two reactive devices per phase, is quite suf-ficient.

These results are valid, of course, as long as the load structure and parameters remain unchanged. An adaptive compensator is needed when this is not true. Conversion of the fixed-parameter compensator into an adaptive one is dis-cussed in the next section.

Adaptive compensator

To control the compensator properties, the capacitance or inductance of its reactive components has to be controlled. The capacitance can be controlled by switches, but a lot of capacitors and switches would be needed for that, so, such control does not have practical merits. Inductance can be controlled by saturating the magnetic core of inductors or by switches. The most common method of the inductance con-trol is based on the use of thyristor-switched inductors (TSI), shown in Fig. 4.

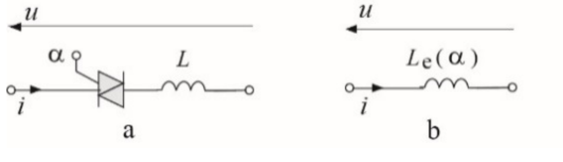

Fig. 4. A thyristor switched inductor (TSI) (a) and its equivalent inductance (b).

When it is connected in parallel with a capacitor, as shown in Fig. 1, it serves [2, 3] as an adaptive compensator of the reactive power.

The current of thyristor-switched inductor changes for some angle switching angle *a*, as shown in Fig. 5. Symbol i_0 denotes thyristor current at $\alpha = 0$.

Let us assume that the voltage $u(t)$ on the TSI is sinu-soidal. The ratio of the crms value $\boldsymbol{I}_1$ of the current $i(t)$ funda-mental harmonic $i_1(t)$ and the voltage crms value

$$(1) \qquad \boldsymbol{Y}_1 = \frac{\boldsymbol{I}_1}{\boldsymbol{U}_1} = jB_1 = (1 - \frac{2\alpha + \sin 2\alpha}{\pi})\frac{1}{j\omega_1 L} = \frac{1}{j\omega_1 L_{\mathrm{e}}(\alpha)}$$

specifies the branch susceptance B_1 for the fundamental frequency. It changes with the change of the firing angle α

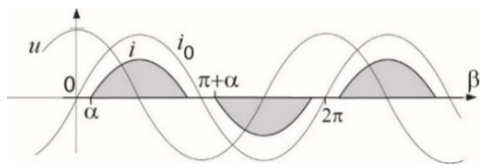

Fig. 5. The currents waveform of a thyristor switched inductor (TSI).
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The TSI is usually a component of the compensator branch, built of a few reactive devices which enable shaping frequency properties of such a branch. Properties of such branches at a few different structures were studied in [5]. In the working point, specified by the branch voltage, such a branch can be approximated, as shown in Fig. 6, by a linear one-port of susceptance $T(\omega)$ and a current source j, compo-sed of current harmonics, originated by the thyristor's switching. Such a branch will be referred to [5] as the thyristor-controlled susceptance (TCS) branch.

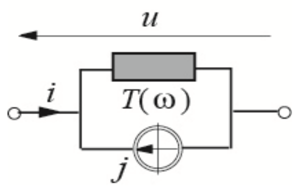

Fig. 6. An equivalent circuit of thyristor-controlled susceptance (TCS) branch.

The TCS branch is a source of current harmonics, in par-ticular, of the 3rd order. When compensation is confined, as it is common, only to the reactive power Q, the compensator is built as a balanced device, meaning, it is configured in Δ and thyristors in particular lines are fired, with the shift of 120 deg, at the same firing angle. Since the 3rd order harmonics gene-rated in the compensator all TCS branches are in-phase and mutually equal, they do not leave the compensator. They are confined to its Δ loop.

When TCSs are used in a balancing compensator, it operates as an unbalanced device. Thyristors are switched at different angles and the 3rd order harmonic generated in particular TCS branches have different values. Consequently, the 3rd order harmonic currents are injected into the supply lines. This causes waveform distortion. Moreover, the reso-nance of the compensator capacitance with the supply system inductance can occur. To avoid it, the capacitor should be replaced by a filter, as shown in Fig. 7, tuned to the frequency of the 3rd order harmonic.

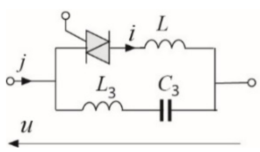

Fig. 7. A TCS branch built of TSI branch and a filter of the 3rd order harmonic.

Although the above-mentioned structure effectively redu-ces harmonics generated by switched thyristors, the filter L_3C_3 stands for a short circuit for the supply source originated 3rd order harmonics. To avoid it, an inductor L_0 can be added as shown in Fig. 8.

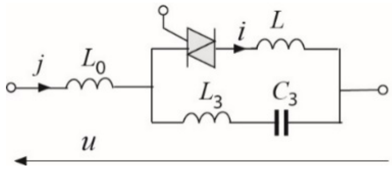

Fig. 8. A TSC branch with 3rd harmonic filter and series inductor L_0.

A fixed-parameter compensator can be converted into the adaptive if each branch is superseded by a TCS branch, as is shown in Fig. 9.

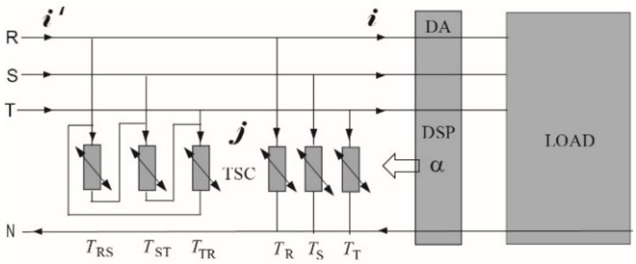

Fig. 9. A structure of an adaptive compensator.

Symbol DA in this figure denotes a Data Acquisition sys-tem which provides samples of the load current and voltage for the Digital Signals Processing (DSP) system which calcu-lates firing angles α for thyristors' switching. The DSP system has to follow the Currents' Physical Components approach to compensation of three-phase loads supplied from four-wire line with a nonsinusoidal voltage,p as presented in [13]. It includes the Fourier analysis of voltages and currents, calcu-lation of the load equivalent parameters, and susceptances of the branches of the fixed-parameters compensator. Having six branches, the compensator state can be updated six times in a single period T. It means that the DSP system has a time interval of T/6 long for completing all calculations. This is ample time for present-day microcontrollers. One could also observe that the compensator is controlled in open-loop, so that the stability issue does not occur.

The load is composed usually of three-phase devices, that do not cause the load imbalance, such as motors, heaters, or converters. The load imbalance is caused by single-phase devices that burden supply lines randomly. In the worst case, such single-phase devices burden only one supply line, as it was assumed in the illustration shown in Fig. 2.

Synthesis of the adaptive balancing compensator requires that before this synthesis, the level of the load imbalance is assessed. It can be done only by the operator of a particular load. It is expected in this paper that the compensator will be able of handling the worst-case scenario, meaning the whole load is supplied from any of line, R, S, or T.

The parameters of the balancing compensator depend on the load equivalent susceptance and unbalanced admittan-ces of the zero and negative sequence. The third unbalanced admittance, namely that of the positive sequence, does not affect the compensator parameters because the unbalanced current of the positive sequence cannot be compensated, as it was discussed in [13] by a reactive compensator. Anyway, it occurs only in the presence of the supply voltage harmonics, and as shown in the numerical example above, its three-phase rms value is substantially lower than that of the zero- and negative sequence unbalanced currents.

Now, let us return to the TCS branch of the structure shown in Fig. 8. When both thyristors are in ON state for the whole half of the period T, i.e., at firing angle α = 0, then the susceptance $T(\omega)$ of such a branch changes with the frequency as shown in Fig. 10.

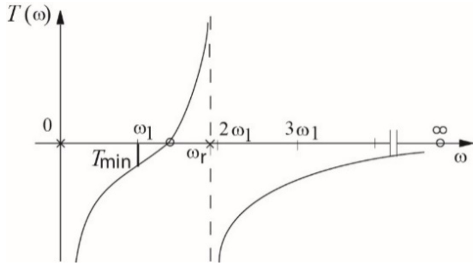

Fig. 10. Change of the TCS branch in the thyristor ON state.

Its susceptance T for the fundamental harmonic has the minimum value, equal to

$$T_{\min} = \frac{9\omega_1^2 L C_3 - 8}{8\omega_1 (L_0 + L) - 9\omega_1^3 L\, L_0 C_3}\,. \tag{2}$$

When the thyristors are in OFF state, i.e., at α = 90°, then the susceptance $T(\omega)$ of such a branch changes with frequ-ency as shown in Fig. 11. Its susceptance for the funda-mental harmonic has the maximum value equal to

$$T_{\max} = \frac{9\omega_1 C_3}{8 - 9\omega_1^2 L_0 C_3}\,. \tag{3}$$

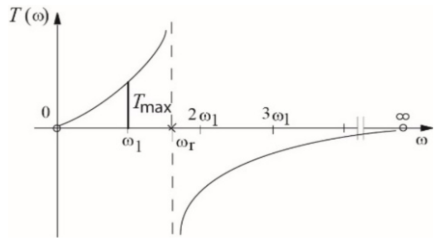

Fig. 11. Change of the TCS branch in the thyristor OFF state.

At some frequency, denoted by ω_r, a voltage resonance of the whole TSC branch occurs. Its susceptance approaches infinity. Since the equivalent inductance of the TSI branch changes with the firing angle, the frequency ω_r changes as well. Its maximum value is in the thyristor ON state over the whole period T and it is equal to

$$\omega_r = \sqrt{8}\,\sqrt{\frac{L_3\,(L + L_0)}{L\,L_0}}\;\omega_1\,. \tag{4}$$

Its relative value, ω_r/ω_1, will be denoted by Ω. To avoid resonance at the 2nd order harmonic, which can be present in the supply voltage, the parameters of the TCS branch should be select in such a way that resonance frequency (4) is below the second harmonic frequency, $2\omega_1$.

The needed range of the change of the branch's suscep-tance depends, of course, on the load, its reactive power value and possible level of imbalance. This relatively complex issue is, however, beyond the scope of this paper, which is to only demonstrate that adaptive balancing in four-wire sys-tems in the presence of the supply voltage distortion is possible. Therefore, the circuit used in the numerical illustra-tion before will be used again to illustrate an adaptive balan-cing. The adaptive compensator will be designed at the assumption that the supply voltage is identical as before, while the individual supply lines are loaded randomly, but no more than to a degree as shown in line T in Fig. 2.

The needed minimum and maximum values of the susceptance, T_{min}, T_{max}, of TCS branches of the Y and Δ sub-compensators can be found having previously calculated and compiled in Table 1 the optimized LC parameters of the fixed-parameters compensator. Thus, for the Y sub-compensator

(5) $$T_{min} = -\frac{1}{\omega_1 L_R} = -\frac{1}{1.730} = -0.578\ \mathrm{S}$$

(6) $$T_{max} = \frac{1}{\frac{1}{\omega_1 C_T} - \omega_1 L_T} = \frac{1}{\frac{1}{0.691} - 0.444} = 0.997\ \mathrm{S}$$

and for the Δ sub-compensator

(7) $$T_{min} = -\frac{1}{\omega_1 L_{ST}} = -\frac{1}{2.60} = -0.385\ \mathrm{S}$$

(8) $$T_{max} = \frac{1}{\frac{1}{\omega_1 C_{TR}} - \omega_1 L_{TR}} = \frac{1}{\frac{1}{0.266} - 1.155} = 0.384\ \mathrm{S}\ .$$

To obtain the required range of susceptance T change, the LC parameters of TCS branches have to be calculated. It can be done as follows.

The minimum and maximum values T_{min}, T_{max}, of the branch susceptance are related to the branch parameters by formulae (2) and (3). The product $L_3C_3 = (3\omega_1)^2$, and Ω value should be selected below 2. When these four conditions are combined and rearranged with regard to one of the TSC parameters, for example, L_0, it has to satisfy condition:

(9) $$a_3 L_0^3 + a_2 L_0^2 + a_1 L_0 + a_0 = 0\ .$$

To compact symbols, let us denote $T_{min} = T_a$, $T_{max} = T_b$. With such symbols, coefficients of eqn. (9) are

(10) $$a_0 = (9 - \Omega^2)$$

(11) $$a_1 = (27 - 11\Omega^2)\omega_1 T_b$$

(12) $$a_2 = [2T_b(9 - 5\Omega^2) + 9T_a(1 - \Omega^2)]\omega_1{}^2 T_b$$

(13) $$a_3 = 9(1 - \Omega^2)\omega_1{}^3 T_a T_b\ .$$

Having equation (9) solved, the branch parameters can be calculated

(14) $$L_3 = (\omega_1 L_0 + 1/T_b)/8\omega_1$$

(15) $$C_3 = 1/(9\omega_1{}^2 L_3)$$

(16) $$L = [T_a T_b\, \omega_1^2 L_0{}^2 + (T_a + T_b)\omega_1 L_0 + 1]\,/\,[(T_b - T_a)\omega_1]\ .$$

Parameters of the Δ and Y sub-compensators TCS bran-ches of the structure shown in Fig. 11, calculated from formu-las (10)–(13), are compiled in Table 2.

Table 2. Coefficients of the inductance L_0 equation.

	a_0	a_1	a_2	a_3
Δ	5.09	– 6.14	– 0.14	1.48
Y	4.89	–18.06	9.19	16.03

Parameters of the TCS branches, calculated from formulas (14) – (16), are compiled in Table 3.

The voltage and current at each TCS branch, in general, are nonsinusoidal. Since the 3rd order harmonic is usually the dominating one in the current of the TSI branch, the L_3C_3 filter reduces the harmonic distortion of the TCS branch current substantially.

Table 3. Parameters of the compensator's TCS branches.

	L_0 [H]	L_3 [H]	C_3 [F]	L [H]
Δ	1.200	0.470	0.230	1.020
Y	0.450	0.180	0.610	0.680

Therefore, the TCS branch as shown in Fig. 8 can be approximated by an equivalent branch for the fundamental harmonic as shown in Fig. 12.

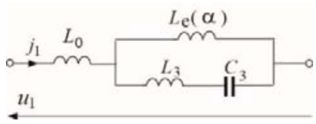

Fig. 12. An equivalent TCS branch for the fundamental harmonic.

The susceptance of such a branch for the fundamental harmonic is equal to

(17) $$T = \frac{9\omega_1^2 L_e(\alpha)C_3 - 8}{8\omega_1[L_0 + L_e(\alpha)] - 9\omega_1^3 L_e(\alpha)\, L_0 C_3} = T(\alpha)\ .$$

This formula, for a given value of the firing angle α, provi-des the branch susceptance T. It cannot be solved, however with regard to the firing angle α. A look-up table, which for angles in the range from 0^o to 90^o specifies the susceptance T of TCS branches is needed.

When the compensated load has the structure and para-meters as the illustration shown in Fig. 2, then for the Y sub-compensator:

(18) $$T_R = T_{min} = -\frac{1}{\omega_1 L_R} = -0.578\ \mathrm{S}; \qquad \alpha_R = 0^o$$

(19) $$T_S = \frac{1}{\frac{1}{\omega_1 C_S} - \omega_1 L_S} = 0.576\ \mathrm{S}; \qquad \alpha_S = 47.3^o$$

(20) $$T_T = T_{max} = \frac{1}{\frac{1}{\omega_1 C_T} - \omega_1 L_T} = 0.576\ \mathrm{S}; \quad \alpha_T = 90^o$$

and for the Δ sub-compensator:

(21) $$T_{RS} = 0; \qquad \alpha_{RS} = 38^o$$

(22) $$T_{ST} = T_{min} = -\frac{1}{\omega_1 L_{ST}} = -0.385\ \mathrm{S}; \qquad \alpha_{ST} = 0^o$$

(23) $$T_{TR} = T_{max} = \frac{1}{\frac{1}{\omega_1 C_{TR}} - \omega_1 L_{TR}} = 0.384\ \mathrm{S}; \quad \alpha_{TR} = 90^o$$

Compensator-generated harmonics

Distortion of the compensator current by thyristors causes that, apart from the supply voltage originated harmonics, also the compensator-originated harmonics can occur in the sup-ply current, $\boldsymbol{i}_S$. Let us denote by $\boldsymbol{i}_{S0}$ the supply current in the system with the compensator but removed the thyristor bran-ches. The difference

(24) $$\boldsymbol{i}_S - \boldsymbol{i}_{S0} = \boldsymbol{i}_G\ .$$

approximates the compensator-generated harmonic current $\boldsymbol{i}_G$. The harmonics of the compensator-generated current $\boldsymbol{i}_G$ are created by thyristors switching. The effect of the voltage harmonics upon thyristors' switching is negligible so that har-monics of the currents $\boldsymbol{i}_{S0}$ and $\boldsymbol{i}_G$ are mutually random, thus these two currents are mutually orthogonal. Hence,

(25) $$||\boldsymbol{i}_S||^2 = ||\boldsymbol{i}_{S0}||^2 + ||\boldsymbol{i}_G||^2\ .$$

This relationship enables calculating the three-phase rms value of the compensator-generated current,

(26) $$||\boldsymbol{i}_G|| = \sqrt{||\boldsymbol{i}_S||^2 - ||\boldsymbol{i}_{S0}||^2}$$

where

$$\|\boldsymbol{i}_{S0}\|^2=\sum_{n\in N}\|\boldsymbol{i}_{S0n}\|^2=\sum_{n\in N}[(Y'_{Rn}U_{Rn})^2+(Y'_{Sn}U_{Sn})^2+(Y'_{Tn}U_{Tn})^2] \quad (27)$$

Results of adaptive compensation

The results of compensation are shown in Fig. 13. These results confirm the possibility of an adaptive compensation of unbalanced linear loads supplied by a four-wire line in the presence of the supply voltage distortion. Although some level of the supply current asymmetry remains, the power factor was improved to λ = 0.99.

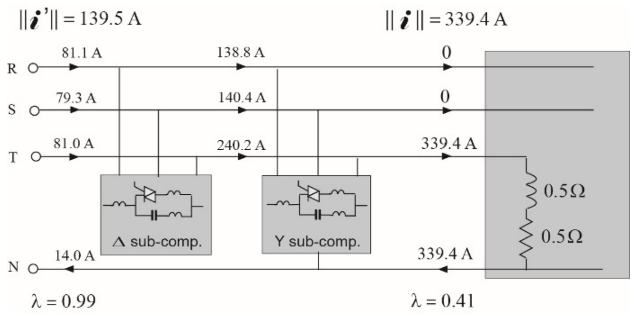

Fig. 13. The load with the adaptive compensator.

It reduces the three-phase rms value of the supply current physical components to

Reactive current: $\|\boldsymbol{i}_s\|$ = 15.5 A

Unbalanced current: $\|\boldsymbol{i}_u\|$ = 4.3 A

while the three-phase rms values of the unbalanced current symmetrical components were reduced to, respectively

Positive sequence component: $\|\boldsymbol{i}_u^p\| = 2.4$ A

Negative sequence component: $\|\boldsymbol{i}_u^n\| = 2.9$ A

Zero sequence component: $\|\boldsymbol{i}_u^z\| = 2.0$ A

The three-phase compensator-generated current, specified according to (26) is $\|\boldsymbol{i}_G\|$ = 5.3 A.

Similarly, as in the case of compensation by a fixed-para-meters compensator of reduced complexity, some residual parts of the reactive and unbalanced currents remain uncom-pensated in the supply current. At the same time, as shown in Fig. 14, thyristors which provide adaptive property of the compensator, did not cause any substantial distortion of the supply current. Figure 14 shows the waveform of the supply current $i_R(t)$ of the compensated load referred to supply voltage $u_R(t)$.

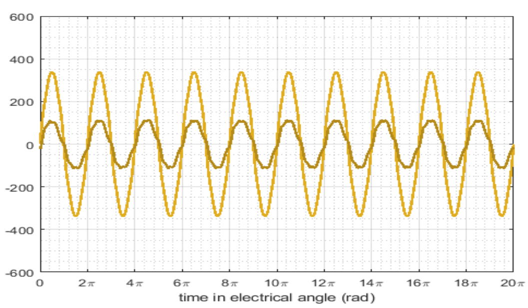

Fig. 14. Voltage and current waveforms in supply line R of the compensated load.

Conclusions

The paper demonstrates that a fixed-parameters balan-cing compensator can be converted, using thyristor-switched inductors, into an adaptive device. Despite the current ha-rmonics generated by thyristors' switching, the structure and parameters of the compensator branches can be selected in such a way that the compensator does not cause any sub-stantial distortion of the supply current.

The adaptive compensator as presented in the paper is build of 24 reactive devices, 12 thyristors, and a sophisticated Digital Signal Processing system. It is a complex device. Probably, only loads with very high energy consumption and very high variability of parameters might need such compli-cated compensators. Nonetheless, the paper shows that such adaptive compensation with very high effectiveness is pos-sible.

The paper presents only a general frame of conversion of a fixed-parameters compensator into an adaptive device with the focus on the possibility of such conversation and conse-quently, several important details are ignored. Further rese-arch could simplify the process of the compensator synthesis and its conversion, as well as could improve the compen-sator. The research could be both of a general nature and on adjusting the compensator to specific situations. Anyway, the Reader should not consider the subject discussed in this paper as completed and closed.

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