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A new method for determining current components in resonant circuits supplied by H-bridge inverter with frequency and single pulse width (PSM) modulation

Nowa metoda wyznaczania składowych prądu w obwodach rezonansowych zasilanych napięciem z falownika mostkowego typu H z modulacją częstoliwości i szerokości pojedynczego impulsu

Abstract: *This paper proposes a method of measuring the current components of a bridge inverter controlled by frequency and pulse width modulation. The method eliminates the third harmonic and its multiples from the measurement result in the absence of filters. The correctness of the method is confirmed by calculations and simulations.*

Streszczenie: *W artykule zaproponowano metodę pomiaru składowych prądu inwertera mostkowego sterowanego z modulacją częstotliwości i szerokości impulsu. Metoda eliminuje z wyniku pomiaru trzecią harmoniczną i jej wielokrotności przy braku filtrów. Poprawność metody została potwierdzona obliczeniami oraz symulacjami.*

Keywords: reactive component of current, bridge inverter, current averaging, low-pass filter
Słowa kluczowe: składowa bierna prądu, falownik mostkowy, uśrednianie prądu, filtr dolno-przepustowy

Introduction

Resonant converters used in wireless energy transmission powered by a bridge inverter (H-bridge) are controlled by modulation of frequency and pulse width of the output voltage (phase shift PWM) [1, 2]. The aim of the control is to achieve the highest efficiency, which is achieved by operating at the own frequency of resonant circuit. The phase shift between the output voltage and current of the inverter, the reactive power or reactive current component should be kept close to zero. These parameters could be measured by different methods [3, 4, 5, 6, 7], based on the fundamental harmonic of the output current and voltage.

One of the solutions is determine the value of the active and reactive components of the current by averaging the fundamental harmonic of the current over a range of time around points when the instantaneous values of one current component reach zero. In each period, both current components can be measured twice. For each second measurement, the averaging result takes on a value proportional to current component with the opposite sign [3]. Fig. 1 shows the averaging window signal for measuring active and reactive current components using the averaging method.

The beginning and end of time window must be the same time away from the crossing point of fundamental harmonic by zero or amplitude value. The instantaneous value of the fundamental harmonic of the current i_f at the moment the fundamental harmonic of the voltage u_f crosses amplitude is proportional to the active component of the current I_P. The voltage u_f crosses the amplitude in $t_P = (2n+1)T/4$, where: T is period and $n=0;1;2\ldots$. The instantaneous value of the current i_f at the moment the voltage u_f crosses zero is proportional to the reactive component of the current I_Q. The voltage u_f crosses the zero in $t_Q = nT/2$. In electronics circuits signal continuity is sought [3]. In the case of measuring a single-phase current component, a continuous signal proportional to the measured current component will be obtained for an averaging window with a time range of $T/2$ (π radians). The beginning and end of averaging window should be away from the sampling point by $T/4$.

The time range of the averaging window for measuring of the active current component should be $t_P \pm T/4$ (integration before and after the voltage reaches amplitude). The averaged value of the first harmonics of the current $i_f = I_m \sin(\omega t - \varphi)$ in the time range $t_P \pm T/4$ is proportional to the active current component, because (1):

$$\frac{k_i}{T_i}\int_{t_P-\frac{T}{4}}^{t_P+\frac{T}{4}} i_f\,dt = \frac{k_i}{T_i}\int_{t_P-\frac{T}{4}}^{t_P+\frac{T}{4}}\left(I_m \sin\left(\frac{2\pi}{T}t - \varphi_f\right)\right)dt = (-1)^{n+1}\frac{k_i T}{\pi T_i} I_m \cos(\varphi_f) = (-1)^{n+1}\frac{k_i T}{\pi T_i} I_P \tag{1}$$

where: – k_i amplification factor of the current measurement path and its transformation to a voltage signal possible to integrate, T_i - integrator constant.

For measurement of the reactive component of the current, the time range of the averaging window should be $t_Q \pm T/4$ (integration before and after the voltage passes through zero). The averaged value of the signal proportional to the current i_f in the time range $t_Q \pm T/4$ is proportional to the reactive current component, because (2):

$$\frac{k_i}{T_i}\int_{t_Q-\frac{T}{4}}^{t_Q+\frac{T}{4}} i_f\,dt = \frac{k_i}{T_i}\int_{t_Q-\frac{T}{4}}^{t_Q+\frac{T}{4}}\left(I_m \sin\left(\frac{2\pi}{T}t - \varphi_f\right)\right)dt = (-1)^{n}\frac{k_i T}{\pi T_i} I_m \sin(\varphi_f) = (-1)^{n}\frac{k_i T}{\pi T_i} I_Q \tag{2}$$

The method described for the active and reactive current component measurement are based on the fundamental harmonic of the current and voltage. The output current i and the output voltage u of inverter are distorted, hence the signals proportional to the current and voltage must be filtered by low-pass filters with the same parameters. Low-pass filters are designed for specific frequency that limit capabilities of the measurement system. This article proposes method of determining the current component for a bridge inverter controlled by the single pulse width modulation and frequency modulation. The method is based on averaging total current over time windows without filters. Due to the presence of odd current harmonics, the solution considers the reduction of the third harmonic and its multiples from measurement result by averaging the current signal in a time window width $T/3$.

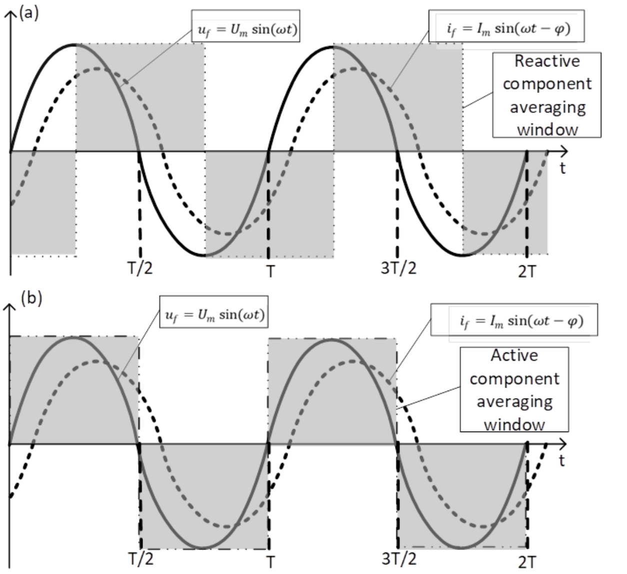

Fig. 1. Illustration of reactive (a) and active(b) averaging window waveforms used to determine current components by averaging the first harmonic of the current over a time interval of *T/2*.

The correctness of the proposed method was confirmed by mathematical calculations and simulation in a Spice program. The block diagram of the circuit is shown in Fig. 2. The averaging time windows are generated based on the signal from the frequency and voltage regulator. The measured value of the reactive component of the current can take positive and negative values, determining the nature of the current.

Measurement of the current component with reduction of the third harmonics from the measurement result

The proposed method determines the current components by averaging the current over time windows. The beginning and end of the averaging window is at the same distance from the point where the instantaneous value of the waveform of the fundamental harmonic of voltage crosses amplitude or zero value. The averaged values of the signal proportional to the total current $i = \sum_{h=1}^{\infty} I_{mh} \sin(h\omega t - \varphi_h)$ in time windows: $t_Q \pm mT$ and $t_P \pm mT$ for $h=2n+1$ are (3), (4):

(3) $$\frac{k_i}{T_i}\int_{t_Q-mT}^{t_Q+mT} \sum_{h=1}^{\infty} I_{mh} \sin(h\omega t - \varphi_h)\, dt = (-1)^n \frac{2k_i}{\omega T_i} \sum_{h=1}^{\infty} \frac{I_{mh}}{h} \sin(2mh\pi) \sin\varphi_h$$

(4) $$\frac{k_i}{T_i}\int_{t_P-mT}^{t_P+mT} \sum_{h=1}^{\infty} I_{mh} \sin(h\omega t - \varphi_h)\, dt = (-1)^{n+1} \frac{2k_i}{\omega T_i} \sum_{h=1}^{\infty} \frac{I_{mh}}{h} \sin(2mh\pi) \cos\varphi_h$$

where: m – the part of the period that is half the width of the averaging window,h - order of harmonic.

The results of averaging of the total current shown in equations (3) and (4) are inversely proportional to the frequency of the current and the order of harmonics. For undistorted current (fundamental harmonic, h=1), the averaging results are proportional to the reactive and active components of the current, because (5), (6):

(5) $$(-1)^n \frac{2k_i}{\omega T_i} \sum_{h=1}^{\infty} \frac{I_{mh}}{h} \sin(2mh\pi) \sin\varphi_h = (-1)^n \frac{2k_i}{\omega T_i} \sin(2m\pi) I_m \sin\varphi_f = (-1)^n K I_Q$$

(6) $$(-1)^{n+1} \frac{2k_i}{\omega T_i} \sum_{h=1}^{\infty} \frac{I_{mh}}{h} \sin(2mh\pi) \cos\varphi_h = (-1)^{n+1} \frac{2k_i}{\omega T_i} \sin(2m\pi) I_m \cos\varphi_f = (-1)^{n+1} K I_P$$

where: $K = 2k_i sin(2m\pi)/\omega T_i$.

For resonant circuits with low damping, the input current waveform is weakly distorted. The input current in these circuits has odd harmonics, the most significant is the third harmonic. An appropriate time range of the averaging window can remove selected harmonics from the measurement result. In the time window with a range of $T/2$, no odd harmonic with period $T_h = T(2n-1)$ fits its full number of periods because $(T/2)/T_h = n - 1/2$, therefore its integral will give a value different from zero. To eliminate influence of the third harmonic and its multiples on the measurement result $sin(2mh\pi) = 0 \rightarrow m = 1/6$. Time window width is: $2mT = T/3$. The measurement result of averaging over time window width $T/3$ contain odd orders harmonics $h = 6n + 1$, and amplification factor of integration method is $\pm\sqrt{3}/2h$, because (7), (8):

(7) $$(-1)^n \frac{2k_i}{\omega T_i} \sum_{h=1}^{\infty} \frac{I_{mh}}{h} \sin\left(\frac{2}{6}(6n \pm 1)\pi\right) \sin\varphi_h = (-1)^n \frac{2k_i}{\omega T_i} \sum_{h=1}^{\infty} \pm \frac{\sqrt{3}}{2h} I_{mh} \sin\varphi_h$$

(8) $$(-1)^{n+1} \frac{2k_i}{\omega T_i} \sum_{h=1}^{\infty} \frac{I_{mh}}{h} \sin\left(\frac{2}{6}(6n \pm 1)\pi\right) \cos\varphi_h = (-1)^{n+1} \frac{2k_i}{\omega T_i} \sum_{h=1}^{\infty} \pm \frac{\sqrt{3}}{2h} I_{mh} \cos\varphi_h$$

Circuit for current component measurement method

Fig. 2 shows the block diagram of circuit for the current component measurement and the gate signal generator for bridge inverter. The proposed measurement circuit is working for variable inverter switching frequency and modulation of single pulse width.

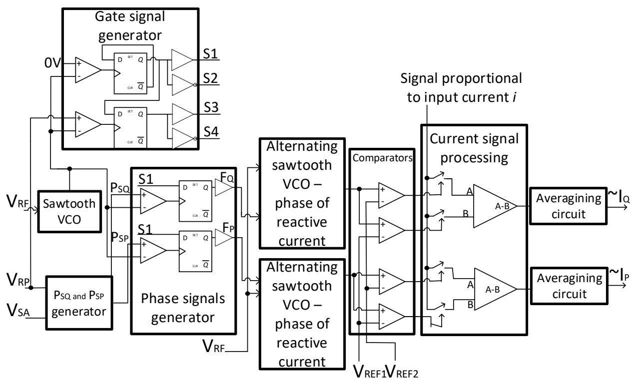

Fig. 2. Block diagram of current measurement circuit.

Switching frequency is set by block “Saw-tooth VCO generator” and controlled by the voltage of frequency regulator V_{RF} (Fig. 3a). The block “Gate signal generator” controlled by voltage of the phase shift regulator V_{RP}, generate gate signals S1-S4. The gate signal S1-S3 and the output voltage of the inverter are presented on Fig. 3b

In the single pulse width control, the phase shift between the averaging windows and the saw-tooth signal is variable and depends on the value of the phase shift regulator output signal. The "Phase signals" block controlled by voltages $P_{SA} = V_{RP}/2$ and $P_{SR} = V_{RP} + (V_{SA} - V_{RP}\ \ )/2$ generates the rectangular signals: with phase of the active current component and F_P with phase of the active current component and F_Q with phase of the reactive current component. The frequency of these signal is equal to the inverter switching frequency and the duty cycle is 0.5.

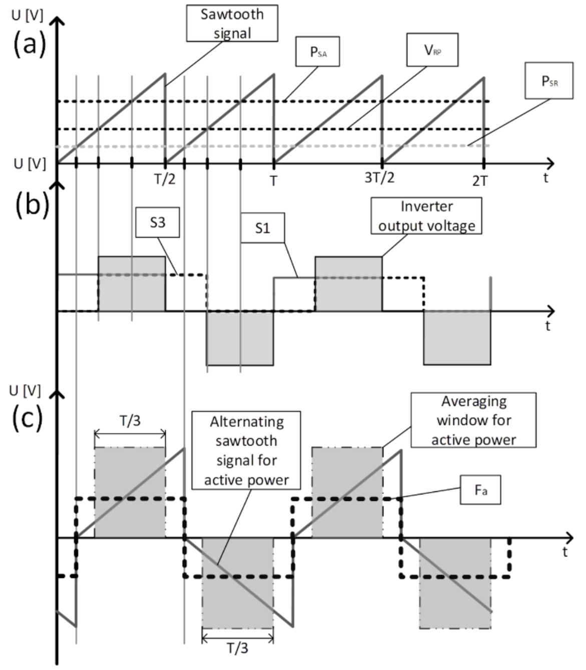

Fig. 3. Illustration of the averaging window generator waveforms.

The block “Alternating sawtooth VCO” generate saw-tooth signals with phase of the active and reactive current components, frequency of switching inverter and constant amplitude. The time windows signals are obtained by comparing the alternating saw-tooth voltage with constant voltages by a comparator block, which define their width V_{REF1} and V_{REF2}. The frequency of time widows is equal to the switching frequency of inverter and the signal width is constant in relation to period (Fig. 3c).

Based on the generated averaging window signals, the “Inverting and blocking” block process signal of the total current for further averaging. Figure 4 and 5 shows waveforms of processed signal by the inverting and blocking circuit. The processed signal is fed to the “Averaging circuit” block. Averaged value of the processed signal in each averaging window is proportional to the active or reactive current component.

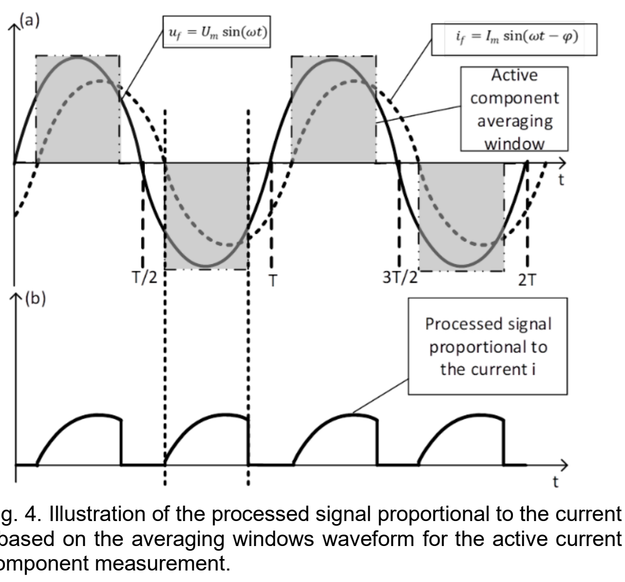

Fig. 4. Illustration of the processed signal proportional to the current i based on the averaging windows waveform for the active current component measurement.

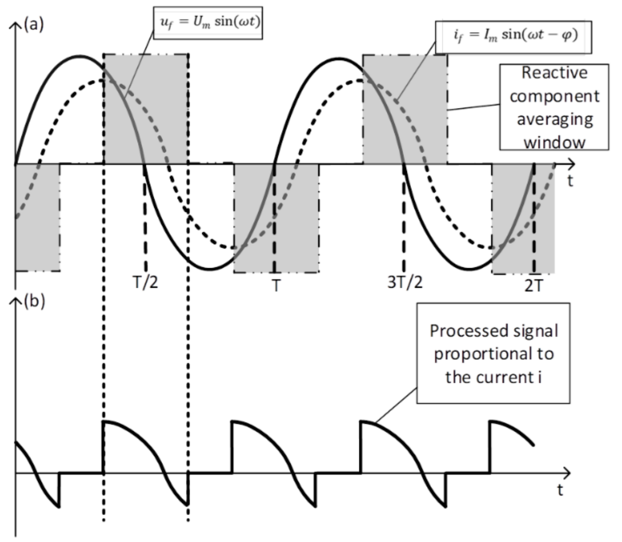

Fig. 5. Illustration of the processed signal proportional to the current i based on the averaging windows waveform for the reactive current component measurement.

Simulation implementation

The proposed circuit for measurement of the active and reactive current component of a bridge inverter is simulated in LTSpice software. The simulations are prepared for variables: width of single pulse s, switching frequency f_{SW}, amplitude of third harmonic I_{m3} and phase shift φ_f.

Figure 6 and Figure 7 shows example waveforms of the measurement circuit. The sinusoidal signal $V(v_{curr})$ corresponding to total current i was set with an amplitude of fundamental harmonic 3V and phase 44,8° and 0°. The signals V(react+,react-) and V(act+,act-) represent time window signals. The signals V(n030) in turquoise and V(n007) in green represent the processed signals, the averaged value of which is proportional to the active and reactive components of the total current, respectively.

Table 1 summarized the simulation results of reactive I_{MQ} and active I_{MP} current measurement. Measurement results are compared with current components (I_{CQ}, I_{CP}) calculated based on phase shift φ_f and fundamental current harmonic amplitude I_{mf}. Inaccuracy between calculated and simulated measured current components is less than 1% of full range. The inaccuracy is due to the limitations of the Spice program.

Table 1. Simulation results of active and reactive current measurement with proposed method.

ID	f_{sw}	φ_f	s	I_{mf}	I_{m3}	I_{CQ}	I_{CP}	I_{MQ}	I_{MP}
	[kHz]	[°]	[%]	[V]	[V]	[V]	[V]	[V]	[V]
1	500	-44,8	100	3	0	-2,11	2,13	-2,07	2,15
2	500	44,8	100	3	0	2,11	2,13	2,15	2,11
3	50	44,8	100	3	0	2,11	2,13	2,14	2,12
4	50	-44,8	100	3	0	-2,11	2,13	-2,11	2,12
5	50	0,0	50	3	0	0,00	3,00	0,00	3,00
6	500	0,0	50	3	0	0,00	3,00	0,05	3,00
7	500	44,8	50	3	3	2,11	2,13	2,15	2,11
8	50	-44,8	50	3	3	-2,11	2,13	-2,11	2,12

To verify harmonics suppression, third order harmonics signal is added to total current i with amplitude of 3V. Measurement circuit suppress third harmonic as confirmed by the simulation (Table 1, ID7 and ID8).

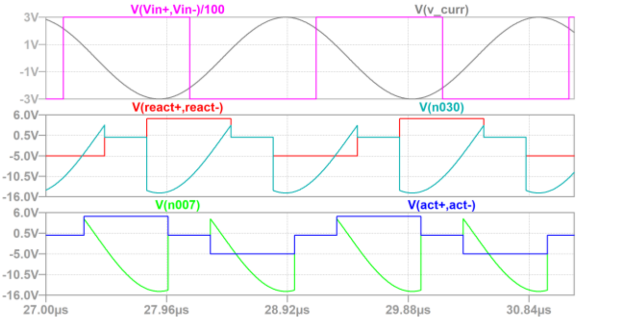

Fig 6. Illustration of waveforms of the simulated H-bridge converter with active and reactive current measurement circuit with frequency 500kHz – case ID2

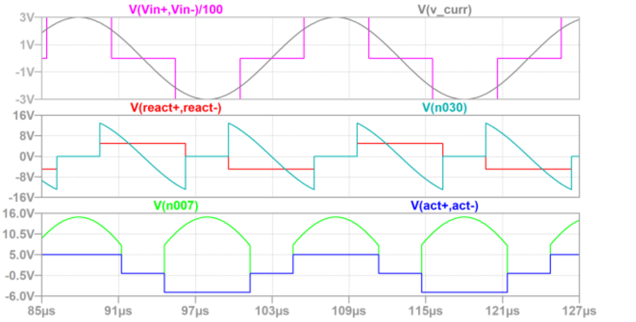

Fig 7. Illustration of waveforms of the simulated H-bridge converter with active and reactive current measurement circuit with frequency 50kHz – case ID5.

Summary

The method of current components measurement based on the total current for bridge inverter controlled by modulation of frequency and width of single voltage pulse is proposed. Proposed approach is based on total current and do not require low-pass filters in contrast to currently known methods [3, 4, 5, 6, 7]. Current components in proposed method are determined by averaging of signal proportional to the total current in time windows. For averaging windows with time range $T/3$, third order harmonic and its multiples are removed from the measurement value as confirmed by the calculations and simulation. The measurement result is inverse proportional to frequency and harmonic order.

Proposed method of current component measurement is simulated in LTSpice software. The proposed circuit determines current components and works for a variable switching frequency of a bridge inverter and a variable width of single voltage pulse. The simulation results have an inaccuracy of no more than 1% of the total range, which is related to the limitations of the Spice program. Simulation analysis showed that the method is sensitive to small changes in the time window signals. The method that determines the components of the current works according to the calculations and requires further work and testing on a real circuit.

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