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Influence of Third Harmonic Injection Signal on Output Current Ripple and Neutral Current of Three-Level PWM Inverter

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Abstract: The influence of injecting third harmonic signal into three-phase sinusoidal reference signal of natural sampled PWM technique on output current ripple and neutral current of three-level inverter is analyzed in this paper. Expressions for both inverter output current ripple and neutral current as a function of PWM reference signal are derived first. Then, it is shown that injecting one fourth or twenty five percent third harmonic signal into three-phase sinusoidal reference signal may produce minimum output current ripple and neutral current. The twenty five percent third harmonic injection signal can simultaneously minimize output current ripple and neutral current of the three-level inverter only for unity power factor operation. Simulation and experimental results are included to show validity of the analysis results.

Keywords: current ripple; neutral current; PWM technique; third harmonic; three-level inverter.

1. Introduction

Multilevel inverter is a technology originally introduced to cope with problems due to use of conventional two-level inverter in high power applications [1-4]. Among many kinds of multilevel inverter structure, diode-clamped three-level inverter or shortly three-level inverter is the most accepted for industrial applications [4-6]. Using three-level inverter gives advantages such as produces lower output current ripple without necessarily using high switching frequency and applies lower voltage stress on inverter switches. However, three-level inverter has a problem of neutral current flow which leads to unbalance neutral voltage.

For many years, pulse width modulation (PWM) has been accepted as a standard technique to control inverter switching process [7-8]. Various PWM techniques have been developed, among them is the popular natural sampled PWM technique. Various methods to develop this natural sampled PWM technique, particularly the ones aimed to reduce or even minimize inverter output current ripple, were also proposed. Most popular one is the third harmonic injection method, in which the reference signal used is three-phase sinusoidal injected by third harmonic signal instead of three-phase sinusoidal signal only [9-11]. For conventional two-level inverter, the twenty five percent third harmonic signal (a sinusoidal signal with frequency three times of reference signal frequency and amplitude one fourth or twenty five percent of reference signal amplitude) has been proven to be the optimum injection signal that results in minimum output current ripple and minimum input voltage ripple for unity power factor operation [11]. Regarding the neutral current or unbalance neutral voltage problem of three-level inverter, many papers describing method to analyze and minimize it were published. Ogasawara et al studied the importance of zero sequence voltage on neutral current of three-level inverter and expression of zero sequence voltage to reduce it has been derived. Unfortunately, use of zero sequence voltage makes the control more complicated [12]. Other papers provided analysis of unbalance neutral voltage based on space vector PWM (SVPWM) technique [13-16]. Basically all these methods have the same principle i.e. utilizing small redundant vectors in such a way to achieve balance neutral voltage. However, determination of

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voltage reference vectors, sequence and duty cycle of active voltage vectors of the SVPWM technique are much more complicated.

This paper presents analysis on the influence of injecting third harmonic signal into three-phase sinusoidal reference signal of natural sampled PWM technique on output current ripple and neutral current of three-level inverters. It is shown that third harmonic injection signal can be used to minimize both output current ripple and neutral current of three-level PWM inverters. The twenty five percent third harmonic injection signal makes inverter output current ripple and neutral current simultaneously minimum only for unity power factor operation. In order to give systematic descriptions, the remaining of this paper will be organized as follows: Section 2 will describes in brief about three-level PWM inverter. In Section 3, the influence of third harmonic injection signal on output current ripple of three-level inverter is analyzed. Meanwhile, influence of third harmonic injection signal on neutral current of three-level inverter is going to be analyzed in Section 4. All analysis results are then verified by simulation and experimental results described in Section 5. Finally, the paper is concluded in Section 6.

2. Three-Level PWM Inverter

Structure of the three-level inverter is shown in Figure 1. As shown by Table 1, this inverter has three switching states namely positive (*Pos*), zero (0) and negative (*Neg*) with the associated output phase voltage levels. These switching states are commonly realized by PWM technique, one example is the natural sampled PWM technique. Natural sampled PWM technique for three-level inverter requires two level-shifted triangular carrier signals, V_{T1} and V_{T2}, with no phase difference between them. The reference signals are three-phase sinusoidal v_u, v_v, and v_w. Figure 2 illustrates how intersections between reference and carrier signals produce the switching states and output phase voltages given in Table 1.

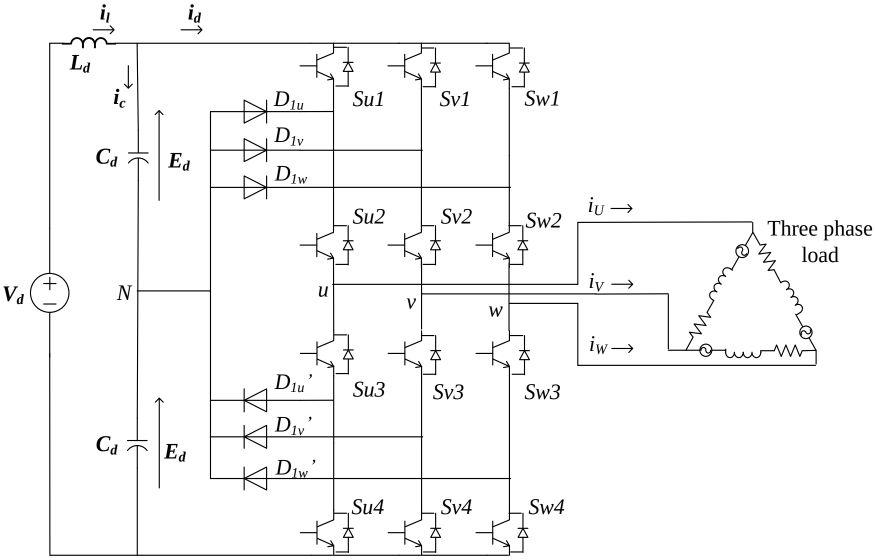

Figure 1. Structure of three-level inverter

Table 1. Switching states and output phase voltages of the three-level inverter.

No	Switch state				Output phase voltage	Remarks
	S_{x1}	S_{x2}	S_{x3}	S_{x4}	v_{xN}	
1	ON	ON	OFF	OFF	E_d	Positive (*Pos*)
2	OFF	ON	ON	OFF	0	Zero (0)
3	OFF	OFF	ON	ON	$-E_d$	Negative (*Neg*)

Note: index *x* refers to phase *u*, *v*, or *w*.

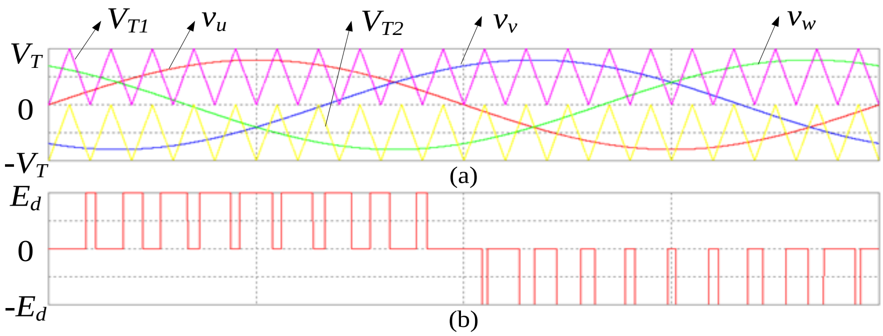

Figure 2. (a) Reference and carrier signals of three-level PWM inverter
(b) Output voltage for phase *u*.

3. Output Current Ripple of Three-Level PWM Inverter

To investigate the influence of third harmonic injection signal on output current ripple of three-level PWM inverter, it is necessary to derive the expression for output current ripple first. Assumptions below are taken when deriving the expression:

a) The input dc voltage, E_d, is ripple free and has a constant value.
b) Carrier/switching frequency (f_s) is much higher than reference frequency (f_r).
c) Dead time effect is negligible.
d) Inverter load is balance three-phase load. Each phase load consists of a resistance (R_L), an inductance (L_L) and a sinusoidal back emf (e) connected in series.

The reference signals are three-phase sinusoidal injected by arbitrary signal, s_0, and expressed as:

$$v_u = k\sin(\theta) + s_0;\ v_v = k\sin\left(\theta - \frac{2\pi}{3}\right) + s_0;\ \text{and}\ v_w = k\sin\left(\theta + \frac{2\pi}{3}\right) + s_0 \quad (1)$$

in which $\theta = 2\pi f_r t$ and k is the modulation index i.e. a ratio between sinusoidal part of reference signal amplitude and the unity value of twice of carrier signal amplitude. To begin the analysis, half of the reference signal period is divided into thirty analysis intervals with thirty different switching states. Figure 3 shows the switching states/output voltages generated in an analysis interval. From this figure, relation between time parameters, carrier signals and reference signals can be easily derived as:

$$t_1 = (T_S/2)v_u;\ t_2 = (T_S/2)(1 + v_v);\ \text{and}\ t_3 = (T_S/2)v_w \quad (2)$$

The phase to phase voltage ripples are derived by applying principle of Fourier series expansion. For example, voltage ripple between phases *u* and *v* is derived as:

$$\tilde{v}_{uv} = \tilde{v}_{uN} - \tilde{v}_{vN} = \sum_{n=1}^{\infty} (a_{n,u} - a_{n,v}) \cos\left(\frac{2\,n\,\pi\,t}{T_s}\right) \quad (3)$$

where:

$$a_{n,u} = \frac{2}{T_s}\int_{-t_1}^{t_1} v_{uN}(t)\cos\left(\frac{2\,n\,\pi\,t}{T_s}\right)\mathrm{d}t; \qquad a_{n,v} = \frac{2}{T_s}\left[\int_{-T_s/2}^{-t_2} v_{vN}(t)\cos\left(\frac{2\,n\,\pi\,t}{T_s}\right)\mathrm{d}t + \int_{t_2}^{T_s/2} v_{vN}(t)\cos\left(\frac{2\,n\,\pi\,t}{T_s}\right)\mathrm{d}t\right] \quad (4)$$

Then, current ripple for load between phases *u* and *v* in delta configuration is going to be:

$$\tilde{i}_{uv} = \sum_{n=1}^{\infty} \frac{\tilde{v}_{uv}}{n\,\omega\,L_L} \quad (5)$$

where $\omega = 2\pi f_s$. Due to high switching frequency, evaluation of (5) is sufficient for $n = 1$. Evaluating (3), (4), and (5) with substitution of (1) and (2) yields the load current ripple expression as follows:

$$\tilde{\imath}_{uv} = \frac{K_1}{\pi^2}\left[\sin\pi(k\sin\theta + s_0) + \sin\pi\left(k\sin\left(\theta - \frac{2\pi}{3}\right) + s_0\right)\right]\cos\left(\frac{2\pi t}{T_S}\right) \quad (6)$$

with $K_1 = \frac{E_d T_S}{L}$. The above analysis steps must be performed to the twenty nine analysis intervals remain. The result is a set of load current ripple expression given by Table 2.

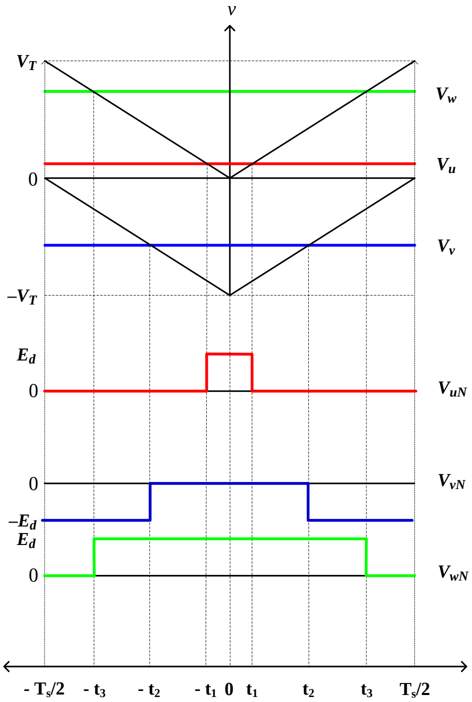

Figure 3. Output voltages generated in an analysis interval.

Table 2. Load current ripple expressions.

Interval	Equation
$0 \le \theta \le \frac{\pi}{3}$	$\tilde{\imath}_{uv} = \frac{K_1}{\pi^2}\left[\sin\pi(k\sin\theta + s_0) + \sin\pi\left(k\sin\left(\theta - \frac{2\pi}{3}\right) + s_0\right)\right]\cos\left(\frac{2\pi t}{T_S}\right)$
$\frac{\pi}{3} \le \theta \le \frac{2\pi}{3}$	$\tilde{\imath}_{uv} = \frac{K_1}{\pi^2}\left[\sin\pi(k\sin\theta + s_0) + \sin\pi\left(k\sin\left(\theta - \frac{2\pi}{3}\right) + s_0\right)\right]\cos\left(\frac{2\pi t}{T_S}\right)$
$\frac{2\pi}{3} \le \theta \le \pi$	$\tilde{\imath}_{uv} = \frac{K_1}{\pi^2}\left[\sin\pi(k\sin\theta + s_0) - \sin\pi\left(k\sin\left(\theta - \frac{2\pi}{3}\right) + s_0\right)\right]\cos\left(\frac{2\pi t}{T_S}\right)$

Using expressions given by Table 2, the effective value of load/output current ripple of three-level PWM inverter will be obtained as follows:

a) For $s_0 = 0$ (no signal injected into reference signal)

b) $\tilde{I}_{uvSIN} = \frac{1}{\sqrt{2\pi^5}}(8.744k^2 - 32.120k^4 + 47.819k^6 - 35.241k^8 + 15.567k^{10} - 4.603k^{12} + 0.976k^{14} - 0.152k^{16} + 0.017k^{18})^{\frac{1}{2}}$ (7)

c) For $s_0 = \frac{1}{4}k\sin[3\theta]$ (injected by twenty five percent third harmonic)

d) $\tilde{I}_{uvSIN34} = \frac{1}{\sqrt{2\pi^5}}(4.917k^2 - 16.145k^4 + 20.227k^6 - 12.162k^8 + 4.325k^{10} - 1.025k^{12} + 0.174k^{14} - 0.022k^{16} + 0.002k^{18})^{\frac{1}{2}}$ (8)

e) For $s_0 = \frac{1}{6}k\sin[3\theta]$ (injected by seventeen percent third harmonic)

f) $\tilde{I}_{uvSIN36} = \frac{1}{\sqrt{2\pi^5}}(5.619k^2 - 17.997k^4 + 21.774k^6 - 12.572k^8 + 4.271k^{10} - 0.962k^{12} + 0.155k^{14} - 0.019k^{16} + 0.002k^{18})^{\frac{1}{2}}$ (9)

Figure 4 shows the line plot of output current ripples expressed by (7) – (9). The figure shows clearly that third harmonic injection signal can be used to reduce output current ripple of three-level PWM inverter and minimum output current ripple is obtained by injecting twenty five percent third harmonic signal into three-phase sinusoidal reference signal.

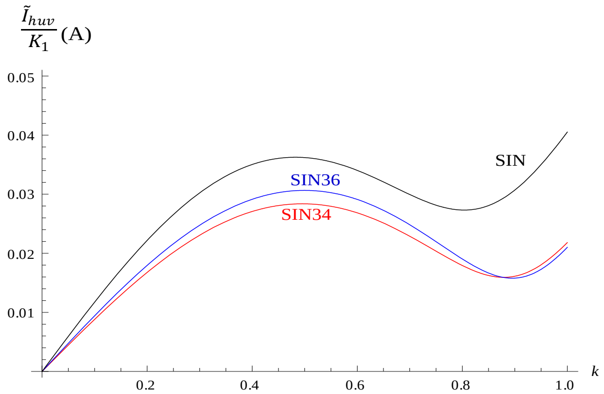

Figure 4. Output current ripples of three-level PWM inverter.

Using twenty five percent third harmonic injection signal to minimize output current ripple of three-level PWM inverter is confirmed by mathematical analysis. By taking the derivation of total mean square value of load current ripple to arbitrary injected signal, s_0, which is followed by equalizing it to zero then expressions of injection signal given by Table 3 will be obtained. These expressions can be approximated as:

$$s_0 = \frac{1}{4}k\sin[3\theta] \quad (10)$$

which is the twenty five percent third harmonic injection signal.

Table 3. Expressions of injection signal for minimizing output current ripple.

Interval	**Equation**
$0 \le \theta \le \frac{\pi}{3}$	$s_0 = \frac{1}{8}(\sqrt{3}\cos[\theta] + \sin[\theta])k$
$\frac{\pi}{3} \le \theta \le \frac{2\pi}{3}$	$s_0 = -\frac{1}{4}\sin[\theta]k$
$\frac{2\pi}{3} \le \theta \le \pi$	$s_0 = \frac{1}{8}(-\sqrt{3}\cos[\theta] + \sin[\theta])k$

4. Neutral Current of Three-Level PWM Inverter

When zero switching state is achieved, the neutral point of three-level inverter (N) is connected to its output phase line allowing current to flow out-of or into neutral point, known as neutral current (I_N), and causing unbalance neutral voltage. Therefor, neutral current of the condition shown previously in Figure 3 can be derived as:

$$I_N = \frac{2}{T_S}\left(\int_0^{t_1}(i_v)\,dt + \int_{t_1}^{t_2}(i_u + i_v)\,dt + \int_{t_2}^{t_3}(i_u)\,dt + \int_{t_3}^{\frac{T_S}{2}}(i_u + i_w)\,dt\right) \tag{11}$$

If the inverter phase currents are defined as:

$$i_u = \sqrt{2}\,I_{rms}\sin(\theta - \emptyset);\;\; i_v = \sqrt{2}\,I_{rms}\sin\left(\left(\theta - (2\pi/3)\right) - \emptyset\right);\;\text{and}\;\; i_w = \sqrt{2}\,I_{rms}\,\sin\left(\left(\theta + (2\pi/3)\right) - \emptyset\right) \tag{12}$$

where $\emptyset$ is phase angle and $\cos(\emptyset)$ is load power factor (pf), then evaluating (11) followed by substitution of (1), (2) and (12) results in:

$$I_N = \frac{I_{rms}(k(\cos[2\theta-\emptyset]-\cos[\emptyset]+\sqrt{3}\sin[2\theta-\emptyset])-2(\sqrt{3}\cos[\theta-\emptyset]+\sin[\theta-\emptyset])s_o)}{\sqrt{2}} \tag{13}$$

Table 4. Neutral current expressions.

Interval	Equation
$0 \le \theta \le \frac{\pi}{3}$	$I_{rms}(k(\cos[2\theta - \emptyset] - \cos[\emptyset] + \sqrt{3}\sin[2\theta - \emptyset]) - 2(\sqrt{3}\cos[\theta - \emptyset] + \sin[\theta - \emptyset])s_o)/\sqrt{2}$
$\frac{\pi}{3} \le \theta \le \frac{2\pi}{3}$	$I_{rms}(k(2\cos[2\theta - \emptyset] + \cos[\emptyset]) - 4\sin[\theta - \emptyset]s_o)/\sqrt{2}$
$\frac{2\pi}{3} \le \theta \le \pi$	$I_{rms}(k(\cos[2\theta - \emptyset] - \cos[\emptyset] - \sqrt{3}\sin[2\theta - \emptyset]) + 2(\sqrt{3}\cos[\theta - \emptyset] - \sin[\theta - \emptyset])s_o)/\sqrt{2}$
$\pi \le \theta \le \frac{4\pi}{3}$	$I_{rms}(k(-\cos[2\theta - \emptyset] + \cos[\emptyset] - \sqrt{3}\sin[2\theta - \emptyset]) + 2(\sqrt{3}\cos[\theta - \emptyset] + \sin[\theta - \emptyset])s_o)/\sqrt{2}$
$\frac{4\pi}{3} \le \theta \le \frac{5\pi}{3}$	$-I_{rms}(k(2\cos[2\theta - \emptyset] + \cos[\emptyset]) - 4\sin[\theta - \emptyset]s_o)/\sqrt{2}$
$\frac{5\pi}{3} \le \theta \le 2\pi$	$I_{rms}(k(-\cos[2\theta - \emptyset] + \cos[\emptyset] + \sqrt{3}\sin[2\theta - \emptyset]) + 2(-\sqrt{3}\cos[\theta - \emptyset] + \sin[\theta - \emptyset])s_o)/\sqrt{2}$

In deriving neutral current of the three-level PWM inverter, analysis interval are identified along the reference period. Thus, a total of sixty analysis intervals are obtained. Table 4 gives the expressions of neutral current obtained after performing the above analysis steps to all sixty analysis intervals have been identified. If we take the derivation of mean square value of inverter neutral current to arbitrary injected signal, s_0, followed by equalizing it to zero then expressions of injection signal given by Table 5 will be obtained.

Figure 5 shows the line plot of the injection signal expressions. It can be seen that it is a third harmonic signal with waveform strongly affected by load pf. As shown by Figure 5 (a), the injection signal takes its simplest form i.e the twenty five percent third harmonic only for unity pf operation. This is also the injection signal that produces minimum output current ripple for three-level inverter (according to analysis results described previously in Section 3) as well as for conventional two-level inverter [11]. For load with pf lower than unity, Figure 5 (b) shows that injection signal turns into a more complex periodic discontinuous signal, although its frequency remains three times reference signal frequency. After performing several mathematical simplification process, this complicated signal can be approximated by a more simple expression as follows:

$$s_0{}' = \frac{k}{5\pi}\left((4\cos\emptyset\sin 3\theta) - (6\sin\emptyset\cos 3\theta)\right) \tag{14}$$

Table 5. Expressions of injection signal for minimizing neutral current

Interval	**Equation**
$(0-\pi/3)$; $(\pi-4\pi/3)$	$s_0=\frac{1}{2}k\left((\cos[2\theta-\emptyset]-\cos[\emptyset]+\sqrt{3}\sin[2\theta-\emptyset])/(\sqrt{3}\cos[\theta-\emptyset]+\sin[\theta-\emptyset])\right)$
$(\pi/3-2\pi/3)$; $(4\pi/3-5\pi/3)$	$s_0=\frac{1}{4}k\left((2\cos[2\theta-\emptyset]+\cos[\emptyset])/\sin[\theta-\emptyset]\right)$
$(2\pi/3-\pi)$; $(5\pi/3-2\pi)$	$s_0=\frac{1}{2}k\left((-\cos[2\theta-\emptyset]+\cos[\emptyset]+\sqrt{3}\sin[2\theta-\emptyset])/(\sqrt{3}\cos[\theta-\emptyset]-\sin[\theta-\emptyset])\right)$

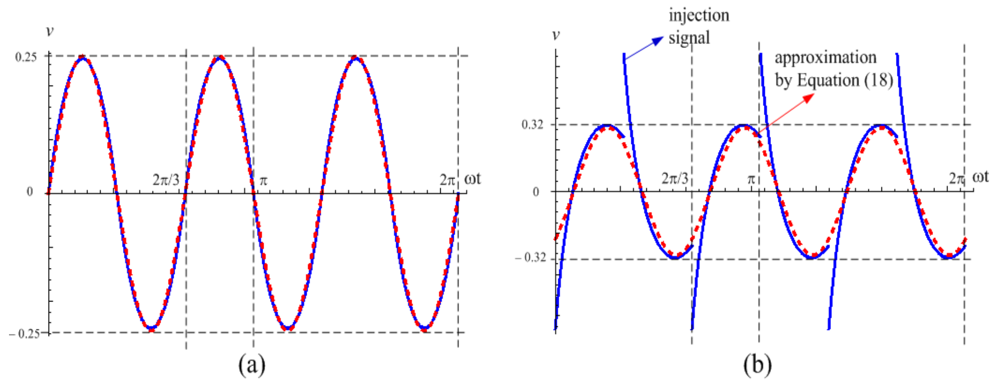

Figure 5. Injection signal to minimize neutral current (a) pf = 1, (b) pf = 0.8.

Using expressions given by Table 4, the effective value of neutral current of three-level PWM inverter can be obtained as:

a) For $s_0=0$ (no signal injected into reference signal)

$$I_{NrmsSIN}=k\,I_{rms}\left[\left(\frac{-3\sqrt{3}+\pi}{4\pi}\right)\cos[2\emptyset]+\left(\frac{-6\sqrt{3}+5\pi}{4\pi}\right)\right]^{\frac{1}{2}} \quad (15)$$

b) For $s_0=\frac{1}{4}k\sin[3\theta]$ (injected by twenty five percent third harmonic)

$$I_{NrmsSIN34}=k\,I_{rms}\left[\left(\frac{3\sqrt{3}-32\pi}{128\pi}\right)\cos[2\emptyset]+\left(\frac{-264\sqrt{3}+176\pi}{128\pi}\right)\right]^{\frac{1}{2}} \quad (16)$$

c) For $s_0=\frac{1}{6}k\sin[3\theta]$ (injected by seventeen percent third harmonic)

$$I_{NrmsSIN36}=k\,I_{rms}\left[\left(\frac{-81\sqrt{3}-24\pi}{288\pi}\right)\cos[2\emptyset]+\left(\frac{-540\sqrt{3}+376\pi}{288\pi}\right)\right]^{\frac{1}{2}} \quad (17)$$

d) For $s_0=\frac{k}{5\pi}\left((4\cos\emptyset\sin 3\theta)-(6\sin\emptyset\cos 3\theta)\right)$ (injected by the approximated injection signal)

$$I_{NrmsSIN3'}=k\,I_{rms}\left[\begin{array}{c}\left(\frac{-90\sqrt{3}\pi-400\pi^2}{200\pi^3}\right)\cos[\emptyset]-\\ \left(\frac{160\pi-594\sqrt{3}+150\sqrt{3}\pi^2-50\pi^3}{200\pi^3}\right)\cos[2\emptyset]\\ +\left(\frac{90\sqrt{3}\pi+80\pi^2}{200\pi^3}\right)Cos[3\emptyset]-\left(\frac{189\sqrt{3}}{200\pi^3}\right)\cos[4\emptyset]\\ +\left(\frac{416\pi+27\sqrt{3}-300\sqrt{3}\pi^2+250\pi^3}{200\pi^3}\right)\end{array}\right]^{\frac{1}{2}} \quad (18)$$

Figure 6 shows the line plot of inverter neutral currents expressed by (15) – (18). This figure confirms that third harmonic injection signal can be used to reduce and minimize neutral current of three-level PWM inverter. The twenty five percent third harmonic injection signal gives minimum neutral current of three-level PWM inverter only for unity pf operation.

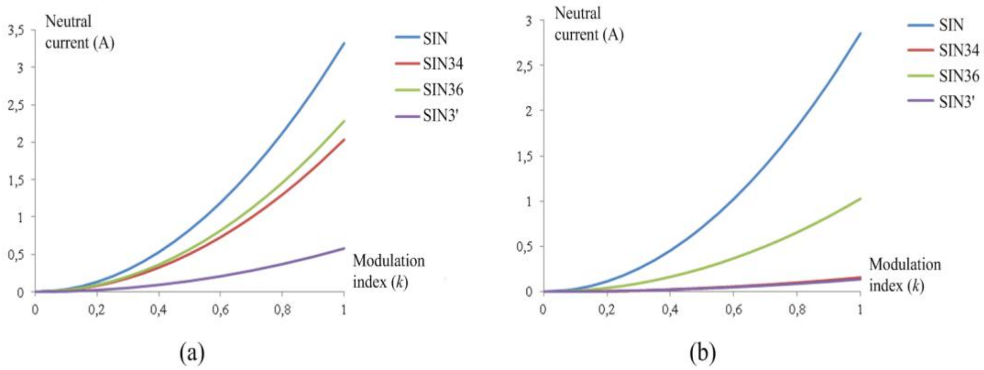

Figure 6. Neutral current of three-level PWM inverter (a) pf = 0.85, (b) pf = 1.

5. Simulation and Experimental Results

An experimental system shown by Figure 7 has been constructed to verify the analysis results. Power MOSFETs with high switching frequency are selected as the switches of three-level inverter. The load is static balance three-phase load. The load impedance and switching frequency have to be carefully determine to assure that load time constant is higher than inverter switching period. Thus, 19.51 ohm per-phase resistance, 5.89 mH per-phase inductance and 1 kHz switching frequency have been selected. The reference frequency of the inverter is 50 Hz. A three-phase full-bridge rectifier is used to generate a 100 V dc voltage fed into the input terminal of three-level inverter. The PWM switching pulse is generated by FPGA modul. To get a more comprehensive comparison, simulations using a software commonly used to simulate electrical power circuit i.e. PSIM@ version 9.0.3 are performed. Figures 8 and 9 show comparison of simulation, experimental and analysis/calculated results for output current ripple and neutral current respectively. Both figures show that simulation results are very close to calculated results. Average errors between simulation and calculated results are about 3.9% and 5,7% for output current ripple and neutral current respectively. Although the average errors between experimental and calculated results are slightly higher i.e 10.4% and 12.3% for output current ripple and neutral current respectively, but the shape and pattern of curves depicted from experimental results are very similar to the curves depicted from calculated results. Experimental results emerge higher error because ideal conditions assumed for analysis are not completely fulfilled such as dead time that is not equal to zero and dc supply voltage that can not be maintained constant and ripple free. Thus, validity of the calculated/analysis results can be appreciated from these simulation and experimental results.

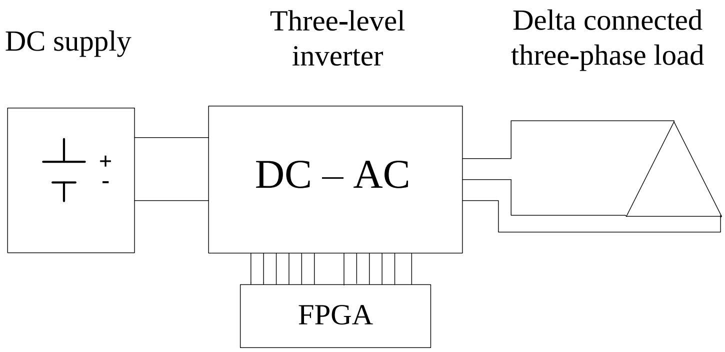

Figure 7. Block diagram of the three-level PWM inverter experimental system.

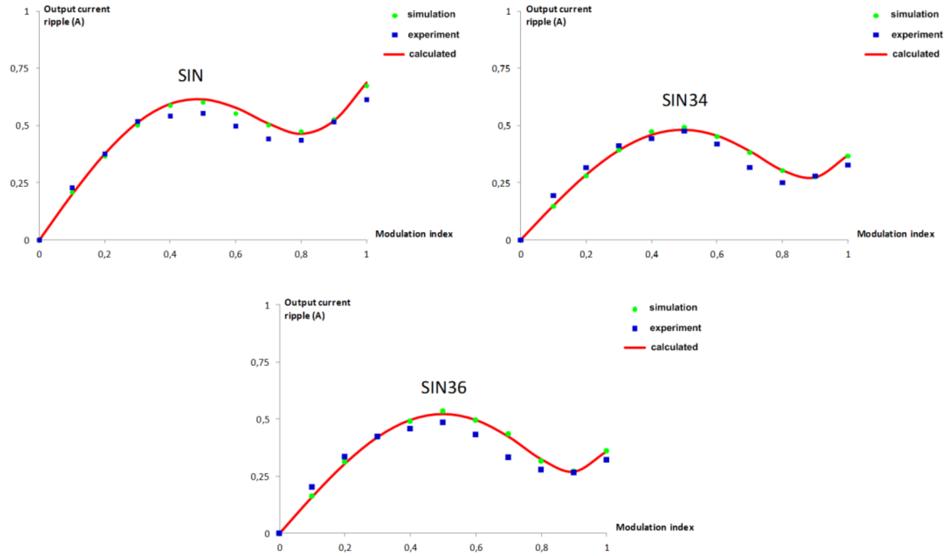

Figure 8. Calculated, simulation and experimental results of output current ripple of three-level PWM inverter.

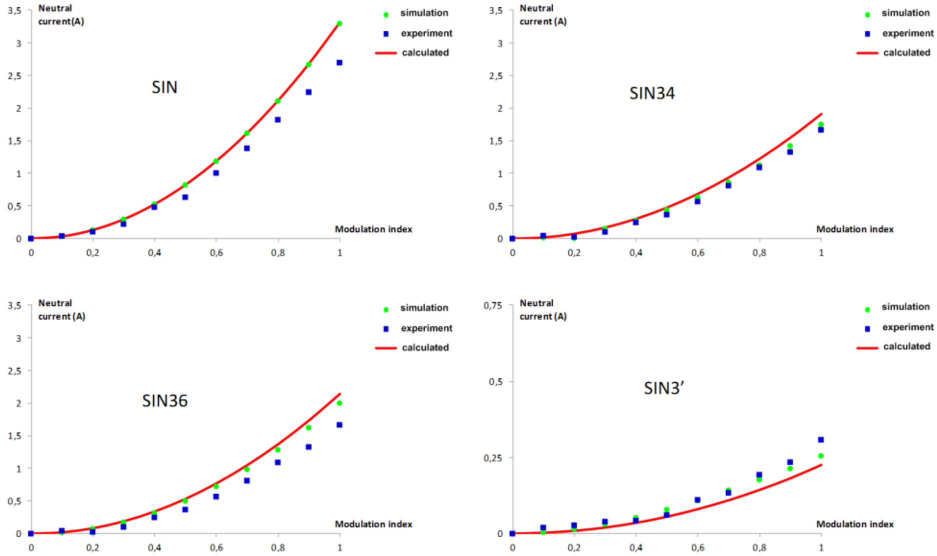

Figure 9. Calculated, simulatioan and experimental results of neutral current of three-level PWM inverter.

Table 6. Output current ripple of three-level PWM inverter

k	Calculated			Simulation			Experimental		
	SIN	**SIN36**	**SIN34**	**SIN**	**SIN36**	**SIN34**	**SIN**	**SIN36**	**SIN34**
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1	0.1992	0.1601	0.1497	0.2091	0.1629	0.1475	0.2291	0.2025	0.1948
0.2	0.3768	0.3048	0.2848	0.3666	0.3124	0.2806	0.3770	0.3352	0.3170
0.3	0.5134	0.4203	0.3917	0.5021	0.4208	0.3938	0.5189	0.4234	0.4132
0.4	0.5948	0.4948	0.4598	0.5886	0.4903	0.4749	0.5425	0.4577	0.4438
0.5	0.6147	0.5204	0.4818	0.6027	0.5351	0.4931	0.5543	0.4852	0.4766
0.6	0.5779	0.4944	0.4559	0.5532	0.4951	0.4527	0.4984	0.4322	0.4199
0.7	0.5085	0.4216	0.3887	0.5026	0.4351	0.3826	0.4424	0.3325	0.3173
0.8	0.4639	0.3233	0.3046	0.4745	0.3162	0.3040	0.4368	0.2786	0.2509
0.9	0.5213	0.2683	0.2736	0.5270	0.2709	0.2759	0.5169	0.2660	0.2802
1.0	0.6882	0.3568	0.3704	0.6747	0.3606	0.3675	0.6141	0.3216	0.3279

Note:
1. The unit for values in table is ampere (A)
2. SIN is without injection signal
3. SIN36 is with seventeen percent third harmonic injection signal
4. SIN34 is with twenty five percent third harmonic injection signal

Table 7. Neutral current of three-level PWM inverter

k	Calculated				Simulation			
	SIN	SIN36	SIN34	SIN3'	SIN	SIN36	SIN34	SIN3'
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1	0.0332	0.0188	0.0168	0.0029	0.0329	0.0165	0.0141	0.0046
0.2	0.1326	0.0822	0.0735	0.0091	0.1321	0.0753	0.0066	0.0149
0.3	0.2981	0.1893	0.1692	0.0199	0.2971	0.1761	0.1545	0.0310
0.4	0.5297	0.3397	0.3037	0.0354	0.5277	0.3175	0.2800	0.0525
0.5	0.8274	0.5336	0.4768	0.0556	0.8231	0.5008	0.4403	0.0790
0.6	1.1916	0.7703	0.6882	0.0805	1.1862	0.7239	0.6351	0.1083
0.7	1.6224	1.0497	0.9377	0.1098	1.6155	0.9851	0.8632	0.1426
0.8	2.1203	1.3714	1.2250	0.1437	2.1090	1.2855	1.1258	0.1773
0.9	2.6853	1.7353	1.5498	0.1819	2.6689	1.6250	1.4215	0.2142
1	3.3179	2.1409	1.9117	0.2257	3.2967	1.9997	1.7511	0.2552

k	Experimental			
	SIN	SIN36	SIN34	SIN3'
0	0.0000	0.0000	0.0000	0.0000
0.1	0.0410	0.0337	0.0335	0.0196
0.2	0.1048	0.0263	0.0263	0.0273
0.3	0.2219	0.1023	0.0926	0.0395
0.4	0.4823	0.2489	0.2285	0.0428
0.5	0.6350	0.3676	0.3273	0.0612
0.6	1.0045	0.5670	0.5160	0.1111
0.7	1.3838	0.8115	0.7715	0.1339
0.8	1.8221	1.0910	0.8510	0.1934
0.9	2.2446	1.3280	1.0230	0.2349
1	2.6966	1.6670	1.2650	0.3081

Note:
The unit for values in table is ampere (A)
SIN is without injection signal
SIN36 is with seventeen percent third harmonic injection signal
SIN34 is with twenty five percent third harmonic injection signal
SIN3' is with approximated third harmonic injection signal

Table 6 and Table 7 show respectively values of output current ripple and neutral current of the three-level PWM inverter as modulation index varies from zero to unity (k = 0 – 1). It can be seen from both tables that injecting third harmonic signal into three-phase sinusoidal reference signal of the natural sampled PWM technique results in significant reduction of both output current ripple and neutral current of three-level inverter. According to Table 6, using seventeen percent third harmonic injection signal gives reduction of output ripple current in range of 14.4% - 48.5% or approximately 24,8% in average (based on calculated data), 10.5% - 48.6% or approximately 23.3% in average (based on simulation data), and 11.1% - 48.5% or approximately 24.0% in average (based on experimental data). More significant output current ripple reduction is achieved when twenty five percent third harmonic injection signal used. It reduce the output current ripple of three-level PWM inverter in range of 21.1% - 47.5% or approximately 29,0% in average (based on calculated data), 18.2% - 47.6% or approximately 28.3% in average (based on simulation data), and 14.0% - 46.6% or approximately 26.2% in average (based on experimental data). Using twenty five percent third harmonic injection signal gives maximum reduction or minimum value of output current ripple of three-level PWM inverter. Further analysis shows that output current ripple reduction higher than 30% will be achieved if the modulation index is higher 0.7. According to Table 7, using seventeen percent third harmonic injection signal gives reduction of neutral current in range of 35.3% - 43.4% or approximately 36,6% in average (based on calculated data), 39.0% - 49.8% or approximately 40.8% in average (based on simulation data), and 40.1% - 53.9% or approximately 43.6% in average (based on experimental data). Higher neutral current reduction is achieved when twenty five percent third harmonic signal is injected into three-phase sinusoidal reference signal of the natural sampled PWM technique. Neutral current reduction is in range of 42.2% - 49.4% or approximately 43,4% in average (based on calculated data), 46.5% - 57.1% or approximately 48.0% in average (based on simulation data), and 44.2% - 58.3% or approximately 51.6% in average (based on experimental data). The highest or maximum neutral current reduction will be achieved if the approximated third harmonic injection signal used. Ranges of neutral current reduction are 91.3% - 93.3% or approximately 93.0% (based on calculated data), 86.0% - 92.3% or approximately 90.3% in average (based on simulation data), and 82.2% - 91.1% or approximately 88.8% in average (based on experimental data). The reduction is very significant and the neutral current is minimum. The approximated third harmonic injection signal will become twenty five percent third harmonic signal if the inverter operates in unity pf. Data of neutral current reduction of three-level PWM inverter listed in Table 7 also show that modulation index has no effect. Percentage of neutral current reduction varies slightly when modulation index varies from zero to unity.

6. Conclusion

The influence of third harmonic injection signal on output current ripple and neutral current of three-level PWM inverter has been analyzed. It is shown that third harmonic injection signal can be used to produce minimum output current ripple and neutral current. However, in general the third harmonic injection signal which produces minimum output current ripple is different from that which produces minimum neutral current. The twenty five percent third harmonic injection signal simultaneously produces minimum output current ripple and minimum neutral current only for unity power factor operation.

7. References

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