Additional Discussion to "Reactive Power Under Non-Sinusoidal Conditions"

Discussion

Leszek S. Czarnecki (Gliwice, Poland): The definition of the "capacitive reactive power" Q_c in nonsinusoidal systems, presented in the Kusters-Moore paper [1] is based on the properties of a nonsinusoidal system with a voltage source model which is too simplified, i.e., with the zero source impedance. For the inductive source impedance, and for the source and the load impedance of the relative levels which occur in power systems, the quantity Q_c may not be the maximal reactive power reducible by a capacitor, and the analyzer described in the paper [1] may not enable us to measure it.

1. Introduction

In their paper [1] N. L. Kusters and W. J. M. Moore bring new decompositions of the apparent power S in nonsinusoidal systems. One of them is

$$S^2 = P^2 + Q_c{}^2 + Q_{cr}{}^2 \tag{1}$$

where P is the active power, Q_c is the "capacitive reactive power, defined as follows

and

$$Q_c \triangleq (U/\dot{U})\,(1/T)\int_0^T i\dot{u}\,dt \tag{2}$$

$$Q_{cr} \triangleq \sqrt{S^2 - P^2 - Q_c{}^2} \tag{3}$$

In formula (2) i denotes the load current, $\dot{u}$ denotes the derivative of the load voltage, U and $\dot{U}$ are the r.m.s. values of u and $\dot{u}$, respectively. Simultaneously, the load current is decomposed into three orthogonal components

$$i = i_p + i_{qc} + i_{qcr} \tag{4}$$

such that

$$i_p \triangleq (P/U^2)u,\ i_{qc} \triangleq [(1/T)\int_0^T i\dot{u}\,dt/\dot{U}^2]\dot{u},$$
$$i_{qcr} \triangleq i - i_p - i_{qc}. \tag{5}$$

Since the authors claim, that if $Q_c<0$, then, the power Q_c is the maximal value of the reactive power which may be wholly compensated by a shunt capacitor, therefore, they propose an instrument for the Q_c power measurement. If the values of U and $\dot{U}$ are known, it enables the compensating capacitance C to be calculated, i.e.,

$$C = -Q_c/U\dot{U} \tag{6}$$

which results in the maximal value of the source power-factor. Unfortunately, the assertion that the quantity Q_c is the maximal value of the reactive power, reducible by a shunt capacitor, is not generally true. In the paper [1], the authors do not mention that this assertion is a consequence of the following simplification.

2. Details

The component i_{qc} of the current, defined by (5) is compensated by the current $-i_{qc}$, i.e., the current of a shunt capacitor of the capacitance

$$C = (1/T)\int_0^T i\dot{u}\,dt/\dot{U}^2 \triangleq C_{opt} \tag{7}$$

which for linear loads is equal to the optimal capacitance, C_{opt} defined by W. Shepherd and P. Zakikhani [2], the capacitance which connected at the load terminals, results in the maximal value of the source power-factor. The quantity Q_c is the apparent power of the capacitor which draws the current $-i_{qc}$ from the source, i.e., the apparent power of a capacitor of the capacitance defined by (7). The capacitance determined by the formula (7) is the capacitance of a shunt capacitor (Fig. 1) which minimizes the r.m.s. value of the source current i_s, equal to

$$i_s = i + C\dot{u} \tag{8}$$

i.e. such a capacitance for which

$$(d/dc)\,[(1/T)\int_0^T (i + C\dot{u})^2\,dt] = 0. \tag{9}$$

However, the condition (9) leads to the formula (7) for optimal capacitance, only if the load current i and the load voltage u do not depend on the connected capacitance C, i.e., if the source impedance is equal to zero. If not, the formula (7) does not determine the capacitance which results in maximal value of the power factor, thus, the quantity Q_c is not the maximal value of the reactive power reducible by a capacitor. Therefore, if the Q_c value is known, then for non-ideal sources, the capacitance calculated from (6) is not optimal. Moreover, even if assume, that for non-ideal sources the value of Q_c defined by (2) is only an approximate value of the maximal reactive power reducible by a capacitor, it may appear that it is not possible to measure it by the analyzer described in [1]. Namely, the value of Q_c, measured before the capacitor of capacitance calculated from formula (6) is connected into circuit, may not be equal to the value of Q_c measured afterwards, so, the repeated calculation of the capacitance C may result in its other value. Successive correction of the connected capacitance value and measurement of Q_c results in a sequence of the Q_c values, which, however, may not be convergent.

Because the impedance of the sources in the power system usually amounts to only a few per cents of the load impedance, one may expect the above made reservations are only of minor importance, and indeed, this may be the case at resistive source impedance. However, if the source impedance is inductive, then, it may be difficult to consider them as insignificant. Such a conclusion may be formed if the following examples are considered.

3. Examples

The load shown in Fig. 1 is supplied by one of the three nonsinusoidal voltage sources of $\omega_1 = 1$ rd/s frequency and with the same e.m.f. e(t) which contains three harmonic components of the r.m.s. value $E_1 = 100$ V, $E_5 = 3$ V, $E_7 = 2$ V and the same source resistance, $R_s = 0,01\Omega$, but with different reactance $\omega_1 L_s$, equal to 0, 0,02Ω and 0,03Ω, respectively. For each source, the dependance of the power factor $PF \triangleq P/S$ on the capacitance C, i.e., the function $PF = f(C)$, and its maximal value PF_{max} was determined. This value was next compared with the power factor value, if the capacitance is calculated from the measured values of Q_c, U and $\dot{U}$.

1. For $\omega_1 L_s = 0$, the function $PF = f(C)$ has the maximal value, $PF_{max} = 0,93$, at $\omega_1 C = 0,770$ S, and the capacitor apparent power, $S_c = 7804$ VA. From the measurement, at $C = 0$, we obtain $Q_c = -7790$ VA, $U = 99,60$ V, $\dot{U} = 101,69$ V/s, so, $\omega_1 C = 0,769$ S. If such a capacitance is connected in the circuit, the values measured previously remain unchanged.
2. For $\omega_1 L_s = 0.02\Omega$, the function $PF = f(C)$ has the maximal value, $PF_{max} = 0.80$, at $\omega_1 C = 0,610$ S and the capacitor apparent power $S_c = 6468$ VA. From the measurement, at $C = 0$, we obtain $Q_c = -7549$ VA, $U = 98,10$ V, $\dot{U} = 100,08$ V/s, so, $\omega_1 C = 0,769$ S. If such a capacitance is connected into circuit, then $Q_c = -6981$ VA, $U = 99,92$ V, $U = 114,52$ V/s, so, $\omega_1 C = 0,610$ S. If the capacitance

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value is corrected to this value, then $Q_C = -7379$ VA, $U = 99{,}42$ V, $\dot{U} = 106{,}65$ V/s, so, $\omega_1 C = 0{,}696$ S. This process is convergent to $Q_C = -7276$ VA, $U = 99{,}59$ V, $\dot{U} = 108{,}74$ V/s, and $\omega_1 C = 0{,}672$ S. Such a capacitor results in the power factor $PF = 0{,}78 < PF_{max}$, and its apparent power must be equal to $S_C = 7278$ VA.

3. For $\omega_1 L_s = 0{,}03\Omega$ the function $PF = f(C)$ has the maximal value $PF_{max} = 0{,}71$, at $\omega_1 C = 0{,}480$ S and $S_C = 5219$ VA. From the measurement, at $C = 0$, we obtain $Q_C = -7433$ VA, $U = 97{,}34$ V, $\dot{U} = 99{,}29$ V/s, so, $\omega_1 C = 0{,}769$ S. If such a capacitance is connected, then $Q_C = -5193$ VA, $U = 101{,}24$, $\dot{U} = 161{,}16$ V/s, so, $\omega_1 C = 0{,}318$ S. This process may be repeated; however, the successive measurement of the Q_C, U and $\dot{U}$ values and the capacitance correction does not result in the convergent sequence of the $\omega_1 C$ values.

4. Conclusions

The capacitive reactive power Q_C is equal to the maximal value of the reactive power which is reducible by a shunt capacitor, only if, the source impedance is equal to zero. If not, it may only approximate this maximal value. For a resistive source impedance, the difference between the Q_C value and the maximal value of this reducible reactive power may be of minor importance. However, the use of this quantity by a power system operator for improving the power factor at an inductive source impedance, equal even to only a few per cents of the load impedance may lead to wrong decisions concerning the optimal capacitance value. It may even be wholly useless, because, it may not be possible to measure it. Moreover, under such circumstances, neither the calculation from the W. Shepherd and P. Zakikhani formula [2] nor the measurement by the convertor described in the paper [3], enable us to determine the optimal capacitance, C_{opt}, which results in the power-factor maximal value.

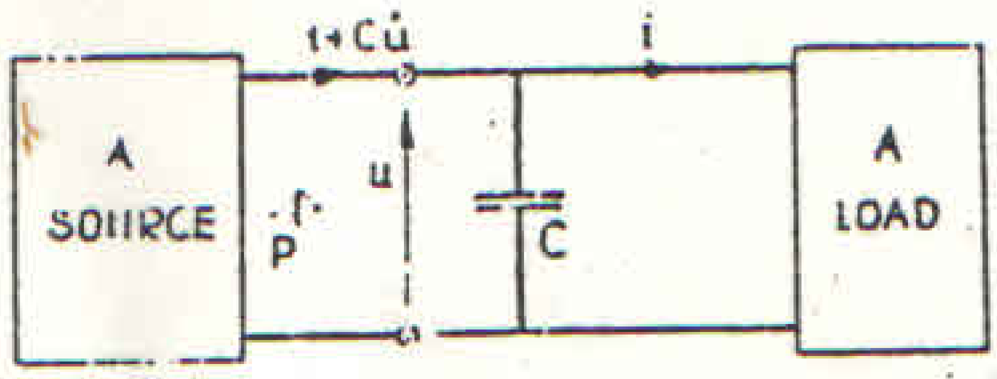

Fig. 1 Circuit structure

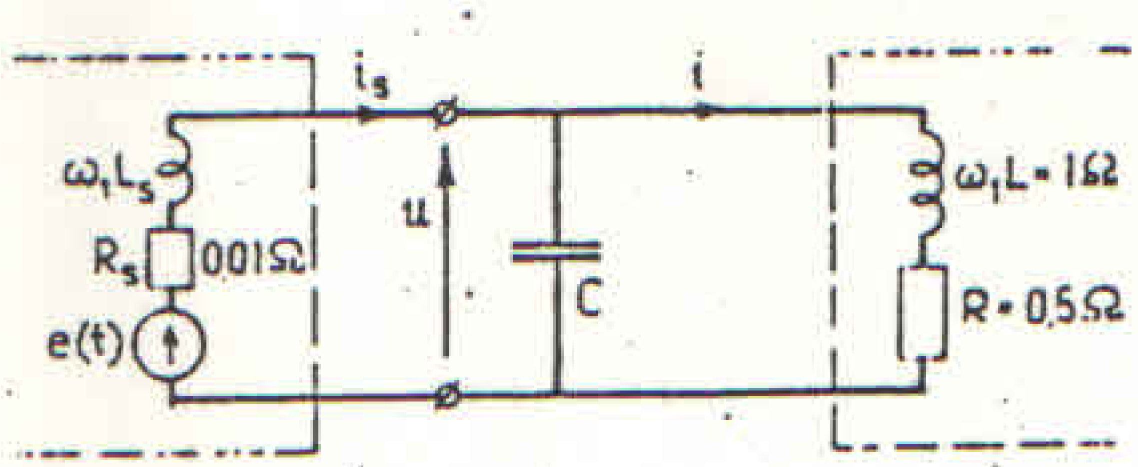

Fig. 2 Example of circuit

As the definition of the capacitive reactive power Q_C and the apparent power decomosition (1) may appear useless at non-ideal sources, thus, it is also doubtful if the power Q_C and the decomposition (1) should indeed be introduced into the power theory of nonsinusoidal systems.

5. REFERENCES

[1] N. L. Kusters, W. J. M. Moore, "On the Definition of Reactive Power Under Nonsinusoidal Conditions", *IEEE Trans. Power App. Syst.*, Vol. PAS-99, Sept. 1980, pp. 1845-1854.

[2] W. Shepherd, P. Zakikhani, "Suggested Definition of Reactive Power for Nonsinusoidal Systems", Proc. IEE, Vol. 120, No. 7, July, 1973, pp. 796-798.

[3] L. S. Czarnecki, "Convertor of the Optimal Capacitance for nonsinusoidal Systems Compensation to DC Voltage", Electronics Lett. 11th June 1981, Vol. 17, No. 12, pp. 426-427.

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N. L. Kusters and W. J. M. Moore: We were very pleased to hear of Dr. Czarnecki's interest in our paper and to receive his discussion. His studies have revealed that the application of the proposed definition may be of doubtful benefit in some circuit configurations. Whether this should be cause for abandonment of this approach however will depend on the seriousness of the deficiency in any particular application and whether it can be minimized by further processing. The original instigation for the development of this method for decomposing reactive power in non-sinusoidal systems arose from the difficulty in overcoming deficiencies in the harmonic analysis method.

The instrument described in the paper provides a means for separating the power into its various components according to the proposed definitions. One result of this separation is an indication of the effect of connecting a capacitor or inductor across the network being measured. Thus, as in Dr. Czarnecki's examples, the instrument indicates the presence of a negative capacitive reactive power which can be reduced by connecting a capacitor in shunt across the load.

It is evident however that if the voltage at the point where the capacitor is connected is not sufficiently compliant, not only the capacitive reactive component but all other components will be affected as well. Successive measurements are required to determine the capacitance that will reduce the capacitive reactive power to zero. And as Dr. Czarnecki has discovered, zero capacitive reactive power does not necessarily correspond to the maximum power factor condition. Further calculations have in fact indicated that where very high distortion is present very little change in power factor can be realized. In such more complicated situations, a more sophisticated compensating network would probably be required.

With respect to the apparent lack of convergence experienced in successive determinations, this is essentially a stability and control problem. If only a portion of the individual capacitance is connected after each measurement, convergence can be achieved.

We are grateful to Dr. Czarnecki for pointing out a deficiency in the proposed definitions. It is only by evaluations such as his that a practical assessment can be made of any new method.

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