A New Fast Action System for Reactive and Unbalanced Currents Compensation in Three Phase Three Wires Systems

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Abstract - **Unbalanced loads in three phase systems produce undesired negative and zero sequence currents. Negative sequence currents will cause excessive heating of electrical machines, saturation of transformers, ripple in rectifiers or even instability problems of generators. Zero sequence currents cause not only excessive power losses in neutral lines but also protection and interference problems.**

The paper deals with a new active scheme aiming to attenuate the negative sequence component of the line currents associated with an unbalanced three phase load. The scheme also assures a unity power factor at the load bus. The proposed structure uses a Y – connected capacitor bank and a Δ - connected switching-controlled reactors, the amount of reactive power being controlled. by active voltage regulators. The compensation system is suitable for on-line control, by measuring and processing phase voltages and currents in real time.

PSpice simulation of the system using real data has been performed. The obtained results prove the correctness of the proposed solution and the possibility of its implementation in industrial power systems.

Keywords: thyristor switched inductor, unbalance, power factor, symmetric components

I. INTRODUCTION

An electric power system is expected to operate in a balanced three-phase condition. Unfortunately, it is very often the situation when asymmetric loads connected to the system produce undesired negative and zero sequence currents, with considerable effects that have to be considered. Thus, negative sequence currents will cause excessive heating of alternator rotors, saturation of transformers, ripple in rectifiers and sometimes even stability problems of generators. Zero sequence currents negative effects are mainly reflected in excessive power losses in neutral lines and the perturbation of the protection system. It is known for a long time in using thyristor switched inductors (TSI) to control the reactive power. If thyristor's firing angles of the compensator system are controlled independently, it can compensate also the load unbalance. Based on the TSI theory, the paper proposes a new reactive and unbalanced currents compensation scheme, designed for three-phase three-wires distribution systems.

There are several reasons for using compensators built of capacitors and TSI, such as:

- the possibility to control the reactive power supplied from the distribution system and to reduce the supply voltage unbalance caused by the load current asymmetry due to the load unbalance;
- fast response of TSI enables to build compensators operating to reduce fast variation of the reactive power and the load unbalance.

II BASIC PRINCIPLES

Let us consider the three-phase distribution system as shown in Fig. 1, where the substation is assumed to be a constant balanced voltage source and the three distribution line impedances are equal. The unbalance of the single phase loads in the system will cause an asymmetry of the line currents, and consequently unequal voltage drops on the distribution lines. In these conditions the load bus voltages will become unbalanced.

In order to improve the load power factor and to balance the line currents a fast action system is connected to the load bus. It consists of a Y connected capacitor bank (Y-CCB) and a Δ connected TSI bank (Δ-TSI). The thyristors in the TSI are driven to provide the necessary amount of reactive power to each phase (Fig. 1).

The meaning of notations in Fig. 1 is as follow:

- $\underline{I}_{12}$, $\underline{I}_{23}$, $\underline{I}_{31}$, the complex values of the fundamental of currents in the TSI branches;
- $\underline{I}'_1$, $\underline{I}'_2$, $\underline{I}'_3$, the complex values of the line currents (supply currents);
- $\underline{I}_{1C}$, $\underline{I}_{2C}$, $\underline{I}_{3C}$, the complex values of the currents in the capacitors;
- $\underline{I}_1$, $\underline{I}_2$, $\underline{I}_3$, the complex values of the load currents.

Using the active (I_{1a}, I_{2a}, I_{3a}) and reactive (I_{1r}, I_{2r}, I_{3r}) components the load currents can be expressed as:

$$\begin{cases} \underline{I}_1 = I_{1a} - jI_{1r} \\ \underline{I}_2 = (I_{2a} - jI_{2r})a^2 \\ \underline{I}_3 = (I_{3a} - I_{3r})a \end{cases} \qquad (1)$$

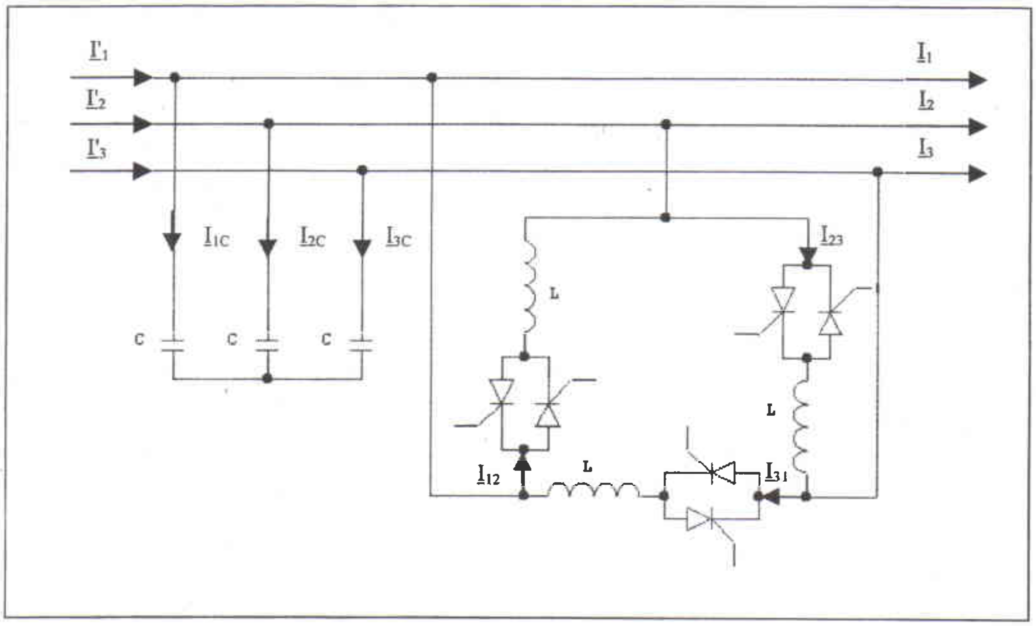

Fig. 1. Circuit diagram of the proposed reactive and unbalanced currents compensator

with: $a = e^{j\frac{2\pi}{3}}$, the rotation operator.
Since there is no neutral connection,

$$\underline{I}_1 + \underline{I}_2 + \underline{I}_3 = 0 . \quad (2)$$

Using (1) and (2) equal to zero, we obtain two equations associating the active and reactive currents, namely:

$$\begin{cases} I_{1a} - \frac{1}{2} I_{2a} - \frac{1}{2} I_{3a} = \frac{\sqrt{3}}{2} (I_{2r} - I_{3r}) \\ \frac{\sqrt{3}}{2} (I_{2a} - I_{3a}) = -I_{1r} + \frac{1}{2} I_{2r} + \frac{1}{2} I_{3r} \end{cases} \quad (3)$$

The currents through the Y-CCB branches are balanced and can be expressed as:

$$\begin{cases} \underline{I}_{1C} = \underline{I}_{1C} \\ \underline{I}_{2C} = a^2 \underline{I}_{1C} \\ \underline{I}_{3C} = a \underline{I}_{1C} \end{cases} . \quad (4)$$

Since the currents in the Δ-TSI bank are in quadrature lagging the line voltages, they have the expressions:

$$\begin{cases} \underline{I}_{12} = -a I_{12} \\ \underline{I}_{23} = -I_{23} \\ \underline{I}_{31} = -a^2 I_{31} \end{cases} . \quad (5)$$

Using first Kirchhoff's law, the supply currents will be:

$$\begin{cases} \underline{I'}_1 = \underline{I}_{1C} + \underline{I}_{12} - \underline{I}_{31} + \underline{I}_1 \\ \underline{I'}_2 = a^2 \underline{I}_{1C} + \underline{I}_{23} - \underline{I}_{12} + \underline{I}_2 \\ \underline{I'}_3 = a \underline{I}_{1C} + \underline{I}_{31} - \underline{I}_{23} + \underline{I}_3 \end{cases} . \quad (6)$$

The symmetric components of the supply current are given by:

$$\underline{I'}_- = \frac{1}{3} (\underline{I'}_1 + a^2 \underline{I'}_2 + a \underline{I'}_3) \quad (7)$$

$$\underline{I'}_+ = \frac{1}{3} \cdot (\underline{I'}_1 + a \cdot \underline{I'}_2 + a^2 \cdot \underline{I'}_3) \quad (8)$$

$$\underline{I'}_0 = \frac{1}{3} (\underline{I'}_1 + \underline{I'}_2 + \underline{I'}_3) \quad (9)$$

By substituting (1), (4) and (5) in (7) and (8), the negative and positive sequence components can be written as:

$$\begin{aligned} \underline{I'}_- = \frac{1}{3} [(& \frac{3}{2} I_{12} - \frac{3}{2} I_{31} + I_{1a} - \frac{1}{2} I_{2a} - \\ & - \frac{1}{2} I_{3a} + \frac{\sqrt{3}}{2} I_{2r} - \frac{\sqrt{3}}{2} I_{3r}) + \\ & + j (- \frac{\sqrt{3}}{2} I_{12} + \sqrt{3} I_{23} - \frac{\sqrt{3}}{2} I_{31} - \\ & - I_{1r} + \frac{1}{2} I_{2r} + \frac{1}{2} I_{3r} + \frac{\sqrt{3}}{2} I_{2a} - \frac{\sqrt{3}}{2} I_{3a})] \end{aligned} \quad (10)$$

$$\begin{aligned}\underline{I}'_{+} = \frac{1}{3}\cdot[I_{1a} + I_{2a} + I_{3a} - \\ - j(I_{1r} + I_{2r} + + I_{3r} - 3 I_{1C} + \\ + \sqrt{3}(I_{12} + I_{13} + I_{31}))]\end{aligned} \tag{11}$$

Decomposing the negative and positive sequences of the supply current in their real and imaginary parts we obtain:

$$\begin{cases}\operatorname{Re}(\underline{I}'_{-}) = \frac{1}{2}\cdot(I_{12} - I_{31}) + \frac{\sqrt{3}}{3}\cdot(I_{2r} - I_{3r}) \\ \operatorname{Im}(\underline{I}'_{-}) = \frac{1}{3}\cdot\frac{\sqrt{3}}{2}\cdot(-I_{12} + 2\cdot I_{23} - I_{31}) + \\ \qquad + \frac{1}{3}\cdot(-2\cdot I_{1r} + I_{2r} + I_{3r})\end{cases} \tag{12}$$

$$\begin{cases}\operatorname{Re}(\underline{I}'_{+}) = \frac{1}{3}(I_{1a} + I_{2a} + I_{3a}) \\ \operatorname{Im}(\underline{I}'_{+}) = \frac{1}{3}[3I_{1c} - \sqrt{3}(I_{12} + I_{23} + I_{31}) - \\ -(I_{1r} + I_{2r} + I_{3r})]\end{cases} \tag{13}$$

In order to balance the distribution line currents it is necessary to cancel out the negative sequence component. If we also wish to operate at unitary power factor, it is necessary to eliminate the imaginary part of the positive sequence component simultaneously, that is:

$$\begin{cases}\operatorname{Re}(\underline{I}'_{-}) = 0 \\ \operatorname{Im}(\underline{I}'_{-}) = 0 \\ \operatorname{Im}(\underline{I}'_{+}) = 0\end{cases} \tag{14}$$

III. CONTROL MODE

The delta configuration of the proposed compensation system allows to control currents $\underline{I}_{12}$, $\underline{I}_{23}$, $\underline{I}_{31}$ separately.

So that, by measuring the values and the phases of the load currents, it is possible to adjust the currents in the Δ-TSI bank such as they fulfil the above mentioned conditions.

The solution of the system (14) gives the values of the currents that must flow in the Δ-TSI branches, in order to obtain the desired effects.

$$\begin{cases}I_{12} = \frac{1}{\sqrt{3}}[I_{1c} - I_{1r} - I_{2r} - I_{3r}] \\ I_{23} = \frac{1}{\sqrt{3}}[I_{1c} + I_{1r} - I_{2r} - I_{3r}] \\ I_{31} = \frac{1}{\sqrt{3}}[I_{1c} - I_{1r} + I_{2r} - I_{3r}]\end{cases} \tag{15}$$

The instantaneous value of the current through one leg of the Δ-TSI bank ca be calculated as function of thirystors firing angle, α and time as:

$$i = \sqrt{2}\frac{U}{\omega\cdot L}[\sin(\omega\cdot t - \frac{\pi}{2}) - \sin(\alpha - \frac{\pi}{2})] \tag{16}$$

Its RMS value, I_{RMS}, is given by:

$$\begin{aligned}I_{RMS} = \frac{U}{\omega\cdot L}\cdot \\ \cdot\sqrt{\frac{4}{\pi}\left[(\pi - \alpha)(\cos^2\alpha + \frac{1}{2}) + \frac{3}{4}\sin 2\alpha\right]}\end{aligned} \tag{17}$$

where $\pi/2 \le \alpha \le \pi$

The relation (17) allows to calculate the values of the firing angle of TSI's thirystors, (one branch) function of I_{RMS}. In order to generalise, these values were calculated as function of I_{RMS}/I^*_{RMS} ratio (Table 1), where I_{RMS} represents the required RMS value of the current through TSI and I^*_{RMS} is the maximum value of the TSI's RMS current ($\alpha = \pi/2$).

Using the above mentioned, the control algorithm has to perform:

- data acquisition of load voltages and currents;
- calculus of active and reactive components of load currents;
- calculus of TSI's currents;
- thyristors firing angle setting

Because of its simplicity, the algorithm can be easily implemented using a microcontroller.

Table 1

$\frac{I_{RMS}}{I^*_{RMS}}$	α [rad]	$\frac{I_{RMS}}{I^*_{RMS}}$	α [rad]	$\frac{I_{RMS}}{I^*_{RMS}}$	α [rad]
0	3.14	0.4	2.112	0.75	1.775
0.05	2.708	0.45	2.058	0.8	1.733
0.10	2.567	0.5	2.006	0.85	1.691
0.2	2.376	0.55	1.956	0.9	1.65
0.25	2.3	0.6	1.909	0.95	1.61
0.3	2.232	0.65	1.863	0.99	1.579
0.35	2.17	0.7	1.818		

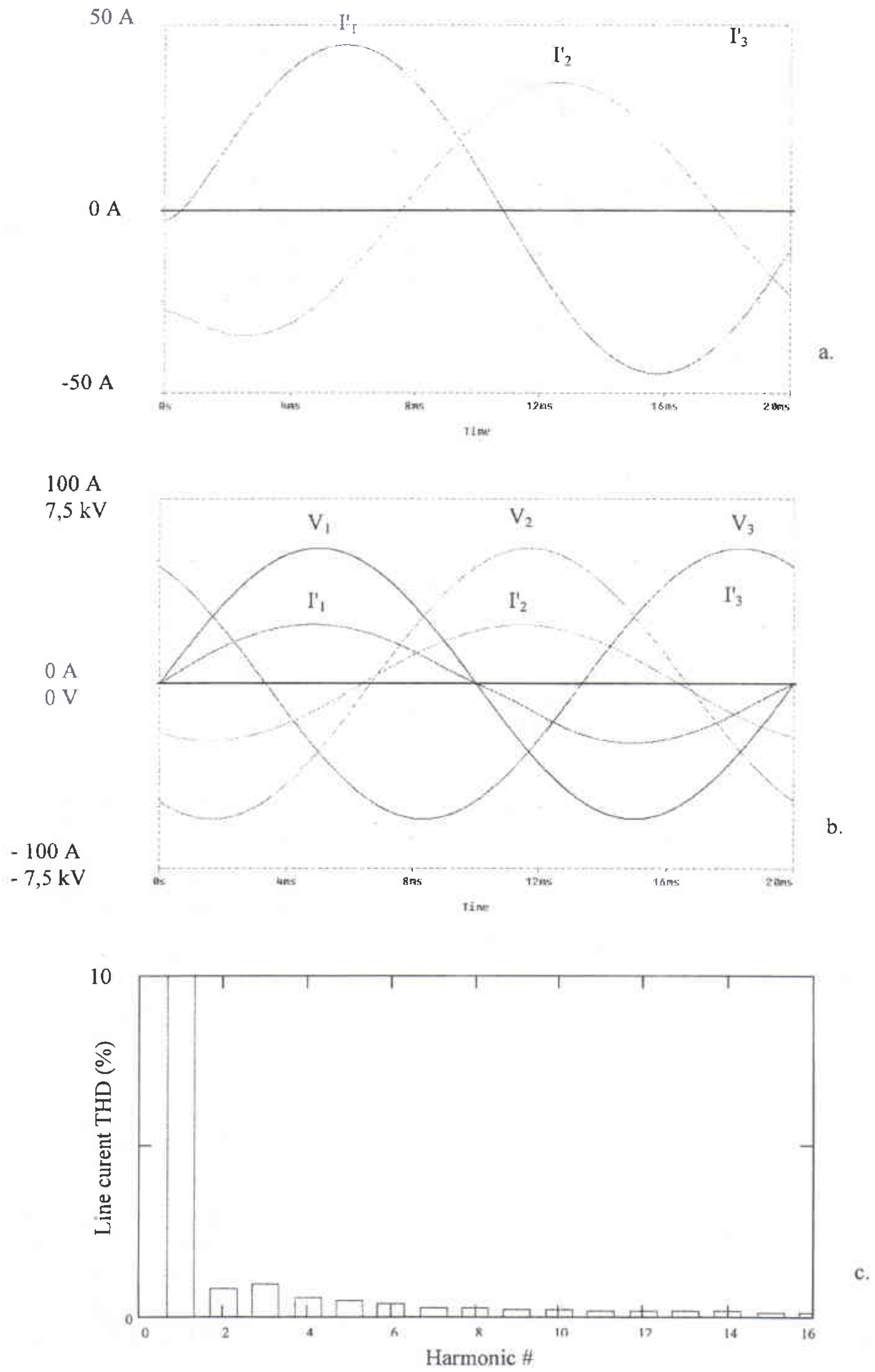

Fig. 2. Simulated results of the proposed compensation system: a) line currents before compensation; b) line currents and voltages after compensation, c) harmonic analysis of line current after compensation.

IV. SIMULATIONS

In order to evaluate the effect of introducing the compensation system, some simulations were performed. The software used was PSpice. The computation results are illustrated in Table 2 and Fig. 2.

Simulation model characteristics are as following:

- load [Ω]: phase A: 25+j12,92; phase B: 45,63+j8,67; phase C: 36,17+j8,09;
- the capacitors of the Y-CCB, C=70 uF;
- the inductors of the Δ-TSI, L=30 mH;
- α and α' represent the firing angle of the thyristors located in the same branch of the Δ-TSI and $\alpha' = \alpha+\pi$ (Table 2)

The waveforms of the line currents at the load bus, without compensation, are presented in Fig. 2a. The currents system is unbalanced and the load bus power factor is low.

Using the proposed compensation system the line currents are balanced and the load bus power factor is increased. The unbalance factor of the currents system was calculated as the ratio of the negative sequence component to the positive sequence. After the compensation, the unbalance factor is improved from 12,742 to 0,698 (Table 2) and the load bus power factor to unity. The line curents and load bus voltages waveforms after the compensation are presented in Fig 2b.

Generally, systems using TSI have a substantial disadvantage: they may cause strong harmonic distortion of the supply current, consequently degrading power quality. Simulated results obtained with the proposed compensation scheme confirm the above mentioned. In order to evaluate this effect the harmonic analysis of the line currents was performed. The results (Table 2, Fig. 2c) show that harmonics are matching both CEI 1000 and IEEE 519-92 recommendations.

V. CONCLUSIONS

The paper deals with an active scheme aiming to compensate the unbalanced line currents and to assure a unity power factor at the load bus. Thyristor switched inductances and constant capacitance battery are used in order to provide a different amount of reactive power to each phase. The load bus voltages and currents are used to calculate the firing angle of the thyristors. Digital simulations with different load data were performed. The results prove that using the proposed system, the line currents are balanced and the power factor is improved to unity. Even if the operation of the TSI introduces some harmonics in the line currents, these are matching the existing recommendations and standards.

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Table 2

LOAD [Ω]		THYRISTOR'S FIRING ANGLE [RAD]		UNBALANCE FACTOR		LEVEL OF HARMONICS [%]		DISTORSION FACTOR δ [%]
		α	α'	before	after	γ_3	γ_5	
				compensation[%]				
A	25+j12.92	2.971	6.113	12.742	0.698	0.43	0.38	0.58
B	45.63+j8.67	2.548	5.69			1.25	1.24	1.7
C	36.17+j8.09	2.789	5.93			1.65	0.925	1.89