ARCHIVES OF ELECTRICAL ENGINEERING VOL. 65(2), pp. 221-234 (2016)

DOI 10.1515/aee-2016-0015

One phase active filter with energy storage for active power surge compensation in feed line

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(Received: 26.12.2014, revised: 17.08.2015)

Abstract: The paper presents a concept of an active filter with energy storage. This solution can be used for the compensation of momentary one phase high power loads with discontinued power consumption (e.g. spot welding machines). Apart from the typical filtering capabilities, the system's task is also the continuity of the input power from the feeder line and limiting its fluctuation. The proposed by the author's solution can produce measurable economic benefits by reducing the rated power necessary to energize periodically operating loads and improving the indicators of electrical energy quality. The developed method of active power surges compensation enables a flexible approach to requirements concerning the rated power of the point to which the periodically operating loads with high peak current value are connected. The tests were conducted on a simulation model specially developed in Matlab & Simulink environment, proving high effectiveness of the presented solution.

Key words: power quality, active power filter, power surge compensation

1. Introduction

One of the key issues of the modern power electronics is the electrical energy quality improvement. Hence, the ever increasing interest in its quality [1], especially if this relates to the transfer system limitations [2]. This comes down to, among other things, the follow-up reactive power compensation and filtering higher current harmonics generated by non-linear electrical energy loads. It is performed by reactive power compensators and active power filters [3, 4], compensating reactive current component according to S. Fryze definition [3, 5, 6]. In the case of intermittent operation, where the operating time of a device in relation to the idle time is relatively short, the feeding system (line, switchgear, transformer) is dimensioned for the peak loads. Thus, in order to ensure the correct operating conditions for other devices supplied from the same line, the fault level of the network at the point of connection must be appropriately high. Using an additional energy storage drawing energy when there is no current consumption by the loads and supporting their supplying during their operation, enables to radically decrease the peak power value, thus lowering the demands concerning, e.g. the feeding system. It should be noted that providing correct conditions for the connection of this type loads to the feeder line is expensive since it forces the user to employ a terminal of appropriately high power.

Currently, the reactive power compensators (or active filters) are connected to non-linear loads working from time to time for variable durations [7-9]. Such solutions allow reduction of voltage drops in feeder line due to surges of active power and reduction of the harmonic content [10-13]. However, do not limit the peak currents in the feeder line and the distribution transformer. Actually few research centers have taken up the work on the current active component compensators based on the supercapacitors [10, 11]. The alternative is to use the kinetic energy storage – flywheel [12, 13], which provides higher density and value of stored energy.

One of the solutions to the issue mentioned before is the employment of one phase active power filter connected to energy storage, whose control algorithm will enable the active power fluctuations suppression in the feeder line (by limiting the variable power component value). Presented solution can produce measurable benefits by reduction of the rated power necessary to feed periodically operating loads and improving the indicators of electrical energy quality. Furthermore the developed method of active power surges compensation enables a flexible approach to requirements concerning the rated power of the point to which the periodically operating loads with a high peak current value (apparent power) are connected.

A single-phase welding machine with a thyristor current regulator was assumed as a compensated and filtered object for which the active power fluctuation suppression will be additionally performed. The welding machines are operating with a variable welding time and variable idle time. During their operation, the devices of this type force distorted currents of high reactive component value to flow through the lines, accounting for the voltage drops on the feeder line reactance. These drops have an adverse effect on the operation of all loads connected to the point of common coupling. This issue concerns also other objects, due to their cyclic operation mode, e.g. crane and lift drives. It also concerns the direct current traction in which during the recovery braking the energy is returned to the grid/traction, which results in the voltage increase, if at the same there is no other object which requires this energy, e.g. during startup [14-18].

2. The operating concept of the active filter with additional energy storage

The operating concept is presented in Fig. 1. In order to do this, a tank system was used, reflecting the respective energy storages physically present in the analyzed structure.

The connections between tanks symbolize the possible energy flow paths executed by respective system functions. The arrows denote the possible directions and the characteristics of the energy flow (continuous or interrupted).

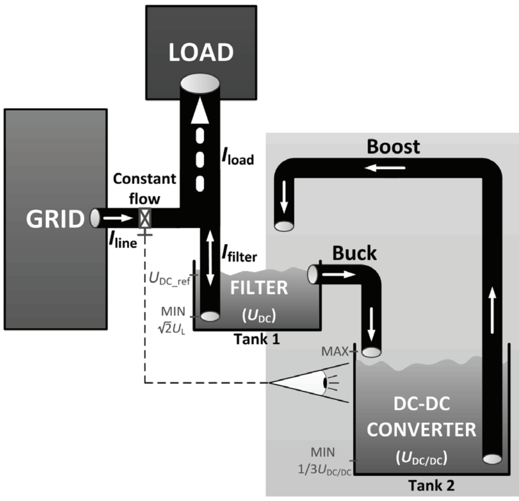

Fig. 1. Schematic diagram illustrating the operating concept of the active filter with additional energy storage

The power grid-feeder line is treated as a tank with infinite volume (Fig. 1). In its terms, the system is supposed to tend to maintain the continuous flow (energy draw), hence a value several times lower than the value momentary forced by the periodically turned on load (I_{load}). In the case of the analyzed object, i.e. the welding machine, it can even exceed 200 A in the peak current value. It would necessitate the appropriate dimensioning of the feeder line components, supplying energy to the load, in order to withstand such substantial flows. It is shown in Fig. 1, with a bolder connection to the load. The system supplying energy to the Load comprises not only the feeder line, but also the filter (Tank 1). In that case, the energy is no longer drawn from the line, but can be also supplied by the filter. Thus, in terms of the feeder line, its total value is significantly decreased. Due to that, the line re-dimensioning is no longer necessary.

In the case of the filter and the DC-DC converter, the Tank volume is analogous to the relation between those volumes also in the real system.

In the tested topology, the filter acts as a buffer responsible for the appropriate line current shaping. It is aimed at obtaining sinusoidal flow (waveform) cophasal with the line voltage, according to the Equation (1):

$$i_{\text{line}}(t) = i_{\text{filter}}(t) + i_{\text{load}}(t)\,, \tag{1}$$

where:

$$\begin{aligned} & i_{\text{line}}(t) = A \cdot \sin(\omega t + \varphi) \\ & A \approx \text{const.} \\ & \omega - \text{angular frequency} \\ & \varphi - \text{initial phase.} \end{aligned} \tag{2}$$

The continuity of the energy draw from the feeder line, performed by the filter and resulting from the Equation (2) means it is necessary to store the energy by the filter (Tank 1) during the load downtime, and return it during its operation. Thus, it supports the load operation and simultaneously reduces the peak value of the energy drawn from the line, at the expense of the previously stored energy.

Assuming that the load operating time is many times shorter than its idle time, an appropriately selected continuous and time-constant flow value (in the 'Constant flow' point, Fig. 1) is able to compensate the periodical load of many times greater value.

In the analyzed structure, shown in Fig. 1, the filter has no information on the current amount of stored energy (Tank 1) ensuring its proper operation. The energy level has no direct effect on the set flow value (on the current I_{line}). However, this type of solution forces the employment of an additional system controlling the energy level stored in the system, as well as a sophisticated control strategy.

A dedicated bidirectional non-separated DC-DC converter system [3, 7, 19-23] (shaded area in Fig. 1) is responsible for the maintaining (stabilization) of the appropriate energy level in the DC-link (including Tank 1). The device enables performing two operation modes:

- Buck mode – decreasing the input voltage by means of the energy storage (capacitor) charging on the output. The energy flows form the source of the higher voltage U_{DC} to the source of the lower voltage $U_{DC/DC}$;
- Boost mode – appropriate increasing the input voltage U_{DC} at the expense of the energy previously stored in the DC-DC circuit.

As a result, the level of the energy stored in the converter storage (Tank 2) will determine the flow value (set current value) executed by the filter system and perceived by the feeder line in the 'Constant flow' point.

The correct operation conditions of the system shown in Fig. 1 are ensured when the energy (voltage $U_{DC/DC}$) level of the converter does not exceed the value above which each succeeding portion could damage it. This corresponds to setting too high current value (or too long period of waiting for next load switching on). Whereas, setting too low current value will not guarantee the correct stabilization of the filter voltage U_{DC} by the converter system. The minimum voltage $U_{DC/DC}$ level equals 1/3rd of the assumed reference value. It corresponds to the storage charging level of 11%, which precludes the further stable operation, e.g. in the boost mode.

Therefore, the control system should be required to set the appropriately low current value. The value should simultaneously ensure the maintaining of the appropriate energy levels in the storages within the structure. Especially between succeeding load switching (I_{load}).

The system should turn off in the event of the lack of the load switching. It is only possible in view of the possibility of exceeding the maximum allowed level of the energy stored by the system (effective feeder line current value I_{line} will be decreased to zero).

The presented operating concept was used to implement the system in the form typical for power electronic systems. Fig. 2 shows the diagram of the power circuit and the control system of the active filter with additional energy storage, performing the previously assumed tasks.

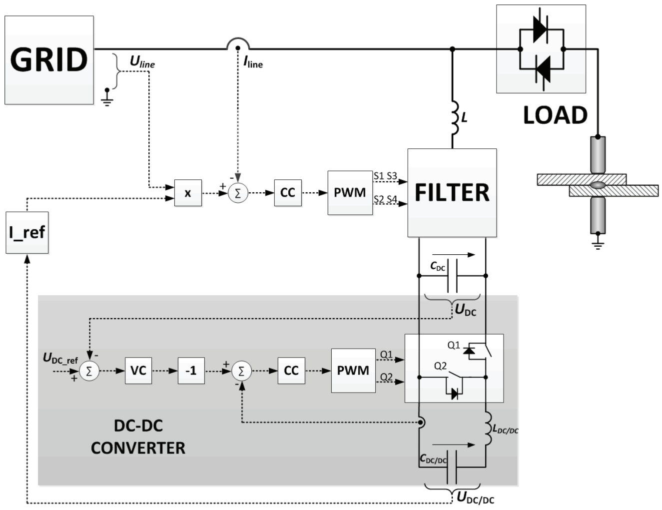

Fig. 2. Block diagram of the filter system with additional energy storage and control system; where: CC – current controller, VC – voltage controller, S1-S3, S2-S4 – filter switches (H-bridge configuration), Q1 Q2- DC/DC converter switches

Welding machines are one phase loads supplied with phase or phase to phase voltage, equipped with thyristor switches connected in counter parallel [24]. This enables full control of the power supplied to the weld point (so called weld nugget).

The one phase filter system is composed of four switches operating in a full bridge [25, 26], executing the unipolar pulse width modulation (PWM), additionally reducing the switching frequency component, and consequently minimizing the size of the filter output choke L [27]. An important aspect in this system is also the correct selection of the choke L. The inductance determination must take into account the interrupted character of the load operation, switching frequency as well as possible voltage level increase in the DC-link (in order to ensure the assumed ripple component filtering while simultaneously maintaining the appropriate system response dynamics).

The filter current waveform (Fig. 2) is shaped on the basis of the instantaneous value of line voltage (U_{line} – reference sinusoid, provided that the line voltage is not distorted; otherwise, it is necessary to use a phase-locked loop PLL [28]).

In the discussed system, the current reference (I_{ref}) is associated with the signal proportional to the energy stored in the DC-DC converter system. It is contrary to the conventional closed loop control structures [3, 5] with voltage regulator output signal (P or PI structure), with voltage error U_{DC} on the filter capacitor fed to its input. Thereby, the DC-DC converter is responsible for the voltage stabilization on the filter capacitor which, as mentioned above, has no information on the current energy level in the DC-link. Due to that, the momentary voltage variations resulting from the load switching have no effect on the line current change which as a result can be maintained at a time-constant level (minimum voltage level on the filter capacitor is determined by the value [3], while the maximum value results from, among other things, the physical parameters of the capacitor and semiconductor elements used).

The two state operation of the bidirectional DC-DC converter is executed by means of the appropriate control of the duty cycle controlling the operation of both switches Q1, Q2. Signals switching on both switches are mutually inverted, which further simplifies the control execution of such systems.

The system responsible for the correct DC-DC converter operation (shaded area in Fig. 2) is based on a classic cascade control structure. It provides voltage stabilization on the converter input (U_{DC}), contrary to the conventional solutions stabilizing voltage on its output ($U_{DC/DC}$). This modification entails the necessity to reverse the direction (sign) of the current reference (from the voltage controller VC). Hence, the product of this signal with value '-1' in the current reference path is required for the correct system operation.

One of the advantages of using a half bridge topology is a small value of the passive element parameters within its structure, resulting from, among other things, the assumed switching frequency and allowed current ripple value (the selection of passive elements within its structure is analyzed separately and will not be mentioned here). Therefore, it is a correct choice for energy storages, irrespective of the energy storage on its output (e.g. flywheel, supercapacitor, etc.). The factors determining the selection of specific energy storage are primarily:

- high density of stored energy;
- low internal impedance, responsible for high rating of current build-up;
- high number of charging and discharging cycles without the loss of energy storage capacity.

The fulfilment of these requirements by the selected solution not only lowers the costs, but also increases the efficiency, and consequently increases the efficiency of the entire system [29]. In the analyzed case, a supercapacitor was used as the energy storage on the DC-DC converter output.

It should be noted that physical aspects related to supercapacitor equivalent circuit [30] were not analyzed in this paper. The complexity of the issue will be subject of separate considerations. However series capacitor resistance needs to be taken into account during planned efficiency studies. The current stage of the project relates to control strategies of the energy transfer between filter, energy store and feeder.

3. Simulation test results

The simulation tests carried out utilizing a model developed in Matlab & Simulink environment, whose block diagram with section division is shown in Fig. 3.

During the works on the system, two examples of current waveforms were used, recorded on a real welding machine, which can occur during welding (of galvanized sheets around 1 mm thick), depending on the manufacturing process requirements (Fig. 4 and 5). During the simulation, the current waveforms were reflected by means of the appropriate selection of the substitute model composed of RL elements and the firing angle of the used thyristors.

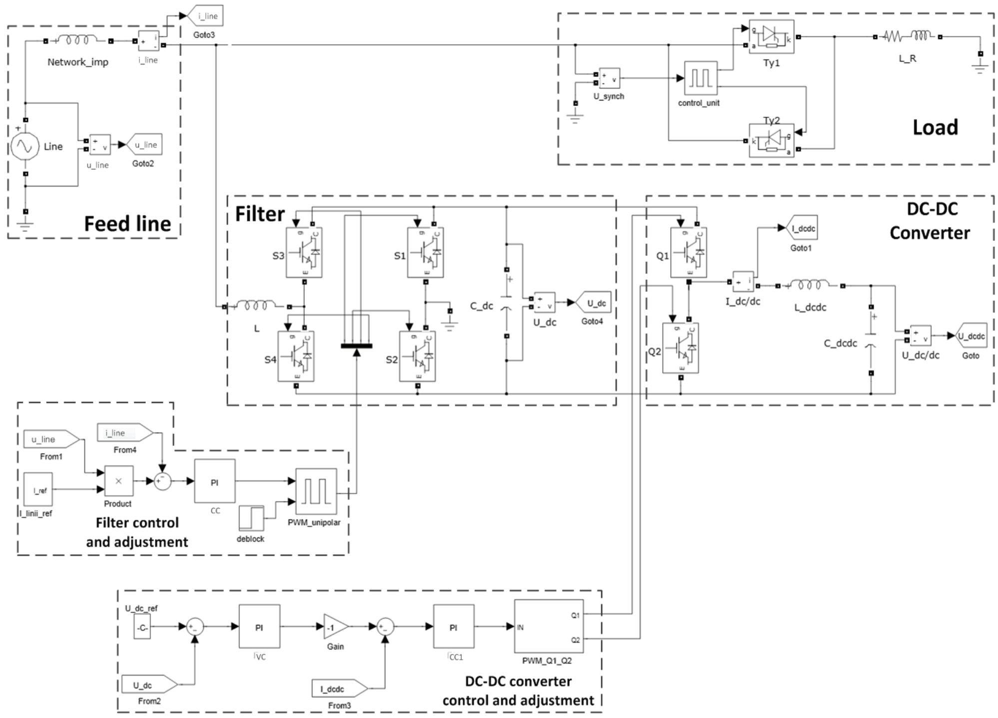

Fig. 3. Simulation model of a system developed in Matlab & Simulink environment

The legitimacy of the analysis of such waveforms results from the fact that they can be primarily used for the proper dimensioning (on the basis of the energy drawn in one cycle) of the designed filter as well as for a more comprehensive analysis of the phenomena occurring at the simulation level in the systems of this type.

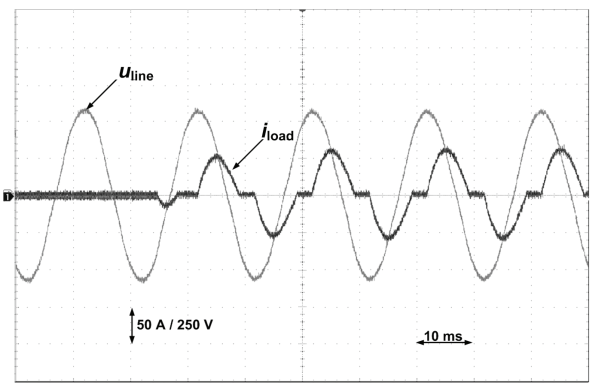

Fig. 4. Current and voltage waveforms during welding, recorded on a real object – case 1

The number of cycles (full supply voltage periods through the switched on system) in real systems results from the thickness of the elements being welded. The intervals between succeeding system switchings result from the manufacturing process in which the electrodes or the material must change position, which directly determines the moment of the next system turning on.

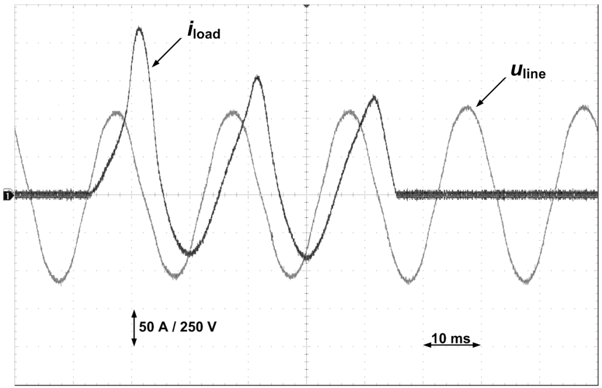

Fig. 5. Current and voltage waveforms during welding, recorded on a real object – case 2

In the case of welding machines, the pulses switching on the thyristors (synchronized with zero-crossing of the line voltage) are generated during a half-cycle, when a given switch may be switched on. However, the appropriate thyristor will not start conduction until the electrodes contact the welded elements, creating a path for the current flow.

Fig. 6 shows the line current and voltage waveforms as well as current harmonic spectrum resulting from the simulation. They are analogous to the real waveforms in Fig. 4. This proves that the simulation results and the results obtained in the real system concur. Odd harmonics occur in the line current, with the fundamental harmonic being predominant. The phase shift of the current and voltage fundamental harmonics results from the firing angle of the thyristor and transformer reactance.

The identical analysis was also made for the waveform in Fig. 5. The simulation results are presented in Fig. 7. Due to a small value of firing angle of thyristor, the current waveform is approximately sine wave. It is similar to currents occurring during short-circuit, in whose an aperiodic DC component can be observed [31]. It is proved by the presented spectrum, where the harmonic predominant in the current, apart from the fundamental harmonic is the zero component which may have an adverse effect on other objects, e.g. transformers, causing additional losses in the core.

Fig. 8 shows instantaneous active power values during the welding machine operation, determined on the basis of the waveforms in Fig. 6 and 7. The presented waveforms indicate that the active power does not flow through the feed line continually, but only for periods of time, and its peak instantaneous value does not exceed 76 kW. The instantaneous power waveforms were consequently used for calculating the energy drawn by the system during a single switching, which is illustrated in Fig. 9.

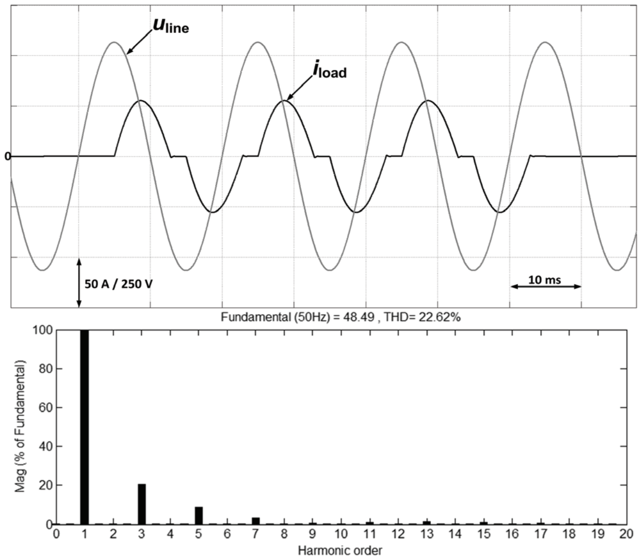

Fig. 6. Current and voltage waveforms during welding and current harmonic spectrum resulting from the simulation – case 1

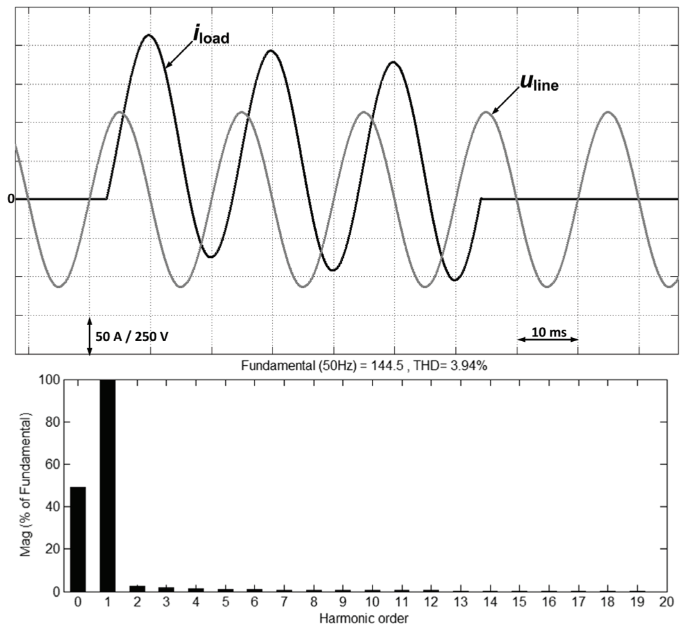

Fig. 7. Current and voltage waveforms during welding and current harmonic spectrum resulting from the simulation – case 2

Fig. 9 also indicates that during the operation, the energy drawn from the feed line by the welding machine equals about 83 mWh when operating with characteristics designated as 1 and 45 mWh in case 2.

Despite the higher maximum current values in case 2, during one operation cycle, the energy value level is significantly lower in comparison to case 1. However, the capacitors used must be dimensioned to account for its peak value.

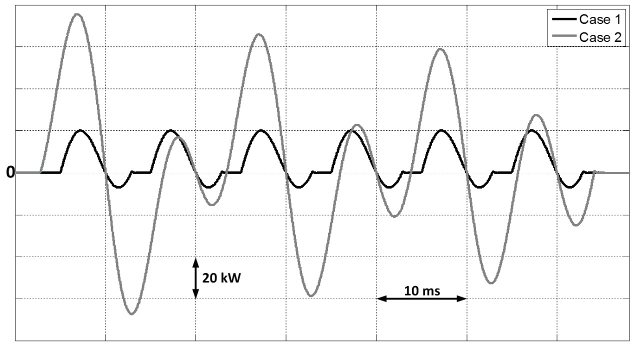

Fig. 8. Momentary active power value waveforms during welding

The minimum value DC-link capacity C_{DC} [3] was determined as a result of the formula (3):

$$C_{DC} \geq \frac{2P_{max}}{f_i(U_{DC\_ref}^2 - U_{DC\_min}^2)} \tag{3}$$

where: P_{max} is the maximum load active power; f_i is the fundamental frequency; U_{DC_ref} is the rated DC-link voltage; U_{DC_min} is the minimum DC-link voltage.

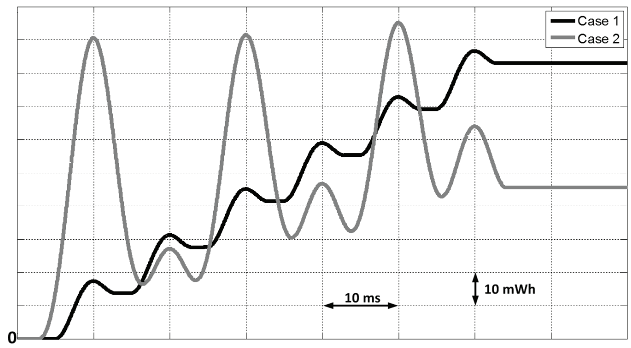

Fig. 9. Energy drawn by the welding machine from the feed line during welding

As a result, assuming the voltage U_{DC} stabilization at 900 V, the minimum value of 570 V and safety margin resulting from the possibility of load occurrence of various characteristics (only two sample current waveforms during welding were analyzed), the capacity value should not be lower than 1.5 mF. Such selected element value was then included in the employed model.

As a result of the simulation tests conducted on the developed model, the average power waveforms were recorded (Fig. 10): in terms of the feeder line, drawn by the load and circulating in the DC-DC converter circuit (the filter was omitted since it was operating as a buffer-assuming zero losses) The power balance developed on their basis proves the high effectiveness of the discussed solution.

The maximum value of the average load active power is around 2.4 kW. In terms of the feeder line, during the system operation, the power was significantly lower, equal around 0.3 kW. However, it is already supplied continuously, limiting surges coming from the periodically switched on device, which was the main assumption during the system designing.

The power waveform in DC/DC converter circuit (Fig. 10c) indicates that the load turning on does not cause the increase of the active power drawn from the feed line, but only the energy loss in the DC-DC converter circuit. In practical terms, it means that no additional welding machine current measurement is necessary in order to estimate the load power. This significantly simplifies the digital implementation.

Fig. 10d shows the instantaneous $U_{DC/DC}$ voltage waveform The set feeder line current value ensures that the average value of this voltage is maintained within a range guaranteeing the correct system operation (U_{DC} waveform is omitted – since it is almost constant due to DC/DC converter stabilization function). Notice that thyristors were operating with constant firing angle and regular intervals between succeeding load turning on.

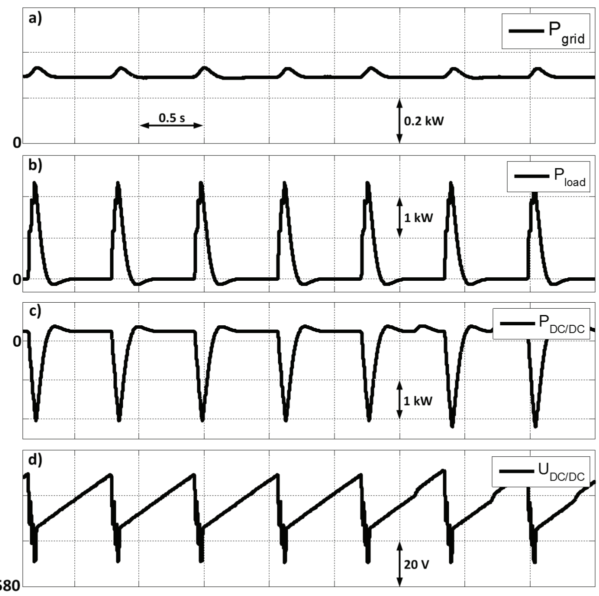

Fig. 10. Active power waveforms recorded in selected system points: a) drawn from the feed line; b) drawn by the load; c) circulating in the DC-DC converter circuit; d) voltage $U_{DC/DC}$ on the DC-DC converter capacitor

Fig. 11 shows the waveforms of the energy drawn from the feeder line by the welding machine during a several cycles of operation, and in the case of using the discussed active filter solution. In the first of the analyzed cases, the energy has a 'stepped' characteristics; it is drawn only when the welding machine is being switched on. Additionally, power surges become visible. The functioning of the presented system eliminates the discussed phenomenon, causing the energy drawn from the line to increase linearly. In practical terms, it means forcing the active power to flow through the feed line, at practically time-constant level; the active power value is determined only by the level of the energy stored in the DC-DC converter capacitor.

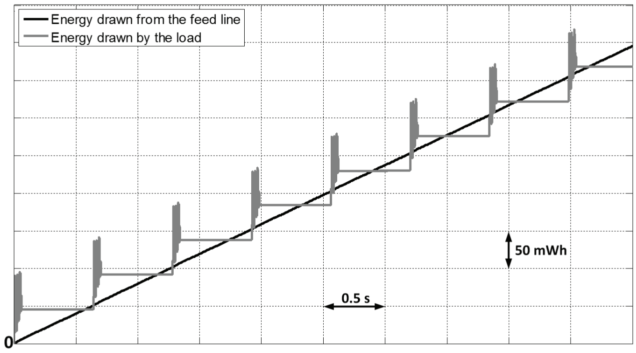

Fig. 11. Waveforms of the energy drawn by the welding machine several cycles of operation and in terms of the feed line

4. Conclusions

The concept of the active filter system with additional energy storage presented in the paper and the conducted tests show the high effectiveness of the proposed solution. The presented simulation results, performed on a specially developed model, illustrate the basic device operation state and correct execution of the set tasks.

A difficulty in developing such system comes from the inability to use an ordinary power balance, as the operating cycle of the load can vary (e.g. change of peak load current value, change of interval between operating cycles, change of operating time). The analysis of the real current waveforms during welding, and the resulting concurrent simulation waveforms based on it, enabled, among other things, the dimensioning of the reactive elements within the structure as well as the testing of the researched solution. However selection of the energy storage capacity is complex task, conditioned by the specific application (i.e. welding machine rated power). It depends on i.e. assumed maximum continuous RMS value of the line current, realized by filter and allowable at the point of connection, due to the feeder line limitation. Chosen capacity should also provide stabile operation of the compensator at the load parameters variation (ensure minimum energy level without increase or changes of the line current).

Due to the random and arbitrary load switching, further optimization of the discussed structure will require the control improvement (e.g. controllers tuning optimization). It will also require a development of an advanced current setting algorithm enabling to predict its values in a wide time frame, taking into account past behaviour of the load.

Appendix

Table 1. Ratings and parameters used during simulations

C_{DC}	mF	1.5
L	mH	4.3 (ripple current less than 5%)
$C_{DC/DC}$	mF	10
$L_{DC/DC}$	mH	1.4 (ripple current less than 5%)

References

[1] Hanzelka Z., *The quality of electric power supply*, AGH University of Science and Technology Press, (2013), (in Polish).

[2] Benysek G., *Improvement in the quality of delivery of electrical energy using power electronics systems,* Springer (2007).

[3] Piróg S., *Power electronics: systems with network and hard commutations*, AGH University of Science and Technology Press (2006), (in Polish).

[4] Maciążek M., Grabowski G., Pasko M., *Active power filters – optimization of sizing and placement*, Bulletin of the Polish Academy of Science Technical Science 61(4): 847-853 (2013).

[5] Bień A., *Measuring systems in the power industry*, AGH University of Science and Technology Press (2013), (in Polish).

[6] Kunjumuhammed L. P., Mishra M. K., *Comparison of single phase shunt active power filter algorithms*, Power India Conference IEEE (2006).

[7] Huann-Keng Ch., Bor-Ren L., Kai-Tsang Y., Kuan-Wei W., *Hybrid Active Power Filter for power quality compensation*, Power Electronics and Drives Systems, PEDS 2005, International Conference on 2: 949-954 (2005).

[8] Chi-Seng L., Wai-Hei Ch., Man-Chung W., Ying-Duo H., *Adaptive DC-Link Voltage-Controlled Hybrid Active Power Filters for Reactive Power Compensation*, Power Electronics, IEEE Transactions on 27: 1758-1772 (2012).

[9] Alcala J., Cardenas V., Miranda H., Perez-Ramirez J., Charre S., *A three-phase back-to-back converter for reactive power compensation, current harmonic filtering and active power compensation*, Energy Conversion Congress and Exposition (ECCE), pp. 2371-2377 (2013).

[10] Belyakov A.I., Sojref D.A., *High power supercapacitor's solutions for reliable power supply*, Power Engineering, Energy and Electrical Drives, POWERENG '09. International Conference on, pp. 348-352 (2009).

[11] Xuancai Z., Xiao L., Guoqiao S., Dehong X., *Design of the Dynamic Power Compensation for PEMFC Distributed Power System*, Industrial Electronics, IEEE Transactions on 57(6): 1935-1944 (2010).

[12] Kato K., Ishigma S., Nakajima Y., Arai H., Ueda T., Iwata T., Ito Y., Sugao, K., *10MW, 3.3MWh Energy Storage System consisting of 4000 Flywheels controlled by ICT network for short cycle power fluctuation compensation*, Power Electronics Conference (IPEC-Hiroshima 2014 – ECCE-ASIA), 2014 International, pp. 403-408 (2014).

[13] Miao-Wiao Ch., Kato S., Sumitani H., Shimada R., *Cache power for stand-alone power systems: Flywheel-based AC power solution*, Power Electronics Conference (IPEC), 2010 International, pp. 2508-2515 (2010).

[14] Park C.H., Jang S.J., Lee B.K., Won C.Y., Lee H.M., *Design and control algorithm research of active regenerative bidirectional DC/DC converter used in electric railway*, Power Electronics 7th International Conference on, pp. 790-794 (2007).

[15] Xiao-li Ch., Da-qiang L., Wei-dong Z., *Braking energy recovery for electric traction based on super-capacitor and Bidirectional DC-DC converter*, Power Electronics and Motion Control Conference (IPEMC) 2: 879-883 (2012).

[16] Baszynski M., *Power factor correction boost rectifiers for the household appliances*, Electrical Review87(3): 237-242 (2011).
[17] Pirog S., Baszynski M., *Modelling a single phase multicell DC/AC inverter using FPGA*, Electrical Review 84(2): 84-87 (2008).
[18] Steiner M., Klohr M., Pagiela S., *Energy storage system with ultracaps on board of railway vehicles*, Power Electronics and Applications, European Conference on, pp. 1-10 (2007).
[19] Kazimierczuk M.K., *Pulse-width Modulated DC-DC Power Converters*, John Wiley & Sons (2008).
[20] Dawidziuk J. *A dual inductor-fed boost converter with an auxiliary transformer and voltage doubler*, Bulletin of the Polish Academy of Science Technical Science 61(4): 787-791 (2013).
[21] Barlik R., Nowak M., Grzejszczak P., *Power transfer analysis in a single phase dual active bridge* Bulletin of the Polish Academy of Science Technical Science 61(4): 809-828 (2013).
[22] Richelli A., Comensoli S., Kovacs-Vajna Z.M., *A DC/DC Boosting Technique and Power Management for Ultralow-Voltage Energy Harvesting Applications*, Industrial Electronics, IEEE Transactions on 59(6): 2701-2708 (2012).
[23] Yen-Shin Lai, Bo-Yuan Chen, *New Random PWM Technique for a Full-Bridge DC/DC Converter With Harmonics Intensity Reduction and Considering Efficiency*, Power Electronics, IEEE Transactions on 28(11): 5013-5023 (2013).
[24] Senderski A., *Formulation of simulation models of power electronics systems*, AGH University of Science and Technology Press (2013), (in Polish).
[25] Wu B., *High-Power Converters and AC Drives*, Wiley-IEEE Press (2006).
[26] Abu-Rub H., Iqbal A., Guzinski J., *High Performance Control of AC Drives with Matlab/Simulink Models*, John Wiley & Sons (2012).
[27] Barlik R., Nowak M., *Power electronics: elements, components, systems*, Oficyna Wydawnicza Politechniki Warszawskiej (2014), (in Polish).
[28] Best R.E., *Phase-locked loops: design, simulation, and applications*, NY: McGraw-Hill (2003).
[29] Zhang X., Tong D., Ding H., Xu D., *Research of digital control bidirectional DC/DC converter based on ultra-capacitor*, Power Electronics and Motion Control Conference (IPEMC), 3: 1545-1549 (2012).
[30] Lingling D., *Study on supercapacitor equivalent circuit model for power electronics applications*, Power Electronics and Intelligent Transportation System (PEITS), 2nd International Conference on, 2: 51-54 (2009).
[31] Electrical Engineering Handbook, *Collective work*, 3, WNT (2011), (in Polish).