Analysis of the uninterruptible power supply influences to the power grid

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Abstract - Systems of uninterruptible power supplies (UPS) are indispensable part of many industrial plants, transportation, telecommunications and other systems, enabling their proper functioning and supply with stable DC and AC voltages. The structure of power section of the UPS system typically consists of a DC link and two converters which perform an indirect AC conversion with bidirectional energy flow. This article provides an overview of the various topologies and structures of the advanced UPS system. UPS input rectifier circuits used to achieve power factor correction (PFC) are specifically described in accordance with the requirements to the load powered by the UPS system. In addition to comparative analysis of these circuits, their main advantages and disadvantages are described. The simulation models of the power and control part of the selected solutions are elaborated for program package MATLAB and PLECS as well. In addition, simulation experiments based on developed models are carried out in order to analyze solution functionality, in terms of PFC and UPS influence to power grid.

Key words – Uninterruptible power supplies, power factor correction, power converter

I. INTRODUCTION

The UPS systems provide reliable and uninterrupted power supply to sensitive devices in communication and transportation systems, data centers, medical equipment, etc. Regardless of input voltage or load variation, outputs of UPS systems are regulated DC or AC voltages with a low Total Harmonic Distortion factor (THD). The structure of the power section of UPS system typically consists of a DC link and two conversion stages that perform an indirect AC conversion with bidirectional power flow. The UPS system emphasised importance of the power factor correction (PFC), total efficiency and dependability. According to the method of connection to the AC power grid and load, UPS systems can be divided into off-line UPS, line interactive UPS and on-line UPS [1]. Depending on common network failures, various UPS systems provide protection against specific errors that occur at the point of common coupling (PCC). PCC is the connection point of the power supply system and many different electrical loads. Off-line UPS systems provide protection against long-term interruptions or network failures, voltage drops and dynamic overvoltage. Line interactive UPS systems are used to provide protection against permanent occurrences of undervoltage, overvoltage and rapid jump of voltage. Active UPS systems are used to provide protection against constant and periodic transient perturbation, harmonic distortion, noise, impulses and frequency changes. In this article, active UPS systems with PFC at the input stage are specifically described. The selected example shows one PFC controller solution. A simulation model of the power section of the converter was developed by PLECS/Blockset, while the control algorithm of the selected PFC controller was developed by MATLAB/Simulink.

II. STRUCTURE AND CLASSIFICATION OF UPS SYSTEMS

Structure of the UPS system consists of three conversion stages: rectifier at the input stage, DC link with the battery, and inverter or DC converter in the output stage, depending on the load (AC or DC), Figure 1. In addition, the UPS system may also have a bypass line that supplies power directly from the grid to the load. Depending on the implementation of bypass lines, the input stage, DC link and the output stage of UPS systems can be divided into: (i) off-line, (ii) line interactive and (iii) on-line.

A. Off-line UPS systems

Off-line UPS systems have three possible operation modes. The first mode is the normal mode where the load is directly supplied from the AC grid, and the battery is charging through the rectifier, Figure 2.
In the second operation mode, which occurs when supply from AC grid cuts off, the static switch is switching off connection to the AC grid and switching on connection to the inverter, i.e. the battery. In this case the load depends only on the energy stored in the battery. The third operation mode occurs if battery or inverter are in failure. In that case, the load depends only on the direct connection to the AC grid and in the case of a power failure the load remains without power supply.

B. Line interactive UPS systems

The specificity of these systems is a two-way rectifier/inverter. There are two possible operation modes for line interactive UPS systems. In the first operation mode, the load is directly connected to the AC grid and the battery is charging through the two-way rectifier/inverter, Figure 3. The two-way rectifier/inverter in this mode acts as a rectifier. It should be noted that this situation is the same as in normal mode of off-line UPS systems.

C. On-line UPS systems

There are three possible operation modes of active UPS systems. In the normal mode, shown in Figure 4, the AC grid is connected to the rectifier, which converts the AC voltage to the DC voltage of the battery. This DC voltage is passed through the inverter to the load.

III. REQUIREMENTS FOR THE UPS SYSTEMS

The power factor of an AC electrical power system is defined as the ratio of the real and the apparent power of the supply network:

$$\lambda = \frac{P}{S} = \frac{UI \cos(\phi)}{UI} = \frac{I_1 \cos(\phi)}{I}.$$  

Where $I_1/I$ is distortion power factor, and $\cos(\phi)$ is displacement power factor. In the case of linear loads the distortion factor is 1. For nonlinear loads, the distortion power factor and displacement power factor differ from one, because of reactive power and higher harmonics influence. Higher harmonics of load current are „soiling“ the grid and lowering the quality of the power supply voltage. They can cause various perturbations and errors in the control devices, harmonic losses and vibrations of the mechanical parts. One way to express distortion of the load current waveform is by the Total Harmonic Distortion (THD). The THD shows the total content of the higher harmonics in the load current and is express by the following formula:

$$\text{THD} = \sqrt{\sum_{n=2}^{\infty} I_n^2},$$

where $I_n$ is the effective value of the n-th harmonic of the load current. Besides the THD, distortion of the current waveform can be expressed by the Total Demand Distortion (TDD). The TDD shows the total content of the higher harmonics in the maximum demand load current at the PCC, and is express by the following formula:

$$\text{TDD} = \sqrt{\sum_{n=2}^{\infty} I_{L_n}^2},$$

where $I_{L_n}$ is the maximum demand load current at the PCC.

Requirements for the loads and devices with regards to the power supply influences, are contained in the valid standards. Some of the most important standards are IEEE 519 and IEC 555 (IEC 61000) [2-3]. The IEC 61000-3 standard limits the amounts of higher harmonics that devices inject into the power supply. The IEC 61000-3-2 standard defines the permitted values from the 2nd to the 40th current harmonic. Table 1. shows the harmonic limits for UPS systems.

<table>
<thead>
<tr>
<th>Harmonic order (n)</th>
<th>Maximum permissible harmonic current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odd harmonics</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.30</td>
</tr>
<tr>
<td>5</td>
<td>1.14</td>
</tr>
<tr>
<td>7</td>
<td>0.77</td>
</tr>
<tr>
<td>9</td>
<td>0.40</td>
</tr>
<tr>
<td>11</td>
<td>0.33</td>
</tr>
<tr>
<td>13</td>
<td>0.21</td>
</tr>
<tr>
<td>15-39</td>
<td>0.15 x 15/n</td>
</tr>
<tr>
<td>Even harmonics</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.08</td>
</tr>
<tr>
<td>4</td>
<td>0.43</td>
</tr>
<tr>
<td>6</td>
<td>0.30</td>
</tr>
<tr>
<td>8-40</td>
<td>0.23 x 8/n</td>
</tr>
</tbody>
</table>
IEEE 519-2014 standard defines the limits of the harmonic voltage distortion based on the measurements and recommended limitations of voltage and current harmonics on PCC. Table 2, shows limits of the harmonic voltage distortion in this standard.

### Table 2. Limits of voltage distortion

<table>
<thead>
<tr>
<th>Bus voltage at PCC</th>
<th>Individual harmonic (%)</th>
<th>Total harmonic distortion THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 1.0 kV</td>
<td>5.0</td>
<td>8.0</td>
</tr>
<tr>
<td>1 kV – 69 kV</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>69 kV – 161 kV</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>&gt; 161 kV</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Limits of current distortion and TDD for systems rated 120 V through 69 kV are shown in table 3. All values in table 3, are in percent of the maximum demand current (I_d) connected to the PCC. This current value is determined as the sum of the currents corresponding to the maximum demand during each of the twelve previous months divided by 12. I_sc is the maximum short-circuit current at the PCC.

### Table 3. Limits of current distortion for systems with a voltage of 120 V to 69 kV

<table>
<thead>
<tr>
<th>Maximum harmonic current distortion in percent of I_d</th>
<th>Individual harmonic order (odd harmonics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_d/ I_sc</td>
<td>3 ≤ h &lt; 11</td>
</tr>
<tr>
<td>&lt; 20</td>
<td>4.0</td>
</tr>
<tr>
<td>20 – 50</td>
<td>7.0</td>
</tr>
<tr>
<td>50 - 10^2</td>
<td>10.0</td>
</tr>
<tr>
<td>10^2 - 10^3</td>
<td>12.0</td>
</tr>
<tr>
<td>&gt; 10^3</td>
<td>15.0</td>
</tr>
</tbody>
</table>

### IV. UPS SYSTEMS WITH PFC

Elements of energy electronics, due to their non-linear characteristics, distort the sine waveform of the voltage and current. The input part of the UPS system consists of a rectifier that loads the network with a current with rich harmonic content. Higher harmonics have a negative impact on the elements in the power system, which is expressed by the appearance of resonance in the network, additional losses in the conductors because of heating, the negative influences on capacitor batteries, elements of protection and the accuracy in the measurements and the reduction of the power factor. Due to adverse effects, the PFC is necessary. There are two common approaches to the PFC, passive and active [4]. Passive filters are used for passive PFC techniques. In case of active PFC, converter with semiconductor switches designed for operation at high frequencies are used. Most used passive filters for PFC are: (i) inductor on the side of the network (ii) inductor on the side of the rectifier (iii) band-pass filter (iv) band-stop filter (v) trap filter (vi) LCD filter. The main disadvantages of passive filters are large mass and volume, significant dissipation of power and high price. High-frequency inverters are used in the active PFC method to reduce the demands on the passive components in the view of mass, volume and price. This section will briefly describe the structure of the UPS systems connected to a single-phase supply network that use the Boost converter, Flyback converter and Boost Integrated Flyback Rectifier/Energy storage DC/DC (BIFRED) converter for the PFC at the input stage.

#### A. UPS system with boost converter for PFC

Figure 5, shows UPS system with boost converter for PFC. In the input stage of the UPS system is a single-phase diode rectifier and a DC boost converter that is used for PFC. In the input stage there is also a forward symmetrical converter with a transformer that is used for galvanic isolation and to achieve DC-link voltage. In the output stage of the UPS system is an inverter that is used to achieve the AC output to the load. This topology has the advantages of small size and weight because of the high-frequency transformer and can also provide galvanic isolation. But high number of active switches decrease the efficiency of the system and add complexity to the circuit.

#### B. UPS system with flyback converter for PFC

Figure 6, shows UPS system that uses flyback converter for PFC [5]. This UPS system serves to supply DC loads through the boost converter in the output stage.
This type of UPS system is suitable for relatively low powers.

C. UPS System with BIFRED converter for PFC

Figure 7. shows UPS system with BIFRED converter for PFC [6].

BIFRED is a combination of boost and flyback converter, and has only one switch and a characteristic bulk capacitor. PFC is achieved with the boost converter, and the galvanic isolation and the output voltage control by the flyback converter. The problem of excessive voltage on the bulk capacitor is solved by the boost and flyback converter operating in the discontinuous conduction mode (DCM). At the input of the boost converter is a full-wave rectified voltage. Characteristic of a boost converter is that in the DCM for a given value of inductance of the boost inductor, and a certain duty cycle, through the single-phase diode rectifier, pulls the sinusoidal current waveform from the network. While the switch is on, energy is accumulated in the boost inductor, the bulk capacitor is connected parallel to the primary of the transformer and the magnetization current flows through the primary of the transformer. During this time the current of the secondary of the transformer is zero and the load is powered form the output capacitor. When the switch is off the boost inductor releases the accumulated energy to the bulk capacitor, the magnetic flux in the core is supported by the current of the secondary of the transformer that supplies the load.

V. PFC CONTROL IN UPS SYSTEMS

This section will discuss the control of the input level of the UPS systems that uses boost converter for PFC. Specifically, the current mode control (CMC) of the boost converter will be described.

A. CMC of the boost converter

Boost converter can be controlled by voltage or current mode control. The primary difference between the voltage and current mode control is in the modulation of the PWM control signal of the converter switch. In voltage mode control only one feedback loop is used. Duty cycle is determined by comparing the fixed internal ramp with the error signal between the reference and the measured output voltage. CMC uses the internal and external feedback loop, figure 8. The external loop is by the voltage and the internal by the current. The external loop provides an error signal between the reference and measured output voltage that is used to determine the reference current in the current loop. The internal current loop compares the obtained current reference value with the measured current of the switch or the inductor, and then based on the error signal between these two currents defines the control signal for the converter switch. The CMC can be divided into average or peak current control. With average current control the momentary mean current value through the inductor or switch (averaged within the switching period) is adjusted. This mode of control ensures very low current distortion, constant switching frequency and there is no need for compensation ramp. In peak current control, the peak current through the inductor or switch (peak value within the switching period) is adjusted. In this mode of control, the system loses stability in DCM when the duty cycle is greater than 50% which results in subharmonic oscillations. For this reason it is necessary to add a compensation ramp in order to stabilize the converter response [7-10], Figure 8.

The input current ripple in the converter can be reduced by using multiple phases of the boost converter. By interleaved switching of the individual phases of the boost converter, the total input voltage ripple and the output current ripple are reduced. The phase shift between the control signals of the inverter switches is determined by the number of phases.

B. PFC controllers

Dedicated integrated circuits – PFC controllers, are used to control the input level of UPS systems that have the PFC capability. Some of the typical commercial PFC controllers are UCC28070 (TExAS Instruments), TDA4819 (Siemens), ML4812 (Micro Linear) and TK84812 (Toko). Figure 9. shows the basic structure of the ML4812 Power Factor Controller by the Fairchild Semiconductor manufacturer [11]. The basic functional parts of this integrated circuit are; error amplifier, current amplifier modulator, compensation ramp and PWM comparator.

Figure 10. shows the basic control structure of the PFC controller coupled to the power part of the current controlled boost PFC converter. Measured output voltage is supplied to the PFC regulator in order to compare it with the voltage reference value to get the error signal. This error signal in the Gain Modulator determines the amplification of the reference current signal.

The waveform of the reference current signal is a fully corrected sinus to which the signal from the compensation ramp is added. The output from the Gain Modulator is supplied to a comparator where it is compared with the signal of the measured current through
the switch. Logic output of the comparator is further brought to the S (set) input of a flip-flop, while an oscillator signal is brought to the R (reset) input of the flip-flop which represents a reset pulse for the flip-flop. Negative output of a flip-flop is the control signal for the inverter switch.

**VI. SIMULATION EXPERIMENT**

In this section, a simulation experiment of the UPS system input section, with a boost converter that has the ability of PFC by using the ML4812 PFC controller, will be displayed. Simulation of the control and power section of the converter is performed by connecting the two programming tools. The controller model is created using MATLAB/Simulink, and the power section model using PLECS/Blockset. Both models (power section and controller) can be connected to one MATLAB/Simulink model.

**A. Simulation model**

The block diagram of the model in which the connection between UPS system control section and power section is achieved, is shown in Figure 11. The power section is realized within the PLECS Circuit block while the control part is realized within the PFC controller block. The topology of the simulated converter within the PLECS Circuit block is shown in Figure 12, and model parameters are given in Table 4. A detailed view of the PFC controller block is shown in Figure 13., and block parameters are given in Table 5.
B. Parameterization of PI regulator

The parameters of the PI controller are obtained by numerical optimization of the system step response. The control structure is defined for optimization purpose as simple loop of the PI controller, and process in direct path and measured output voltage as the feedback signal. The process consists of boost converter with current control circuits. Error signal, i.e. difference between reference signal (Step from 150V to 350V) and feedback signal is used as controller input. For optimization purpose the constant input DC voltage of 150V is used. The objective function is defined as ISE (integral square error criterion). The characteristic of the system with controller optimized according to ISE criterion is overshoot of the output variable over 20%. As the goal of system response in our case is 1.5% overshoot, constraint function is applied beside ISE criterion. The constraint function forces the optimization procedure to choose controller parameters in the area where the overshoot does not exceed 1.5%. These conditions determine that system response should be as close as possible to critically damped system response. The optimization procedure was performed by fmincon function from MATLAB optimization toolbox. The method is based on Newton optimization with constraints. Controller parameters obtained by optimization are as follows: P = 0.0011, I = 0.478778.

C. Simulation results

Figure 14. shows the comparison of the input current response with the fixed duty cycle (D = 0.2) and the input current response with the built-in PFC regulator. The result of the use of the PFC regulator is the input current of approximately sinusoidal waveform without phase shift in relation to the voltage, i.e., the approximate unit power factor is obtained.

Figure 14. Waveforms of input voltage and input current with or without PFC

Figure 15. shows a comparison of the inductor current response when a compensation ramp is used and when is not used. It has been shown that using a compensation ramp, even in a critical area where the duty cycle is greater than 0.5, the system stabilizes and achieves a controlled response of the sinusoidal input current.

VII. CONCLUSION

A review of various PFC solution is shown in this article. One of the above structures based on single phase diode rectifier and PFC controlled boost converter is selected for demonstration by simulation. The peak current control of the boost converter has been designed, and simulated using two program tools. Simulation results show that an approximately unit power factor was successfully achieved. In the conclusion, the development of new control algorithms and electric components will further enhance the control of PFC and integrated circuits that are used as PFC.

REFERENCES