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Multilevel V^{3}F Drive Application in Industries- A Survey and Comparison

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ABSTRACT

The multilevel inverter has gained wide importance in imperative applications because of reduction in harmonic distortion and switch stress replacing the conventional two-level converters. The selection of switching technique to control the inverter plays an important role on harmonic elimination while generating the ideal output voltage. Extensive survey has been performed on the industrial application of variable frequency drive using two-level and multilevel inverter – in the selection of topology and control techniques, and the best control technique is suggested according to various application areas. In this paper comparison of SPWM, SFOPWM and SVM techniques applied on nine-level diode clamped multilevel inverter fed induction machine for industrial applications is presented for various modes of operation. In normal and high modulation indices SPWM and SFOPWM are preferable and in low and normal modulation index, SVM is preferred. The constant flux control method is used for speed control of induction machine.

Keywords: VSD, VFD, CFC, SPWM, SFOPWM, SVM, THD

1. INTRODUCTION

A variable frequency drive is used in electromechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage. The first stage of variable speed drive is the diode rectifier and second stage is inverter. Rectifier converts ac energy to dc and inverter does the reverse. Primary benefit of variable speed drive is increased energy efficiency. Power consumption by a VSD as a function of speed is considerably lower than a motor alone controlling flow rate by valves, especially when run at less than full speed. VFD is programmable for smooth start up, thus reducing high starting torque and current surges. Figure1 is a VFD system with three phase AC source, VFD, and induction motor driving a load [19].

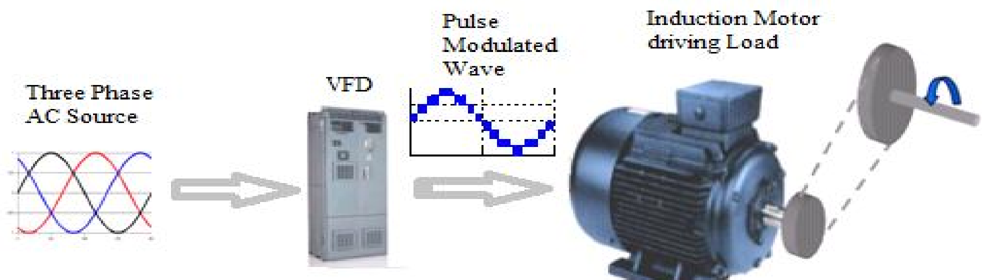

Figure 1 Variable Frequency Drive

Among ac motors, workhorse of industry: asynchronous machine which contain a cage are very popular is present in VSD applications due to its simple construction, robustness, inexpensiveness, reliability, good efficiency and good self-starting capability and availability at all power ratings. Progress in the field of power electronics and microelectronics enables application of induction motors for high-performance drives, where traditionally only dc motors were applied. Progress of usage of VFD in global market is shown in Figure2 [19].

Most of the industrial loads are operated based on constant Volt/Hertz (Variable Voltage Variable Frequency- VVVF or V^{3}F) speed control method because of its simplicity. During the adjustment of speed, value of the air-gap flux is kept unchanged. If the magnetic flux is very small, the iron core of the motor cannot be fully utilized and therefore cannot output a high torque. However, if the magnetic flux is very large, iron core of the motor will be saturated, which leads to an excessive exciting current and even a failure of the motor. For this reason, frequency conversion speed control must be performed on the premise of a constant air-gap flux. This paper considers nine-level diode clamped multilevel inverter driven constant flux control induction motor drive run with SPWM, SFOPWM and SVPWM.

2. LITERATURE AND INDUSTRIAL SURVEY

Development of squirrel cage induction motor in the year 1887 by Tesla, and three phase dc-ac power inverters by David Prince in 1925 coined invention of variable speed drives in early 1960's by Martti Harmoinen. Major global manufacturers of VFD are Fuji, Mitsubishi, Danfoss, Siemens AG, ABB, Rockwell Automation, Schneider, Vacon, Yaskawa, Toshiba, and Emerson [19]. Fans are the major share in VSDs for cooling purpose in all industries.

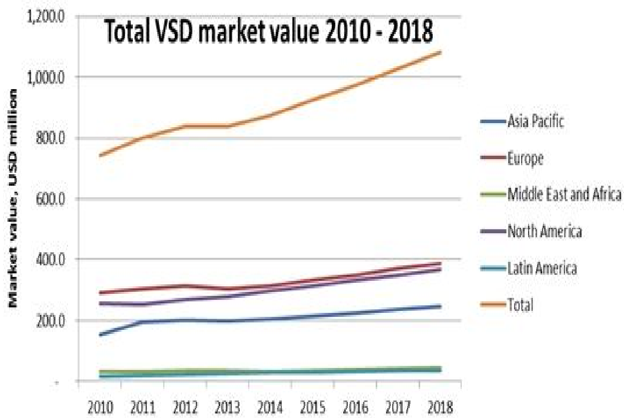

Figure2 Global VSD Market Share

Chookiat (2005) presented control on 3 HP drive using automatic torque boost and acceleration/ deceleration methods and tested experimentally for constant v/f control which can be used in small scale industries. Burak Ozpineci (2003) presented simulation analysis on constant flux, direct vector and indirect vector control in motoring and generating mode concentrating on synchronously rotating reference frame for induction motor.

Akira Nabea in 1975 invented multilevel concept in converters and presented a paper in 1980. Abdul Rahiman Beig (2002) presented about the self balancing of clamped capacitors and improved performance of SVPWM over SPWM in 10kVA, IGBT three-level diode-clamped inverter powering 10kW induction motor. Subrata K.Mondel (2003) presented about the three-level inverter in under modulation and over-modulation region to extend the operation of v/f controlled induction motor into field weakening mode using SVPWM technique. Lalili (2007) presented about five-level DCMLI for improved performance controlled with simplified SVPWM technique. Pandian (2008) presented about the three-level inverter fed induction motor for industrial applications. Mohan M. Renge (2008) presented about five-level DCMLI to eliminate common mode voltage and to reduce dv/dt stress in medium voltage rating induction motor drives. Mohammadreza Derakhshanfar (2010) in his thesis of Master of Science, presented comparison on three multilevel topologies for two-level, five-level and nine-level based on theoretical analysis of switching losses and power losses. The nine-level DCMLI is designed by cascading two five-level DCMLIs. Calculations and simulation results on THD are presented based on cost and weight with transmission line as load.

Kiruthika (2012) presented about the SPWM technique controlled nine-level DCMLI concentrating on total harmonic distortion. S.Shalini (2013) presented on capacitor voltage balancing on nine-level DCMLI using SPWM technique. Surendar (2013) presented on nine-level DCMLI operated with SPWM technique. Mohan Teja (2014) presented about the SPWM technique run nine-level DCMLI. Rathinam Angamuthu (2016) presented detailed analysis on reduction of components in five-level diode clamped multilevel inverter using carrier based techniques feeding single phase induction motor experimentally for an industrial application. Narmadha (2016) presented about fuzzy logic operation to balance the capacitor voltages in nine-level DCMLI. Abhay Kumar (2016) presented about nine-level and eleven-level inverter fed permanent magnet synchronous motor for grid connected renewable energy sources using SPWM technique. The previous papers discussed above did not cover SVPWM for nine-level diode clamped multilevel inverter for industrial applications. In this paper, analysis on SVPWM, SFOPWM and SPWM techniques for a nine-level DCMLI is simulated and the results are compared for an industrial application of three phase induction motor controlled with constant v/f (CVF) method in open loop.

3. DIODE CLAMPED MULTILEVEL INVERTER AND MODULATING TECHNIQUES

3.1 Multilevel converter topologies

Three basic multilevel converters are: Diode Clamped multilevel inverter based on neutral point converter, Flying Capacitor multilevel inverter and Cascaded or Hybrid multilevel inverter. Figure3 shows generalized multilevel inverter topology per phase leg, where each switching device, diode, or capacitor's voltage is $1V_{dc}$, i.e., 1/(N-1) of dc link voltage. Any inverter with any number of levels including conventional two-level inverter can be obtained from this generalized topology [14], [15].

3.2 Modulation techniques

The two popular approaches used to generate PWM signals for multilevel inverters are:

1. Multilevel Sine-Triangle Carrier Pulse Width Modulation-SPWM or Sub Harmonic or Sub-Oscillation carrier based PWM
2. Multilevel SFOPWM
3. Space Vector PWM-space vector modulation based on a rotating vector in multilevel space

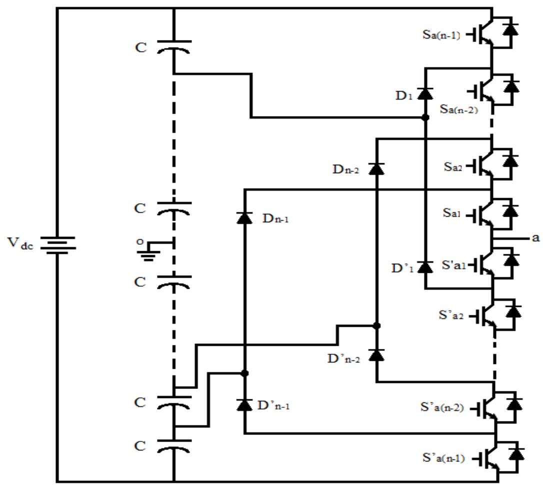

Figure 3 Single leg of 'N' level Diode Clamped Multilevel Inverter

Carrier based PWM methods employ per carrier cycle volt-second balancing principle to program a desirable inverter output voltage waveform. Multilevel SPWM involves comparison of reference signal with a number of level or phase shifted carriers to generate PWM signal. Carrier based PWM methods can operate with high switching frequency and offer high waveform quality and implementation advantages. Carrara considered different methods of disposing many carrier bands required in multilevel PWM.

Steinke proposed SFOPWM, a carrier based method where addition of triplen harmonic to fundamental frequency sinusoidal lowers peak magnitude, thus allowing operating in over-modulation region. This increases inverter output voltage without compromising on quality of output waveform. The method takes instantaneous average of maximum and minimum of three reference voltages and subtracts the value from each of individual reference voltages to obtain modulation waveforms.

Programmed PWM technique: SVPWM involves synthesizing reference voltage space vector by switching among nearest voltage space vectors. SVPWM is considered a better technique of PWM owing to its advantages

(i) Improved fundamental output voltage
(ii) Reduced harmonic distortion
(iii) Easier implementation in microcontrollers and Digital Signal Processor.

3.3 Constant flux control of induction machine

Open loop control of the machine with constant ratio of variable voltage to variable frequency may provide a satisfactory variable speed drive when the motor has to operate at steady torque without stringent requirements on speed regulation.

4. RESULTS AND DISCUSSIONS

The simulation model for nine level diode clamped inverter shown in Figure4 is developed for switching frequency of 1.5 kHz for SPWM, SFOPWM and SVPWM technique and results are presented for various modulation indices of 30kW, 400V, 4 pole, 1470rpm induction machine. SVPWM is simulated for conventional switching sequence (CS) and optimized switching sequence (OS) for multicarrier multi-modulation (MCMM) and single carrier multi-modulation (SCMM) technique [14], [15].

Table1 shows at various instants how SPWM, SFOPWM and SVPWM respond to different torque and speed requirements.

Figure5 to Figure10 show the response of industrial application induction machine for various control techniques. Figure5 presents the response for stator currents, electromagnetic torque and rotor speed for SPWM control mode. Figure6 presents the response for stator currents, electromagnetic torque and rotor speed for SFOPWM control. Figure7 and Figure8 represent response for conventional switching sequence in SVPWM technique and Figure9 and Figure10 for optimized switching sequence. Figure7 and Figure9 are for MCMM mode and Figure8 and Figure10 are for SCMM mode.

Table 1 CVF Control Parameter Values for SPWM, SFOPWM and SFOPWM

Parameter	SPWM	SFOPWM	SVPWM
t- time	[0 .4 .8 1.2 1.6 2 2.4 2.8]	[0 .4 .8 1.2 1.6 2 2.4 2.8]	[0 .4 .8 1.2 1.6 2 2.4 2.8 3.2]
mi-modulation index	[0.11 0.31 0.5 0.5 0.52 0.58 0.41 0.21]	[0.11 0.35 0.577 0.577 0.6 0.678 0.47 0.24]	[0.275 0.5325 0.866 0.866 0.866 0.778 0.618 0.45 0]
f-frequency	[10 30 50 60 50 -50 -40 20]	[10 30 50 70 50 -50 -40 20]	[10 30 50 70 90 -45 -35 25 0]
T-Torque	[10 50 80 20 50 70 -50 -40]	[10 50 100 40 70 70 -50 -40]	[100 100 190 100 50 150 -120 -150 0]

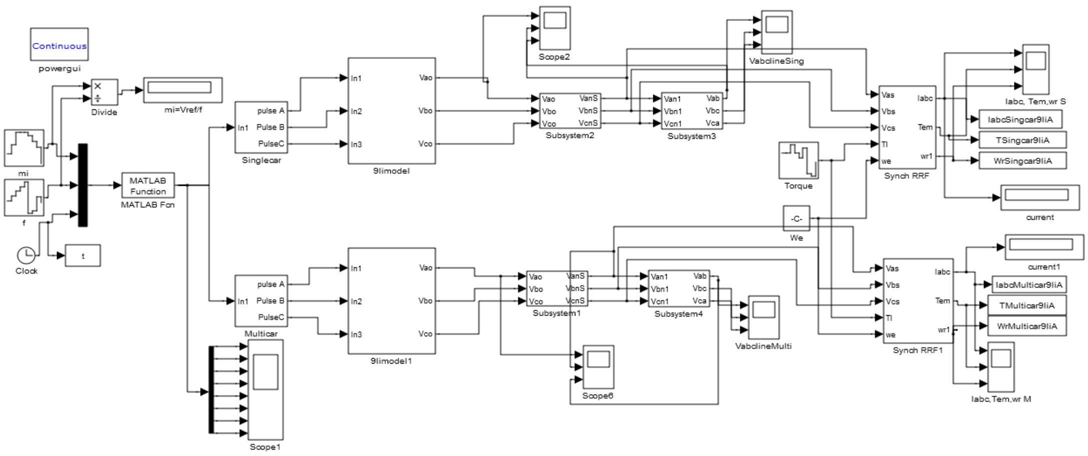

Figure 4 Simulink Model of 9-level DCMLI fed Induction Machine for Constant V/f Control

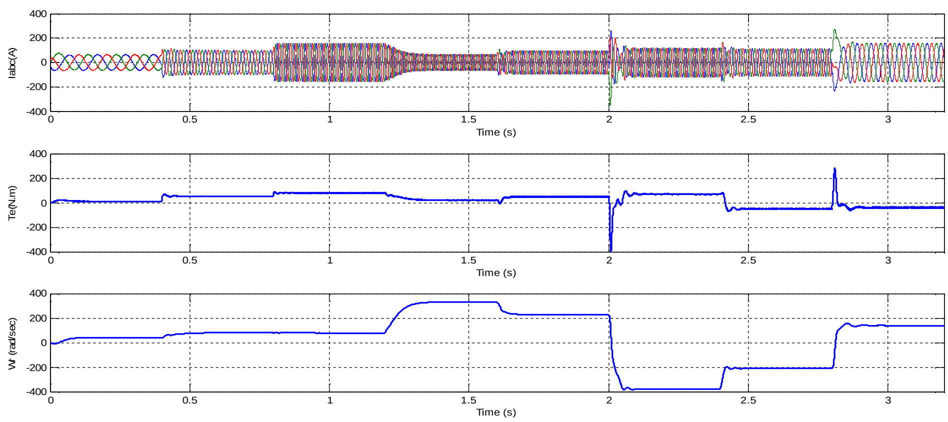

Figure 5 Stator Currents, Electromagnetic Torque, and Rotor Speed for SPWM

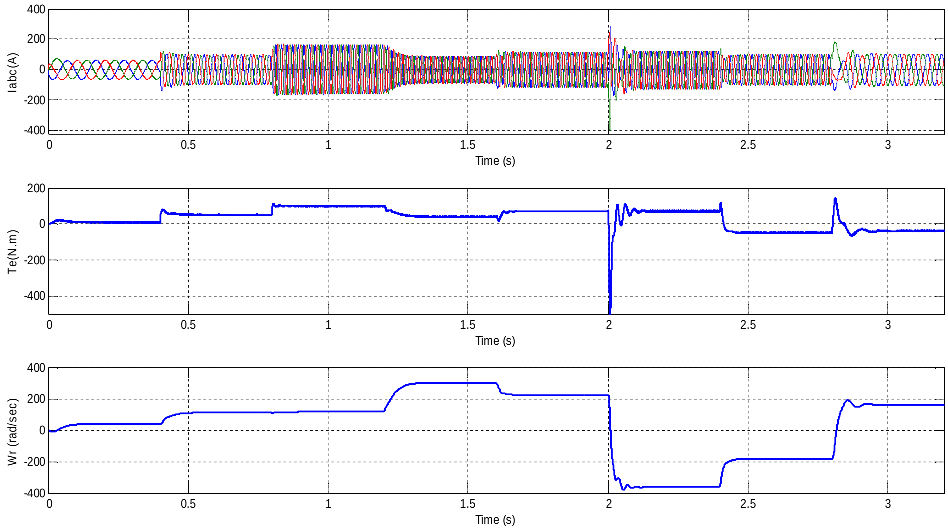

Figure6 Stator Currents, Electromagnetic Torque, and Rotor Speed for SFOPWM

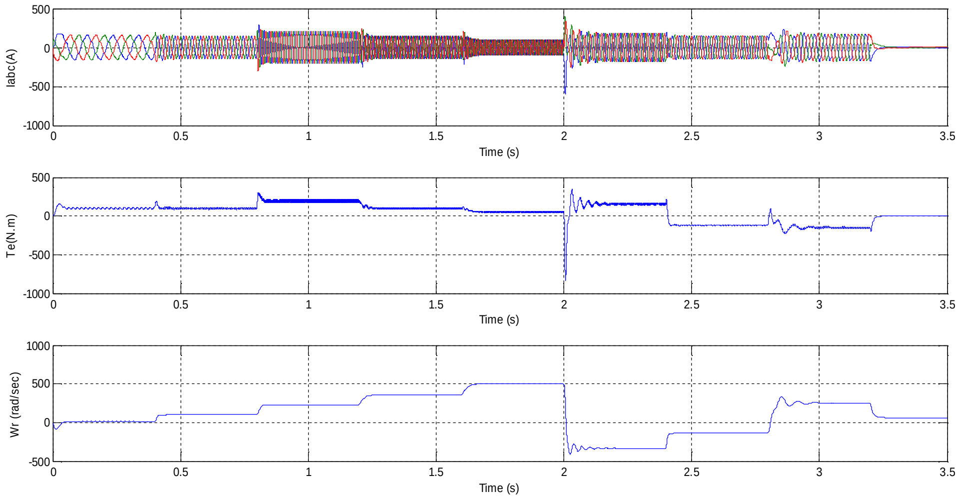

Figure7 CS MCMM Stator Currents, Electromagnetic Torque and Rotor Speed

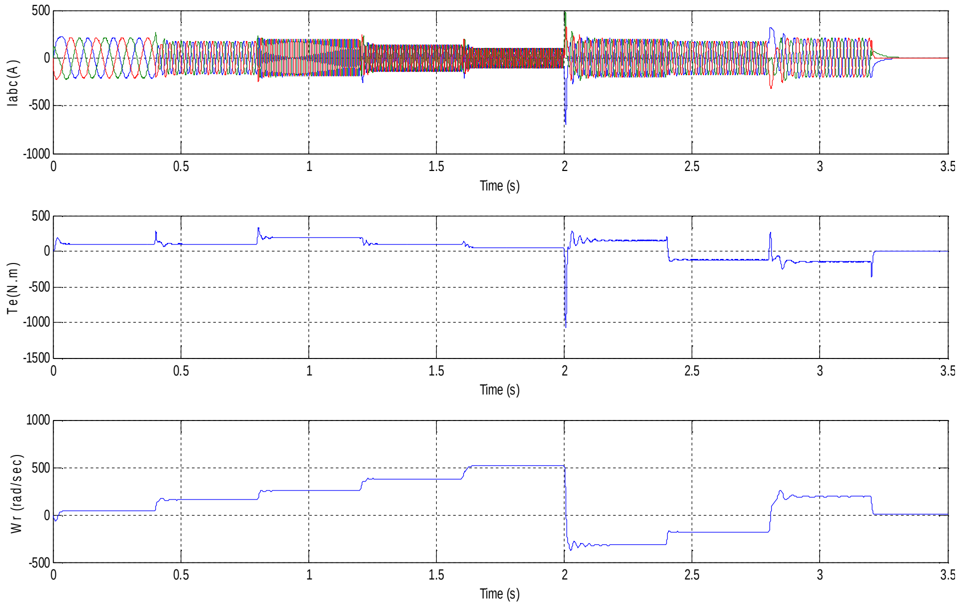

Figure8 CS SCMM Stator Currents, Electromagnetic Torque and Rotor Speed

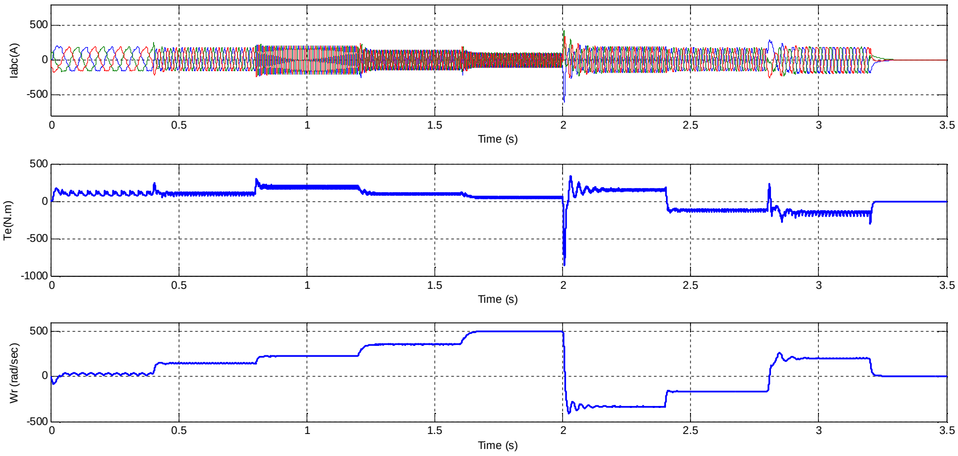

Figure9 OS MCMM Stator Currents, Electromagnetic Torque and Rotor Speed

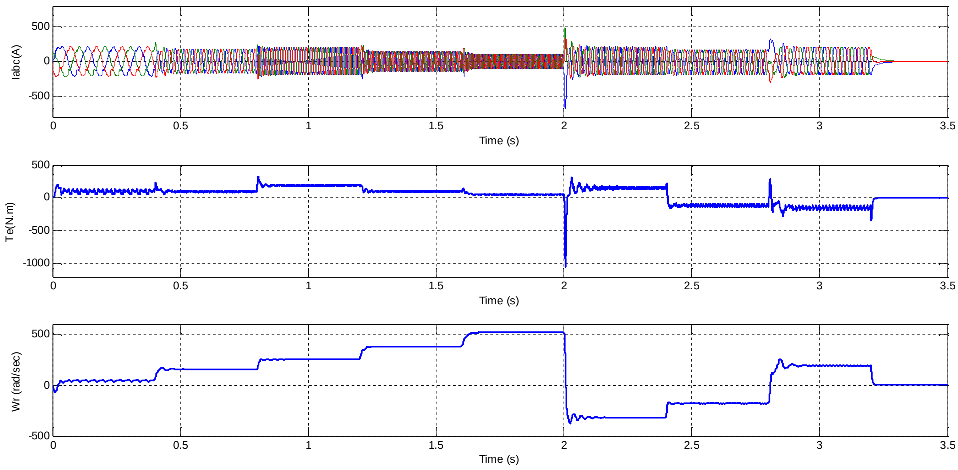

Figure10 OS SCMM Stator Currents, Electromagnetic Torque and Rotor Speed

Table2 presents voltage and current THD for SPWM, SFOPWM and SVPWM techniques. The order of superior performance is SVPWM, SFOPWM and SPWM technique.

Table 2 Voltage and Current THD of SPWM, SFOPWM and SVPWM Techniques

	SPWM	**SFOPWM**	**SVPWM**			
			CS-MCMM	CS-SCMM	OS-MCMM	OS-SCMM
Voltage THD	16.87	13.50	10.94	7.09	11.90	9.01
Current THD	1.17	1.31	4.79	0.88	6.22	5.75

5. CONCLUSIONS

1. SVPWM allow operation in low and normal modulation index, however SPWM and SFOPWM allow for normal and over mi.
2. In all the techniques, at low modulation indices THD is more because of low order harmonics present with instantaneous inequalities in dc sources.
3. Compared to SPWM, SVPWM response to load requirement is good.
4. Conventional switching sequence or optimized switching sequence SCMM works for low modulation indices however MCMM do not.
5. The conventional switching sequence SCMM show more linear output wave and drastic increase in fundamental component of voltage compared to MCMM.
6. The optimized switching sequence improved output voltage response for MCMM compared to conventional switching sequence MCMM even at low modulation index of 0.1.

7. In both MCMM and SCMM the THD decreases as modulation index increases from low to normal value.
8. In optimized sequence switching losses are decreased instead of THD decrement. For same region number of switching states has been reduced to 8 or 10 with optimized sequence compared to conventional sequence.
9. In constant V/f control required torque is available at the outlet of machine by accessing more stator currents in SPWM, SFOPWM and SVPWM.
10. Ripple in torque is reduced in SVPWM compared to SPWM and SFOPWM.
11. Time required reaching steady state increased in SVPWM due to complexity in calculations.
12. Reduced THD is observed in MCMM, SCMM conventional and optimized switching sequence SVPWM compared to SPWM.
13. Increased switching frequency decreased low order harmonics thus increasing higher order harmonics which can be filtered out easily by filters in output voltage in SPWM, SFOPWM and SVPWM.

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