New algorithm for estimation of correctness of active and reactive power distribution among generating sets operating in parallel

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Abstract— **The criterion currently used for the estimation of proportionality of active and reactive power distribution was introduced by ship classification societies many years ago, when the problem of non-active power compensation was not as serious as today. One of the important questions in the wake of the above-cited criterion is the meaning and interpretation of the Q reactive power. Due to of many doubts concerning those aspects, as well as methods of determination of the δP and δQ coefficient values, a new approach to solve the problem is presented. This approach is based on the concept of the power correlation functions $\Psi(t)$, which are the basis for determining sinusoidal power function $\Psi_s(t)$ and cosinusoidal power function $\Psi_c(t)$. The specific mathematical properties of the $\Psi_s(t)$ and $\Psi_c(t)$ functions have been used to estimate the appropriate active and reactive power distribution among generating sets working in parallel in the ship system under consideration. Proposed new algorithm for solving above mentioned problem and related calculations is shown on the example of the real ship power station configuration.**

I. INTRODUCTION - A SHORT CHARACTERISTICS OF SHIP ELECTRIC POWER NETWORKS

The ship electric power network is flexible ("soft") one. The exemplary configuration of the network under consideration is illustrated in Fig. 1. Such network is specific for its large variations of voltage and frequency (Fig. 2) resulting from comparable powers of the ship electric power plant (usually a few generating sets operating in parallel, sometimes aided by shaft generators or turbo-generators) and of switched-on consumers, e.g. bow/stern thrusters, pumps, cranes, compressors.

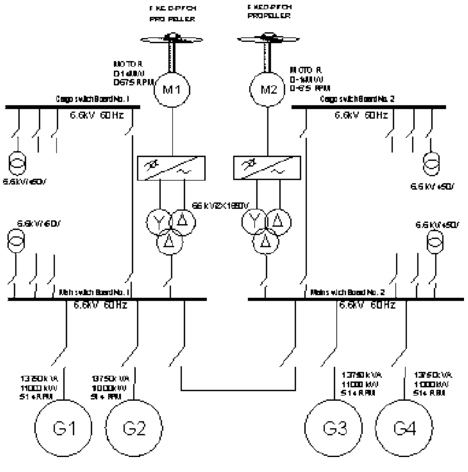

Figure 1. Exemplary configuration of the ship electric power network for all-electric-ship

A short-circuit power in the system under consideration has a limited, relatively small value. But first of all a varying frequency, dependent on, e.g. the dynamic load changes of the system in question should be indicated as its specific property, totally different compared to land-based electric power systems.

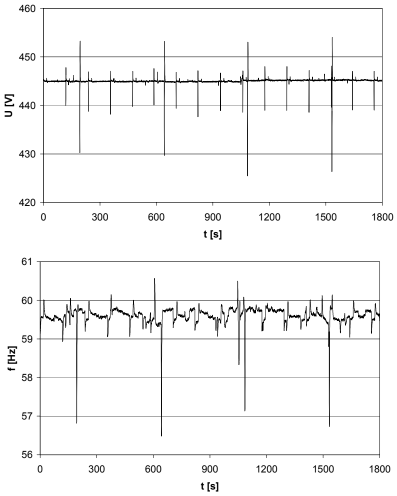

Figure 2. Exemplary fluctuations of voltage rms and frequency values on busbars in the ship electric power system (440V/60Hz) during the ship unloading

For electric power quality in the system in question, first of all a continuity of delivery is decisive, secondly, appropriate parameters characterizing electrical energy produced, distributed and utilized in the system under consideration. The first aspect is mainly related to the proportional distribution of active and reactive power among generating sets operating in parallel, while the second one regards appropriate values of voltage and frequency on the main busbars of the ship electric power plant, a correct waveform of supply voltage, and a balance of its components [1].

II. ACTIVE AND REACTIVE POWER DISTRIBUTION – STATE OF THE ART

The importance of proper power distribution should be strongly emphasized, because this factor may cause an apparent overload of the ship's electric power plant. In consequence, cut-offs of less important receivers or even blackout in the ship power system can happen. Therefore, some ship classification codes, e.g. DNV, ABS, or Polish Register of Shipping [2], impose δL_p permissible levels on the active and reactive power distribution in the form of the δL_i active or passive power distribution coefficients for

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the i-generator operating in parallel, which may be defined as follows:

$$\delta L_i = \frac{L_i - \alpha_i \cdot \sum_{i=1}^{p} L_{in}}{L_m} \cdot 100\% \le \delta L_p \qquad (1)$$

where: L_i – active (P) or passive (Q) load of the i-generator; L_m - active or passive rated load of the generator operating in parallel; p - number of generators operating in parallel; α_i - proportionality coefficient dependent on the number and power of generators operating in parallel.

The criterion (1) currently used for the estimation of proportionality of active and reactive power distribution was introduced by ship classification societies many years ago, when the problem of non-active power compensation (i.e. reactive power compensation and harmonics suppression) was not as serious as today. One of the important questions in the wake of the above-cited criterion is the meaning and interpretation of the Q reactive power. Due to of many doubts concerning those aspects, as well as methods of determination of the δP and δQ coefficient values (mean or max value, phase, and generator number dependent on the averaging process, static and / or dynamic condition estimation), a new approach to solve the problem is presented.

III. NEW APPROACH

The new approach is based on the concept [3] of the power correlation functions,

$$\Psi(x) \overset{def}{=} \frac{1}{T}\int_0^T u(\tau)\cdot i(\tau - x)\, d\tau \qquad (2)$$

which are the basis for determination of sinusoidal power function $\Psi_s(t)$

$$\Psi_s(t) \overset{def}{=} \frac{1}{2}\left[\Psi(-t) - \Psi(+t)\right] \qquad (3)$$

and cosinusoidal power function $\Psi_c(t)$

$$\Psi_c(t) \overset{def}{=} \frac{1}{2}\left[\Psi(-t) + \Psi(+t)\right] \qquad (4)$$

Specific mathematical properties of the $\Psi_s(t)$ and $\Psi_c(t)$ functions were used to estimate the appropriate active and reactive power distribution among generating sets operating in parallel in the ship system under consideration. Having converted the phase current and phase voltage of a generator into the Fourier series for the n-th harmonics, we obtain:

$$S_n^2 = P_n^2 + Q_n^2 \qquad (5)$$

where: S_n, P_n, Q_n are respectively: the apparent power, active power and reactive power of n-th harmonic. The equation (5) is the result of application of superposition principle for the n-th voltage and current harmonic. Summing with sides of the equation (5), we obtain for all "n":

$$\sum_n S_n^2 = \sum_n (P_n^2 + Q_n^2) \qquad (6)$$

or in the form that is called the correlative equation of power [3]:

$$S_s^2 = P_s^2 + Q_s^2 \qquad (7)$$

whereas: S_s, P_s, Q_s are the correlative apparent power, the correlative active power and the correlative power, respectively, whereas, these powers:

$$S_s = \sqrt{\sum_n S_n^2} \qquad (8)$$

$$P_s = \sqrt{\sum_n P_n^2} \qquad (9)$$

$$Q_s = \sqrt{\sum_n Q_n^2} \qquad (10)$$

may be determined on the basis of the known $\Psi(t)$ function. It means that the powers under consideration may be calculated without any harmonics analysis, but taking into account some properties of the correlation power functions for periodical waveforms $\Psi_s(t)|_{t=x}$, $\Psi_c(t)|_{t=x}$, i.e.:

$$\sqrt{2}\cdot\left\|\Psi(t)\right\| = \sqrt{2}\cdot\left\|\Psi_c(t) + \Psi_s(t)\right\| = S_s \qquad (11)$$

$$\sqrt{2}\cdot\left\|\Psi_c(t)\right\| = P_s \qquad (12)$$

$$\sqrt{2}\cdot\left\|\Psi_s(t)\right\| = Q_s \qquad (13)$$

Power function have some very interesting properties for linear circuits, e.g. the following dependencies are especially relevant for the operation under consideration:

$$\Psi_s(t) = \sum_n [I_n U_n \cdot \sin(\theta_n)]\cdot \sin(n\omega t) \qquad (14)$$

$$q(t) = \sum_n [I_n U_n \cdot \sin(\theta_n)]\cdot \sin(2n\omega t) = \Psi_s(2t) \qquad (15)$$

$$\Psi_c(t) = \sum_n [I_n U_n \cdot \cos(\theta_n)]\cdot \cos(n\omega t) \qquad (16)$$

$$p(t) = \sum_n I_n U_n \cdot \cos(\theta_n)\cdot\left[1 - \cos(2n\omega t)\right] = \Psi_c(0) - \Psi_c(2t) \qquad (17)$$

$$\Psi(0) = \Psi_c(0) = \sum_n I_n U_n \cdot \cos(\theta_n) = P \tag{18}$$

More information about properties of the presented power functions can be found in the [3].

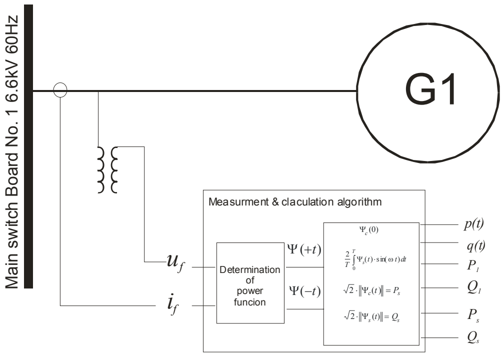

Figure 3. Measurement and determining of basic parameters and instantaneous powers p(t) and q(t) for estimation of correct powers distribution

Fig. 3 shows a block diagram for determination of powers: $p(t)$, $q(t)$, P_1, Q_1, P_s and Q_s is shown. A basic element of this structure is the DPF (Determination of Power Function) module, responsible for determination of power functions in accordance with definitions (2), (3) and (4). The DPF module is designed with application of Simulink®-Matlab® by means of the S-FUNCTION. The module under consideration has two inputs, where the measured instantaneous values of voltage (u, i) are delivered, two outputs ($\Psi_s(t,x)$, $\Psi_c(t,x)$) as well as two parameters introduced by the user, namely: N – number of samples per cycle; Ts – sampling period.

IV. A NEW ALGORITHM FOR SOLVING THE PROBLEM AND ITS EXPERIMENTAL VERIFICATION

A part of the investigated electric system is shown in Fig. 5. A separation of the part of the considered system was necessary with regard to an extended time of simulation resulting from the complexity of the simulation system. Nevertheless it does not reduce a generality of presented considerations.

The simulation research was conducted so that generators connected with the system as shown in Fig. 5 were loaded evenly. Then, at t=0.5s, the G1 generator excitation current was increased, whereas, the G2 generator excitation current was reduced. At the same time of the shaft moving the G1 generator a mechanical power has been increased with simultaneous reducing of mechanical power on the shaft moving the G2 generator. In this way a load angle of both machines has been remained all the time the same. In Fig. 4, the U_{rms} value curve on busbars is shown.

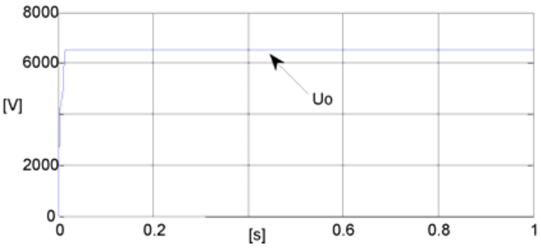

Figure 4. Rms voltage values for the main busbars

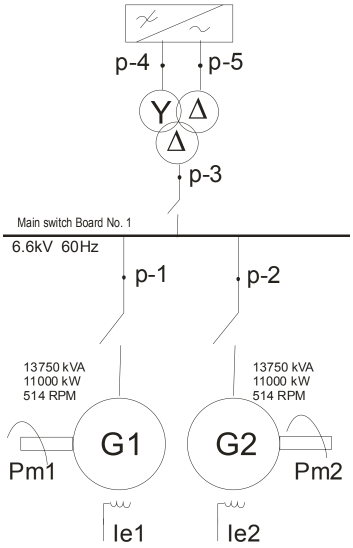

Figure 5. A fragment of the tested ship electric system with analysis points shown

Figures 6a, 6b, 6c show momentary current values for points p-3, p-4, p-5.

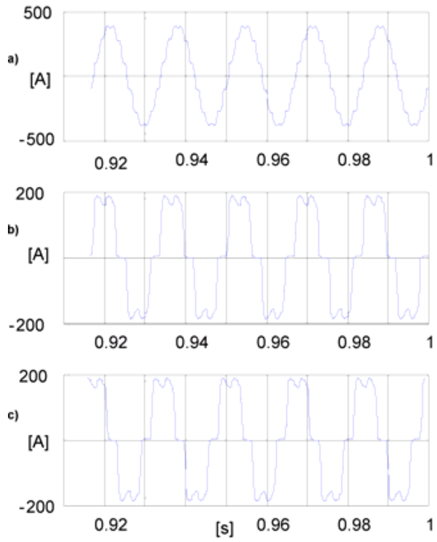

Figure 6. Momentary currents: a) p-3, b) p-4, c) p-5

Figures 7a, 7b, 7c show effective currents for points: p-3, p-1, p-2 respectively.

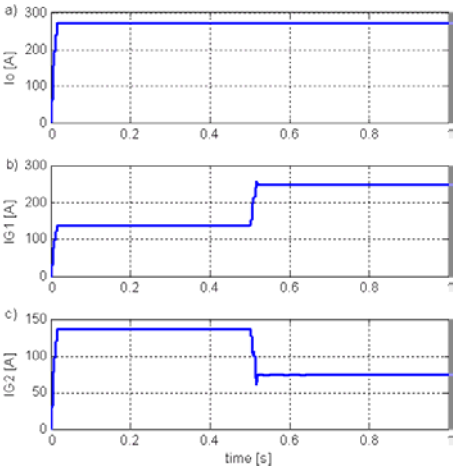

Figure 7. Effective currents: a) p-3, b) p-1, c) p-2

For comparison, original SimPowerSystems measurement blocks were used for power determination:

$$P=\frac{1}{T}\int_{t-T}^{t}u(t)\cdot i(t)\,dt \qquad (19)$$

and

$$Q_D=\frac{1}{T}\int_{t-T}^{t}u(t)\cdot i(t-\frac{T}{4})\,dt \qquad (20)$$

(reactive power definition acc. to Depenbrock). Fig. 8 shows active power P; Fig. 9 shows reactive power Q_D.

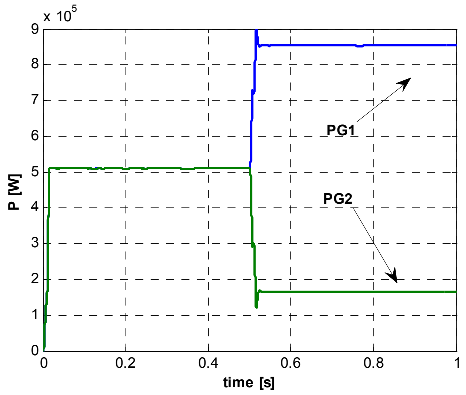

Figure 8. Active power changes

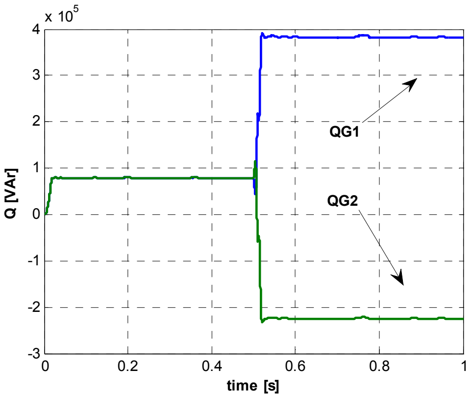

Figure 9. Reactive power changes

For nearly-periodical processes, a double-parameter correlation power function should be applied, such as:

$$\Psi(t,x)\overset{def}{=}\frac{1}{T}\int_{t-T}^{t}u(\tau)\cdot i(\tau-x)\,d\tau \qquad (21)$$

And respectively:

$$\Psi_s(t,x)\overset{def}{=}\frac{1}{2}\left[\Psi(t,-x)-\Psi(t,+x)\right] \qquad (22)$$

$$\Psi_c(t,x)\overset{def}{=}\frac{1}{2}\left[\Psi(t,-x)+\Psi(t,+x)\right] \qquad (23)$$

Measurements were made in point p-1 (G1) as follows:

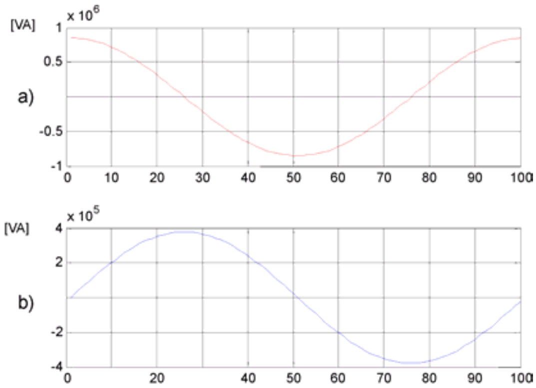

Figure 10. Power function curves: a) cosinusoidal curve, b) sinusoidal curve for p-1 point for time length of t = 1s.

Figures 11, 12 show 3D diagrams for power functions: cosinusoidal and sinusoidal respectively, for G1, in p-1 point, from x (100 corresponds to x=T) until t (6000 corresponds to t=1s).

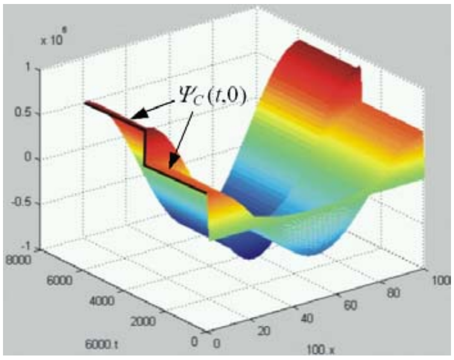

Figure 11. Cosinusoidal power function, in p-1 point

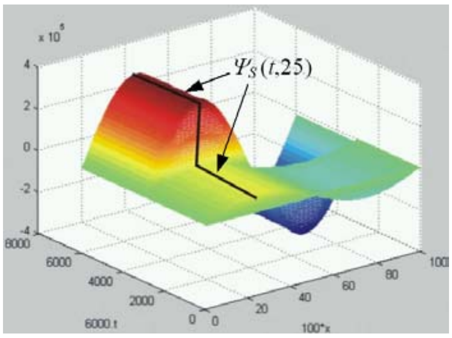

Figure 12. Sinusoidal power function, in p-1 point

Figures 13, 14 show the same function as figures 11, 12, except for G2, which means: in point p-2.

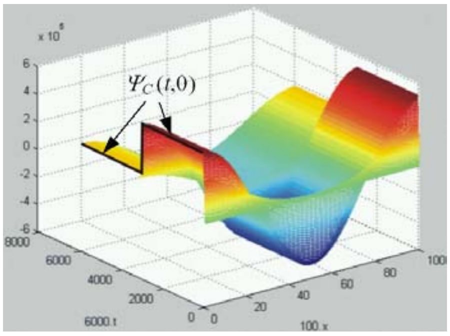

Figure 13. Cosinusoidal power function, in point p-2

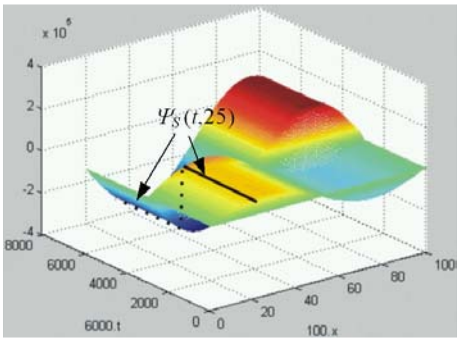

Figure 14. Sinusoidal power function, in point p-2

As mentioned before, calculation results for the active power P and reactive power Q_D (as shown in Fig. 9), which were calculated based on the Depenbrock definition, were compared against power figures as calculated based on the algorithm proposed by the authors of this paper. Results of the new algorithm are shown in Figures 11, 12, 13, 14. A conclusion based on this comparison was that: active power curves (as shown in Fig. 8 for generators connected in parallel) are exact equivalents of power curves in Fig. 11 (for G1) and 13 (for G2) for the time point of x=0. The calculated active power is shown in these illustrations with a continuous line $\Psi_c(t,0)$. Fig. 9 shows a similar situation. The reactive power curves Q_D are exact equivalents of reactive powers shown in Figures 12 and 14 for G1 and G2 respectively. As for the active power, the reactive power is marked with a continuous line $\Psi_s(t,25)$ for time point of x=25, this being equivalent of T/4.

In order to summarize the description, the following formulas can be written:

$$P = \psi_c(t,0) \tag{24}$$

$$Q_D = \psi_s(t,25) = \psi_s(t,T/4) \tag{25}$$

Due to properties of the $\Psi_s(t,x)$ and $\Psi_c(t,x)$ functions (i.e. the power function facilitates the determination of power according to different definitions), various evaluation criteria for the active/reactive power distribution among a number of generators operating in parallel can be selected, e.g. based on values determined as in Figure 3. Nevertheless, it is the general condition, which must be regarded, and that is: equality of relative momentary values as obtained from the DPF (Determination of Power Function) block:

$$\forall_{x,t} \, |\delta\psi^* s(t,x)| \leq \delta_{Sp} \tag{26}$$

$$\forall_{x,t} \, |\delta\psi^*{}_C(t,x)| \leq \delta_{Cp} \tag{27}$$

whereas: $\delta\psi^* s(t,x)$ and $\delta\psi^* c(t,x)$ mean the relative (e.g. in relation to the rated power of the given generator) difference between the cosinusoidal and sinusoidal power functions for the two generators operating in parallel, and δ_{Sp} and δ_{Cp} being the values adopted as maximum allowed.

Conditions (26) and (27) require a special attention for two reasons: firstly, in all cases, this is a real-time evaluation; and secondly: if the conditions (26) and (27) are met for two generators operating in parallel, it means that these generators are loaded to a similar extent when defining the power based on various definitions such as: $p(t)$, $q(t)$, P (active), Q_D (Depenbrock), Q_B (Budeanu), Q_I (Illovici), P_s, Q_s, S_s (active, reactive, apparent correlation power), etc.

V. FINAL REMARKS

This paper discusses the evaluation of power distribution among co-operating generators based on the new-developed correlative power function [3].

The paper discusses the issue of active power/reactive power distribution in ships. As the authors are aware, numerous references (e.g. [3], [4]) related to the „power theory", dealt with, for example, description, interpretation, compensation and filtration of reactive power. Still, the issue of power distribution among co-operating generators has not been discussed yet, mainly for the reason, that previously mentioned papers concern basically land power networks (grids). This issue under consideration is of a special importance for ship operations because the number of electric power devices and their capacities increase permanently, which results in harmonics increasing for both voltage and current. Classification institutions' regulations specify the allowed differences in terms of power distribution between co-operating generators, yet, these regulations do not define any method thereto. On the other hand, a number of definitions of power components is significant, and that is the source of doubts, which definition should be the basis for power distribution evaluation. The authors proposed a criterion featuring several advantages: firstly, this criterion guarantees that the power distribution evaluation based on the newly-developed correlative power function is consistent with evaluations based on different power definitions, e.g. the classic Depenbrock's definition of active power P and reactive power Q_D. Secondly, this is a real-time evaluation, and can be easily implemented into signal processors; thirdly, power functions are conservative functions (i.e. the power balance is maintained), which is particularly important for analysis of power distribution among generators co-operating in parallel.

ACKNOWLEDGMENT

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