Line Conditioning with Grid Synchronized Inverter's Power Injection of Renewable Sources in Nonlinear Distorted Mains

Péter Görbe, Attila Magyar, Katalin M. Hangos

***Abstract*— A novel "line-friendly" method of controlling the small domestic power plants using renewable energy is described in this paper. This method is not only capable of optimizing the working point of the plant but also implements active power factor correction and lowers the extant harmonic distortion in the line. The novel element in the proposed complex multifunctional controller unit is the upper harmonic controller that minimizes the amplitudes of the 3rd and 5th upper harmonic component in the output voltage by using a version of the gradient method. The proposed controller has been investigated by simulation in Matlab environment, and as a result, substantial improvement of the output voltage and current waveform could be achieved.**

I. Introduction

Nowadays the price of electric energy is raising and many people are making up their minds to lower the CO_2 emission to save the environment and to lower their cost of living. In the European Union the small domestic power plants are coming into general use, too (in the range of 1kVA-5kVA). The isolated working mode of these plants with using battery storage system for energy storage is not an efficient way, because of the high price and limited lifetime (max 6-10 years) of the storage system. There are no cost effective alternatives for energy storage, because the flywheels, the high pressured H_2 with fuel cell, compressed-air energy storage (CAES), supercapacitors, superconducting magnetic energy storage (SMES) or pumped-hydroelectric storage (PHS) [1] are all in development phase and too expensive for comprehensive applications.

In many countries the national law of power supply has been changed in recent years to give possibility for using grid tie inverter systems to inject the spare power to the local low voltage mains through two-way power meters. This power is utilized in the local neighborhood, not far from the injection point so the loss is small. In addition, the construction of this type of inverters makes them suitable for conditioning the line, correcting the accurate voltage forms, and repairing the reactive power in the mains. Therefore, this additional functionality doesn't need expensive change of the constructions (like the "line-friendly" working methods of DC converters), we should only modify the control methods and regulators to develop the ability of line conditioning. The cost of changing the controlling processor and control software negligible to the cost of equipment.

Several papers deal with power injection to the grid [1], [2], others with power factor correction [2], [3], [5] and nonlinear distortion reduction [6] and [8]. In [6] and [8] the author uses the DSP based current control technique for distortion reduction with active power filters (APF) for compensating an exact nonlinear load. Sensing the nonlinear current time function and the ideal sinusoid current with phase locked loop (PLL) technique, they inject the exact deviation current into the grid with radical distortion reduction.

The aim of this paper is to develop and investigate control methods for performing active power factor correction and lowering the extant harmonic distortion in the line without exact current sensing, addition to control the maximum power operating point from the renewable source (wind generator or photovoltaic panel) by adding new elements to the schematic construction designed for the built-in elements.

II. Background and Motivation

The use of low consumption equipments with simple switching power supplies (mobile phone chargers, notebooks, networking products, small variable frequency motor drives, telecommunication consumer electronics) is more and more widespread nowadays. These equipments use a simple performance input stage (Figure 1.) configuration that is a capacitive load with high nonlinearities.

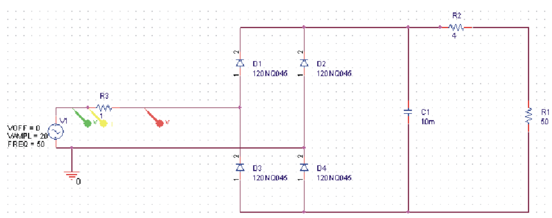

Fig. 1. Capacitive input stage model

These appliances create significant 3th and 5th upper harmonic current components, which cause serious distortion in the voltage shape. Figure 2. depicts the time-domain shape of the periodic power and current signals of the capacitive input stage model (Figure 1.). Figure 3. shows the frequency domain description of the above signals, and indicates that there is a significant 3th and 5th upper harmonic component in the current.

This work was supported by the Hungarian National Research Fund through grant K67625

P. Görbe is with Department of Electrical Engineering and Information Systems, University of Pannonia, 8200 Veszprém, Hungary gorbep@almos.vein.hu

A. Magyar is with Department of Electrical Engineering and Information Systems, University of Pannonia, 8200 Veszprém, Hungary amagyar@almos.vein.hu

K. M. Hangos is with Department of Electrical Engineering and Information Systems, University of Pannonia, 8200 Veszprém, Hungary, and with the Process Control Research Group, Computer and Automation Research Institute, 1518 Budapest, Hungary hangos@scl.sztaki.hu

It is difficult to compensate the reactive power of this type of nonlinear distorted voltage shape with traditional shunt capacitances (compensator) based on the so-called cyclodissipativity property [3], since the definition of the reactive power is useless for nonlinear networks.
The distortion of the voltage shape is commonly characterized by the overall reactive power

$$Q_B = \sum_{k=1}^{n} Q_k = \sum_{k=1}^{n} \frac{|\hat{V}_s(k)||\hat{I}_l(k)| \sin \phi(k)}{2}$$

where the positive integer n is the (highest) number of harmonics of interest, Q_k, $\hat{V}_s(k)$, $\hat{I}_l(k)$ and $\phi(k)$ are the the reactive power, the source (s) peak voltage, the load (l) peak current and the phase-angle difference of the k-th harmonic, respectively. The power factor (PF) of the source is defined by [3] as

$$PF = \frac{\langle V_s, I_s \rangle}{||V_s||||I_s||}$$

where $P = \langle V_s, I_s \rangle$ is the active (real) power and the product $S = ||V_s||||I_s||$ is the apparent power calculated from effective values. From the Cauchy-Schwartz inequality, it follows that $P \leq S$. Hence $PF \in [-1, 1]$ is a dimensionless measure of the energy-transmission efficiency. The total harmonic distortion (THD) is defined as [5]:

$$THD = \sqrt{\frac{\sum_{k=2}^{\infty}(|V_k|^2)}{|V_1|^2}}$$

where V_1 equals to the voltage amplitude of the fundamental frequency and V_n is the voltage amplitude of the nth harmonic. In applications with capacitive input stage the $THD > 0$ holds.

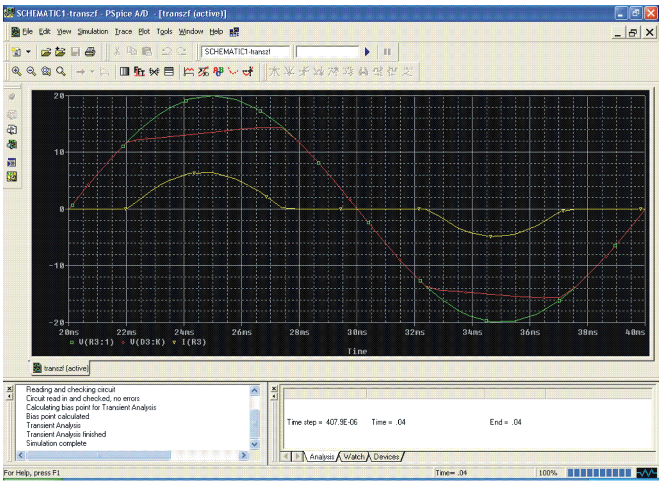

Fig. 2. Capacitive input stage model time domain analysis.

This type of distortion occurs in every mains plug in every home. In the near future this distortion, this nonlinear reactive power and the THD will probably increase because of the growing rate of simple switching type power sources in household appliances.

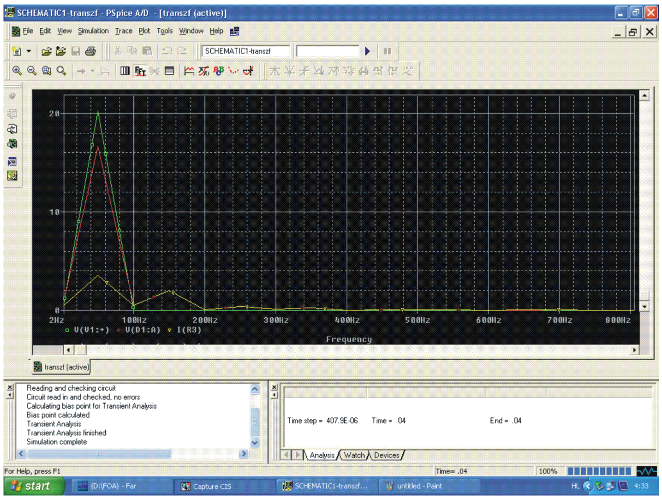

Fig. 3. Capacitive input stage model frequency domain analysis.

III. Problem Statement

As it is indicated in the above discussion, it is desirable to develop a control method that can compensate the distortion caused by the capacitive nonlinear load using the built-in and available controller of small domestic power plants. The controller unit of these plants can be extended with new elements to form a complex multifunctional controller unit.

The first function of this complex control unit is a conventional maximum power controller that is used to inject base harmonic in phase sinusoid current to the mains. The second function to be implemented is the compensation of the undesirable effects of the linear network with production base harmonic current being not in phase, to inject reactive power to compensate the inductive and capacitive loads. The third function to be implemented would be the compensation of the nonlinear distortion that is achieved by injecting upper harmonic (mainly 3th and 5th) sinusoid current components to reduce the harmonic distortion and to lower the reactive power of the upper harmonic load currents.

The task to be solved is to implement the missing two elements and their relationship, the main directive for the implementation is to use the simplest possible method for them. The main goals of the two new elements are to approach unity power factor for the complete system with several loads, and to reduce THD. There is a trade-off between these goals that should be taken into account. The intervention to these factors is limited by the renewable source maximum power point, the semiconductors of the bridge and the serial inductances, and by the speed and cycle time and the computational capacity of the control device. The optimum would be the unity PF and the zero THD, unfortunately this optimum is not achievable in practice, just approachable. The practical aim is to compensate the 3th and the 5th upper harmonic component. As a first step we will monitor only the output voltage of the system and compute the necessary upper harmonic current components using Fourier transformation. These values will be used to reduce the nonlinear distortion at the output.

A. The Elements of the Multifunctional Complex Controller Unit

A simple model of the grid tie inverter [2] is used for the controller structure design, that is shown in Figure 4.. It contains a simple booster stage with an IGBT bridge, connected to the grid through serial inductance.

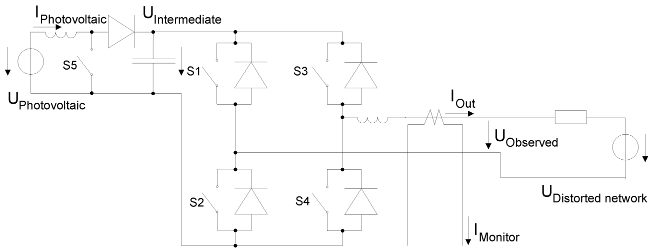

Fig. 4. Grid Tie Inverter model

The control system can be divided to four main functional parts:

(1) the maximum power controller,
(2) the intermediate voltage controller,
(3) the upper harmonic controller, and
(4) the current waveform generator.

These blocks influence each other directly, and also through some measurable parameters (voltages, currents) of the inverter (see Figure 5.).

The **maximum power controller** is a general part of the control system, independent from the other control parts. Its' only task is to operate the renewable power source (photovoltaic panel or wind generator) at the optimal working point in any wind and solar condition to get the maximal amount of electric power from the source (to reduce the payback time of the financial investment). The controller has to move the working point current up and down continuously to sense the sign of the power derivative in order to preserve the optimal power point in changing solar and wind condition. If the solar or wind conditions change, the controller senses the same sign of the power derivative in both end of the power function $P_{PV}(I_{PV})$. This error will be accumulated and the new maximal power point will be reached by a PI controller.

The output of the maximum power controller is the input current setpoint of the inverter. The input current control is a simple on/off switching nonlinear hysteresis controller [6]. This booster stage consist of an IGBT switch, diode and serial inductance. The hysteresis of the controller and the value of the inductance define the switching frequency of the boost controller. We have to compromise with the input current deviation amplitude, the switching frequency (booster IGBT switching time, dissipation), and the serial booster inductance value (price and ohmic loss of inductance).

The **intermediate voltage controller** senses the intermediate voltage, and observes the difference between the measured and the setpoint value. The controller changes the fundamental harmonic amplitude of the injected current using a simple P controller based on the difference. Upper harmonic components have no effect on the intermediate voltage so they are not used by the controller. The controller adjusts the effective power injection to the grid.

The *measuring device* analyzes the investigated part of the network. It measures the assigned voltage or current of the circuit and calculates the 3th and 5th upper harmonic component amplitude and phase of the distorted shape variables using Fourier transformation. The frequency domain behavior of the currents and voltages are monitored at an assigned point by measuring the the inverter's output voltage U_{Out} and calculating the amplitude and phase of the 3th and 5th harmonic components.

The main controller of the complex multi-functional unit is the **upper harmonic controller**. Its' inputs are the computed 3th and 5th upper harmonic component amplitudes of the measured voltage, the outputs are the output current base, and its 3th and 5th upper harmonic components' amplitudes and phases. These currents are used for compensating the nonlinear distortion (see later in sub-section III-B).

The output current base, 3th and 5th components amplitude and phase data are then fed to the **current waveform generator**. This block calculates the necessary exact time function of the output current setpoint with the help of analytic sine functions, amplitude multipliers and time delayers for correct amplitude and phase conditions. This is the setpoint of the bridge current controller.

The *bridge controller* calculates the difference between the measured output current and the output current setpoint, and switches the IGBT bridge two half's control signal (S1-S4, S2-S3) on and off in alternate way using a simple Schmitt trigger comparator, that realizes a simple on/off switching hysteresis controller [6]. The same compromise has been made between the output current deviation amplitude, the switching frequency of the IGBT bridge (switching time, dissipation), and the output serial inductance value (price and ohmic loss of inductance) as before.

B. Compensation of the Nonlinear Distortion

The upper harmonic controller calculates the necessary optimal amplitudes and phases of the 3th and 5th output current components. A simple static optimization algorithm is used for this purpose that minimizes the following error function:

$$Error = (U_{3ampl} - U_{3amplSP})^2 + (U_{5ampl} - U_{5amplSP})^2$$

where U_{3ampl} and U_{5ampl} are the amplitudes of the 3th and 5th output voltage component, $U_{3amplSP}$ and $U_{5amplSP}$ are the setpoints, respectively in steady-state conditions. The setpoints are set to zero because we would like to reach or approach the zero 3th and 5th amplitude to approach the sinusoid voltage and current shape of a linear system.

It is important to note, that by changing the amplitudes and phases of the 3th and 5th output current component, each one influences both components of the connection point voltage because of the nonlinear nature of the network.

The optimizer uses a version of the gradient method, but it only changes a single input in an optimization step. In each step the following operations are performed:

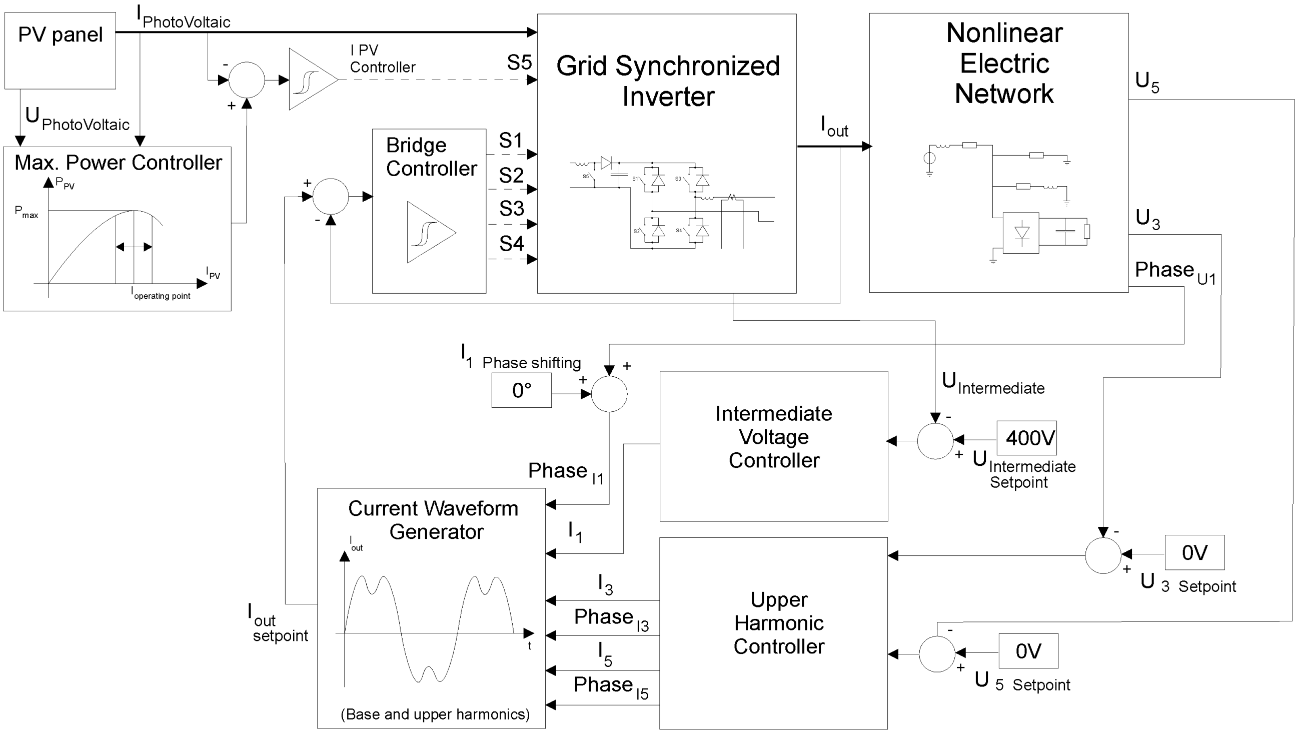

Fig. 5. Control Flow Chart diagram

1) all inputs are changed slowly as a linear function of the error function value (cycle time 0.5s), it doesn't disturb the measuring device computing the 3rd and 5h upper harmonic components,
2) the influence on the error function is observed by approximating the parameter derivative by finite difference,
3) a variable step in the optimization space is performed in the direction of the decreasing gradient of the parameter where the step size depends on the error function value.

Four input parameters are considered:

(1) the amplitude of the 3rd upper harmonic component,
(2) the phase of the 3rd upper harmonic component,
(3) the amplitude of the 5th upper harmonic component,
(4) the phase of the 5th upper harmonic component.

An optimization cycle consists of four steps where each of the above parameters are changed in turns in the direction of its parameter gradient. This way the parameters of the upper harmonic controller converge to a value in the four dimensional parameter space that corresponds to the minimal error function value.

C. Modeling and Simulation

The mathematical model of the nonlinear distorted network has been implemented in Matlab Simulink using Power electronics toolbox [7].

1) Modeling the elements of the system: The low voltage transformer was built with sinusoid voltage source and a serial inductance. The Ohmic loss of the line between the transformer and the connection point was considered with a serial resistance. This point connects the customer to the grid and here is the electric meter that measures the effective power. The grid tie inverter can also be connected here.

Three type of loads have been modeled: (i) an ohmic one, that represents, for example, heating devices, traditional bulbs, (ii) an ohmic with serial inductance representing motors and rotating household appliances (washing machine, lawnmower etc.) and (iii) a capacitive input stage load for representing the simple nonlinear switching mode power supplies.

The next step of the modeling was to build the simple synchronized inverter. Thereafter controller loops, maximum power controller, intermediate voltage controller, IGBT bridge and booster controllers and finally upper harmonic controller have been implemented. The control flow chart of the complete model can be seen in Figure 6.

2) Simulation experiments: As a first step of model verification, the basic elements of the system, the load part, the maximum power controller, and the intermediate voltage controller have been tested using the parameter values collected in TABLE II. These results served as reference values for comparison. Figure 7. shows these simulated voltage and current values as functions of time.

Thereafter the upper harmonic controller and the influence of this control to the shape of the voltage and the current time functions at the connection point was tested by simulation. The upper harmonic controller worked fine, it was stable.

If the inverter is switched on but the upper harmonic controller is set to off mode, then the time-functions of the voltage and the current change as it can be seen in Figure

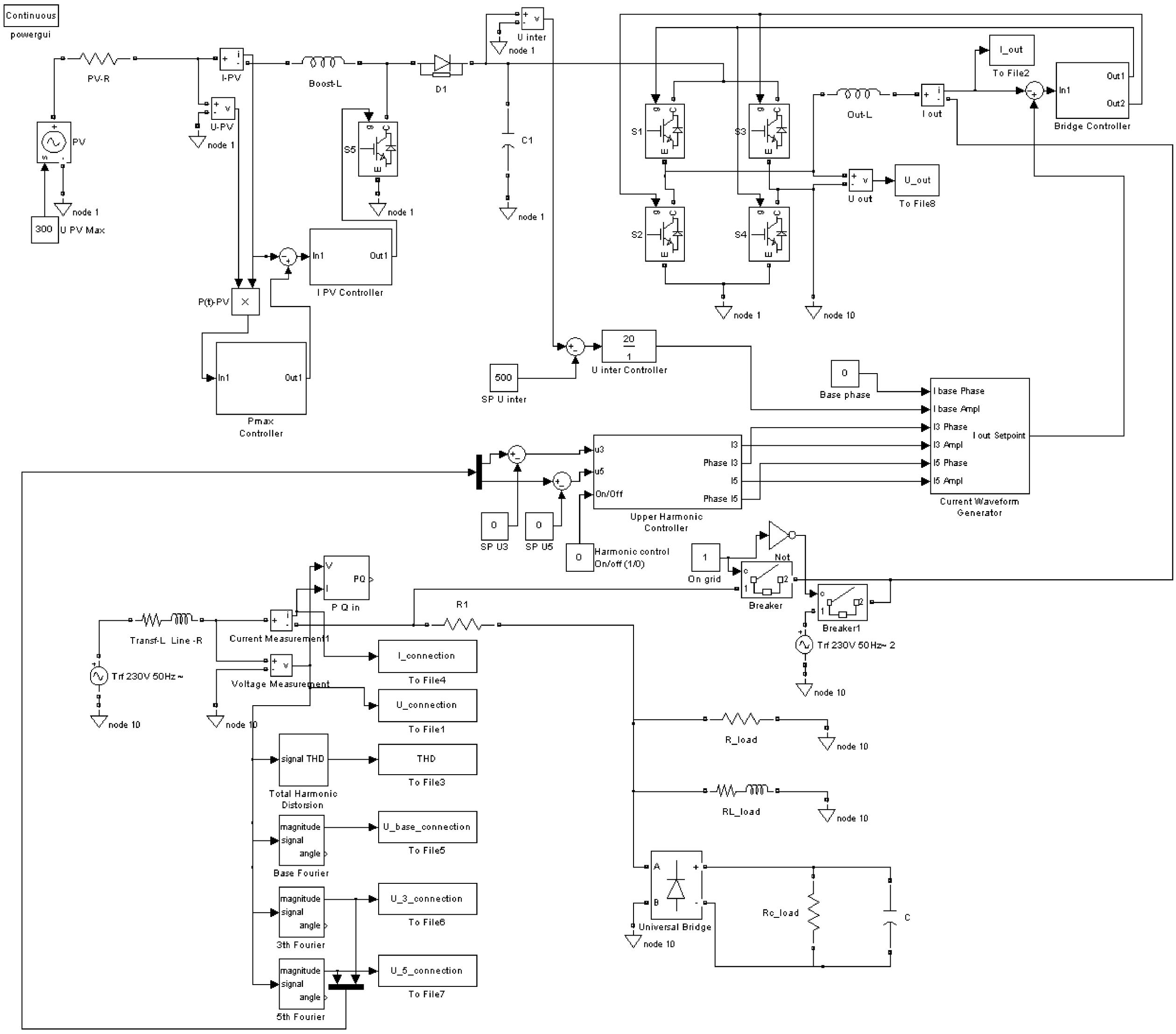

Fig. 6. System Matlab Simulink model

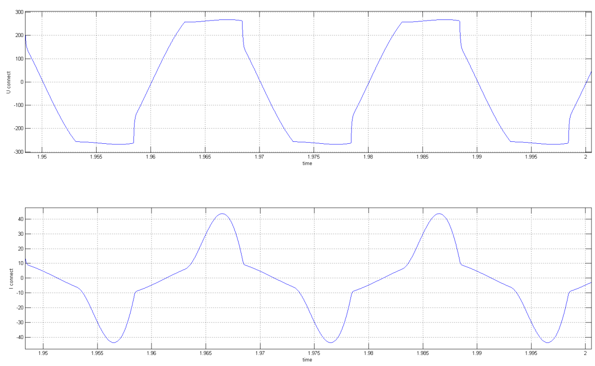

Fig. 7. Simulated voltage and current at the conn. point inverter OFF

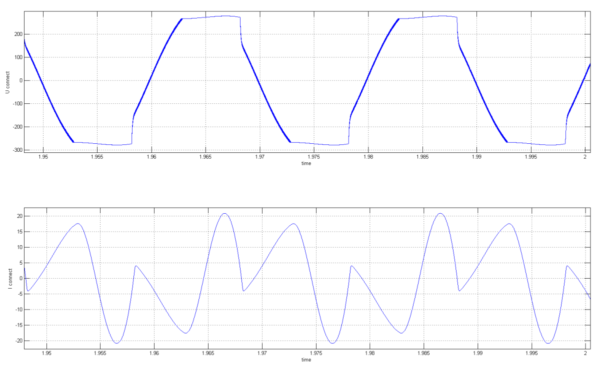

Fig. 8. Inverter ON without upper harmonic control

8. The switching type working mode of the inverter creates a little waviness of the voltage, that causes a high frequency disturbance.

The simulation results with the upper harmonic controller switched on can be seen in Figures 9 and 10. The influence of the upper harmonic controller is apparent on the time plot of

TABLE I

PERFORMANCE RESULTS

Mode	U_{3-Ampl}	U_{5-Ampl}	Error	THD
Inverter OFF	34.52V	16.99V	1480.29V^2	14.26%
Upper h.contr OFF	38.62V	16.28V	1756.54V^2	14.75%
Upper h.contr ON	2.51V	3.41V	17.92V^2	9.30%

TABLE II

PARAMETER VALUES

Parameter	Value	Parameter	Value	Parameter	Value
U_{trf}	230V 50Hz	L_{trf}	3.185mH	R_{sline}	0.5Ω
R_1	0.2Ω	R_{Load}	50Ω	R_{RLload}	35.35Ω
L_{RLload}	112.5mH	R_{RCload}	25Ω	C_{RCload}	10mF
L_{Boost}	100mH	L_{out}	10mH	C_{inter}	100mF

the voltage and the current functions: their shape approaches the sinusoid shape as compared to the uncontrolled function shapes.

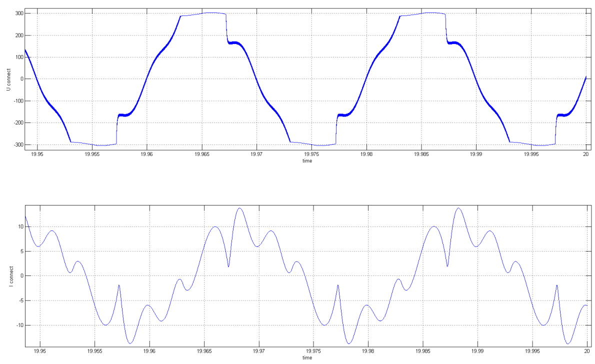

Fig. 9. Simulated voltage and current with upper harmonic control

The operation of the optimization algorithm within the upper harmonic controller can be seen in Figure 10, where the time evolution of the output current parameters (the amplitude and phase of the 3rd and 5th upper harmonic component) and the error function is depicted.

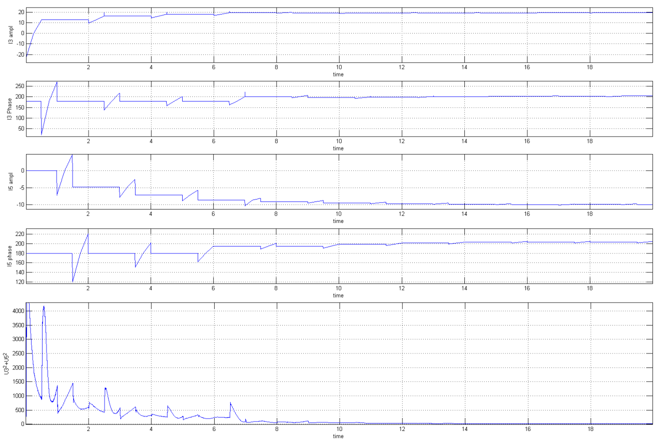

Fig. 10. Output current parameters and error function

The performance values of the simulation results are presented in Table I: the operation of the upper harmonic controller can lower the THD from 14.7% to 9.3% while the error function radically decreases from $1480V^2$ to $17V^2$.

IV. CONCLUSION

A novel "line-friendly" control method for small domestic power plants using renewable energy is described in this paper. It is capable of not only optimizing the working point of the plant but also implements active PF correction and lowers the extant harmonic distortion in the line.

The proposed controller consists of four main parts: (1) the maximum power controller, (2) the intermediate voltage controller, (3) the upper harmonic controller, and (4) the current waveform generator. The novel element in the proposed complex multi-functional controller unit is the upper harmonic controller that minimizes the amplitudes of the 3rd and 5th upper harmonic component of the output voltage by using a version of the gradient method.

The proposed controller has been investigated by using Matlab simulation, and a substantial improvement of the output voltage and current waveform could be achieved. We had difficulties during the research with the upper harmonic controller, because of the the deviations and noisy behavior of the error function, it needs serious filtering and it slows the controlling method radically. Our future aim is to modify the control method to enhance its performance: on the one hand a more effective derivative computation and filtering should be implemented, on the other hand a more effective optimization algorithm should be used. In our application it is impossible to reduce THD as much as in [8], since in our case it is impossible to perform exact current measurement at the connection point.

REFERENCES

[1] J.M. Carrasco, L.G. Franquelo,J.T. Bialasiewicz, E. Galvn,R.C.P. Guisado, Ma..M.Prats, J.I. Len and N.M. Alfonso: Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey, *IEEE Transactions on Industrial Electronics, VOL. 53, NO. 4*, (August 2006.),pp. 1003-1015

[2] Y.K. Lo, T.P. Lee, and K.H. Wu:Grid-Connected Photovoltaic System With Power Factor Correction, *IEEE Transactions on Industrial Electronics VOL. 55, NO. 5*,,(May 2008.),pp. 2224-2227

[3] E. Garca-Canseco, R.Grino, R.Ortega, M.Salichs, and A.M. Stankovic: Power-Factor Compensation of Electrical Circuits, A framework for analysis and design in the nonlinear nonsinusoidal case, *IEEE Control Systems Magazine*, (April 2007)

[4] C.I. Budeanu, Puissance Ractives et Fictives. Bucarest: Institut National Roumain pour l'tude de l'amnagement et de l'utilisation des sources d'nergie, 1927 [Online]. Available: http://wwwl.lib.uchicago.cdu/e/index.php3

[5] A. Cerdeira, M.A. Alema, M. Estrada, D. Flandre: Integral function method for determination of nonlinear harmonic distortion *Solid-State Electronics Volume 48, Issue 12,* (December 2004), pp. 2225-2234

[6] L. R. Limongi, R. Bojoi, G.Griva, A Tenconi: Comparing the Performance of Digital Signal Processor-Based Current Controllers for Three-Phase Active Power Filters *IEEE Industrial Electronics* (March 2009 Volume 3 Number 1), pp. 20-31

[7] Matlab Simulink Power Electronics Toolbox *http://www.mathworks.com*

[8] L. R. Limongi, R. Bojoi, A. Tenconi, L. Clotea: Single-phase inverter with power quality features for distributed generation systems *Optimization of Electrical and Electronic Equipment, 2008. OPTIM 2008. 11th International Conference* (May 2008) pp.313-318