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A new method of feedback control for power inverter based on a single voltage sensor

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Abstract- The main objective of static power inverters is to produce an AC output waveform from a DC power supply. These are the types of waveforms required in adjustable speed drives (ASDs), uninterruptible power supplies (UPS), static VAR compensators (SVC), active filters, flexible AC transmission systems, and voltage compensators, which are only a few of the possible applications. For sinusoidal AC outputs, the magnitude, frequency, and phase should be controllable. The purpose of this research, in collaboration with Astrid Energy Enterprises, is to design and realize an innovative method of feedback control for inverter systems based on a single voltage sensor. This paper gives a detailed description of the system carried out and its potentiality as compared to the state of the art.

I. Introduction

In the UPS application inverters are used to generate stabilized AC waveforms from a DC power supply to feed, for instance, critical loads such as computers, medical equipments and so on. As the load conditions usually change so the AC waveforms should be adjusted to these new conditions. Also, as DC power supplies are not ideal and DC quantities are not fixed, the inverter should compensate for such variations. Such adjustments can be done automatically by means of a closed-loop approach.
There are two alternatives for closed-loop operation — the feedback and the feed-forward approaches. It is known that the feedback approach can compensate for both perturbations (DC power variations) and load variations (load changes) [1], [2].
However, the feed-forward strategy is more effective in mitigating perturbations as it prevents their negative effects at the load side.
Unlike the feed-forward approach, feedback techniques correct the input to the system (gating signals) depending upon the deviation of the output to the system (e.g., AC load line currents in VSIs). Another important difference is that feedback techniques need to sense the controlled variables. In general, the controlled variables (output to the system) are chosen according to the control objectives. For instance, in UPS, it is usually necessary to the output voltage to be equal to a given set of sinusoidal references. Therefore, the controlled variables become the AC output voltage. There are several alternatives to implement feedback techniques in Voltage Source Inverters (VSI):
- **Inner Current Loop (ICL)** [3], [4]: the main purpose here is to force the AC line current to follow a given reference in order to stabilize the output voltage. The main control techniques associated with ICL can be implanted by using:
    - *Hysteresis current control*: unfortunately, there are several drawbacks associated with the technique itself. The main one being that, the switching frequency cannot be predicted as in carrier-based modulators.
    - *Linear control in Rotating Coordinates*: the direct-quadrature-zero transformation allows AC three-phase circuits to be operated as if they were DC circuits.
- **Pure Voltage Loop (PVL)** [5], [6]: the main purpose here is to directly force the output voltage to follow a given reference. Using these control techniques no ammeters are required in the loop as there is no current signal included in the control. The main control technique associated to PVL can be implanted by using a resonant controller and harmonics compensator. The typical loop structure is shown in figure 1.

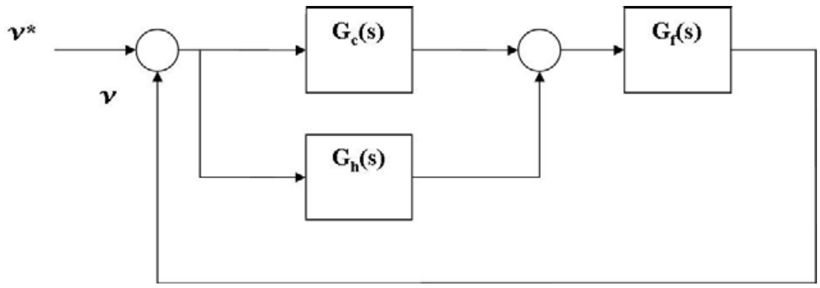

Figure 1 - Voltage loop with Proportional Resonant (PR) and Harmonic Compensator (HC) controllers.

The PR controller is defined as:

$$G_c(s) = K_p + K_i \frac{s}{\left(s^2 + \omega_0^2\right)} \quad [1]$$

and the harmonic compensator is defined as:

$$G_h(s) = \sum_{h=3,5,7...} K_{i_h} \frac{s}{\left(s^2 + \left(h \bullet \omega_0\right)^2\right)} \quad [2]$$

Apart from stability problems, unfortunately the digital implementation of these regulators requires the intensive use of multiplications and time shift operations. These operations can easily be done by means of power-full digital microprocessors only.

II. A new PVL closed loop control technique

A new control structure based on feed-back technique PVL is shown in figure 2. The proposed approach is based on a two parallel voltage loops. For three phase operation three separate loops can be used.

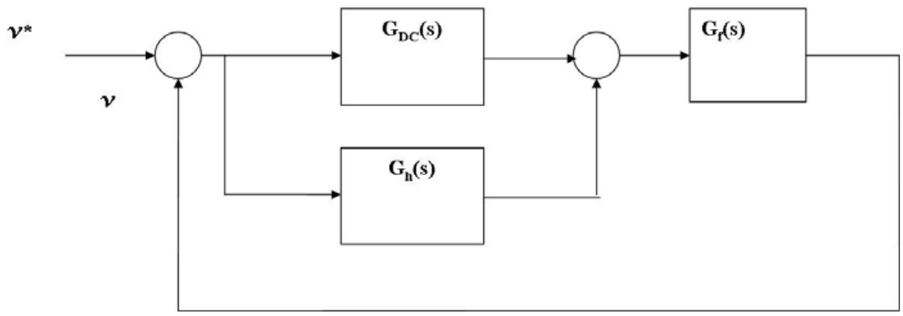

Figure 2 - Voltage loop with DC Proportional (DCP) and Harmonic Corrector (HC) controllers.

In the present study a solution has been found by splitting the regulation in two voltage loops $G_{DC}(s)$ to force the DC proportional to output voltage to an equal given set-point and $G_h(s)$ to correct the harmonics of the output regulated voltage. If the total harmonic distortion of the output voltage is negligible the following relationship becomes true:

$$V_{O_{rms}} = V_{O_{DC}} \bullet \sqrt{2} \quad [3]$$

this allows the DCP regulator to warranty a very good the static stability of the output voltage by the means of its very high DC gain.
A more detailed block diagram is represented in figure 3.

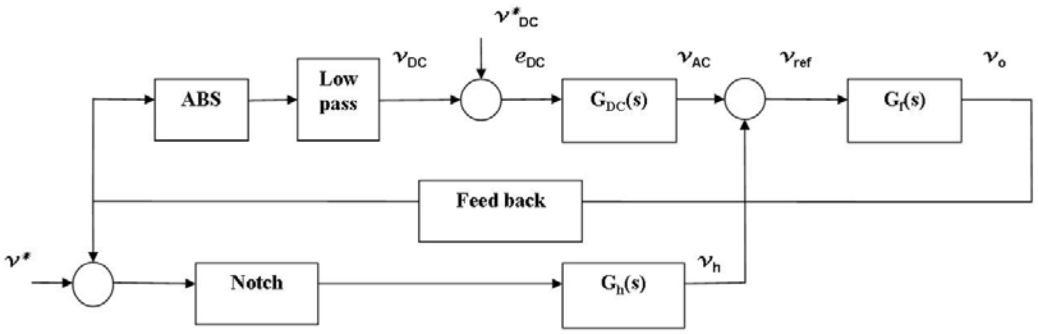

Figure 3 - Voltage loop with DC proportional (DCP) and harmonic corrector (HC) controllers.

The output of the cascade of ABS block (absolute value block) - which performs the full wave rectification of the feed-back signal - and Low-pass filter is a DC signal proportional to the regulated output voltage V_{DC}. Analog implementations would be involved for the ABS block.
The output of the DCP controller is a pure sine-wave reference the amplitude of which is regulated by the PI regulator (Proportional and Integral (PI) regulator included in the $G_{DC}(s)$ transfer function) to zero the DC error signal e_{DC} at the input.
The DC gain of $G_{DC}(s)$ regulator can be kept very high without creating stability problems, to achieve very good static stability of the regulated output voltage. Unfortunately the digital implementation of these regulators requires intensive use of multiplications and time shift operations. The $G_{DC}(s)$ regulator can be implemented by means of a very simple digital PI regulator plus a proportional sine-wave output digital PLL (Phase Locked Loop).
The Harmonic Corrector (HC - $G_h(s)$ block) function is to zero all the harmonics of the output voltage with exception of the fundamental component (50 or 60 Hz). This block performs a pre-distorted signal (harmonics compensation) added to V_{AC} to create an harmonically compensated reference signal V_{ref} at the input of the power stage $G_f(s)$.
The gain of the $G_h(s)$ harmonics controller can be lower to avoid to create stability problems. The gain and band of this regulator can by selected to achieve a very low level of Total Harmonic Distortion (THD) of the output voltage keeping the phase and amplitude margins quite large, so the stability of the closed loop system is very good. A very low THD of the regulated output voltage can be achieved by means of a unitary gain 500 Hz band low pass filter. The digital implementation of this regulator doesn't require intensive use of multiplications and time shift operations and can be performed by a low cost microcontroller. Analog implementations would be involved for the Notch block; a digital implementation of this block is also possible without increasing the computational cost of the regulators too much.
Therefore the complete regulation closed loop composed of DCP and HC achieves the goals of very high static stability, good compensation of harmonics and large phase and amplitude margins.

III. Experimental results

In this section experimental results and case implementation of the above described control technique are described. The below reported tests of the loop are based on the pure voltage PVL with DCP and HC control system implemented on a test motherboard designed for an Infineon Tricore® microcontroller, the main technical characteristics which are:

- Built in main DSP functions
- 32 bits CPU core
- 25 ns instruction cycle
- Two AD converters: 16 channels 12 bits
- Twin CAN interface

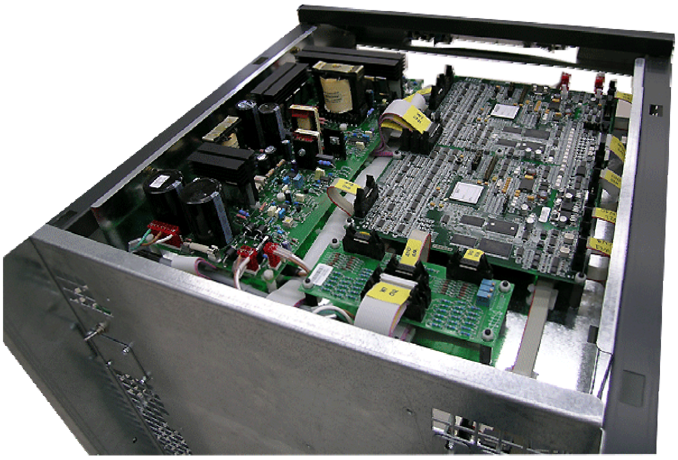

Figure 4 - Control electronics of Astrid's high power UPS based on Infineon Tricore® microcontroller

The dynamic response of the inverter to a linear load step from 20% to 100 % is shown in figure 5.

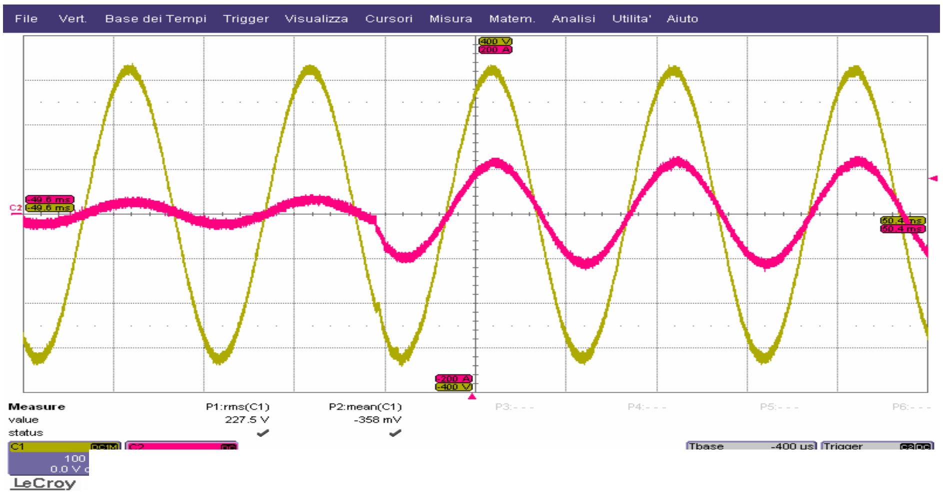

Figure 5 - Load step from 20 to 100% linear load: Inverter output voltage - Ch1 [100V/div] and current – Ch2 [100A/div]

The voltage variation and THD are reported in table 1, under the following test conditions: DC voltage at the input of the inverter is 680 V_{DC} , output frequency 50 Hz output voltage 230/400 V_{AC}. The same test using 70% not linear load according to EN62040 is also reported.

	Linear Load 100%		**Not linear load 70 %**	
Voltage	Voltage [V rms]	Voltage [%]	Voltage [V rms]	Voltage [%]
V_1	231	100	229	100%
V_3	0.7	0.30	2.5	1.09
V_5	2.0	0.87	5.2	2.30
V_7	1.70	0.74	3.5	1.53
V_9	0.40	0.17	0.5	0.22
V_{11}	0.30	0.13	0.40	0.17
V_{13}	0.05	0.02	0.20	0.09
THD_v	1.2		3.0	

Table 1: Measurements of output voltage amplitude and distortion at 100 % full linear load and 70 % not linear load, according to EN62040.

The experiments show that the dynamic response of the system is very fast and stable by means of the optimized tuning between the output LC filter values and the gain-band of DCP and HC controllers. Static stability is also very accurate and voltage distortion is quite low even in the case of not linear load.

IV. Conclusions

This paper describes the control circuit realized and implemented in inverter systems produced by Astrid Energy Enterprise. This circuit shows, due to the carrying out of choices made in the design phase, two fundamental advantages: the presence of one only voltage sensor and the simplifying of computation cost compared to the actual state of the art.
A further strong point in favour of this control circuit is that it can already be applied even in inverter systems with three phase transformers associated with the space vector technique [7], so improving the use of the battery voltage.

References

[1] Timothy L. Skvarenina, *The power electronics handbook*, New York, CRC Press, 2002.
[2] N. Mohan, T. Undeland and W. Robbins, *Power Electronics*, New York, Wiley, 2003.
[3] N. H. Kutkut and G. Luckjiff, "Current Mode Control of a Full Bridge DC-to-DC Converter with a Two Inductor Rectifier", *Proceeding of the 1997 IEEE Power Electronics Specialists Conference*, vol.1, pp. 203-209.
[4] L. Dixon, "Avarage Current Mode Control of Switching Power Supplies", *Unitrode Application Note U-140*, 1999.
[5] Ziener R.E, Tranter W.H., Fannin D.C., *Signals and System: continuous and discrete*, MacMillan, N.Y., USA, 1993.
[6] L. Asiminoaei, R. Teodorescu, F. Blaabjerg, U. Borup, "A digital controlled PV-inverter with grid impedance estimation for ENS detection", *IEEE Trans. on Power Electronics*, Volume 20, Issue 6, Nov. 2005 Page(s):1480 – 1490.
[7] Keliang Zhou and Danwei Wang, "Relationship between SpACe-Vector Modulation and Three-Phase Carried Based PWM: a comprehensive analysis, *IEEE Trans. Ind. Electronics*, vol. 49, pp. 186-195, 2002.