Evaluating Sources of Distortion: Applying Czarnecki's Power Definitions for Nonsinusoidal Situations as Discriminative Distortion Source Evaluators.

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Abstract - **An agreed method for the localisation of sources of power system distortion, making use of network measurements, has yet to be determined. This paper presents a proposal based on the power definitions of LS Czarnecki for a three phase system comprising non-linear asymmetrical loads fed by a non-sinusoidal voltage source. The usefulness of these definitions as Discriminative Source Evaluators is demonstrated in a three-phase system. Finally, distortion-power data, generated by means of an ATP simulation, is evaluated by means of a Mathcad interpretation to illustrate this.**

Keywords: Distortion, Harmonics, ATP, Active Power, and Mathcad.

I INTRODUCTION

The emergence in power systems of an increasing number of *power electronic* loads has resulted in old academic problems acquiring new pertinence. Flexible ac transmission, using semiconductor devices, is challenging established power system paradigms. Where AC-systems traditionally employed only sinusoidal currents and voltages, these devices are now introducing non-linearity through active switching, either in line-commutated- or PWM mode resulting in non-sinusoidal supply currents.

Distorted power system currents are not problematical in itself, but introduces voltage drops in system impedances that correspond to the frequency content of these currents. That introduces the corresponding harmonic components into the different nodes, and especially those of consumers where their presence can be least afforded. The situation is aggravated in the case of developing economies where long transmission lines and distribution equipment of limited rating is the norm. Many economies have adopted a regulatory approach to non-linear loads, penalising distortion and low fundamental power factor, through the introduction of new tariff structures. Where loads of this type have to be supplied through long transmission lines, difficulties are inevitable and the onus for mitigation of the distortion has to rest on the consumer. In cases like these, appropriate tariff structures that penalise distortion generation at its origin appears to be the most effective means of regulating the problem. If one is to penalise consumers with non-linear loads by this means, however, then the location and identification (characterisation) of these loads must be able to be carried out in a reliable and in a dependable manner. In short, an essential element of a workable distortion evaluator must be a method of establishing the *direction* from where the distortion is originating [7], [8], and [9].

This paper shows that the Discriminative Decomposition of Distortion Power [5] furnishes one possible method by means of which this aim of characterizing a subsystem adjacent to the measurement cross-section, can be achieved. This knowledge is of use to the utility when designing penalising tariff structures and characterising distortion sources. Similarly, the customer will understand the need and nature of compensating actions better. The proposals made here should not be regarded as a final word on the matter, however, and it is suggested that other methods also be investigated [7], [8], and [9] to complement it in the general endeavour.

II POWER FLOW

Admitting that the term '*power flow*' is actually a misnomer[1], it has been hallowed through long use and is universally employed [1]. It will therefore be used here as well. The question of power flow is settled quite satisfactorily at an elementary level in standard textbooks [1]. One can define positive active power, negative active power and reactive power in systems with sinusoidal currents and voltages only. With these *a priori* definitions, using calibrated wattmeters and var-meters, the question of the direction of power flow has been settled for sinusoidal supplies feeding linear time-invariant loads.

When the load or supply no longer comply with the above conditions, new questions arise. This has been shown by Budeanu in 1927 [2] when he observed that the sinusoidal equation for apparent power,

$$|S|^2 = P^2 + Q^2 \tag{1}$$

no longer applies and a new quantity called *distortion power* D had to be defined to satisfy the equation for the apparent power:

$$|S|^2 = P^2 + Q^2 + D^2 \tag{2}$$

Although many researchers have made suggestions towards mathematically and physically defining this concept of "*distortion*" power, it remains a topic of active research. A number of definitions were recently

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[1] Energy 'flows'. Power is the rate of transfer of energy and the concept of 'flow' cannot be made to stick to it.

suggested for the practising engineer by Emannuel et al, One only has to study the published response [14] that that paper has elicited to appreciate how intense the current disagreement on the issue is. At this point in time, agreement is still to be reached on the most appropriate definitions [3]. This immediately leads to a serious problem, because the analysis of distortion power flow, with the object of pinpointing the sources of distortion, depends upon such a theory. The definition of *distortion power*, as defined by Budeanu, has been shown to be a physically meaningless concept [3], and alternative definitions will have to be sought in its place. The Czarnecki orthogonal decomposition of currents[5] offers an alternative approach and ascribes a physical interpretation to the different current components. The power definitions used in this approach are then based on this current decomposition. Because of the relative ease by means of which these components can be obtained and processed from practical measurements, the Czarnecki-approach will be used in this paper.

III Czarnecki's Decomposition of Distortion Power

The selective or discriminative decomposition of currents [6], presents a promising approach. It makes use of the sign of the active power at each frequency to group voltage and current quantities on which the power definitions can be applied. Czarnecki [6] has succesfully demonstrated the application of the sign of the individual harmonic active powers as distortion source locator for a single-phase situation.

It is well known that active power flow at different frequencies can be in both directions at a measuring cross-section. This single-phase approach [6] has to be extended to three-phase systems to be useful; this extension is thus demonstrated in this paper.

Czarnecki [6] has demonstrated the decomposing of the single-phase current under distorted conditions into three orthogonal components; the active, the reactive and the scattered current. A three phase non-linear load fed by a non-sinusoidal voltage source will draw a source current that can be decomposed [5] into five orthogonal components:

$$\overline{i_{source}} = \overline{i_a} + \overline{i_s} + \overline{i_r} + \overline{i_u} + \overline{i} \qquad (3)$$

Each component has as distinctive different physical meaning and calculation procedure:

- **i_a** : The only component indispensable for active power transmission, called *"active current"*. It is calculated (rms value) as

$$|i_a| := G_e \cdot |u| \qquad (4)$$

with

$$G_e := \frac{P}{(|u|)^2} \qquad (5)$$

where:
u: The total effective voltage
P: The total active power

- **i_s** : Appears when the equivalent conductance of the load changes with harmonic order and is useless for active power transmission. It is called *"scattered current"* and the rms value is calculated as:

$$|i_s| := \sqrt{\sum_{n \varepsilon N_u} \left(G_{ne} - G_e\right) \cdot (|u|)^2} \qquad (6)$$

with:

N_u : the set of harmonics the voltage source contains.

G_{ne} : The equivalent harmonic conductance of the load:

$$G_{ne} := \frac{P_n}{\left(|u_n|\right)^2} \qquad (7)$$

u_n : The effective three phase harmonic value which is calculated as follow:

$$u_n := \sqrt{\frac{u_{An}^2 + u_{Bn}^2 + u_{Cn}^2}{3}} \qquad (8)$$

- **i_r**: Although called *"reactive current"* it is not the Budeanu reactive current, this one is due to the harmonic reactive powers, Q_n, when there is a phase shift between voltage and current harmonics. The rms value is calculated as:

$$|i_r| := \sqrt{\sum_{n \varepsilon N_u} B_{ne}^2 \cdot \left(|u_n|\right)^2} \qquad (9)$$

B_{ne} is the equivalent susceptance of the load:

$$B_{ne} := \frac{-Q_n}{\left(|u_n|\right)^2} \qquad (10)$$

- **i_u**: Called the *"unbalanced current"* and it represents the source current increase due to load asymmetry. The rms value is calculated as:

$$|i_u| := \sqrt{\sum_{n \varepsilon N_u} \left[\left(|i_n|\right)^2 - \left(G_{ne}^2 + B_{ne}^2\right) \cdot \left(|u_n|\right)^2\right.} \qquad (11)$$

i_n : the effective harmonic current value.

- **i_g**: The *"generated current"* which consists of the current harmonics due to the load non-linearity or periodical variance of its parameters. The rms value is calculated as:

$$|i_g| := \sqrt{\sum_{n \varepsilon N_g} \left(|i_n|\right)^2} \qquad (12)$$

N_g: The set of harmonics not contained in the voltage source.

When equation 3 is multiplied by$(|u|)^2$, the following power equations results:

$$S^2 = P^2 + D_s^2 + Q_r^2 + D_u^2 + D_g^2 \tag{13}$$

with

$$P = |u| \cdot |i_a|, \qquad D_s = |u| \cdot |i_s|$$
$$Q_r = |u| \cdot |i_r|, \qquad D_r = |u| \cdot |i_r|$$
$$D_g = |u| \cdot |i_g| \tag{14}$$

III.1 Applying the Harmonic Active Power as a Discriminator:

Calculation on only one set of data in a three-phase system when using the Joint Harmonic Active Power is useless. It was shown [7] that a single measurement at a cross section in three phase systems cannot be used in localising disturbance source due to the stochastic nature of operation of a power system. It was demonstrated [7] that harmonic active power generated by one converter can actually be consumed by another for a certain firing angle condition in the power system, but to be fed into the P.C.C. when firing angles change relatively to one another. It is important however to keep in mind that in [7] the Joint Harmonic Active Power was used which merely represent the net effect of all harmonic powers present at the measuring cross section. However, the arguments presented in [7] proved clearly that in an interconnected grid with distributed distortion sources, a technique to tell who have contributed what and how much distortion at the P.C.C., is still to be found.

It was demonstrated in [6] for a single-phase system that the sign of the harmonic active power could be used to assign currents and voltages (and thus powers) at a measuring cross section to adjacent subsections.

Applying the sign of the harmonic active power as a discriminator in three phase systems can be found in [8] and [10]. In these two references indices are defined aimed at localization of disturbance sources. These indices are demonstrated to find applications given certain requirements are met. But, these limitations restrict the practicality thereof. On the other hand, indices in themselves can be a pitfall [11].

Therefore, the principles in [6] based on the sign of the harmonic active power are used to extend the principle to three phase situations. A situation, which is relatively independent to specific configurations of the subsystems adjacent to the measuring cross-section, can now exist. This is because voltage and current frequency components (and thus powers based on a valid power theory) can be grouped with the sign of the Harmonic Active Power as the discriminator. One can then quantify which powers have originated where and thus form an idea of the localisation of a certain disturbance.

The major advantage is in the quantified characterisation of the subsystems. These numerical results can form the basis of compensator design. It can also be used in a tariff system that creates enthusiasm towards minimum influence on the supply network by the customer. In addition, the tariff system can be such that it motivates the supplier towards supplying a voltage of single frequency because it could maximise collectable income. Observe that the term "*characterisation*" of the adjacent subsystem is preferred in the procedure of "*Discriminative Distortion Source Evaluator*" as the exact localising of specific distortion sources could still be unknown.

IV The Calculation Procedure and results.

When a nonsinusoidal voltage source is feeding an asymmetrical nonlinear load, harmonics will be found in the current not present in the voltage source. Therefore it is important to note that in the formulas (3) – (14), summation is done on different numbers sets. Subscripts X and Y refers to subsystem X and Y respectively. To clarify to the reader how the Czarnecki's equations are discriminatively applied, a cryptic summary is given:

Step 1: Calculate the frequency content of the measured three phase voltage and current quantities.

Step 2: For each phase and frequency, calculate the apparent power according to the classical definition. ($S=VI^*$)

Step 3: Apply a criteria (set a value of voltage to discard voltage values smaller then this voltage value) to establish which harmonics are the result of the product of system impedance and generated current harmonics (due to load nonlinearity) and which are the "pure" voltage harmonics existing only in the voltage source. Two number sets results.

Step 4: Sort the current and voltage harmonics into group A and B according to the sign of the harmonic active power.

The sorted decomposed currents are related to the total measured value:

$$i_{total}^2 = \left(i_{Xa}^2 + i_{Xs}^2 + i_{Xr}^2 + i_{Xu}^2 + i_{Xg}^2\right) + \left(i_{Ya}^2 + i_{Ys}^2 + i_{Yr}^2 + i_{Yu}^2 + i_{Yg}^2\right) \tag{15}$$

Their squared sum applies, as they are mutually orthogonal [5].

Step 5: For each group of voltage and current harmonics, the effective values of voltage and current are used to quantify the five decomposed powers. Make sure to summate over the correct number set (found in step 3) required by the Czarnecki formulas (3) – (14).

Step 6: (Proposed extension of method) Plot these values for each subsystem and repeat the process from step 1 to 6 after a time interval set in relation to the time constant of the operational characteristics of that power system. Integrating these powers thus leads to an "*energy value*".

It is important to keep in mind that the squared sum of the Czarnecki powers calculated for each subsystem is not the total apparent power. A "*forced apparent*" power (S_F) has to be defined [6].

Because $(|S|)^2 := (|i|)^2 \cdot (|u|)^2$ with $(|i_{total}|)^2 := (|i_X|)^2 + (|i_Y|)^2$; it follows that $S^2 := S_X{}^2 + S_Y{}^2$ where $S_X{}^2 := (|i_X|)^2 \cdot (|u|)^2$ and $S_Y{}^2 := (|i_Y|)^2 \cdot (|u|)^2$.

As $(|u|)^2 := (|u_X|)^2 + (|u_Y|)^2$; The following expansion results:

$$S_X{}^2 := S_{0X}{}^2 + S_{YX}{}^2;\quad S_Y{}^2 := S_{0Y}{}^2 + S_{XY}{}^2$$

It is S_{0X} and S_{0Y} that decompose into the Czarnecki powers:

$$S_{0X}{}^2 := P_{aX}{}^2 + D_{sX}{}^2 + Q_{rX}{}^2 + D_{uX}{}^2 + D_{gX}{}^2$$

$$S_{0Y}{}^2 := P_{aY}{}^2 + D_{sY}{}^2 + Q_{rY}{}^2 + D_{uY}{}^2 + D_{gY}{}^2 \tag{16}$$

$S_{XY}{}^2$ and $S_{YX}{}^2$ are thus defined as:

$$S_{XY}{}^2 := (|u_X|)^2 \cdot (|i_Y|)^2$$

$$S_{YX}{}^2 := (|u_Y|)^2 \cdot (|i_X|)^2 \tag{17}$$

The squared sum of S_{XY} and S_{YA} accounts for S_F :

$$S_F{}^2 := S_{XY}{}^2 + S_{YX}{}^2$$

This S_F which is called *"forced apparent power"* [6], is not to be confused with the *"voltage and current distortion power"* defined in [14] which is merely the product of voltage fundamental and current harmonics and vice versa.

An ATP simulation on a fictitious power system is used to demonstrate the procedure. A subsystem X consisting of a nonsinusoidal voltages source (of which the frequency characteristics is a simulation controllable) feeding a 6-pulse rectifier, is connected to another subsystem Y comprising a combination of a linear load and two non-linear loads. Subsystem Y represents unbalanced non-linear loading. This knowledge does not influence the interpretation of results. The procedure suggested here does not rely on such prior knowledge which may not exist in practice.

The measuring cross-section is between these two subsystems and data represents the three voltages and currents. These data are used in a Mathcad 6.0 program implementing the calculation procedure suggested.

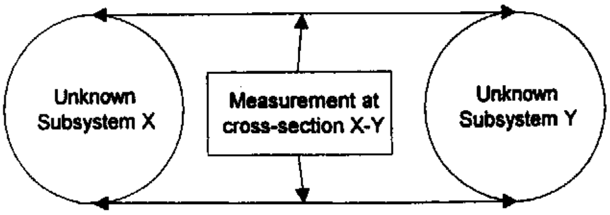

Fig. 1: The measurement cross-section

Measurement at the terminals X-Y is done without prior knowledge towards the direction of the dominant active power flow. For reference purpose, the current is flowing from left to right. Measured quantities are line currents and line-neutral voltages.

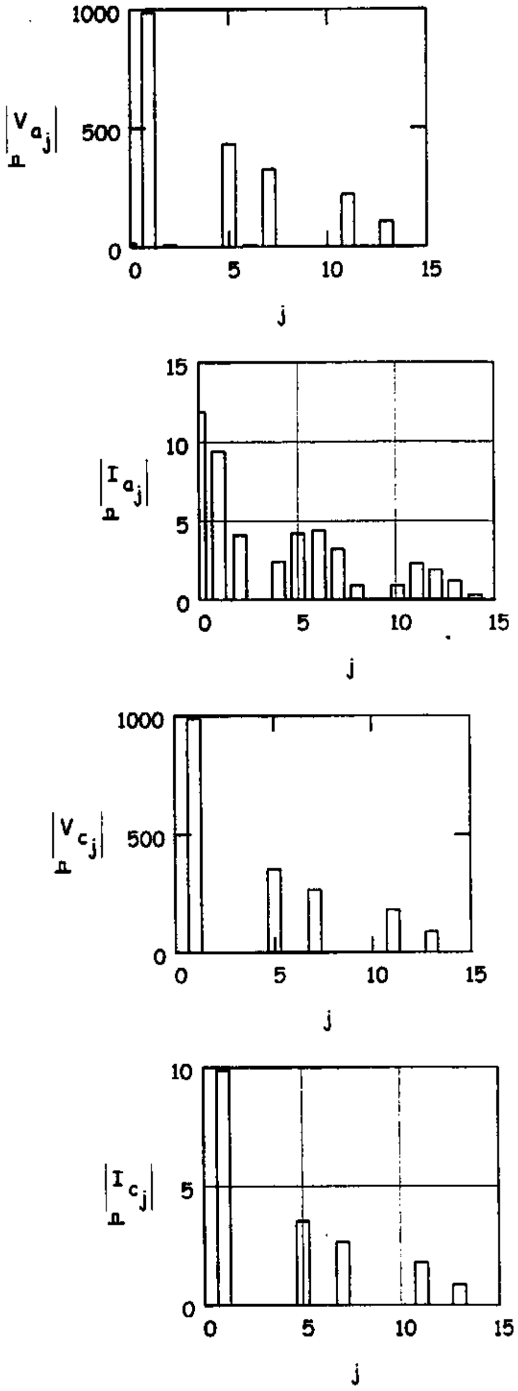

Fig. 2: Frequency content of phase A and C.

(Note the difference in spectrum in current and voltage for phase A.. Phase B (not shown) is similar to phase A with current harmonics not contained in the voltage. Phase C however, is only linearly loaded.)

Applying these data to the suggested distortion characteristication procedures, lead to the following results:

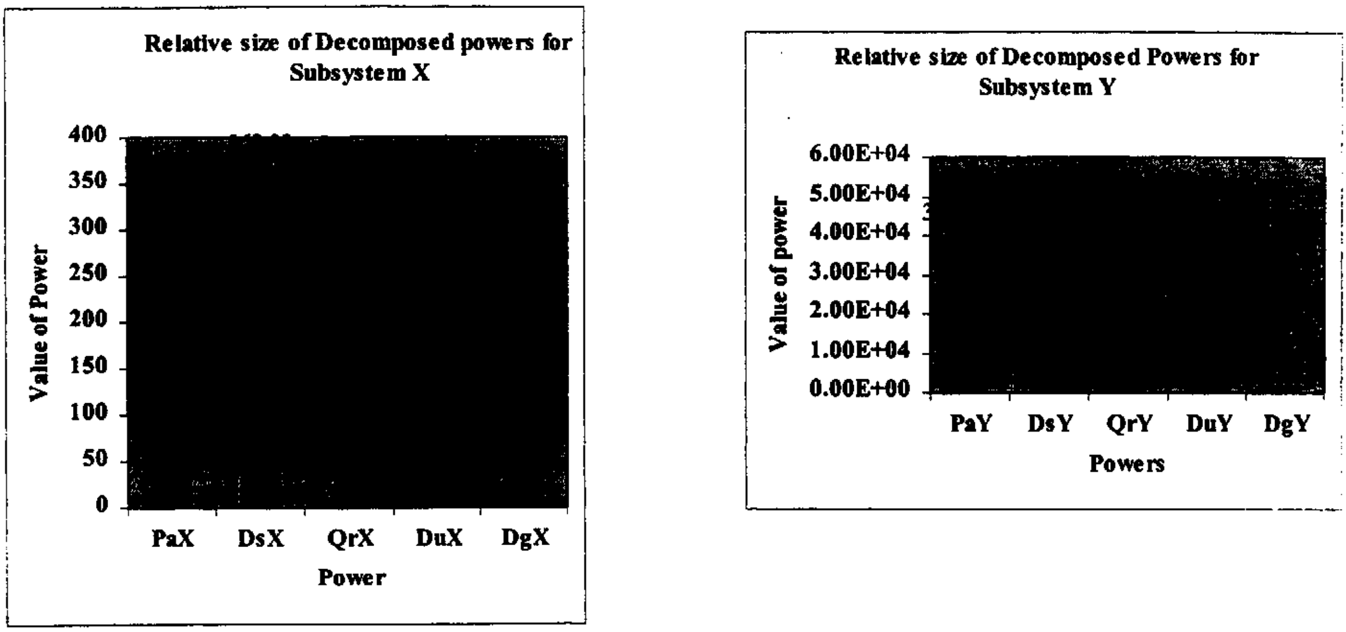

Fig. 3: The Decomposed Powers for Subsystem X and Y. The subscripts X and Y refers to the corresponding subsystem.

Figure 3 represents the decomposed powers consumed by the adjacent subsystems respectively. The results above indicates that the voltage source is located in subsystem X because the major active power consumption is in subsystem Y. Although subsystem Y does not have a voltage source, active power of 94.07 watt is exported to X , which is due to the non-linear load in Y. It is significant to observe that D_{sX} is the most significant power on comparison (to S_X = 456 VA) that is exported from subsystem Y to X (80 %). It is due to the frequency dependency of resistance in A. D_{gX} is the second most significant power and is due to the non-linearity that exists in X.

The active power consumption of subsystem Y (S_Y = 6.81E+4 VAR) is 56% of the apparent power consumption. There is thus a lot of unnecessary loading of the supply compared to the useful energy transmitted. Minimising each of the other four power components will result in striving to a unity power factor ($|S|$ =P). The value of the decomposed powers is thus in the distinct different physical meaning of each. Apparent power reduction possibilities are contained in the decomposition: Q_r, D_s and D_u may be fully compensated by a shunt linear reactive compensator [12], [13]. D_g needs active compensation.

The Budenu's relation for a nonsinusoidal system ($|S|^2 = P^2 + Q^2 + D^2$) indicate that Budeanu's D value will be 3.09E+3 VA, but knowledge about it is useless because no physical interpretation can be linked to it and thus it can't be used for compensation of penalty tariff usage.

V Conclusions

The Czarnecki decomposition of the current at the point of measurement allows the discriminative grouping of powers according to their origin. It is thus possible to distinguish what the nature of the subsystems is that contribute towards total distortion at the measurement point concerned in applying the characterization procedure suggested.

The simulated results have demonstrated the principle of calculation on a simplified system and deliver explicable results. It is important to realize that the process of calculating the Joint Harmonic Power (7) would have indicated only the nett flow of the Harmonic Power at the terminals. Thus we would have only known that subsystem B is generating an amount of Harmonic Power without knowing that some Harmonic Power is actually flowing from subsystem A and consumed by B simultaneously with the Fundamental Active Power delivered by the voltage source.

Noting that the essence of 50Hz power flow studies is the flow of energy from a higher potential to a lower potential, the synchronous measurement at various points in the network [7] is a promising aid in the search of reliable Distortion Source Locators, which should be combined with the Czarnecki's Discriminative procedure presented. It will be extended to include the time integration of the different powers. This discriminative distortion power calculation procedure will then lead to much more reliable characterisation of a source of disturbance when it is repeated over time in order to calculate the "*energy value*" of the different powers. It implies integrating each of the five power components at the cross-section against time where the total time span is representative of the operational characteristics of the power system. Calculating the "*energy*" value of a disturbance in order to predict the origin thereof was recently successfully demonstrated in [15]. This "*energy information approach*" can be an important element of any corrective actions applied to a specific disturbance source with the origin known, hence naming the proposed extension of the above described process, "*Discriminative Distortion Source Locators* ".

This preliminary result thus renders further investigation towards a more real world situation.

The authors are confident that the network data obtained from the ATP simulation is of sufficient validity to verify the argument presented, the simulation investigation will still be complemented by physical measurements.

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