A Robust SVM Technique to Minimize the Effects of Unbalanced Voltage Disturbances

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Abstract

Space vector modulation (SVM) is one of the most popular PWM techniques in the control methods of multilevel inverters. The assignment of the reference vector location is very important to obtain the exact switching times and to determine the correct space vectors in this technique. The location of the reference vector is determined by utilizing the phase angle of the system. It can be obtained from Clarke Transformation for SVM technique or phase-locked loop (PLL) for other methods. The unbalanced disturbances occurred in the three-phase systems affect the switching times obtained by utilizing the phase angle. The output waveform of the multilevel inverters is affected as well. In this study, the effects of disturbances such as line to line faults, unbalanced voltage sags/swells are investigated on conventional SVM technique. In order to minimize these affects, a new technique based on Clarke Transformation is proposed and applied to the two-level inverter. PSCAD/EMTDC simulation program is used to apply the case studies and to take the simulation results.

1. Introduction

The developments in the power electronic and the semiconductor technology have lead improvements in the power electronic systems recently. Hence, the different circuit configurations namely multilevel inverters have became more popular and considerable interest by researchers [1]. It provides the convenient means for the regulation of the real and reactive power flow, voltage support and improvement of the dynamic performance of the power networks [2]. Multilevel inverters structures, in their two configurations cascaded and neutral-point clamped (NPC), are well-known since 1980 [3]. They were investigated with the requirement of quality and efficiency in high power systems. It offers many advantages, such as increased power ratings, improved harmonic performance and reduced electromagnetic interference (EMI) emission [4]. Many different PWM techniques have been developed to achieve in the following aims [5].

- Wide linear modulation range,
- Less switching losses,
- Less total harmonic distortion (THD) in the spectrum of switching waveform,
- Easy implementation and less computation time.

Space vector modulation (SVM) is one of the most popular PWM techniques recently. This technique reduces the switching losses and provides the more utilized from the DC source. Implementation of this technique in the multilevel inverters is complex and intensive computationally because of the calculation the reference vector location, the switching times and determination the switching state vectors. The assignment of the reference vector location is very important in order to calculate the switching times without any error. It is determined by utilizing the phase angle of the three-phase system. Clarke Transformation (α-β Transformation) is used to calculate the phase angle [6]. The balanced and unbalanced disturbances of the three-phase systems such as voltage sag/swell, single-phase or double-phase voltage sag/swell affect this angle. The output waveform of multilevel inverter is affected by these disturbances as well.

In the literature, the effects of the unbalanced voltage disturbances on conventional SVM technique are observed insufficiently. However, the effects of the unbalanced voltage disturbances on phase angle are observed. Several studies are summarized given in the following.

The generation of negative sequence by voltage sags and/or unbalance is observed in [7] and its effects on phase angle are shown as an oscillating error in a synchronous reference frame (SRF). The sag detection algorithm for Dynamic Voltage Restorer (DVR) is proposed and compared to other sag detection algorithms in [8]. The effects of the voltage sag are examined on sensitive loads and phase angle of three phase system. The unified approach of the SVM technique for voltage source inverter is studied in [9]. Five inverters topologies are analyzed to exemplify the proposed methodology. Switching vectors, separation, boundary planes and some possible switching sequences are given for each one of the inverters. The over modulation strategy for SVM technique is observed and it is applied with neural network to the system in [10]. The system analysis, algorithm development and its equivalent Digital Signal Processor (DSP) based implementation have been described systematically. A simple SVM technique is presented instead of generalized method and its implementation in [11]. The proposed SVM technique uses the basic two-level modulation to calculate the on-times and computation process for n-level inverter. A doubled modulation strategy for matrix converters is given in [12]. It is based upon an indirect conversion scheme which models the matrix converter as two independent stages performing rectification and inversion.

In this study, the effects of the balanced/unbalanced voltage disturbances on conventional SVM technique are observed with several case studies. To minimize the affects of disturbances, a new technique based on α-β Transformation is proposed and applied to the two-level inverter. A simple test system is created to analyze the effects of the voltage disturbances on SVM technique and to show the validation of proposed technique. PSCAD/EMTDC simulation program is used to construct the test system and to apply the case.

2. The Effects of the Unbalanced Disturbances on Conventional SVM Technique

A short duration increase in the current somewhere of the system for instance, during faults, motor starting and the power transformer energizing causes the voltage sags. Voltage swell are not as common as sags and its main causes are the switching off of a large load, energizing a capacitor bank, voltage increase of the unfaulted phases during a single line-to-ground fault and reversed power somewhere in the distribution systems [13]. SVM technique is based on foundation of the reference voltage vector and the phase angle of the system. Especially, the phase angle not affected by the disturbances is needed to calculate the switching times without any error. The oscillation is occurred on the line of the phase angle during the voltage sag/swell and it affects the output waveform of the inverter. However, these affects of disturbances on the phase angle are observed insufficiently in the literature.

2.1. The Ratings of the Test System and Inverter

In this study, PSCAD/EMTDC program is used to simulate the test system and construct the two-level inverter. It is given in Fig.1.

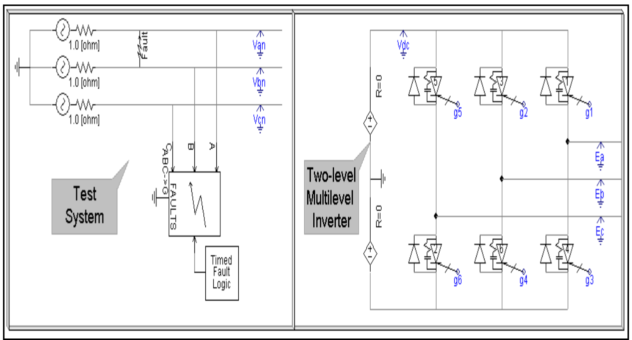

Fig.1. Test system and two-level inverter

In the test system, six-pulse voltage source inverter (VSI) is used. Generally, isolated-gate bipolar transistor (IGBT) is used in the applications of VSI because of its fired in the range of high frequency. V_{an}, V_{bn}, V_{cn} are the phase voltages of the test system and E_a, E_b, E_c are the phase voltages of multilevel inverter. V_{dc} is the voltage of DC sources. The gates of IGBTS are named as g_1, g_2, g_3, g_4, g_5 and g_6.

The ratings of the test system are selected as 270 V (line-line) for the reference three-phase AC source and 165 V for each DC source. The sampling time of the simulation is selected as 25 µs and the switching time of SVM technique simulation is selected as 500 µs.

2.1. Application of the Balanced / Unbalanced Voltage Disturbances

The phase angle is affected any unbalanced voltage disturbances occurred anywhere of the system. The output waveform of the inverter is affected by these disturbances as well. Especially, the phase angle of the system is more affected by the disturbances than the inverter outputs have. The reason of these effects on phase angle is explained as mathematically in Section 3.2. To see the effects of disturbances on phase angle and output waveform of multilevel inverter, several disturbances are applied to the test system in the case studies. The phase angle of the test system is changing between -180˚ to 180˚ in the nominal conditions. In this study, the phase angle of the test system is shifted by adding 180˚ and the variation of its value from 0˚ to 360˚ is supplied. For case study 1, the balanced voltage sag/swell faults are applied. The output waveform of the inverter is affected as shape-changing. But, the phase angle of the system is not affected. The results of case study 1 are given in Fig.2.

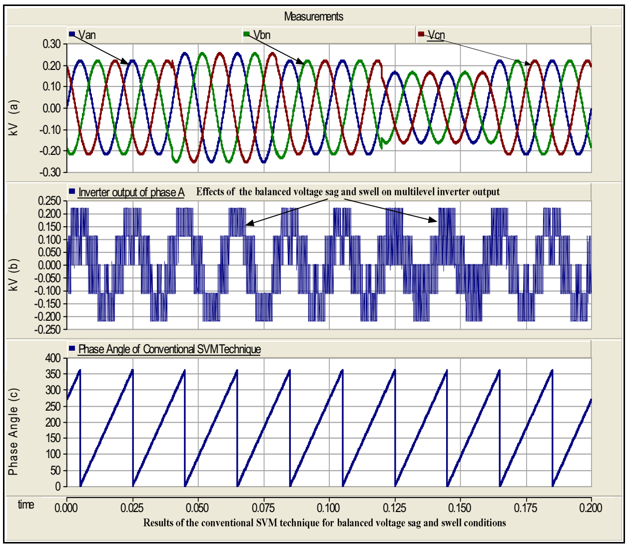

Fig.2. (a) Phase voltages of the test system, (b) Output waveform of phase A, (c) Phase angle of the test system

To create the unbalanced voltage disturbances in case study 2, a line-line fault between phases A and B and single-phase voltage swell at phase C are applied to the test system. The output waveform of the inverter is affected as shape-changing whereas the phase angle of the system is affected as oscillation occurred on its line. These effects of the unbalanced voltage disturbances are given in Fig.3.

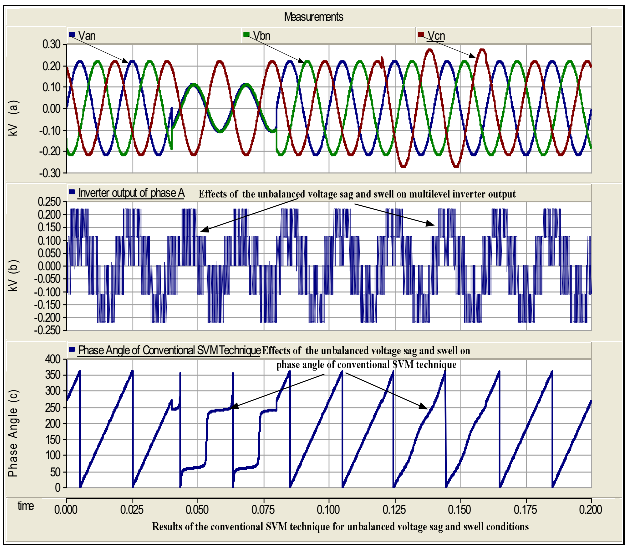

Fig.3. (a) Phase voltages of the test system, (b) Output waveform of phase A, (c) Phase angle of the test system

3. Proposed SVM Technique

3.1. Principles of Proposed SVM Technique

In conventional SVM technique, the reference voltage vector $\vec{U}$ rotates in α-β plane at constant amplitude with fundamental angular speed and it is sampled instantly in each 60° sector. In each sector, the projections vectors of $\vec{U}$ are formed on axes of α-β plane. These projections vectors are calculated by using trigonometric functions. The projection vectors of $\vec{U}$ in α-β plane are shown in Fig. 4.

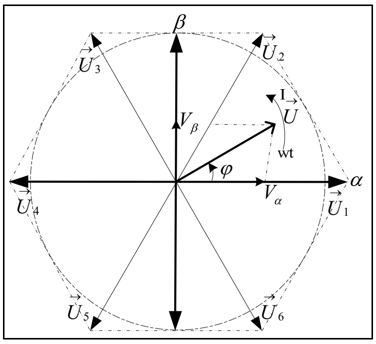

Fig.4. Reference voltage vector in α-β plane

The vector $\vec{U}_\alpha$ is the projection vector of $\vec{U}$ in α-axe and the vector $\vec{U}_\beta$ is the projection vector of $\vec{U}$ in β-axe. $\vec{U}_\alpha$ and $\vec{U}_\beta$ vectors are calculated by measuring the phase voltages from the test system instantly. Any disturbance in the system directly affects these vectors and the phase angle as well. Hence, the output waveform of the multilevel inverter is affected. These affects must be reduced to find the non-affected phase angle of the system. In this study, a new technique dependent on α-β transformation for SVM technique is proposed.

3.2. Mathematical Derivation of SVM Technique

The equations of vectors $\vec{U}_\alpha$ and $\vec{U}_\beta$ which are given in the following can be calculated by using geometric functions from Fig.4.

$$\vec{U}_\alpha = \vec{U} * \cos(\omega t + \varphi) \tag{1}$$

$$\vec{U}_\beta = \vec{U} * \sin(\omega t + \varphi) \tag{2}$$

where φ is the phase angle of the system.

According to Equation (1) and Equation (2), there is a 90° degree differences between vectors $\vec{U}_\alpha$ and $\vec{U}_\beta$. Then, the trigonometric relationships the similar with complementary angles are found between vectors $\vec{U}_\alpha$ and $\vec{U}_\beta$. The phase angle φ between vectors $\vec{U}_\alpha$ and $\vec{U}_\beta$ is found by utilizing the Equation (3).

$$\varphi = \tan^{-1}\left(\frac{\vec{U}_\beta}{\vec{U}_\alpha}\right) \tag{3}$$

If the derivation of the trigonometric relations between vectors V_α and V_β are continued between these vectors, Equation (6) is obtained by utilizing the equations given in the following.

$$\vec{U}_\alpha^{\,2} + \vec{U}_\beta^{\,2} = \vec{U}^2 * [\cos^2(\omega t + \varphi) + \sin^2(\omega t + \varphi)] \tag{4}$$

$$[\cos^2(\omega t + \varphi) + \sin^2(\omega t + \varphi)] = 1 \tag{5}$$

$$\vec{U}_\alpha^{\,2} + \vec{U}_\beta^{\,2} = \vec{U}^2 \tag{6}$$

If the vector $\vec{U}_\alpha$ is taken instead of x-axes and the vector $\vec{U}_\beta$ is taken instead of y-axes in the graph properties of PSCAD/EMTDC, the circle can be obtained given in Fig.5.

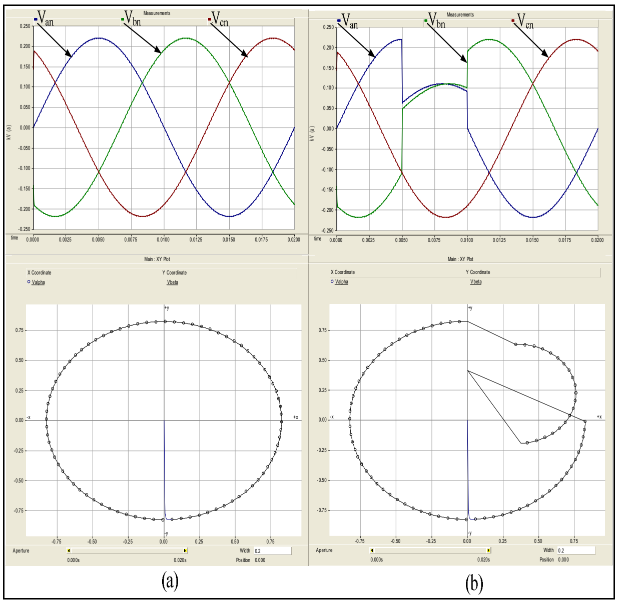

Fig.5. Trajectory of the Reference Voltage Vector, $\vec{U}$

There is a fix ratio between vectors $\vec{U}_\alpha$ and $\vec{U}_\beta$ and they affect each other's values during the unbalanced voltage disturbances because of this fixed ratio. If the system is in steady state conditions without any fault or disturbances, its trajectory is similar with the circle given in Fig.5.(a). If any unbalanced voltage disturbances are occurred in the three phase system, the phase angle φ and the trajectory of the system are affected. It is given in Fig.5.(b).

The interaction between vectors $\vec{U}_\alpha$ and $\vec{U}_\beta$ must be minimized during the calculation of the phase angle. This interaction can be reduced, if vectors $\vec{U}_\alpha$ or $\vec{U}_\beta$ are written as type of each others. The trigonometric functions give the opportunities to write vectors $\vec{U}_\alpha$ or $\vec{U}_\beta$ in the type of each others. According to this, if the first derivation of Equation (1) or Equation (2) is taken, vectors $\vec{U}_\alpha$ or $\vec{U}_\beta$ can be rewritten in the type of each others. Such as, if the first derivation of the vector $\vec{U}_\alpha$ is taken, the vector $\vec{U}_\beta$ can be rewritten in the type of vector $\vec{U}_\alpha$. These formulations are given in the following.

$$\frac{d}{dt}\left(\vec{U}_\alpha\right)=\vec{U}*\frac{d}{dt}\left(\cos(\omega t+\varphi)\right) \tag{7}$$

$$\left(\vec{U}_\alpha\right)'=(-1)*\omega*\vec{U}*\sin(\omega t+\varphi) \tag{8}$$

$$\vec{U}_\beta=(-1)*\frac{\left(\vec{U}_\alpha\right)'}{\omega} \tag{9}$$

In the proposed method, the interaction between vectors $\vec{U}_\alpha$ and $\vec{U}_\beta$ is reduced by using Equation (9) instead of $\vec{U}_\alpha$ in Equation (3). In proposed method, the phase angle of the system is found by using Equation (10).

$$\varphi=\tan^{-1}\left[\frac{(-1)}{\omega}*\frac{1}{\vec{U}_\alpha}*\left(\vec{U}_\alpha\right)'\right] \tag{10}$$

3.3. Application of the Proposed SVM Technique

In PSCAD/EMTDC software, new components can be created by using FORTRAN language. In this study, the component blocks namely as '*alpha-beta transform*', '*phase angle*' and '*Firing pulse generator of IGBTs*' are created by using FORTRAN codes. These component blocks are used to calculate α-β transformation, to find the switching times and to give the firing pulses of IGBTs.

The phase voltages V_{an}, V_{bn}, V_{cn} are used to find the vector V_α by using Equation (1) in the alpha-beta transform block. For the proposed technique, the first derivation of the vector V_α is taken in the derivation block to calculate the vector V_β. The phase angle φ is obtained by using Equation (10) in the phase angle block. The firing pulses of IGBTs are created in the firing pulse generator of IGBTs block. The other inputs are DC voltage (V_{dc}) source and the sampling time (T_s) of SVM technique. The application of the conventional SVM technique and the proposed SVM technique in PSCAD/EMTDC are given in Fig.6

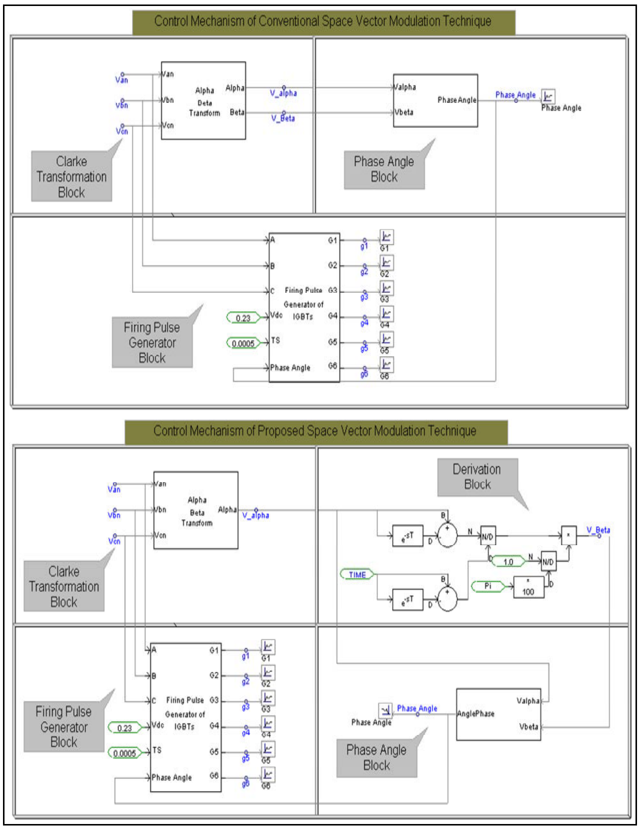

Fig.6. Calculation of the phase angle and the firing pulses of IGBTs for both techniques

4. Case study of Proposed SVM Technique

For the case study, the double-phase voltage sag (between phases A and B), single-phase voltage sag and voltage swell are applied to the test system, respectively. The phase angle of the conventional SVM technique is affected as oscillations occurred on its line whereas the phase angle of the proposed SVM technique is not affected during the unbalanced voltage disturbances. But, only a notch is occurred at the start time of the double-phase voltage sag. The affects of the unbalanced voltage disturbances are given in Fig.7.

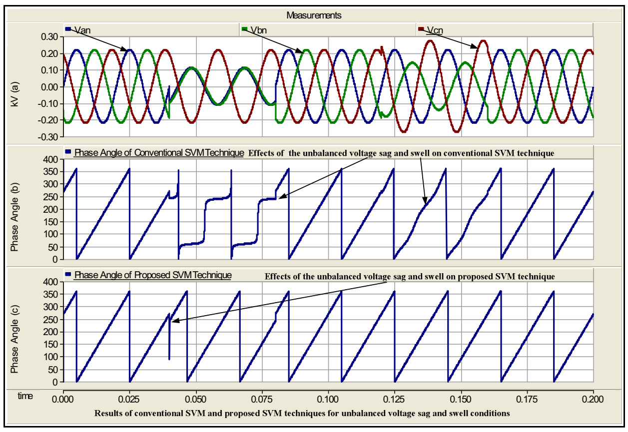

Fig.7. Simulation results of case study for unbalanced voltage sag and swell

5. Conclusions

In SVM technique, the location of the voltage vector and switching times of IGBTs are determined by utilizing the phase angle of the system. The disturbances occurred in the system affect this angle. However, effects of the disturbances can be seen in the output of multilevel inverter. The phase angle non-effected is already needed for SVM technique. In the literature, the affects of the disturbances are observed insufficiently.

In this study, a new technique based on Clarke transformation is developed to minimize the effects of the unbalanced voltage disturbances on phase angle and SVM technique as well. Several disturbances are applied to the test system to show their affects on phase angle and the output of multilevel inverter. To show the validation of the proposed technique, various unbalanced voltage disturbances are created and applied to the test system in the case study. The results of conventional SVM technique and proposed SVM technique are given by comparing their phase angle in the last section. The simulation results show that the proposed SVM technique can be used instead of conventional SVM technique for all systems where the balanced and unbalanced voltage disturbances are occurred. If proposed technique is improved, it can be used to detect the voltage sag/swell for Custom Power or FACTS devices.

7. References

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