Power Conditioning System (PCS) based on a Shunt Active Power Filter with Supercapacitor

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***Abstract*-This paper describes a concept of Power Conditioning System (PCS) variety and its proposed application in distribution system. Suggested areas to use of the presented PCS system can be centered around two topics : grids with unstable power consumer and main apply which is ship's power systems. The proposed PCS can compensate the reactive power, harmonic currents and power surges. This paper refer also to problems with power quality and to methods of improving it. Summing up presented system can be operated as a Power Quality Conditioning Device in system where exist problem with unstable power source or power consumer.**

I. INTRODUCTION

For over the last several years we can observe the dynamic development of power electronic systems for application in both small and large power. The interest in system of this type, due to the fact that they provide to transform electricity from conventional sources, to form which is necessary for control and supply different type of loads. In additional to providing basic function with the highest energy efficiency from power electronic devices, it's also require high reliability and low interference on the mains and the other connected to the system receivers.

Systems based on power electronic converters popular in land-based application, are also increasingly used in marine solutions. In this case power electronic devices are mainly applying as a ship main propulsion system (e.g. ABB ACS series) or intermediary in the process of energy production (e.g. in a system with shaft generator).

In most applied power electronics converters, which are characterized by variability of their electrical parameters during operation, these devices shall be considered as a non-linear loads. This situation occurs even if the typical voltage inverter is supplying from the AC network. It is then a situation where in additional to active power, inverter also takes deformation power (including reactive power), which is an undesirable component.

Compensation methods for current waveform, which include deformation induced by power converter and other non-linear loads, are now one of the main branch of the development power quality improving systems. In this dimension of the problem, application of a APF solves the problem and it solution seems to be the most effective [1],[2]. However, deformed waveform of currents associated with occurrence of higher current harmonics is not the only one problem with the use of a energy system. Among the many disorders, analyzed during the operation of ship's power system, particular attention was paid to power fluctuation caused by unstable loads or accidentally attached. Problem with instantaneous and often accidental demand for power is particularly important in ”soft” systems, where the power of loads are close to the power of installed sources. This situation occurs on ships, oil rigs or in isolated terrestrial system which are often supported by renewable energy sources.

In this paper proposed a combination of shunt APF with power surge compensation circuit based on Supercapacitor as a energy storage. In publication like [3] and [4] presents a solution based on a similar design, but performing other functions like UPS. That system can be classified into Power Conditioning Systems or as a **Power Smoothing System (PSS)** to emphasize power surge compensation properties.

II. PROBLEM IDENTIFICATION

Power converters which are installed in power system with soft characteristic, poses a number of difficulties associated with [5]:

- converters with a basic structure do not have the ability to energy storing, which makes that each impact of load is perceptible by power system;
- thyristor firing angle changes is accompanied by changes of active and reactive power
- current induced during commutation are a reason of voltage distortion

In ship system operated without any conditioning system in most cases, the harmonic distortion greatly exceed limit values which, according to major classification societies are determined at 10% of THD [5].

Mechanism of the harmonic formation can be easily analyzed on the electrical circuit shown in Figure 1. If to the circuit powered by sinusoidal source is attached a non-linear load, then from circuit theory point of view it becomes a current source, that generates current harmonics. Those harmonics cause a voltage drop across the equivalent impedance of the power line. Given this situation, in the illustrated circuit there will be voltage and current harmonics of the same order.

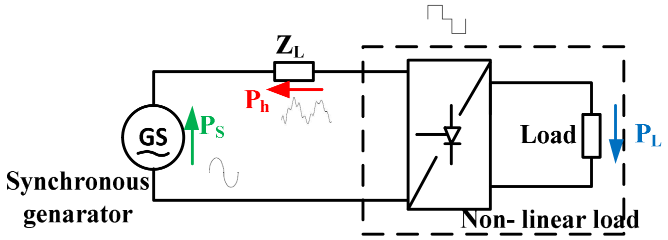

Fig. 1. Power flow in system with non-linear load.

To emphasize the problem of grid cooperation with non-linear load in Figure 2 and 3 shows respectively load current and inter-phase voltage waveforms. In case of Figure. 2 waveforms are the result from computer simulation of the system based at a typical grid. As a comparison in Figure 3, shows the equivalent current and voltage waveforms recorded during simulation with "soft" grid.

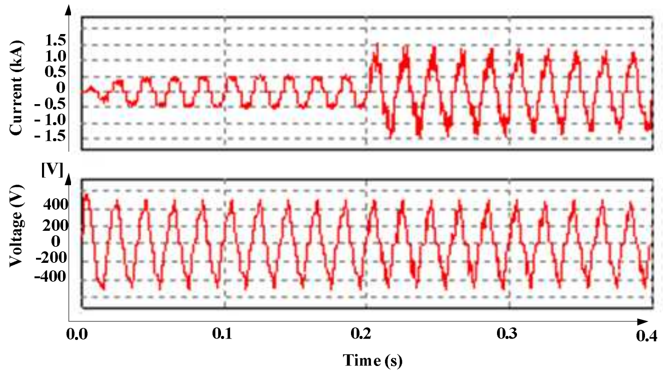

Fig. 2. Load current and inter-phase voltage measured in typical grid.

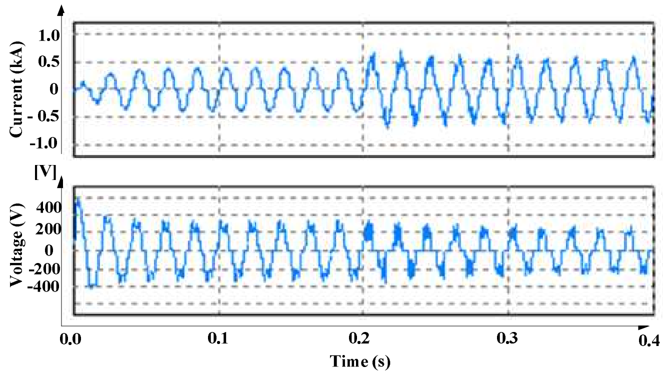

Fig. 3. Load current and inter-phase voltage measured in "soft" grid.

Both the cases were analyzed for a system in which the load was a six pulse rectifier with RLC load. As can be seen in the system with "soft" grid outside the waveform distortion additionally is also a decrease in voltage amplitude. Thus, there is a strong relationship between the line impedance and susceptibility to distortion. Table I shows the grid parameters used during simulation.

TABLE I

GRID PARAMETERS

Soft grid	Typical grid
R = 0.5 [Ω]	R = 0.005 [Ω]
L = 0.1 [mH]	L = 0.01 [mH]

III. CONFIGURATION OF PROPOSED PCS

Figure 4 shows demonstrative concept of proposed PCS. System has a additionally DC/DC converter as a element of responsibility for cooperation of energy store (supercapacitor) with rest of the system. With the implementation of the bi-direction DC/DC converter, during a periods when the system is in filtration mode, voltage at the supercapacitor is stabilized by the converter on the nominal level. Keeping the same the energy store in full readiness to compensate for power surge.

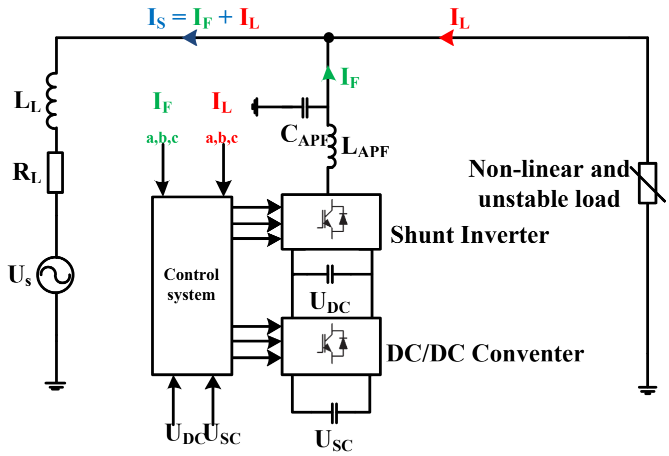

Fig. 4. Concept of proposed PCS system

When a load power consumption is changing, which is related with voltage drop in the inverter DC link, signal from voltage sensor is changing the direction of energy flow through DC/DC converter. Thereby ensuring the commitment of the stored energy by the PCS to the power system, and thus compensatory changes in load. All this process are carried out, while maintaining the ability to distortion filtration caused by harmonics.

Control system structure of the proposed PCS is presented in Figure 5. It can distinguish two main parts : a system of harmonic compensating and dc-link voltage level controller.

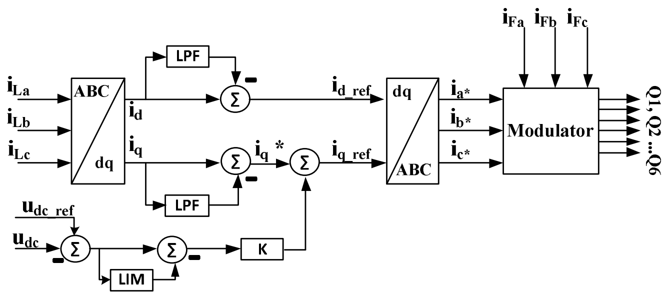

Fig. 5. Control structure of the proposed PCS.

In such adopted structure, preset current designation is equivalent to the equation 1 and 2:

$$i_{d\_ref} = i_d - i_d^{\tau} \ , \tag{1}$$

$$i_{q\_ref} = i_q - i_q^{\tau} + \Delta u_{dc} \ , \tag{2}$$

Where $i_d{}^{\tau}$ and $i_q{}^{\tau}$ are the results of the filtration made by the filter which has a transmittance :

$$G_{LPF} = \frac{\omega_c^2}{s^2 + 2 \cdot \xi \cdot \omega_c \cdot s + \omega_c^2} \quad . \tag{3}$$

Appearing in the above equations the coefficients describe: ω_c - cut –off pulsation of filters, ξ - damping ratio.
In the equation (2), expression Δu_{dc} is a simplification for the deviation of DC link's voltage regulation (eq. 4)

$$\Delta u_{dc} = k \cdot \int_0^t u_{dc\_err} dt \, , \tag{4}$$

where k – is a correction factor of the regulator's.

Representation of the load current phases in synchronous coordinates are calculated as

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \sqrt{\frac{2}{3}} \quad . \tag{5}$$

In Figure 6 shows the used DC/DC converter. It is based on a bi-direction dual full bridge. To ensure proper fit of voltage level between energy storage and inverter's DC link was used a transformer with transformation ratio 4. Analyzed converter is operates according to the PCS state in two modes:
-during harmonic filtration as a buck converter with supercapacitor voltage stabilizing
-during power surge compensation as a boost converter with energy putting to the grid

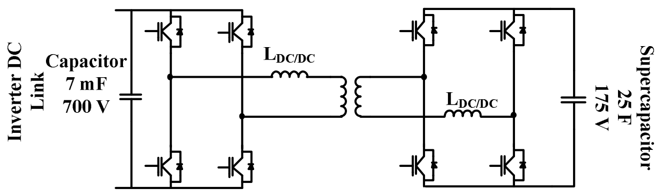

Fig. 6. DC/DC converter

Activation of the converter transistors is formed in the monostable modulator in which the modulating signal is used from DC link voltage sensor.

IV. Computer Simulation

For the simulation of presented PCS, was used PSIM software. The power circuit is modelled as a 3- phase 3 – wire system (similar as in the case of ship's power system). As a non-linear load used not controlled three phase rectifier with RLC load.

The time in which the simulation was analyzed is 0.4 [s] with calculation step 1 [us]. Maintaining data and parameters carried out simulation are presented in the Table II.

TABEL II

Parameters of the Simulation

Source - voltage - impedance	 400 [V] R = 0.5 [Ω], L = 0.1 [mH]
DC link - capacitor - reference voltage	 C = 7 [mF] 700 [V]
Shunt inverter - filter - switching frequency	 L = 0.3 [mH], C = 2 [uF] f = 15 000 [Hz]
DC/DC converter - transformer ratio - switching frequency - induction	 4 f = 15 000 [Hz] L = 1 [mH]
Supercapacitor - capacity - reference voltage	 25 [F] 175 [V]

Figure 7 present successively distorted load current in situation of switching load. Presented results are the timing analysis of filter part of the PCS . The recorded waveforms are from phase A.

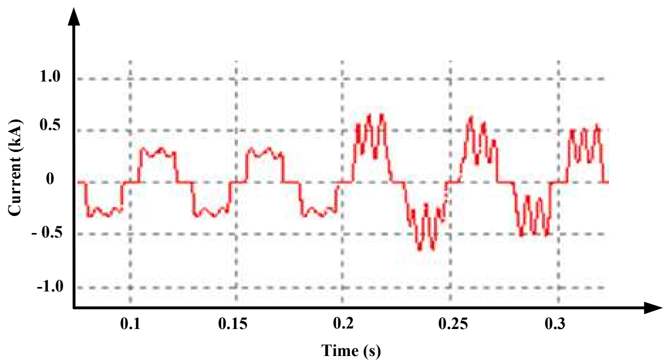

Fig. 7. Load current.

Figures 8 and 9, shows the respectively records of the additional compensating currents generated by analyzed PCS. After adding the load current to compensating current at the PCS attachment point.

Presenting timing confims that the proposed control algorithm and the topology of PCS, allow for power quality improvement. After applying of PCS the line current is slightly differs from the ideal shape of the sine wave.

The next stage of PCS functionality verfication is a analyze of the PCS ability to power surges compensate. For this purpose, timming of the power sonsumed by receiver was made and shows at Figure 10.

It can be seen that the power as must be delivered to the receiver is variable in time and the dynamics of these changes is dictated by the characteristics of load changes.

In the plans for the implementation of proposed PCS, changes of the load (like this presented at Figure 10) have to be compensated by the PCS. For this situation waveform of power which is generated from the PCS is presented in Figure 11.

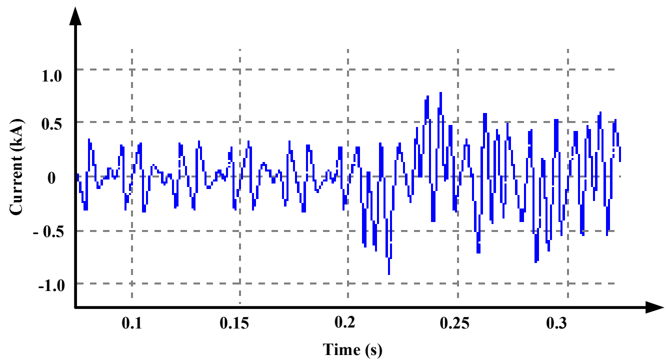

Fig. 8. Additional compensating current.

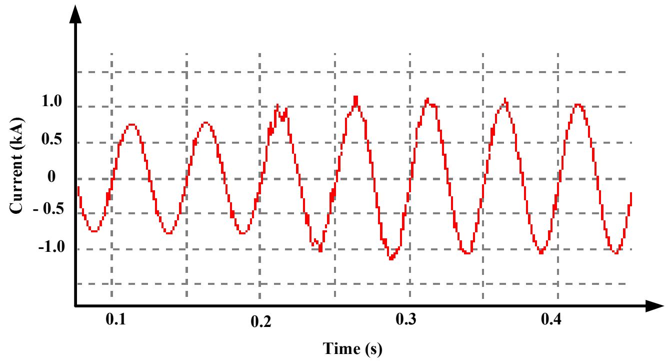

Fig. 9. Line current after compensation by PCS.

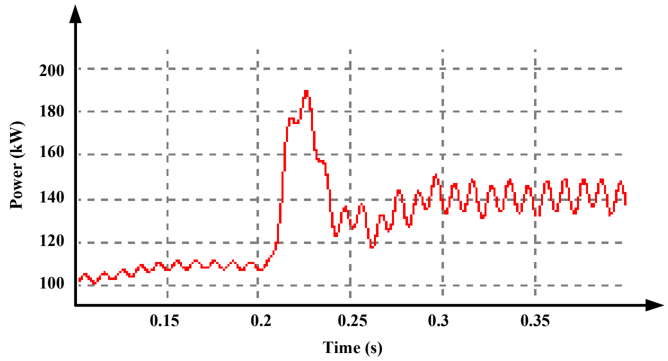

Fig. 10. Power consumed of unstable load

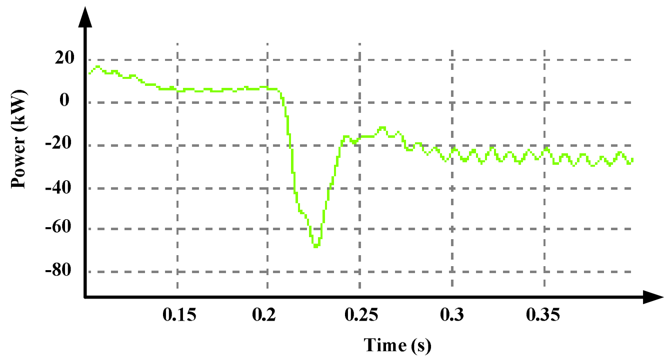

Fig. 11. Compensating power from PCS.

A collaboration of PCS with grid is shows in Figure 12. It clear that use of the proposed system made it possible to eliminate power fluctuation and stability a source power at a constant level even when the load changes is occurs.

Analyzing the simulation results, shows in Figure 9 and. 12 can be see that the proposed system satisfies the assumption posed in the project phase. Both the compensation function are sati factionary. Obtained during the simulation power surges compensations about 30 [kW] with this type of supercapacitor.

Additionally, in Figure 13 shows the voltage waveform on the DC link. This voltage is stabilized at 700 [V] and supported by the energy storage.

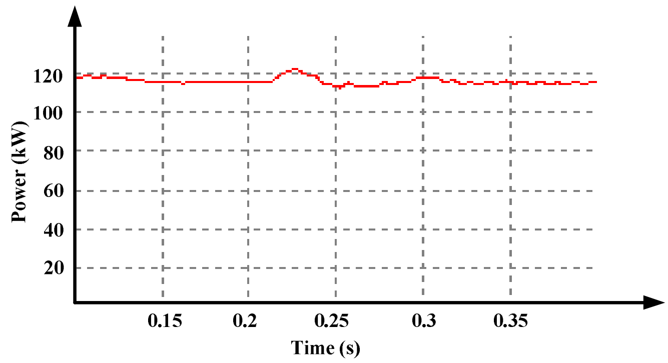

Fig. 12. Power of the line after compensation by PCS.

In Figures 10 and 11 shows the situation in which the load was changed once. For additional analysis was performed a simulation in which the load was switched periodically. The time horizon of the simulation was increased to 1 [s].

The results of the test are shown in figures 14 and 15. Situation of the random load changes is quite common in a exploitation of ship's power systems. The randomness connection of different power consumers, a influence of sea waves and soft power system in comparison to the typical grid create many opportunities to appear of power fluctuation. Therefore, the designed PCS should provide improved system stability.

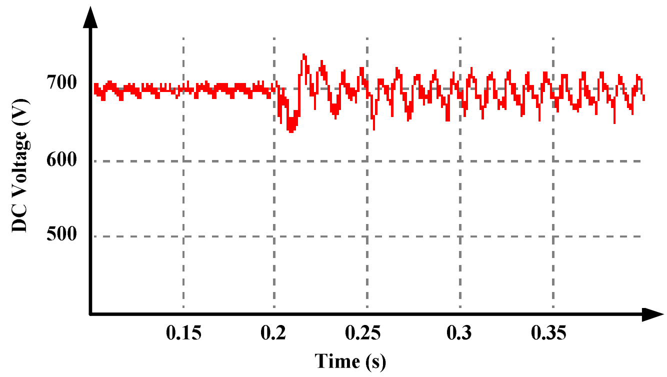

Fig. 13. DC link voltage waveform.

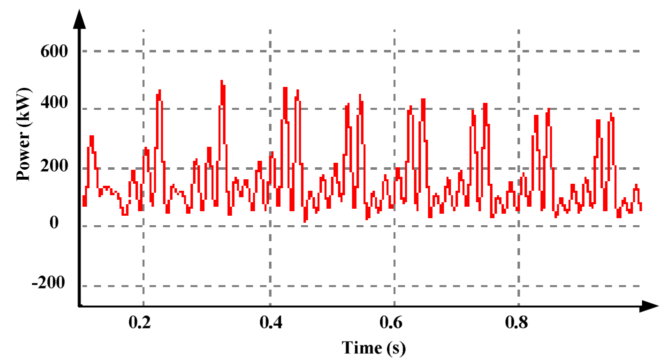

Fig. 14. Load power waveform in situation of switching.

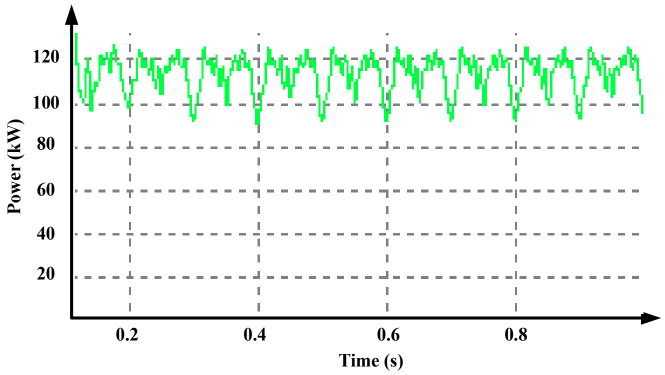

Fig. 15. Line power waveform with PCS compensation.

As can be seen from these figures, use of the PCS allows to decrease in amplitude of the oscillations and ensure stability of the demand power on a level of 100 - 120 [kW]. That is, the system provides elimination of power surges with power exceeding 400 [kW] occurring with a repetition.

V. CONCLUSION

Proposed in this paper PCS system, at this stage has been developed as a simulation model. Created model is the base system which is used for continuous improvements. Work is currently underway to develop new methods of control and provide new system functionality, such as uninterruptible power supply. The aim is to realize an integrated power conditioning system, which could be used not only in marine but also in typical application. In this situation PCS can be use in grid connected to wind turbine or as a support required at events where big instantaneous power is demand (e.g. during concerts) Simultaneously with the work connected with the project agreement, there will be ongoing research work related to the identification of power quality problems on ships. In a further phase of work will be built experimental model, which will be used to verify of proposed system in real conditions. The results of computer simulations suggest that the proposed concept of the PCS system can significantly improve a quality of a electricity grid in which it will work. The long-term test of PCS concept under real condition will constitute a complete knowledge base regarding the influence of PCS at grid.

ACKNOWLEDGMENT

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VI. REFERENCES

[1] J. K. Phipps, J.P. Nelson, P. K. Sen.: (1994), *Power Quality and Harmonic Distortion on Distribution Systems*, IEEE Trans. on Ind. Appl., vol. 30, No 2,. 176-184.

[2] M. Aredes, K. Heuman and E. Watanabe.: (1999) *An Universa Active Power Line Conditioner*, in IEEE Trans. on Power Delivery, vol. 13, no 2, pp. 545-551.

[3] Byung M. H., Bae B. : *Unified power quality conditioner with super-capacitor for energy storage*. Europen Transactions On Electrical Power 2008. Published online 18 April 2007 in Wiley InterScience, 327-343

[4] Casadei D., Grandi G., Rossi C.,(2002).: *A supercapacitor-Based Power Conditioning System for Power Quality Improvement and Uninterruptible Power Supply*. Proc. on the ISIE’2002, vol.4, L’Aquila (Italy), 1247 - 1252

[5] Polish Registry of Shipping, (2007), Rules for the Classification and Construction of Sea-going Ships, Part VIII, Electrical Installations and Control System