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Optimal control of booster phase shifters using HVSO pulse width modulation

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Pulse width modulation (PWM) phase shifters allow smooth control of power flow in transmission lines. Previous publications present a multimodal structure based on PWM control of GTO to achieve high-voltage and high speed switching. A new control scheme based on the high voltage sub optimal PWM modulation is proposed for semiconductor-controlled static phase shifters and its performance is compared with SPWM and optimal regular-sampled PWM techniques. This paper proposed a new single-module; six- switch structure based on high voltage sub optimal (HVSO) PWM technique with high voltage and limited harmonic injection. Simulations and comparisons of different PWM techniques for semiconductor-controlled static phase shifter (SPS) are used to illustrate the advantages and fine performance of the proposed structure.

INTRODUCTION

Transmission and distribution of power are mostly based on mechanically operated controllers (e.g., tap-changing transformers) that suffer from long response time (due to inertia of moving parts) and limited switching frequency (due to life span of mechanical contacts which tends to wear out very quickly). Application of semiconductor switches and power electronic converters have tremendously improved the performance of phase shifters. Much research has been preformed regarding the structure, application [1–4], modeling [9, 15] and placement [11, 12] of semiconductor-controlled static phase shifter (SPS), as well as, their application for optimal power flow [13], phase shifting control [5–8], security [10], economic dispatch, load flow control and power flow control [17] and transient stability [16]. Phase shifting is performed by adding to the bus voltage a controllable voltage whose components are in quadrature with the phase shifter input voltage. This can be done mechanically using a shunt transformer with tap's, a mechanical on-load tap changer and a series transformer [18]. Figure 1 illustrates the diagram used for phase shifting without any magnitude change. For the replacement of mechanical tap changers, several SPS's with thyristor–based ac controllers have been proposed [7]. References [5], [6] and [8] introduce a PWM quadrature booster phase shifter based on ac controllers with four switches. However, its implementation for high power SPS's is fairly complicated due to the low switching frequency ratio of GTO and the trouble of some connection of series switches. Recently, a high–power PWM quadrature booster phase shifter based on multimode ac controllers is

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proposed which uses multi module converters with phase shifters carriers to allow harmonic cancellation and voltage built up [5, 6]. This technique requires many switches when SPS's phase (φ) is increased. This paper uses a high voltage sub-optimal HVSO-PWM technique to propose a new single-module and high-voltage SPS structure with six switches and limited harmonic injection. Simulations and applications of different PWM technique for SPS are used to illustrate fine performance and advantages of the proposed structure.

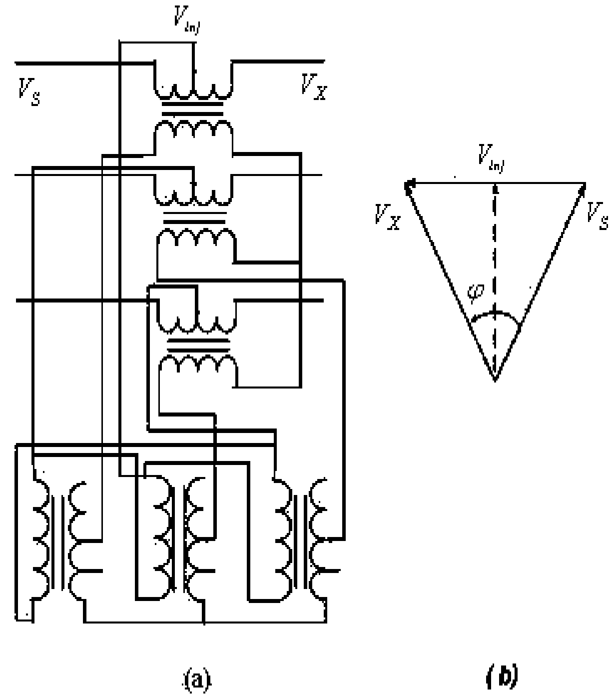


Figure 1.

(a) Mechanically controlled device for phase shifting without magnitude change, (b) phasor diagram

1. PRINCIPLES OF a SPS

Figure 2 shows the equivalent circuit diagram of a phase shifter consisting of admittance in series with an ideal transformer having a complex turn's ratio $k\angle\varphi$. Network analysis is used to obtain the mathematical model of phase shifter as follows [13]:

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} y'_{ij} + y_i & -y'_{ij} \\ -y'_{ij} & y'_{ij} + y_j \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix}, \tag{1}$$

$$Y_i = y'_{ij}[\frac{1}{k^2} - 1 + (1 - \frac{1}{k\angle(-\varphi)})\frac{V_j}{V_i}], \tag{2}$$

$$Y_j = y'_{ij}[(1 - \frac{1}{k\angle\varphi})\frac{V_i}{V_j}], \tag{3}$$

where $I_i, I_j, V_j\angle\varphi_i$ and $V_j\angle\theta_j$ are complex currents and voltages at buses i and j, respectively, $k\angle\varphi$ is the complex turns ratio of the phase shifter and $y'_{ij} = g'_{ij} + jb'_{ij}$ is the series admittance of line i–j.

According to Eq.1, the mathematical model of phase shifter makes bus voltages unsymmetrical.

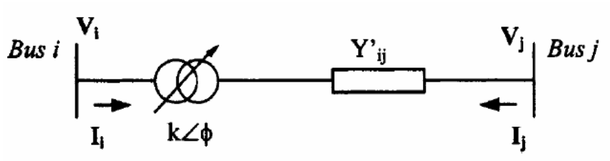


Figure 2.
Circuit diagram of a phase shifter

2. MODULATION TECHNIQUES

2.1. Sinusoidal PWM

The general features of double-edge, two-level, asymmetric, sinusoidal pulse-width-modulation (SPWM) is shown in Figure 3. A triangular carrier wave 'a' is used to sample the sinusoidal modulating wave 'b' twice every carrier cycle at regularly spaced intervals (corresponding to the positive and negative peaks of the triangular wave) to produce the sampled-hold or amplitude-modulated wave 'c'. Comparison of the sampled modulating wave 'c' with the carrier wave 'a' defines the points of intersection used to determine the switching instants of the width-modulated pulses. Thus the "real-time" comparisons between modulating and carrier signals, which cause difficulties in natural-sampling, have been eliminated. Therefore, SPWM overcomes most disadvantages of the natural-sampled PWM technique. A disadvantage of this method is the nonlinear relationship between switching angles and voltage.

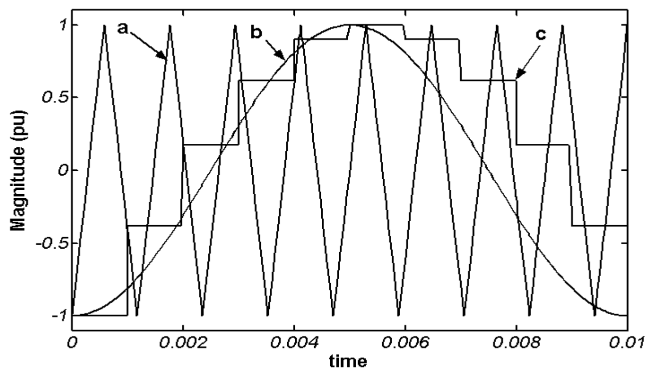


Figure 3. Simulated asymmetric SPWM, consisting of the carrier signal 'a', the reference modulating signal 'b' and the sampled hold modulating signal 'c'

2.2. Optimal Sampling PWM

The optimal modulation process, based on asymmetric regular-sampling, is illustrated in Figure 4. The optimal modulating wave 'a' is assumed to be an arbitrary non-sinusoidal waveform, the exact form of which is determined by the optimization process described below. As a consequence of using the regular-sampling process it is possible to define the PWM switching angles 'α_k' directly in terms of the non-sinusoidal modulating wave samples 'm(T_k)' using a relationship of the form [6]:

$$\alpha_k = T_k + (-1)^{k+1}\frac{T}{4}m(T_k)\,, \tag{4}$$

where $T_k = kT/2$ are the sampling instants.

Additionally, the harmonic spectrum of the PWM waveform can be expressed in terms of switching angles as follows:

$$A_n = \frac{4}{n\pi}[1 + 2\sum_{k=1}^{N}(-1)^k \cos(n\alpha_k)]\,, \tag{5}$$

where N equals the number of switches per quarter-cycle.

Combining Eqs. 4 and 5 provides a direct relationship between the optimal sampled modulating wave '$m(T_k)^*$' and harmonics of the optimized PWM waveform.

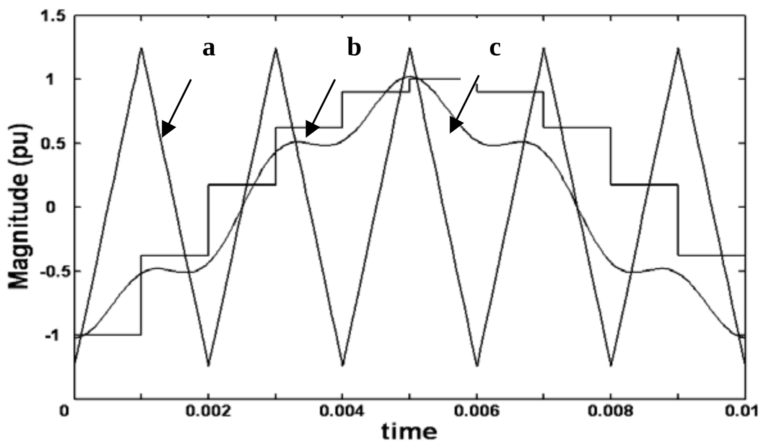


Figure 4. Simulated optimal regular PWM, consisting of the modulating wave 'a', the carrier wave 'b' and the sampled hold modulating signal 'c'

2.3. High Voltage Sub Optimal PWM

The undesirable harmonics of square waveform can be eliminated and the fundamental voltage component can be controlled as well by what is known as the harmonics elimination method. In this method notches are created on the square wave at predetermined angle, as show in Fig. 5. Half-cycle output is shown with quarter-wave symmetry. It can be shown that the five notch angles $\alpha_1, \alpha_2, \alpha_3, \alpha_4$, and α_5 can be controlled to eliminate three harmonic components and to control fundamental voltage. A larger number of harmonic components can be eliminated if the waveform can accommodate additional notch angle. In many applications of power system controller there is a need to provide a smooth, low harmonic distortion, transition from PWM to Quasi-Square Wave (QSW) to achieve maximum output voltages. It has been shown [7] that optimized PWM can provide this transition with extremely low THD, using very low switching frequency ratios N or equivalently low PWM pulse numbers, p = (2N + 1). It is also shown that as the optimized PWM voltage level increases towards the QSW voltage, the optimum pulse positions migrate towards the extremities (0, 180 and 360) of the PWM waveform. This explains the superiority of optimized PWM over other PWM strategies.

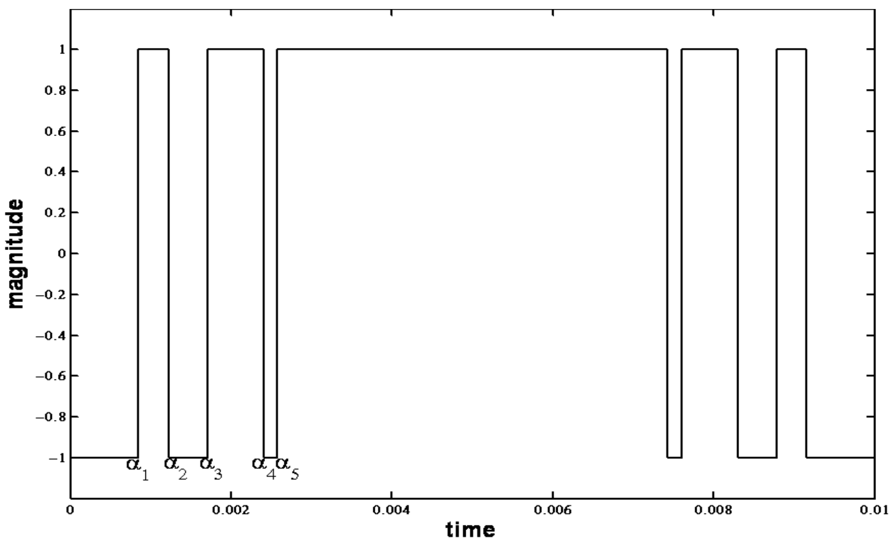


Figure 5. Voltage wave in harmonic elimination method

In general, there are a large number of possibilities for achieving this requirement. However, the simplest approach involves linearly shifting all the regular sampling points, in proportion to their relative positions, towards the edges of the PWM waveform as the voltage level increases. This method (Fig.6) can be viewed as "pre-modulation" of the sampling (carrier) signal which modulates the positions of the pulses, or alternatively as being equivalent to an increase in the carrier frequency when a triangular carrier waveform is used to define the sampling points. It is important to note that the frequency ratio F_R (ratio of pre-modulated carrier to modulating frequency) is "fictitious" in the sense that it is not, as is usual, directly related to the PWM pulse number. Indeed the important feature of the pre-modulation technique, illustrated in Figure 6, is the possibility of producing low switching frequency (e.g., low PWM pulse numbers) optimized PWM waveforms using high (fictitious) carrier frequencies.

Comparison of various PWM strategies indicates that the new HVSO high voltage sub optimal sampling PWM (involving simple equations, simple voltage control and simple microprocessor implementation [8]) is superior to the harmonics elimination technique and is equally as good as the optimized PWM method. Main advantages of this method are:

- Low harmonic injection
- Minimum switching loss
- Fast calculation of fire angle
- No requirement for fast switches

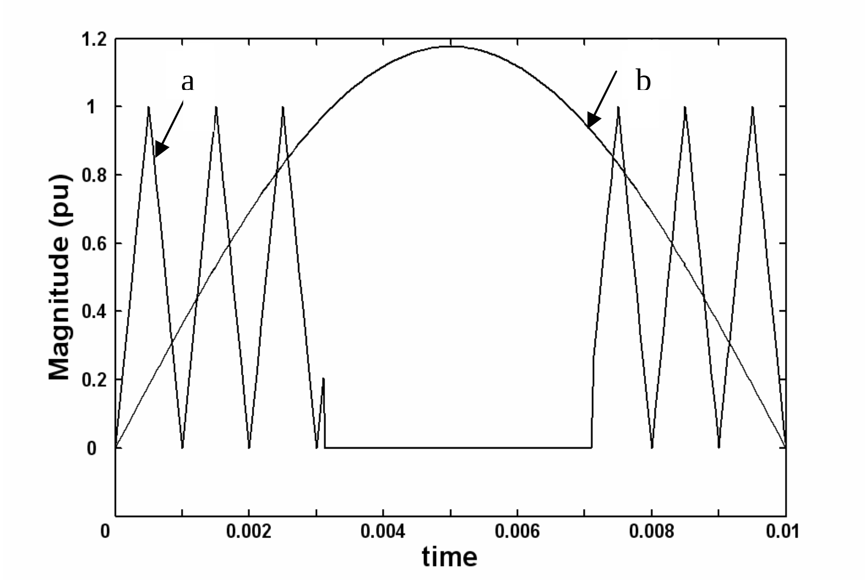


Figure 6. Simulated high voltage sub optimal PWM:
a) Modulating waveform; b) carrier wave

3. THE PROPOSED HVSO-BASED SPS

Phase angle regulating transformers (phase shifters) are used to control the flow of electric power over transmission lines. Both the magnitude and the direction of shift across the series transformer.

3.1. Principle of the operation

The phase shift is obtained by extracting the line-to-ground voltage of one phase and injection a portion of it in series with another phase. This is accomplished by using two transformers: the regulating (or magnetizing) transformer, which is connected in shunt, and the series transformer. The star-star and star-delta connections used are such that the series voltage being injected is in quadrature with the line-to-ground voltage. A portion of the line voltage is selected by the switching network and inserted in series with the line voltage. The added voltage is in quadrature with the line voltage since, e.g., the added voltage on phase 'a' is proportional to V_{bc}. The angle of a phase shifter is normally adjusted by on-load tap-changing (LTC) devices. The series voltage can be varied by the LTC in steps determined by the taps on the regulating winding. Progress in the field of high-power electronics has made it possible for thyristors to be used in the switching network. The proposed SPS uses HVSO-PWM technique to increase output voltage and to limit injected harmonics. We have also included and simulated two other sampling strategies (regular SPWM and sub optimal PWM) to investigate the performance of the new static phase shifter.

3.2. SPS Model in MATLAB

Figure 7 shows the proposed SPS model and the detail control blocks in MATLAB/ SIMULINK. The ET block is an exciter transformer and the BT block is a booster transformer model. We have used the SPS control block for simulating the proposed PWM methods. SPS controller block include Regular PWM, Sub Optimal PWM and HVSO PWM controller. In the control block, we have used a PWM generator and six switches for the SPS main structure.

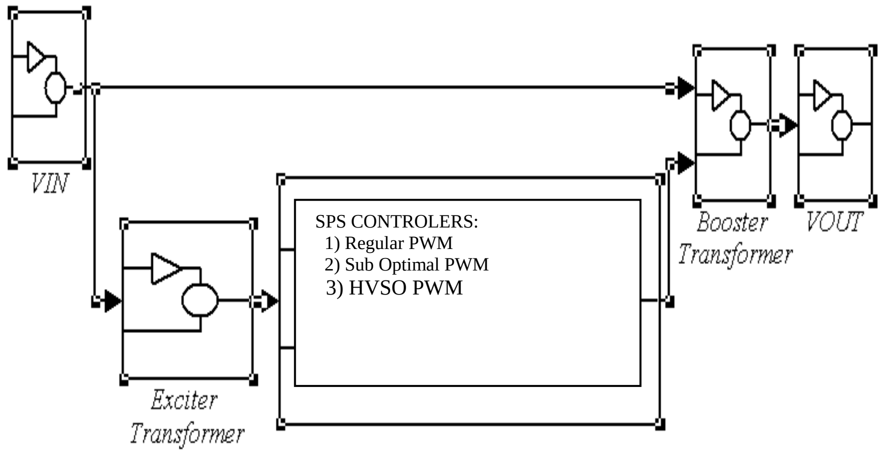


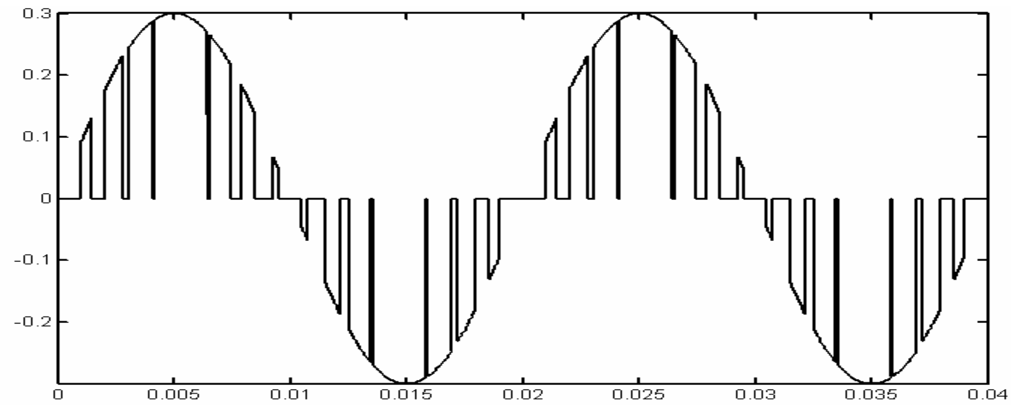
Figure 7. The Proposed SPS model and control blocks in MATLAB/SIMULINK

3.3. Simulation of SPS Modulation Techniques

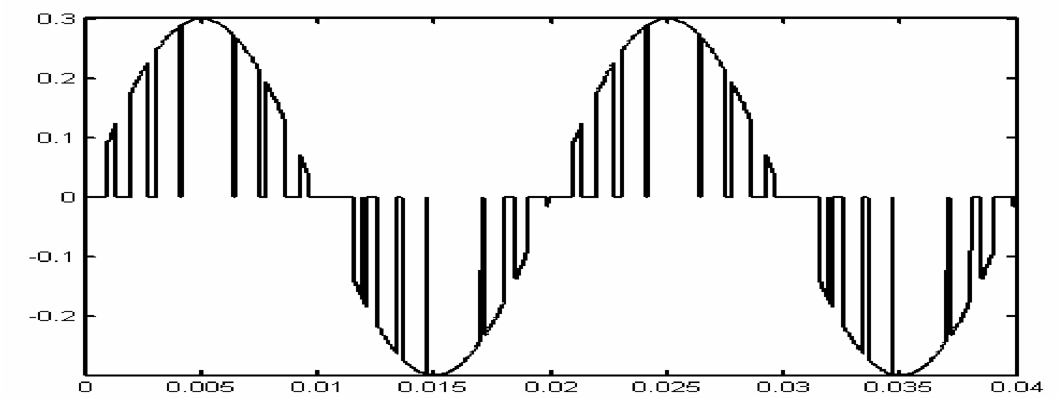
Three PWM strategies (SPWM, sub optimal PWM, HVSO-PWM) are simulated and their performances are compared. Figures 8–10 illustrate the injection voltage, bus voltage, and bus THD, respectively.

Main advantages of proposed HVSO strategy are:

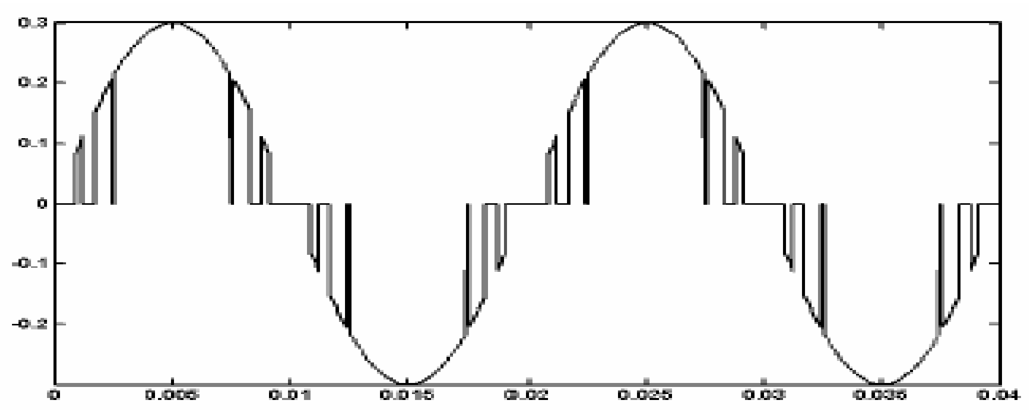
- Selection and control of SPS phase shift by adjusting the firing angle.
- Less number of switches and better harmonic spectrum, as compared with the other PWM techniques.



(a)



(b)



(c)

Figure 8. The injection voltage by SPS for different modulation techniques:
a) SPWM; b) optimal regular-sampled PWM; c) proposed HVSO-PWM

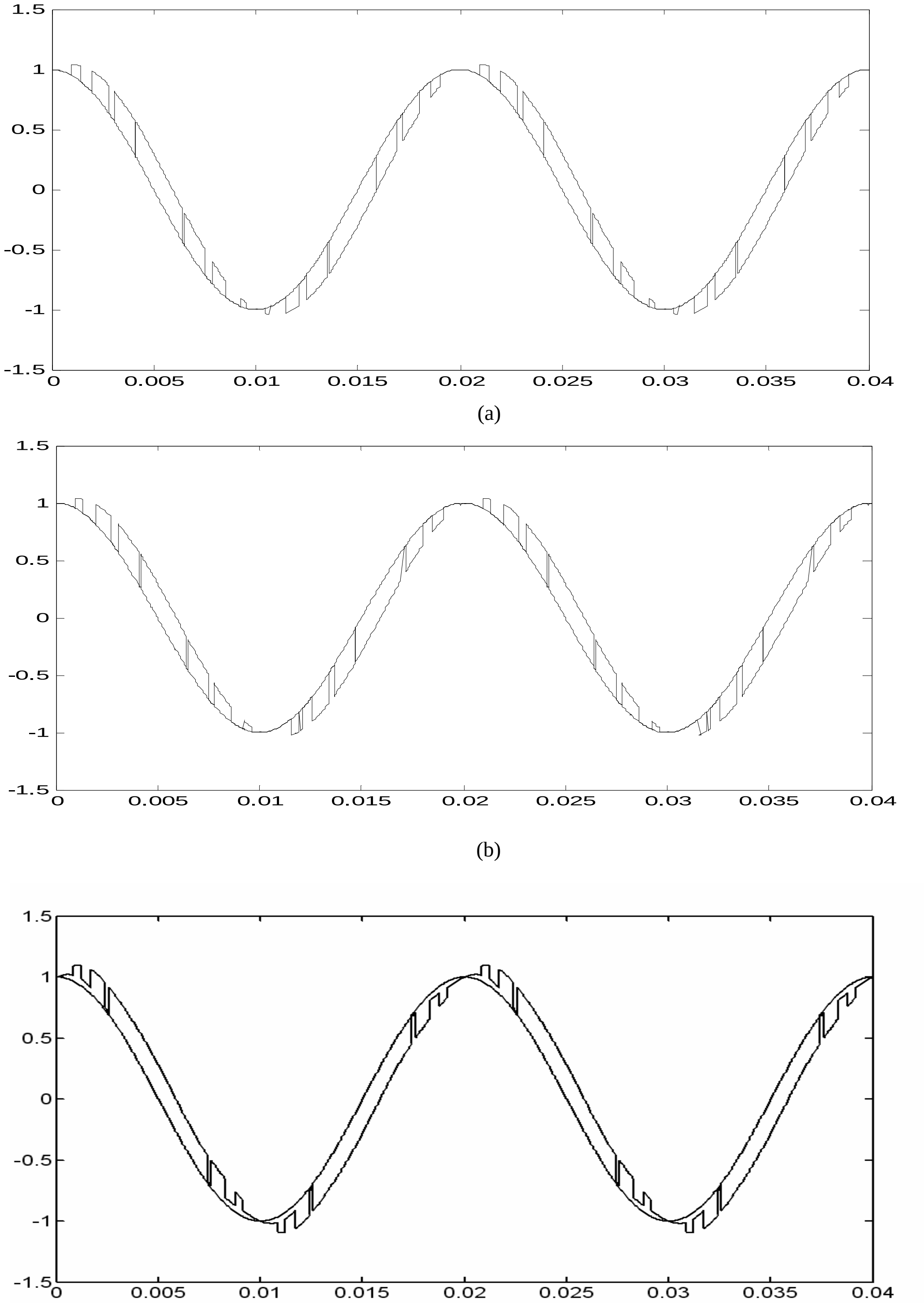


Figure 9. Bus voltage after the application of SPS for different modulation techniques: a) SPWM; b) optimal regular-sampled PWM; c) proposed HVSO-PWM

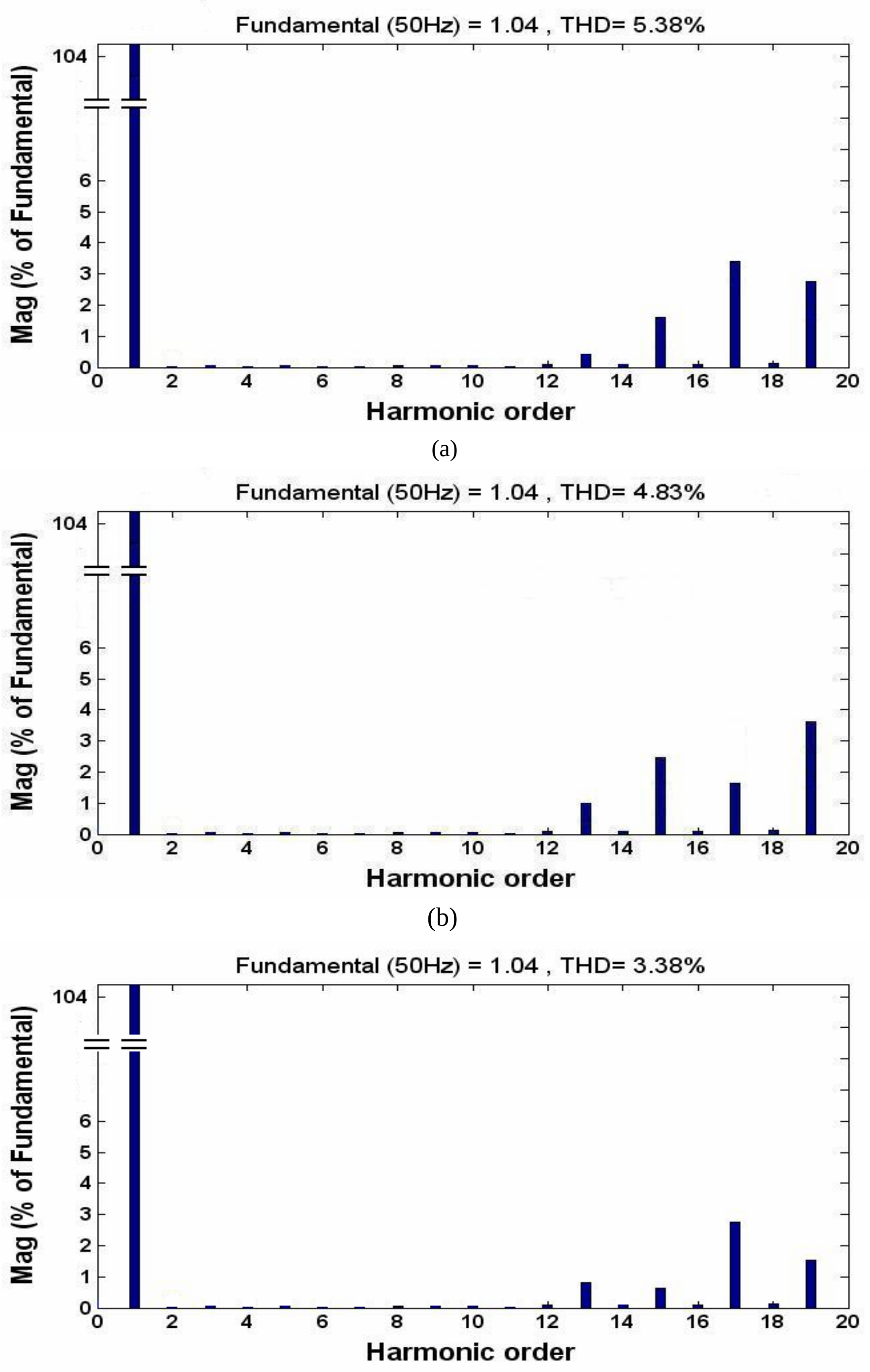


Figure 10. THD injection to power system for different modulation techniques: a) SPWM; b) optimal regular-sampled PWM; c) proposed HVSO-PWM

4. CONCLUSION

A new control scheme based on the high voltage sub optimal PWM modulation is proposed for semiconductor-controlled static phase shifters and its performance is compared with SPWM and optimal regular-sampled PWM techniques. Main advantages of the proposed SPS are:

- low injection of harmonics into power system,
- high efficiency with low switching losses,
- low computing time, and
- No requirement for fast switches.

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