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Compensator configurations for load currents' symmetrization

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Abstract. This paper approaches aspects regarding the mitigation effects of asymmetries in 3-phase 3-wire networks. The measure consisting in connecting of load current symmetrization devices at the load coupling point is presented. A time-variation of compensators parameters is determined as a function of the time-recorded electrical values. The general sizing principle of the load current symmetrization reactive components is based on a simple equivalent model of the unbalanced 3-phase loads. By using these compensators a certain control of the power components transits is ensured in the network. The control is based on the variations laws of the compensators parameters as functions of the recorded electrical values: $[B]=[T]\cdot[M]$. The link between compensator parameters and measured values is ensured by a transformation matrix [T] for each operation conditions of the supply network. Additional conditions for improving of energy and efficiency performance of the compensator are considered: i.e. reactive power compensation. The compensator sizing algorithm was implemented into a MATLAB environment software, which generate the time-evolution of the parameters of load current symmetrization device. The input data of application takes into account time-recording of the electrical values. By using the compensator sizing software, some results were achieved for the case of a consumer connected at 20 kV busbar of a distribution substation, during 24 hours measurement session. Even the sizing of the compensators aimed some additional network operation aspects (power factor correction) correlated with the total or major load symmetrizations, the harmonics aspects of the network values were neglected.

1. Introduction

Different types of perturbations distort the power supplying of the actual loads. The loads are also responsible for unfavorable effects on the power system operation and consequently required a great number of study initiatives. Their purpose is to clarify the power related phenomenon or finding efficient methods for load symmetrization.

In case of an unbalanced operation of power network the symmetrization can be achieved either by a mono-phase loads repartition on the three phases of the network, or by using special devices, e.g. compensators for load currents symmetrization [1-3].

A wide-spread solution for symmetrization of the electrical values' in the unbalanced power systems is offered by SVC's, having an independent control of the each phase reactive powers.

The asymmetry mitigation is one of the measures applied for optimization of processes in power systems. The design of these devices aims also some other aspects regarding the quality and efficiency of delivered electricity (i.e. harmonics, power factor).

2. Load currents' symmetrization

Designing of the most efficient devices for power quality disturbances' mitigation registered already multiple alternatives, even in fact the principle is almost a common one: the power flow control on the network phases [4], [5].

This paper presents a solution for a symmetrization device used in 3-phase 3-wire distribution networks. This solution was developed based on the symmetrical components theory.

The general strategy for load currents symmetrization can be applied (Figure1) by taken into account the consumers' operational particularities.

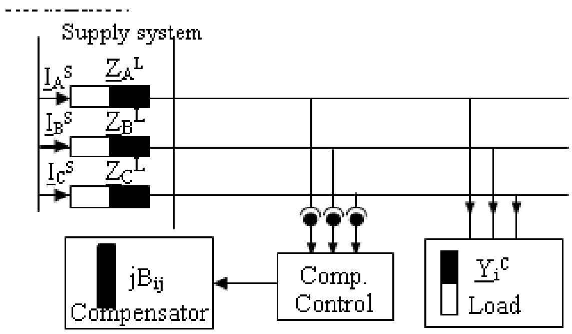


Figure 1. Supply configuration for an unbalanced load assisted by a load currents symmetrization compensator

For the load current symmetrization a SVC configuration (Δ or open-Δ) can be connected in the load common coupling point (CCP). The compensator is designed to ensure different reactive power injections on each phase, depending on the measured values.

In the case of unbalanced loads in 3-phases 3-wires networks the compensator is designed so that the negative sequence components of the load currents to be annulled. The compensator-load ensemble will appear as symmetrical in CCP.

Mathematically speaking, the symmetrization principle can be described by the following equations:

$$\Re e\left(\underline{I}_-^C + \underline{I}_-^\Delta\right) = 0; \quad \Im m\left(\underline{I}_-^C + \underline{I}_-^\Delta\right) = 0, \tag{1}$$

where, $\underline{I}^C$ is the negative component of the load current and $\underline{I}^\Delta$ - negative component current trough the compensator's branches.

Establishing of the most efficient configuration of the symmetrization equipments totally depends on the load representation model, adjusted to the network operation characteristics.

In this paper, the configuration of the symmetrization equipment is based on a simplified model of the unbalanced three-phase load.

For simplifying reasons, only the hypothesis of symmetrical voltages is considered:

$$\underline{U}_A = \underline{a}\underline{U}_B = \underline{a}^2 \underline{U}_C = U_+, \tag{2}$$

where, $\underline{U}_i$ are the supply phase voltages (i = A, B, C) and U_+ - positive component voltage.

An unbalanced load model is developed as in Figure 2 [3] and it contains an equivalent load two phases connected through and admittance $\underline{Y}_m$ given by eq. (3) and a symmetrical equivalent 3-phase load represented by three phase admittances $\underline{Y}_e$.

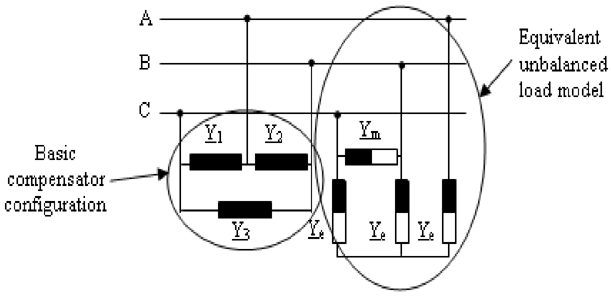


Figure 2. The equivalent electrical configuration of the unbalanced consumer – compensator ensemble

$$\underline{Y}_m = -\left(\underline{a}\underline{S}_A^* + \underline{a}^2 \underline{S}_B^* + \underline{S}_c^*\right)/U_+^2 = \\ = \frac{\left[\left(P_A - \sqrt{3}Q_A + P_B + \sqrt{3}Q_B - 2P_C\right) + j\left(-\sqrt{3}P_A - Q_A + \sqrt{3}P_B - Q_B + 2Q_C\right)\right]}{2U_+^2}, \tag{3}$$

with, $\underline{S}_i$ – complex phase powers at CCP and P_i, Q_i – active, reactive phase powers at CCP.

The symmetrization configuration can be of Δ-type, or it can be endorsed simply by connecting two reactive components. So that the displacements from a balanced load behavior can be mitigated, and an equivalent symmetrical structure can be achieved. The solution of system (1) gives the susceptances of the on-line symmetrization compensator. A representation of compensator parameters depending on time-recording of electrical values is given by eq. (4).

$$[B] = [T] \cdot [M], \tag{4}$$

where, $[B] \overset{not}{=} [B_1 \quad B_2 \quad B_3]_t$ is the column vector of the SVC's susceptances; $[M] \overset{not}{=} \left[P_A^C/\left(U_A^C\right)^2 \quad P_B^C/\left(U_B^C\right)^2 \quad P_C^C/\left(U_C^C\right)^2 \ \middle|\ Q_A^C/\left(U_A^C\right)^2 \quad Q_B^C/\left(U_B^C\right)^2 \quad Q_C^C/\left(U_C^C\right)^2\right]_t$ - the column vector of the measured electrical values in the load connection bus and *[T]* – susceptances / electrical values transformation matrix.

An adjustment of this measure for the power factor correction at load's CCP is an additional criterion supplementing the undetermined equations system (1) from mathematically point of view.

3. Load currents symmetrization without additional objective

If only a simple load currents symmetrization is aimed, the compensator configuration can be of Steinmetz type [7], [8] or contains only two reactive elements – see Figure 3. The compensator's elements, $\underline{Y}_1$ and $\underline{Y}_2$, can be placed on the branches complementary to that corresponding to the equivalent 1-phase load. Therefore, the chosen configuration will cancel the negative sequence current ($\underline{I}_- = 0$).

The phase currents at the load coupling point in the compensator presence can be written as:

$$\left[I_f\right] = \left[Y_{l-c}\right] \cdot \left[U_f\right], \tag{5}$$

where, $\left[I_f\right] \overset{not}{=} \left[\underline{I}_A \quad \underline{I}_B \quad \underline{I}_C\right]_t$ is the phase currents column vector and admittance matrix of the load – compensator ensemble is $\left[Y_{l-c}\right] \overset{def}{=} \begin{bmatrix} \underline{Y}_e + \underline{Y}_1 + \underline{Y}_2 & -\underline{Y}_2 & -\underline{Y}_1 \\ -\underline{Y}_2 & \underline{Y}_e + \underline{Y}_2 + \underline{Y}_m & -\underline{Y}_m \\ -\underline{Y}_1 & -\underline{Y}_m & \underline{Y}_e + \underline{Y}_1 + \underline{Y}_m \end{bmatrix}$.

The condition (1) for compensator sizing can be written as in eq. (6):

$$\underline{I}_- = -\left(\underline{a}\underline{Y}_1 + \underline{a}^2\underline{Y}_2 + \underline{Y}_m\right)U_+ = 0 . \tag{6}$$

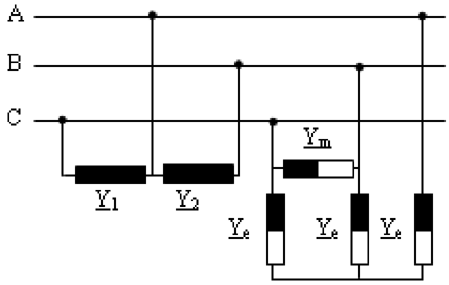


Figure 3. Compensator for load current symmetrization (no additional measures)

So that, the compensator's parameters are given by the following equations:

$$B_1 = G_m / \sqrt{3} + B_m ; B_2 = -G_m / \sqrt{3} + B_m , \tag{7}$$

with, $G_m = \Re e(\underline{Y}_m)$; $B_m = \Im m(\underline{Y}_m)$ as parameters of equivalent two-phases admitance given by (3).

The transformation susceptances/measured electrical values matrix [T] is given by:

$$[T] = \left[\begin{array}{ccc|ccc} -1/\sqrt{3} & 2/\sqrt{3} & -1/\sqrt{3} & -1 & 0 & 1 \\ -2/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} & 0 & -1 & 1 \end{array}\right], \tag{8}$$

The active power on the each phase of the load-compensator group is given by eq. (9) [6]:

$$\begin{aligned} P_A^{ce} &= U_+\left[\sqrt{3}\left(I_{1,a} + I_{2,a}\right) - I_{1,r} + I_{2,r}\right]/2 \\ P_B^{ce} &= U_+\left[-\sqrt{3}\left(I_{2,a} - 2I_{m,r}\right) - I_{2,r}\right]/2 \quad , \\ P_C^{ce} &= \frac{1}{2}U_+\left[-\sqrt{3}I_{1,a} + I_{1,r} + 2I_{m,r}\right]/2 \end{aligned} \tag{9}$$

where, P_i^{ce} are the phase active powers of the set compensator/equivalent mono-phase load and $I_{1a},$ $I_{1r},$ I_{2a}, I_{2r}, I_{ma}, I_{mr} is active and reactive currents on the branches of the ensemble compensator/equivalent mono-phase load.

In the compensator presence the consumer absorbs from the network an active power P_{tot} and behaves as a symmetrical load, since $P_A^{ce} + P_B^{ce} + P_C^{ce} = 0$. The three phase active powers are redistributed in the system, without changing their flow sense (from load to other balanced components of the network).

$$P_{tot} = P_A + P_B + P_C = 3G_e U_+^2 . \tag{10}$$

4. Mathematical modeling through Least Squares Method

In this case, a compensator configuration of Δ-type is recommended, as in Figure 2.

The bus admittance matrix of ensemble load-compensator can be written as:

$$[Y_{l-c}] = \begin{bmatrix} \underline{Y}_{AA} & -\underline{Y}_2 & -\underline{Y}_1 \\ -\underline{Y}_2 & \underline{Y}_{BB} & -\underline{Y}_3 - \underline{Y}_m \\ -\underline{Y}_1 & -\underline{Y}_3 - \underline{Y}_m & \underline{Y}_{CC} \end{bmatrix}. \tag{11}$$

with $\underline{Y}_{AA} \overset{not}{=} \underline{Y}_e + \underline{Y}_1 + \underline{Y}_2 ; \underline{Y}_{BB} \overset{not}{=} \underline{Y}_e + \underline{Y}_2 + \underline{Y}_3 + \underline{Y}_m ; \underline{Y}_{CC} \overset{not}{=} \underline{Y}_e + \underline{Y}_1 + \underline{Y}_3 + \underline{Y}_m$

The correspondent symmetrical components are given by:

$$\underline{I}_- = -\left(a\underline{Y}_1 + a^2\underline{Y}_2 + \underline{Y}_3 + \underline{Y}_m\right)\cdot U_+ ; \ \underline{I}_+ = \left(\underline{Y}_1 + \underline{Y}_2 + \underline{Y}_3 + \underline{Y}_m\right)\cdot U_+ . \tag{12}$$

The compensators' parameters result from by annulling the negative sequence current, in assisted by the reactive power compensation, as in eq. (13):

$$\left\{ \Re e\left(\underline{I}_-\right) = 0; \quad \Im m\left(\underline{I}_-\right) = 0; \quad \Im m\left(\underline{I}_+\right) = min \right. \tag{13}$$

In this case, the compensation of reactive power at the load CCP is considered, aiming a minimum power factor with a value imposed by the network operator, λ_p^{impus}. This value imposes consequently the argument of positive component current [5], resulting from a cos-function given by (14):

$$\cos \varphi^{+}_{UI,comp} = \frac{G_m}{\sqrt{G_m^2 + \left(B_1 + B_2 + B_3 + B_m\right)^2}} = \lambda_p^{impus} . \tag{14}$$

The three compensator's susceptances result as in eq. (15):

$$B_1 = \frac{2G_m}{\sqrt{3}} \cdot K_2 ; \ B_2 = \frac{2G_m}{3} K_1 ; \ B_3 = \frac{G_m}{3} \cdot K_1 - B_m , \tag{15}$$

with $K_1 \overset{not}{=} \sqrt{1/\left(\lambda_p^{impus}\right)^2 - 1}; \quad K_2 \overset{not}{=} 1 + K_1/\sqrt{3}$.

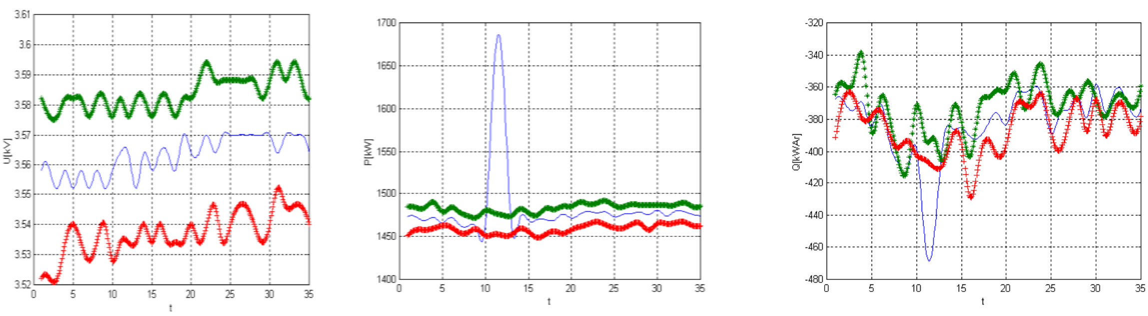
The transformation susceptances/measured electrical values matrix [T] is:

$$[T] = \left[\begin{array}{ccc|ccc} K_2/\sqrt{3} & K_2/\sqrt{3} & -2K_2/\sqrt{3} & -K_2 & K_2 & 0 \\ K_1/3 & K_1/3 & -2K_1/3 & -K_1/\sqrt{3} & K_1/\sqrt{3} & 0 \\ \sqrt{3}+K_1/6 & -\sqrt{3}+K_1/6 & -K_1/3 & 1-K_1/2\sqrt{3} & 1+K_1/2\sqrt{3} & -2 \end{array} \right] \tag{15}$$

5. The model simulation results

For each of the previous cases a set of MATLAB developed algorithms was achieved. These algorithms allow to draw the the time-evolution of the parameters of load current symmetrization devices. The application takes into account time-recording of the electrical values.

The algorithms were applied for the case of a consumer connected at 20 kV busbar of a distribution substation, for a 24 hours measurement session (Figure 4. a...c).



a. b. c.

Figure 4. Time variation of the state values and compensator elements (U_A – reference): a. voltages variation; b, c – active/reactive powers variation

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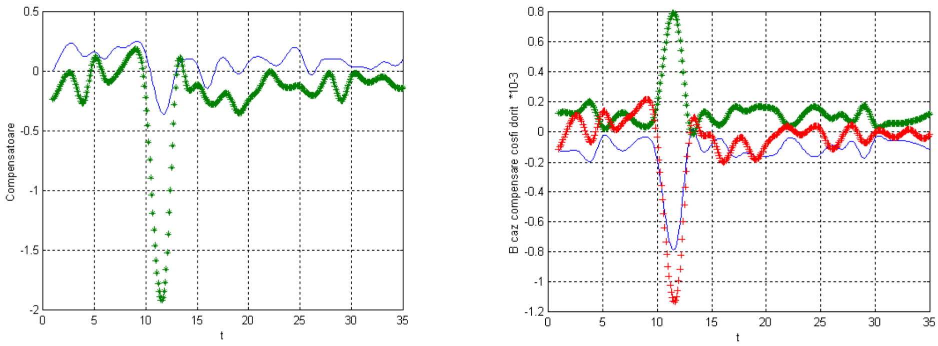
The curves represented by these algorithms can supply the on-line control strategy of the compensators' parameters for any dynamic load with an estimated evolution. The results of proposed cases simulations were concluded in Table 1.

Table 1. The results of symmetrization compensators behavior

Interest values	Case &3 (Figure 5)	Case &4 (Figure 6)
I_+^C (A)	0.074...133.328 (initial values)	
I_-^C (A)	0.058...4.452 (initial values)	
Suscept. Δ□[mS]:		
B_{AB}^{Δ}	-0.420...0.270	-0.790... 0.015
B_{BC}^{Δ}	-1.850..0..240	-1.170…0.250
B_{CA}^{Δ}	-	-0.080…0.800

As it can be observed, the variation of the state values in the load coupling point results in a variation of the compensator's parameters in the inductive field, as well as in the capacitive one (Figure 5).



a. b.

Figure 5. Time variation of the symmetrization compensator elements : a. case &3; b – reactive power compensation within an imposed PF (case &4)

Each additional condition refering to the performances of the consumer-compensator set can lead to a majoring of the variation limits for the compensator parameters.

6. Conclusions

The paper proposes some configurations of devices used for load currents symmetrization in 3-phases 3-wires networks, and additional for improving of some energy and efficiency aspects.

The general sizing principle is based on a simple equivalent model of the unbalanced 3-phase loads. By using these compensators a certain control of the power flow is ensured in the load CCP. The control is based on the variations laws of the compensators parameters as functions of the measured electrical values. The link is ensured by a transformation matrix *[T]*, with different representation for each considered case.

The sizing of the compensators aimed also some additional energetical aspects (power factor correction) correlated with the total or major load symmetrization, the harmonics aspects of the state values being neglected. The structure of these compensators determines in most of the cases important current or voltage distortions. This disadvantage can be overcome by choosing the compensator configuration based on a correlated sizing, more precisely by considering simultaneous the influence of asymmetries and harmonics [8], [9].

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