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ABOUT THE EFFICIENCY OF THE REACTIVE POWER COMPENSATION IN NETWORKS THAT OPERATE IN NONSYMMETRICAL STATES

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Abstract - **In a ramified three phase network exist, in general, many kinds of consumers. In the paper it is considered that they can be replaced through two equivalent impedances disposed in parallel, a symmetrical one and a nonsymmetrical one, having a certain low of variation of the loads on the three phases. Regarding the nonsymmetrical receiver, the symmetrical one can have a much less, comparable or greater apparent power. Considering that on the bars of one of the two equivalent receivers there is a capacitors bank connected to improve the power factor, the reactive load can be thus modified in steps. In the hypothesis that the energy is supplied from bars where the voltage is symmetrical through a symmetrical line, it is studied the active and reactive powers' flow on symmetrical components between the elements of the circuit, in different energetic situations, how the active and reactive charges can influence the flow of the active and reactive powers on symmetrical components and where, from an economically point of view, it is better to install the capacitors banks, on the bars of the symmetrical receiver, or on the bars of the other one.**

Keywords – *unbalanced state, nonsymmetrical state, symmetrical components*

1. INTRODUCTION

The operating steady state of an electric network is nonsinusoidal and nonsymmetrical. The cause of the apparition of the nonsinusoidal state is represented by the presence of the nonlinear or parametric elements of circuit in the network. In the hypothesis, generally fulfilled, that the source of voltage or current is symmetrical, the cause of the appearance of the nonsymmetrical state is represented by the impossibility to balance, for a long period of time, the three phases.

Against the manifestation of the nonsinusoidal state, can be taken different measures, more or less efficient, especially, because of its manifestation: the nonlinear or parametric charges are variable in time, their connection points in the network are diverse, a.s.o. Anyhow, in many situations, the operation state closes enough to a sinusoidal one.

Referring to the electrical energy, the aim of the supplier is to provide to the consumer a sinusoidal voltage, symmetrical on the three phases, of values and frequencies maintained between contractually defined limits. Through the term of quality of the electric energy, usually, it is understand the quality of the production, transformation, transmission, distribution and utilization process of electromagnetic energy in the electromagnetic power systems. From the quantitative point of view, the quality of the electrical energy may be watched after some parameters that express the nonsymmetrical powers, the global power factor, the coefficients of nonsymmetry for voltages and currents, a.s.o. The analysis of the parameters or indicators of the quality of the electrical energy, as an obligation of the supplier, must be performed in close connection with the perturbations that might be introduced in the distribution network by the consumers during their operation.

There are many causes, temporary or permanent, that can determine the appearance of the nonsymmetrical (unbalanced) state. In the assembly generator, line, receiver, the main cause of the appearance of a nonsymmetrical state is the nonsymmetry of the receiver that has different impedances on phases.

2. THE PRESENTATION OF THE NETWORK AND OF THE METHODS OF ANALYSIS

It is considered an equivalent three phase ramified network in which:

- the generator (subscript *g*) is of infinite power and at its bars the voltage is symmetrical;
- the distribution line (subscript *l*) is symmetrical, of impedance $\underline{Z}_l = R_l + jX_l$ and carry the energy to two equivalent receivers connected in parallel, both star connected with neutral (subscript *N*) grounded through a null impedance;
- one receiver is symmetrical (subscript *s*) of impedance $\underline{Z}_s = R_s + jX_s$;
- the other receiver (subscript *n*) is nonsymmetrical of impedances on the three $\underline{Z}_1 = \alpha(R + jX) = \alpha\underline{Z}$, $\underline{Z}_2 = \alpha^{-1}\underline{Z}$, $\underline{Z}_3 = |\alpha - 2|^{-1}\underline{Z}$. The nonsymmetry is marked by the coefficient of nonsymmetry of the receiver $\alpha \in (0, \infty)$. Giving different values for α, the impedances on the three phases vary and thus the charges, too. For example, $\alpha = 1$, $\underline{Z}_1 = \underline{Z}_2 = \underline{Z}_3$ and the receiver is symmetrical. The charges on the phases influence with those on the other phases, when it is high on one, on the others is low. For certain values for α, can be modeled the faulty conditions of running, such as the short circuit on one phase with the interruption of an other ($\alpha = 0$), the interruption of a phase, the others remaining in operation, or the interruption of one phase because on the other two a

short circuit appeared ($\alpha \to \infty$). The signals from the network (voltages and currents), which are nonsymmetrical, can be decomposed into symmetrical components given by Fortesque's theorem, of positive (superscript +), negative (superscript -) and zero (superscript 0) sequences. With their help can be determined the active and reactive powers on different sequences at every element of circuit.

3. THE POWERS' FLOW BETWEEN DIFFERENT ELEMENTS OF CIRCUIT

The only source of active power on positive sequence is the generator. If all the reactive elements of circuit are inductive, the generator is the only source of reactive power on positive sequence, too. Being symmetrical, the generator doesn't supply the network with powers on negative and zero sequences:

$$P_g^+ > 0, P_g^- = 0, P_g^0 = 0, Q_g^+ > 0, Q_g^- = 0, Q_g^0 = 0. \qquad (1)$$

The neutrals being grounded, the zero sequence current has a path to flow and in the network flow powers of zero sequences.

The only source of active and reactive powers on negative and zero sequences is the nonsymmetrical receiver. It receives the powers on positive sequence, uses only a part of them and transforms the rest into powers of negative and zero sequences, which flow in the network.

$$P_n^+ > 0, P_n^- < 0, P_n^0 < 0, Q_n^+ > 0, Q_n^- < 0, Q_n^0 < 0. \qquad (2)$$

The symmetrical line receives the powers, on positive sequence from the generator and on negative and zero sequences from the nonsymmetrical receiver.

$$P_l^+ > 0, P_l^- > 0, P_l^0 > 0, Q_l^+ > 0, Q_l^- > 0, Q_l^0 > 0. \qquad (3)$$

The symmetrical receiver acts as the line.

$$P_s^+ > 0, P_s^- > 0, P_s^0 > 0, Q_s^+ > 0, Q_s^- > 0, Q_s^0 > 0. \qquad (4)$$

In the neutral flows only the zero sequence current. The impedance being null, the powers on zero sequence are null, too. Because there is no current on positive and negative sequences in the neutral, the corresponding powers are null, also.

$$P_N^+ = 0, P_N^- = 0, P_N^0 = 0, Q_N^+ = 0, Q_N^- = 0, Q_N^0 = 0. \qquad (5)$$

At every element of circuit can be found the following active powers, the reactive powers being the same:

$$\begin{aligned} P_g &= P_g^+ \\ P_l &= P_l^+ + P_l^- + P_l^0 > P_l^+ \\ P_s &= P_s^+ + P_s^- + P_s^0 > P_s^+ \\ P_n &= P_n^+ + P_n^- + P_n^0 < P_n^+ \end{aligned} \qquad (6)$$

The balances of active powers can be written as in expression (7), for the reactive powers being identically:

$$\begin{aligned} P_g^+ &= P_l^+ + P_n^+ + P_s^+ \\ 0 &= P_l^- + P_n^- + P_s^- \\ 0 &= P_l^0 + P_n^0 + P_s^0 \end{aligned} \qquad (7)$$

4. THE POWER FACTOR IN NONSYMMETRICAL STATES

The power factor represents a quantity that appreciates the efficiency with which an equipment, installation, a.s.o., generic named as receiver, is able to use the electric energy. Any symmetric three phase receiver running in symmetrical states has a power factor given by its resistance and reactance:

$$PF = \frac{R_s}{\sqrt{R_s^2 + X_s^2}} \qquad (8)$$

For a symmetric three phase receiver that operates in nonsymmetrical states, the global power factor, K_P, calculated with the help of the powers on symmetrical components, is:

$$K_{P(s)} = \frac{P_s^+}{\sqrt{(P_s^+ + P_s^- + P_s^0)^2 + (Q_s^+ + Q_s^- + Q_s^0)^2}} \qquad (9)$$

The only utile power is P_s^+, Q_s^+ being demanded for the proper operation of the receiver. The symmetric receiver is "obliged to support" the other powers that are injected by the nonsymmetrical receiver, with whom it is connected in the same network.

For a nonsymmetrical three phase receiver that operates in nonsymmetrical states, the global power factor, K_P, calculated with the help of the powers on symmetrical components, is:

$$K_{P(n)} = \frac{P_n^+ + P_n^- + P_n^0}{\sqrt{\left(P_n^+\right)^2 + \left(Q_n^+\right)^2}} \qquad (10)$$

The nonsymmetrical receiver is not able to use the whole received P_n^+ because it transforms a part of it in "damageable powers" P_n^- and P_n^0, utile remaining only $P_n^+ + P_n^- + P_n^0$.

In Fig. 1 is presented the variation of the global power factors of the two receivers versus the coefficient of nonsymmetry, α. For the taken example, it was realized a good compensation of the reactive charge and so, for the symmetrical state, obtained for $\alpha = 1$, the global power factor is 0.95.

$$K_{p(n)}\Big|_{\alpha=1} = PF = \frac{R_n}{\sqrt{R_n^2 + X_n^2}} = 0.95 \qquad (11)$$

In this example, for the symmetrical state, the symmetric receiver has a power factor, $PF = 0.7$. During operation in the nonsymmetrical states, $K_{p(s)}$ is not very much influenced by the coefficient α and takes almost a constant value, with the exception of the faulty condition $\alpha = 0$, when it takes a very low value.

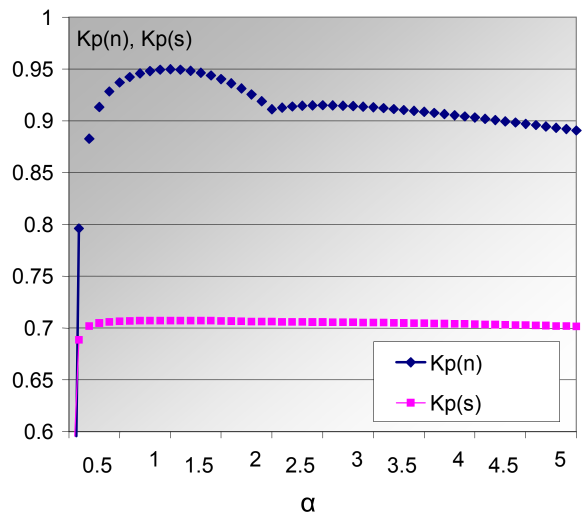

Fig.1.- The variation of the global power factors of a symmetrical and of a nonsymmetrical receiver that run in nonsymmetrical steady states **vs** the coefficient of nonsymmetry of the receiver

With regard at $K_{p(n)}$, the faulty situations are observed: $\alpha = 0 \Rightarrow K_{P(n)} \to 0, \alpha \to \infty \Rightarrow K_{P(n)} \to 0$. If $\alpha = 2$, $K_{p(n)}$ takes a pretty high value because in this situation remain two phases in operation. Being realized a good compensation, for a large interval of variation for α, $K_{p(n)}$ takes values higher than 95% of PF. Speaking from this point of view the unbalance is light.

5. WHERE TO COMPENSATE, TO BE MORE ECONOMICALLY EFFICIENT

It is known that the most efficacious method to improve the efficiency of a receiver is to locally compensate the reactive power. In this way, the economic agent doesn't buy from the supplier the necessary reactive power, or at least buys less. In the case that the same economic agent has in exploitation a network as this described above and has at his disposal to install only one unit of capacitors bank, where is it more profitable for him to connect it, at the bars of the nonsymmetrical receiver, or at the bars of the other one? Of course, we consider here that, installing the capacitors bank, there are no other technical or economic criteria in discuss beside the energetic economic efficiency, criterion that will be defined in what follows.

The economic agent buys at a *p* price the unit of active power and at a *q* price of reactive power. He buys energy to obtain a merchandise which is sold after that and which brings an amount of money to him. In this way, it can be quantified the price at which the agent sells an unit of active power. Let it be *m* for the nonsymmetrical receiver and *m'* for the other one. In this way the agent pays $pP_n^+ + qQ_n^+$ for the nonsymmetrical receiver and $pP_s + qQ_s = p\left(P_s^+ + P_s^- + P_s^0\right) + q\left(Q_s^+ + Q_s^- + Q_s^0\right)$ for the symmetrical one. He obtains $mP_n = m\left(P_n^+ + P_n^- + P_n^0\right)$ and $m' P_s^+$. Of course, here can be a lot of discussions about the values that the quantities *p, q, m, m'* might have, but, as point of view, the situation doesn't change. The division of what he obtains and what he pays is a quantity named energetic economic efficiency, noted E_f and, in our case is the objective function to be optimized:

$$E_f = \frac{m\left(P_n^+ + P_n^- + P_n^0\right) + m' P_s^+}{pP_n^+ + qQ_n^+ + p\left(P_s^+ + P_s^- + P_s^0\right) + q\left(Q_s^+ + Q_s^- + Q_s^0\right)}$$

There were taken into consideration three possible situations:

- A: the apparent power of the symmetrical receiver is much less than of the nonsymmetrical one;
- B: the two apparent power are comparable;
- C: the apparent power of the symmetrical receiver is greater than of the nonsymmetrical one.

The case in which the network operates without any compensation is considered as the reference one (case 0). In the case 1, the entire capacitive power is installed at the bars of the symmetrical receiver and in the case 2 it is installed at the bars of the nonsymmetrical one. In any of the two cases, the installation of the capacitive power modifies the currents, the powers flow, the global powers factors at both receivers and the energetic economic efficiency. There were studied every of the three situations, A, B, C in all the cases 0,1,2, observing the variations of E_f versus the coefficient of nonsymmetry, α, giving many values for *m, m'*, *p* and *q*. For example, in Fig. 2 is shown this evolution in situation C, for the case 2.

There can be observed that the aspects of the global power factor for the nonsymmetrical receiver and of the energetic economic efficiency versus the coefficient of nonsymmetry is very much the same in these two figures. It is normal to be so, as both quantities reflect the same thing, efficiency, the first one being for a receiver and the second one, for the whole network

For this example, the place where it is recommended to install the capacitors bank is at the bars of the nonsymmetrical receiver because the effects are more benefic, the values of E_f being higher for this situation.

In every situation there were marked the values of the global power factors for the symmetrical state, $K_{p(n)}\Big|_{\alpha=1}$, $K_{p(s)}\Big|_{\alpha=1}$, observing what values they take before and after the installation of the capacitors bank.

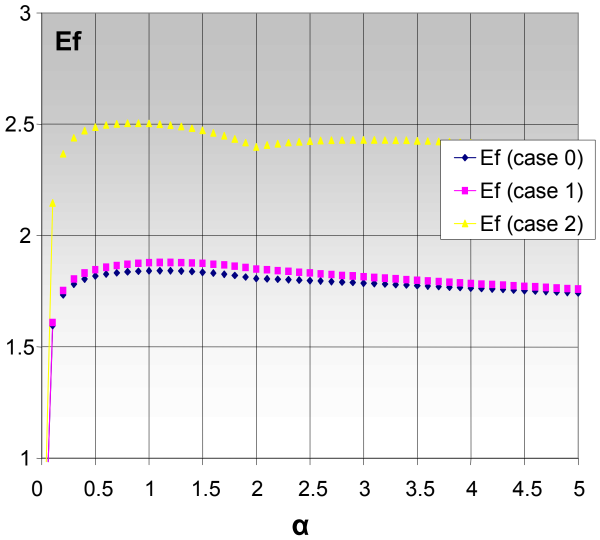

Fig.2. – The variation of the energetic economic efficiency, for different places of installation of the capacitive power **vs** the coefficient of nonsymmetry

From every situation was selected the best results for every case. Synthetic, the obtained results are given in Table 1.

Sit.	Case	$K_{p(n)}\big\vert_{\alpha=1}$	$K_{p(s)}\big\vert_{\alpha=1}$	Best results for:
A	0	0.6	0.7	
	1	0.6	0.8	$K_{p(s)}\big\vert_{\alpha=1}$ $0.7 \rightarrow 0.8$
	2	0.61	0.7	
B	0	0.6	0.7	
	1	0.6	0.8	$K_{p(s)}\big\vert_{\alpha=1}$ $0.7 \rightarrow 0.8$
	2	0.67	0.7	
	0	0.6	0.7	
C	1	0.6	0.78	
	2	0.95	0.7	$K_{p(n)}\big\vert_{\alpha=1}$ $0.6 \rightarrow 0.95$

Table 1. Best results obtained in every situation

If, in the situation described by the Fig. 2, the best results were obtained for situation C, case 2, in the other situations, A and B, there were obtained the best results for the case 1, so, the recommendation is to install the capacitors bank at the bars of the symmetrical receiver.

6. CONCLUSIONS

- The quantity named energetic economic efficiency can be utile in the appreciation of the efficiency of a network that operates in nonsymmetrical states. It is defined as the division between what the economic agent obtains by selling its merchandise (and thus, conventionally, of a part of the utile power supplied to him) and what he pays for the powers that are delivered to him.

- In ramified networks that supply energy both to the symmetrical and nonsymmetrical receivers and which operates in nonsymmetrical states, having as unique criterion of appreciation the energetic economic efficiency, the installation of the capacitors bank is better to be done at those bars where, through this action, is achieved the highest power factor, for any of the receivers, in the symmetrical state.

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