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Three-Phase inverter Controlled by ISCPWM and DPWM-S1

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Introduction

Nowadays, it is possible to use sophisticated control techniques due to the permanent technical developments which, by means of microcontrollers, DSPs or FPGAs, allow solving complex equations characterizing various modulation techniques. Here are some of them: Third Harmonic Injection Pulse Width Modulation (THIPWM) [1], Discontinuous Pulse Width Modulation (DPWM) [2], Space Vector Modulation [3], etc. These modulation techniques are used in order to enhance the performances of the power electronic circuit, lower cost, reduce size and increase reliability. Implementing a complex control technique that runs in real time on a computer system implies using many resources such as RAM/ROM memory, work speed, internal blocks: PWM, ADC, PLL, DAC, Timers, UART, etc.

This paper uses as a reference wave a Discontinuous Pulse Width Modulation S1 signal (DPWM-S1) modulated by an Inverted Sine Carrier Pulse Width Modulation (ISCPWM) carrier signal. The use of the DPWM-S1 signal is beneficial, since it has the value 1 or -1 on two intervals out of six (i.e. a full period). This is important because, in these time intervals, the power transistors within a three-phase inverter are in continuous conduction or blocked, therefore there are no switching losses. Overall, the efficiency of the three-phase inverter will be higher, since the switching losses on the power transistors are lower and thus, they need smaller heat sinks, their life span will be longer and the price of such a circuit will be lower.

Theoretical considerations

Fig. 1 presents the waveform of the Discontinuous Pulse Width Modulation S1 (DPWM-S1) reference signal (green-colored waveform), modulated by an Inverted Sine Carrier Pulse Width Modulation (ISCPWM) carrier signal (red-colored waveform). Each intersection between the two waveforms is marked with p1, p2, p3, etc. As long as the amplitude of the DPWM-S1 reference signal waveform is higher than that of the ISCPWM modulating signal, the control signal for the Q^+_A transistor has the value *ON* corresponding to its conduction state. Fig. 2 presents the electric circuit of a three-phase inverter, which includes the following transistors: Q^+_A, Q^-_A, Q^+_B, Q^-_B, Q^+_C and Q^-_C. The control signal for Q^-_A transistor is obtained by inverting the Q^+_A signal. For Q^+_B and Q^+_C transistors, control signals resulted from the intersection of other DPWM-S1signals with the ISCPWM modulating signal. These are phase-shifted by 120º and 240º respectively from the reference signal corresponsding to the Q^+_A transistor.

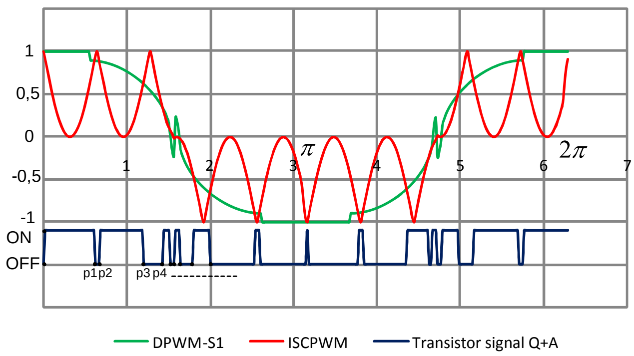

Fig. 1. Waveforms of the Discontinuous Pulse Width Modulation S1 (DPWM-S1) reference signal, Inverted Sine Carrier Pulse Width Modulation (ISCPWM) carrier signal and command signal for Q^+_A transistor

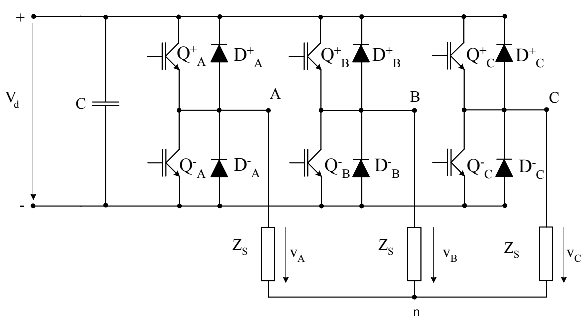

Fig. 2. Schematic of the three-phase inverter

The intersection points (p1, p2, p3, p4, p5, etc.) between

DPWM-S1 and THIPWM signals can be calculated based on the following equations:

$$y = 1 - \sin\left[M_f \cdot p_x - \frac{\pi}{2}(x-1) \right],\ x = 1,3,5\ \ldots; \quad (1)$$

$$y = 1 - \sin\left[M_f \cdot p_x - \frac{\pi}{2}(x-2) \right],\ x = 2,4,6\ \ldots; \quad (2)$$

where M_f is the frequency ratio, p_x stands for the points of intersection between DPWM-S1 and ISCPWM and x represents the number of points.

If we consider the DPWM-S1 equations:

$$\begin{cases} 1; & 0 \le \omega_m t \le \pi/6\,; \\ \sqrt{3}m_a \cos\omega_m t + m_a \sin\omega_m t - 1; & \pi/6 \le \omega_m t \le \pi/2\,; \\ \sqrt{3}m_a \cos\omega_m t - m_a \sin\omega_m t + 1; & \pi/2 \le \omega_m t \le 5\pi/6\,; \\ -1; & 5\pi/6 \le \omega_m t \le 7\pi/6\,; \\ \sqrt{3}m_a \cos\omega_m t - m_a \sin\omega_m t + 1; & 7\pi/6 \le \omega_m t \le 3\pi/2\,; \\ \sqrt{3}m_a \cos\omega_m t - m_a \sin\omega_m t - 1; & 3\pi/2 \le \omega_m t \le 11\pi/6\,; \\ 1; & 11\pi/6 \le \omega_m t \le 2\pi \end{cases} \quad (3)$$

and substitute for each interval of time equations (3) in (1) and (2), we can find intersection points p1, p2, p3, p4, p5, etc. [7]. Based on these points we can draw the new ISCPWM-DPWM-S1 signal which can be seen in Figure 3. Next to this signal, the original DPWM-S1 signal is illustrated, used only for comparison purposes; it is thus obvious that DPWM-S has lower amplitudes than the new signal ISCPWM-DPWM-S1 at the same points in time.

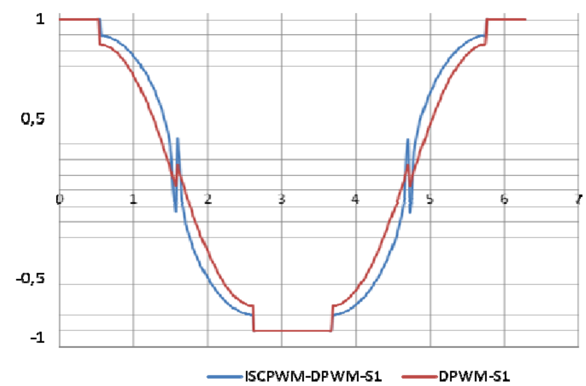

Fig. 3. Waveforms of the ISCPWM-DPWM-S1 and DPWM-S1 signals

Fig. 4 presents a period of an ISCPWM modulating signal and of a triangular PWM signal, respectively. These two modulating signals were compared only in order to show that the conduction time resulting from the intersections of ISCPWM and DPWM-S1 – marked as d_1 – is longer than the time resulting from the intersection between DPWM-S1 and a classic triangular PWM modulating signal – marked as d_2. The d_1 time has the amplitude value 1 as long as ISCPWM has a higher amplitude than DPWM-S1, which means that one transistor within the three-phase inverter will be in conduction.

Software algorithm

The software was designed to be implemented on the C8051F120 microcontroller, made by Silicon Laboratories. It was chosen because it is fast (100MIPS) and has numerous internal blocks suitable for the implementation of our software (such us: PWM, ADC, Timers, PLL, Ports, XRAM). Fig. 5 presents the flowcharts underlying the C software applied for the C8051F120 microcontroller.

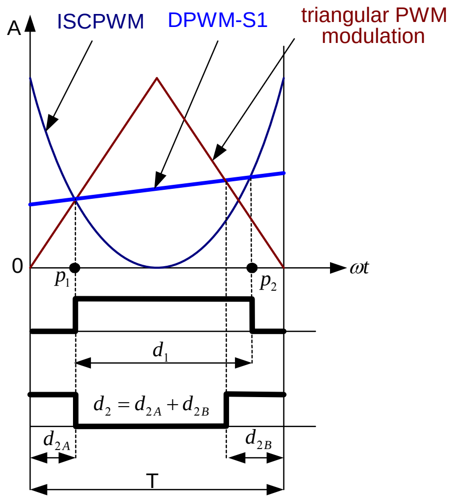

Fig. 4. Waveforms of the ISCPWM, DPWM-S1 and classical PWM signals

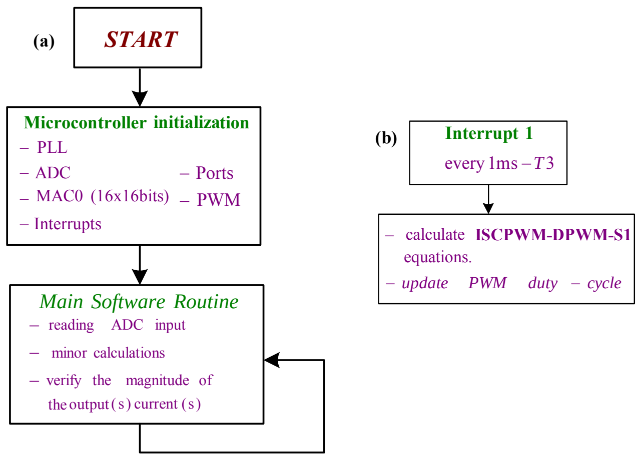

Fig. 5. (a) Main control flowchart and (b) flowchart of interrupt 1 generated by T3 Timer

Fig. 5(a) presents the main software flowchart, where the internal blocks of the microcontroller are initialized, analogical inputs are read, intermediate calculation values are transmitted by means of the UART interface to a computer and the functioning values of currents and voltages within the power circuit are checked. Fig. 5(b) presents the flowchart corresponding to the software part called on every 1 ms (by the T3 timer), the routine involving the calculation of equations ISCPWM-DPWM-S1 and, then, the updating of the PWM blocks values in order to obtain the control signals of the six transistors within the three-phase inverter. We present below the C programming language software for the generation of signals f0, f1 and f2, corresponding to the signals ISCPWM-DPWM-S1, also called f0 – for phase A, f1 – for phase B and f2 – for phase C. Since the calculation volume of the microcontroller is enormous, in this program we resorted to some approximations in order to facilitate the microcontroller's task in solving the equations.

```
void iscpwm_dpwm_s1(void)
{
signed char s;           // signed sine
unsigned char o;         // output value
unsigned int p;          // 16 bit product
unsigned char SFRPAGE_SAVE = SFRPAGE;
idata    float f0, f1, f2, tr0, tr1, tr2, f0a,
f1a, f2a;

Sum += (freq << 6);
q0 = (Sum >> 8);
tr0 = (q0/40.6);

if(!reverse)
    {
        tr1 = tr0 + xx1;
        tr2 = tr0 + xx2;
    }
else
    {
        tr2 = tr0 + xx1;
        tr1 = tr0 + xx2;
    }

SFRPAGE   = PCA0_PAGE;
f0 = dpwm_s1(tr0);
     if (tr0 <= 1.57)
          {
               f0a = 3.1415 - 2*asin(1 - f0);
          }
     else if(tr0<=4.71 && tr0>1.57)
          {
                    f0a = 2*asin(1 + f0) - 3.1415;
          }
     else  if(tr0<=4.71+3.14 && tr0>4.71)
          {
               f0a = 3.1415 - 2*asin(1 - f0);
          }
     else      f0a = 2*asin(1 + f0) - 3.1415;
     f0a = f0a / 3.1415;
     s = f0a*0x7F;
p = amplitude * (signed int)s;   // multiply by v
o = p>>8;               // throw away low byte
o += 0x80;              // center sinewave at 50%
PCA0CPH0 = o;

     f1 = dpwm_s1(tr1);
     if (tr1 <= 1.57)
          {
               f1a = 3.1415 - 2*asin(1 - f1);
          }
     else if(tr1<=4.71 && tr1>1.57)
          {
               f1a = 2*asin(1 + f1) - 3.1415;
          }
     else  if(tr1<=4.71+3.14 && tr1>4.71)
          {
               f1a = 3.1415 - 2*asin(1 - f1);
          }
     else      f1a = 2*asin(1 + f1) - 3.1415;

f1a = f1a / 3.1415;
s = f1a*0x7F;
p = amplitude * (signed int)s;   // multiply by v
o = p>>8;             // throw away low byte
o += 0x80;            // center sinewave at 50%
PCA0CPH1 = o;

     f2 = dpwm_s1(tr2);
     if (tr2 <= 1.57)
          {
               f2a = 3.1415 - 2*asin(1 - f2);
          }
     else if(tr2<=4.71 && tr2>1.57)
          {
               f2a = 2*asin(1 + f2) - 3.1415;
          }
     else  if(tr2<=4.71+3.14 && tr2>4.71)
          {
               f2a = 3.1415 - 2*asin(1 - f2);
          }
     else      f2a = 2*asin(1 + f2) - 3.1415;

f2a = f2a / 3.1415;
s = f2a*0x7F;
p = amplitude * (signed int)s;   // multiply by v
o = p>>8;          // throw away low byte
o += 0x80;         // center sinewave at 50%
PCA0CPH2 = o;
SFRPAGE = SFRPAGE_SAVE;}
```

Simulation and experimental results

After implementing the above software on the C8051F120 microcontroller, the ISCPWM-DPWM-S1 and the DPWM-S1 signals can be seen in Fig. 6.

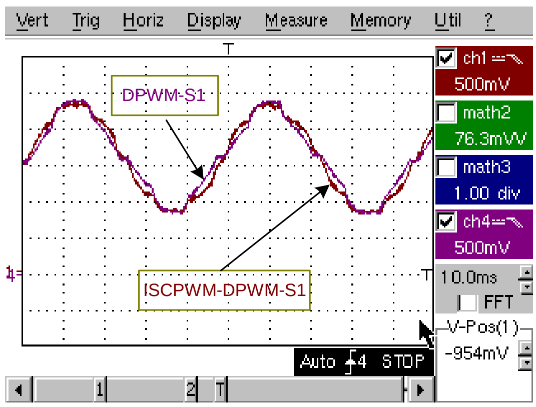

Fig. 6. Oscilloscope waveforms of the ISCPWM-DPWM-S1 and DPWM-S1 signals implemented on the microcontroller

For both the simulation and the practical part we used a 315V supply voltage, a 17,25Khz switching frequency and as a load – a 0,37KW motor. Fig. 7 shows the phase A voltage – simulation on the right and practical part on the left – for comparison purposes. Its frequency spectrum is presented below.

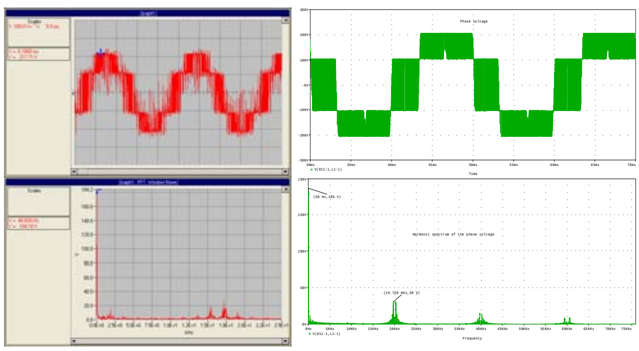

Fig. 7. Waveforms of the phase voltage and harmonic spectrum of this voltage obtained by simulations and from oscilloscope

The amplitude of the fundamental of the phase A voltage is 185V for the simulation, and 184.18V for the practical circuit.

Fig. 8 shows the AB line voltage – simulation on the right and practical part on the left – for comparison purposes. Its frequency spectrum is presented below.

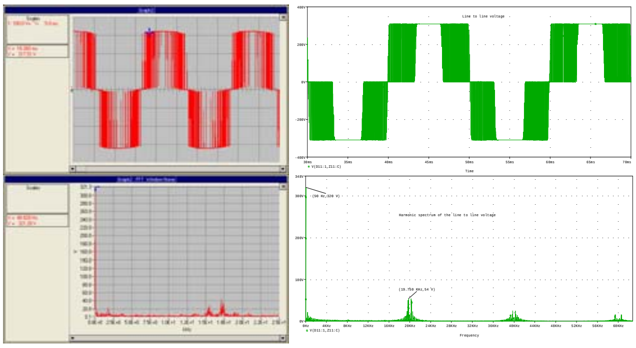

Fig. 8. Waveforms of the line voltage and harmonic spectrum of this voltage obtained by simulations and from oscilloscope

The amplitude of the fundamental of the voltage between the A and B phases is 320V for the simulation and 321.28V for the practical circuit.

Fig. 9 shows the A phase voltage – simulation on the right and practical part on the left – for comparison purposes. Its frequency spectrum is presented below.

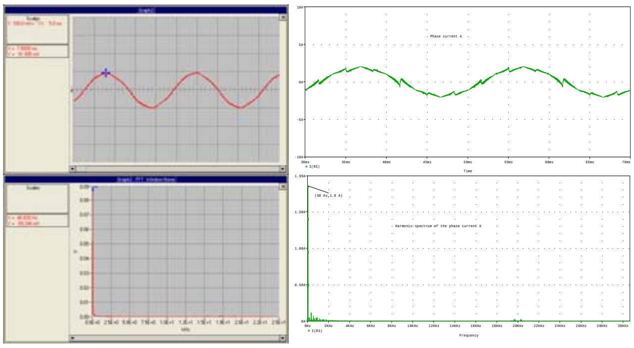

Fig. 9. Waveforms of the phase current and harmonic spectrum of this current obtained by simulations and from oscilloscope

Conclusions

In this paper we used the ISCPWM-DPWM-S1 algorithm implemented on a microcontroller to command a three-phase inverter. This algorithm was tested by simulations and practically. We compared the results of the simulations to the results obtained with the practical circuit in order to emphasize the performances of this control algorithm. High performances were obtained in terms of low power losses on the power transistors within the three-phase inverter and high amplitudes of the line and phase voltages fundamentals. However, this control technique has got a drawback: it requires a high calculation volume from the microcontroller.

Acknowledgements

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C. Aghion, O. Ursaru. Three-Phase inverter Controlled by ISCPWM and DPWM-S1 // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 3(119). – P. 87–90.

This paper presents the implementation of the ISCPWM-DPWM-S1 control technique on a microcontroller. This technique was developed due to the modulation of a discontinuous signal DPWM-S1 with an inverted sinusoidal signal ISCPWM. Good results were obtained for the switching losses on the power transistors, which are lower, and for the amplitudes of the fundamental frequency, which are higher for the phase and line voltages. Ill. 9, bibl. 7 (in English; abstracts in English and Lithuanian).

C. Aghion, O. Ursaru. Trijų fazių inverteris, valdomas invertuota sinusinio nešlio impulso pločio moduliacija ir nenutrūkstamu impulso pločio moduliacijos signalu S1 // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 3(119). – P. 87–90.

Pateikiamas ISNIPM-NIPM-S1 valdymo metodas įdiegtas mikrovaldiklyje. Metodas buvo sukurtas panaudojant nenutrūkstamo signalo NIPM-S1 moduliaciją invertuotu sinusiniu signalu ISNIPM. Gauti geresni rezultatai vertinant galios tranzistorių perjungimo nuostolius, kurie yra mažesni, bei pagrindinio dažnio amplitudę, kuri yra aukštesnė. Il. 9, bibl. 7 (anglų kalba; santraukos anglų ir lietuvių k.).