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# Fuzzy Control of Reactive Elements in Steinmetz Symmetrizing Circuitry

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**Abstract**. Load compensation at the load bus is an effective method to eliminate the undesired effects of power systems unbalance (excessive heating of electrical machines, saturation of transformers, ripple in rectifiers, protection and interference problems etc) produced by high power single-phase receivers. The Steinmetz circuitry, consisting of a reactor, a capacitor (both with appropriate but fixed values) and the receiver, suitable connected with each other's is widely used for this purpose.

Unfortunately, as usually the load characteristics fluctuate, the parameters of the supplementary reactive elements should also vary. The paper introduces a novel solution, namely the implementation of controlled reactive elements in order to compensate the load variation. For this purpose, taking into account the load characteristics, a fuzzy controller is proposed; the efficiency of the suggested circuitry, expressed by the values of the unbalance factor, as well as its influence on power quality are analyzed.

**Key words:** Steinmetz circuitry, variable reactive elements, fuzzy controller, power quality

## 1. INTRODUCTION

The industrial electrical networks normally contain high power single-phase receivers as mains frequency induction or resistance furnaces, welding transformers etc. If the load is unbalanced, the distribution line currents are also unbalanced and may cause additional losses and damages to power system: excessive heating of electrical machines, saturation of transformers, ripple in rectifiers, supplementary losses in neutral lines and protection problems etc. The unbalance of the line currents also causes unequal voltage drops on the distribution lines so that load bus voltages are unbalanced; the supply voltage asymmetry mainly affects the performance of three-phase rotating motors and increases the harmonic distortion produced by high-power electronic loads.

The issue of developing technical countermeasures for power system imbalance becomes particularly urgent with installation of single-phase high power electrothermal receivers. Load compensation at the load bus is an effective method to eliminate the line current unbalance; one of the mostly spread solution for this purpose is represented by the Steinmetz circuitry - Figure 1: the load (having the equivalent impedance $\underline{Z}_0$) is $\Delta$ - connected with the reactive symmetrizing elements $L_s$ and $C_s$. In order to annul the line current unbalance factor $k_I^-$, the reactance of the supplementary reactive components should be selected according to the following relationships [1,2]:

$$X_{Ls} = \frac{\sqrt{3}(R_0^2 + X_0^2)}{R_0 + \sqrt{3}X_0}, \qquad (1)$$

for reactor, and

$$X_{Cs} = \frac{\sqrt{3}(R_0^2 + X_0^2)}{R_0 - \sqrt{3}X_0} \qquad (2)$$

for capacitor, respectively.

It can be seen that there is a severe correlation between the reactive elements value and the load parameters: if the latter change during the technological process, the former should also vary, otherwise the power system balance is no more accomplished. The paper proposes the implementation of fuzzy controlled reactive elements (continuously variable for the inductance and step by step variable for the capacitance) in order to fulfill the abovementioned conditions.

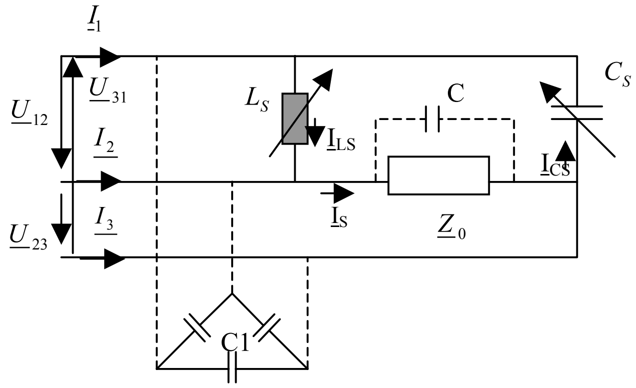


Fig. 1. Basic Steinmetz circuitry

## 2. LOAD VARIATION

Due to the varying temperature of the heated products, the resistance and the power factor of electrothermal loads can be expressed as functions of initial values:

$$R_0^* = er_0 \cdot R_0, \qquad (3)$$

respectively

$$\lambda^* = er_\lambda \cdot \lambda \qquad (4)$$

($er_R$ and $er_\lambda$ are error coefficients taking into account the technological variation of load characteristics).

If we consider that load parameters have got new values, while the symmetrizing elements calculated according to (1) and (2) remain unmodified, the unbalance factor can be expressed as [3,4]:

$$k_I^- = \sqrt{\frac{\left(\frac{3}{2}\cdot\frac{1}{\omega\cdot L_S}+\frac{3}{2}\cdot\omega\cdot C_S-\sqrt{3}\cdot\frac{\lambda^2}{er_0R_0}\right)^2+\left(-\frac{\sqrt{3}}{2}\cdot\frac{1}{\omega\cdot L_S}+\frac{\sqrt{3}}{2}\cdot\omega\cdot C_S+\sqrt{3}\cdot\frac{\lambda^2}{er_0R_0}\cdot\sqrt{\frac{1}{\lambda^2}-1}\right)^2}{\left(\sqrt{3}\cdot\frac{\lambda^2}{er_0R_0}\right)^2+\left(-\sqrt{3}\cdot\frac{1}{\omega\cdot L_S}+\sqrt{3}\cdot\omega\cdot C_S-\sqrt{3}\cdot\frac{\lambda^2}{er_0R_0}\cdot\sqrt{\frac{1}{\lambda^2}-1}\right)^2}} \qquad (5)$$

The values of the line current unbalance factor for a given single-phase variable load supplied by a Steinmetz circuitry with fixed reactive elements are presented in Figure 2; the picture highlights quite large deviation from the ideal behavior.

## 3. THYRISTOR-CONTROLLED REACTIVE ELEMENTS

As any deviation of load parameters will bring out the system unbalance, the load variation has to be considered in the design of Steinmetz symmetrizing circuitry.

The obvious solution of this problem consists in using variable reactive elements. Unfortunately, the typical reactors and capacitors have fixed values; however, the development of power electronics in the past years has assured the introduction of thyristor-controlled reactive elements.

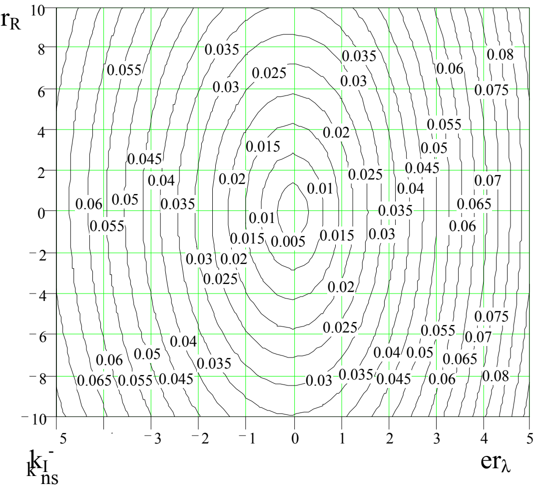
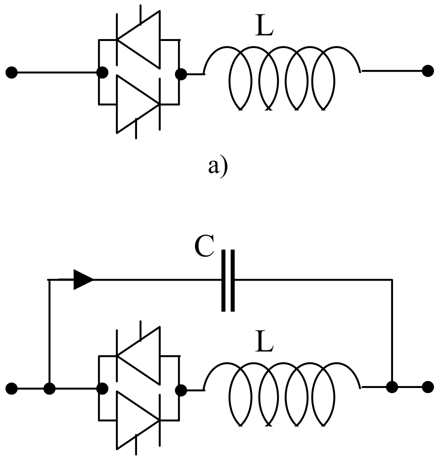


Fig. 2. Line current unbalance factor for a variable single-phase load supplied by a Steinmetz circuitry

The thyristor- controlled reactive elements or thyristor - controlled susceptances have the basic structures presented in Figure 3 and can be implemented either as thyristor - switched inductor (TSI) or as thyristor - switched capacitor (TSC). However, it is very difficult to implement the TSC structure so that the authors have preferred to use a classical step-by-step variable capacitor.



a)

b)

Fig. 3. Structure of thyristor - controlled reactive elements: a) TSI; b) TSC

The variable reactance of the TSI can be calculated according to the relationship [5]:

$$X_L = \frac{X_{L\max}}{\sqrt{\frac{4}{\pi}\cdot\left[(\pi-\alpha)\cdot\left(\cos^2\alpha+\frac{1}{2}\right)+\frac{3}{4}\cdot\sin(2\alpha)\right]}} \tag{6}$$

where $\alpha$ is the thyristor's firing angle.

## 4. FUZZY CONTROLLER FOR STEINMETZ CIRCUITRY

It was shown before that for a Steinmetz circuitry, the value of the unbalance factor depends on load variation and the use of controlled reactive elements was suggested. However, for a given value of the unbalance factor, it is very difficult to establish the real reason of the deviation from the ideal run. Taking into account both the complexity of this problem and the important part played in this field by the experience of the running people, the use of a fuzzy controller was studied.

Figure 4 presents the proposed configuration of the Steinmetz circuit: it contains a Thyristor Controlled Reactor *L* and a 17 steps variable capacitor bank. A fuzzy controller is used to calculate the appropriate values of both thyristor's firing angles and the capacitor step.

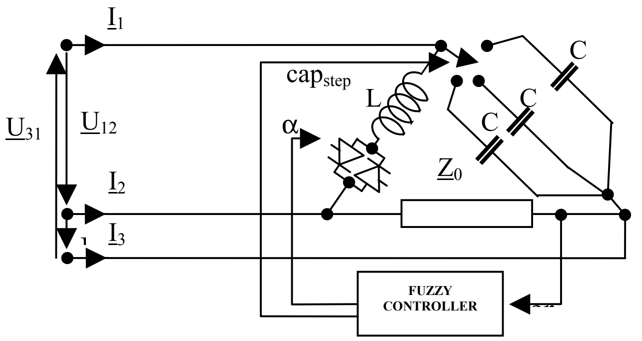


Fig 4. Steinmetz symetrizing circuitry using fuzzyy logic controller

The internal structure of the proposed fuzzy controller is presented in Figure 5 and contains the following four basic components [6, 7,8]:

- Fuzzification unit that converts the crisp input variables into fuzzy ones so that they are compatible with the fuzzy set representation of the process state required by the inference unit.
- Knowledge base consisting on two parts: a rule base that describes the control actions and a database that contains the definition of the fuzzy sets representing the linguistic terms used in the rules.
- Inference unit generates fuzzy control actions applying the rules in the knowledge base to the current process state.
- Defuzzification unit converts the fuzzy control action generated by the inference unit into a crisp value that can be used to drive the actuators.

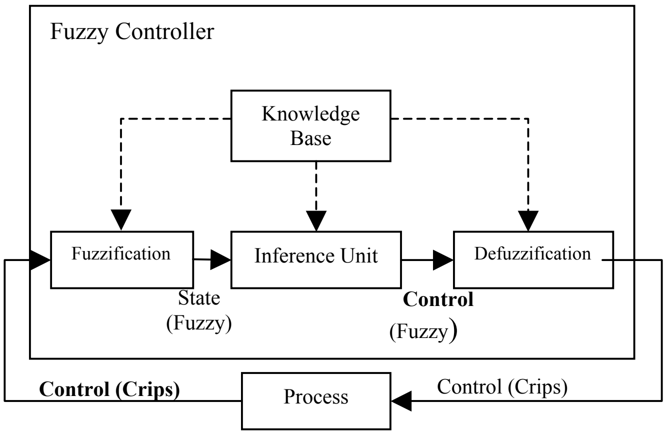


Fig. 5. Basic structure of fuzzy logic controller

## 5. SIMULATED RESULTS

In order to prove the correctness of the proposed system some simulations have been performed. A Steimnetz symmetrizing circuit containing a TSI and a variable capacitor has been considered and the fuzzy controller has been tested for several sets of values corresponding to $er_R$ and $er_\lambda$. The results are illustrated in Table 1 and compared with the basic Steimetz circuitry (as the proposed solution causes the line current distortion, the total harmonic distortion coefficient THD was also calculated).

For all studied cases, the performances of the proposed solution (expressed by $k_I$ *FUZZY*) are much better than those of the basic circuitry (expressed by $k_I$ CLASSIC) and the dissymmetry coefficients fit the values provided by the Romanian dissymmetry standard PE 143/94 [9].

Table 1.

| Case | $er_\lambda$ [%] | $\lambda_0$ | $er_R$ [%] | $R_0$ [Ω] | $k_I^-$ [%] CLASSIC | $C_{sim}$ [µF] | $\alpha_{FUZZY}$ [rad] | $k_I^-$ [%] FUZZY | $THD_I$ [%] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $I_1$ | $I_2$ | $I_3$ |
| 1. | -4 | 0.86 | -6 | 0.164 | 6.58 | -5 | 1,643 | 0,423 | 5.16 | 4.92 | 0.72 |
| 2. | -4 | 0.87 | 0 | 0.175 | 5.58 | -5 | 1,694 | 0,675 | 8.43 | 8.13 | 0.17 |
| 3. | -2 | 0.89 | -4 | 0.168 | 3.17 | -2 | 1,66 | 0,694 | 6.3 | 6.1 | 0.6 |
| 4. | -2 | 0.89 | 0 | 0.175 | 2.9 | -2 | 1,694 | 0,801 | 8.6 | 8.35 | 0.55 |
| 5. | 0 | 0.906 | -4 | 0.168 | 2.35 | 1 | 1,66 | 0,885 | 6.4 | 6.3 | 0.5 |
| 6. | 0 | 0.906 | -2 | 0.171 | 1.17 | 1 | 1,677 | 0,864 | 7.6 | 7.38 | 0.6 |
| 7. | 2 | 0.924 | -6 | 0.164 | 4.86 | 3 | 1,643 | 1,214 | 5.4 | 5.34 | 0.7 |
| 8. | 2 | 0.924 | -4 | 0.168 | 4.02 | 3 | 1,66 | 1,038 | 6.5 | 6.4 | 0.5 |
| 9. | 2 | 0.924 | -2 | 0.171 | 3.42 | 3 | 1,677 | 0,832 | 7.6 | 7.4 | 0.23 |
| 10. | 4 | 0.942 | -6 | 0.164 | 7.85 | 7 | 1,66 | 1,196 | 6.5 | 6.45 | 0.3 |
| 11. | 4 | 0.942 | -4 | 0.168 | 7.31 | 7 | 1,677 | 0,962 | 7.8 | 7.7 | 0.2 |

## 6. CONCLUSIONS

Due to presence of high-power single-phase loads, electrical networks are normally unbalanced and their degree of imbalance depends on the networks composition and load operation. The supplementary negative and zero sequence currents and/or voltages that appear in unbalanced systems may cause additional losses and damages to electrical networks.

Load compensation at the load bus is an effective method to mitigate or even eliminate those undesired sequence components; systems consisting of reactors, capacitors and receivers, suitably connected with each other, make it possible to load the network with symmetrical currents. Unfortunately, the efficiency of this solution depends on very precisely defined relationships between the load and the supplementary reactive elements; as any deviation of load parameters will produce the power system imbalance, the load variation has to be considered in the design of Steinmetz symmetrizing circuitry. The obvious solution of this problem consists in using variable reactive elements.

The paper proposes a Steinmetz circuitry consisting of a thyristor-controlled reactor and a variable capacitor bank; a fuzzy controller is used to calculate the appropriate values of both thyristors' firing angles and capacitor step. The input variables of the control systems are the deviation of load parameters (resistance and power factor) expressed by two error coefficients ($er_R$ and $er_\lambda$); the output of the fuzzy logic controller are the reactor and capacitor values that assure the power system balance (in an imposed range).

The simulation has proved the correctness of the proposed solution; however, its practical implementation can arise new problems regarding power quality as the presence of controlled power electronic devices distorts the line current waves.

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