Abstract: In this paper we introduce a four switch PWM (Pulse Width Modulation) inverter controlling the operation of PMSM (Permanent Magnet Synchronous Motor). The inverter is controlled with 49 rule base fuzzy controller controlling the current component in the feedback loop. The torque of the machine is reduced with the help of second order filter stabilizing the output from the fuzzy controller. The second-order torque harmonics produced by DC capacitor voltage fluctuations are first demonstrated, and a very simple compensation method is presented by introducing a novel non-orthogonal coordinate transformation. The design of the three phase four switch PWM inverter is modeled in MATLAB software with all graphical representations and reports generated with dynamic characteristics.

Keywords: Vector Control (VC) and Direct Torque Control (DTC), PMSM.

I. INTRODUCTION

Industry automation is mainly developed around motion control systems in which controlled electric motors play a crucial role as heart of the system. Therefore, the high performance motor control systems contribute, to a great extent, to the desirable performance of automated manufacturing sector by enhancing the production rate and the quality of products. In fact the performance of modern automated systems, defined in terms of swiftness, accuracy, smoothness and efficiency, mainly depends to the motor control strategies. The advancement of control theories, power electronics and microelectronics [1] in connection with new motor designs and materials has contributed largely to the field of electric motor control for high performance systems. Traditionally commutator motors, also known as direct current (dc) motors were preferred for variable speed drives while induction motors were used for constant speed applications. Advances in solid state devices helped in development of suitable controllers possessing provision of vector control. Such controllers made it possible to incorporate in the induction motor [2] almost all the characteristics of a dc motor. In vector control scheme, torque and flux are decoupled from each other like in dc motors. Newly developed permanent magnet synchronous motors (PMSM) with high energy permanent magnet materials particularly provide fast dynamics, efficient operation and very good compatibility with the applications but only if they are controlled properly.

However, the ac motor control including control of PMSM motors is a challenging task due to very fast motor dynamics and highly non-linear models of the machines. Therefore, a major part of motor control development consists of deriving mathematical models in suitable forms. The dynamic models of the motors can be presented in different reference frames to lay down a basis for the motor control design. The mathematical formulations [3] and the equivalent circuit models can be provided to help in better controller design for PMSM drives. There are two competing control strategies for ac motors viz vector control (VC) and direct torque control (DTC) for PMSM [4]. Vector control scheme with several benefits is the most applied control strategy. The decoupling of torque control and flux linkage control are the basis of vector control technique [5]. The motor phasor diagrams can provide better understanding of different control schemes used for PMSM drives. It is the most straightforward approach for motor modeling and control. It also reduces the analytical burden. The momentum of this popularity will considerably increase in the near future due to the recent availability of the high-energy low-cost Neodymium-Iron-Boron (NdFeB) Permanent magnet.

![Fig.1. TPSS inverter topology of PMSM.](image)

In TPSS inverter-fed PMSM drives, the neutral point voltage of the DC bus is constant, which has no effect on the torque performance as shown in Fig.1. In contrast, in a TPFS inverter-fed PMSM drive, one phase of stator current directly flows into the midpoint of the DC split capacitors, resulting in periodical fluctuations of the capacitor voltages. However, the modulation techniques for TPFS inverters discussed in [8]-[12] ignore the capacitor voltage oscillations; thus, imbalanced stator currents are produced, resulting in
pulsating torques. Moreover, due to the absence of zero vectors in the TPFS inverter, various equivalent zero vector synthesis approaches in the space vector modulation (SVM) are proposed in [8]-[12]. However, the effects on the high frequency torque harmonics of the zero vector synthesis methods have not been analyzed in detail. Therefore, an in-depth analysis of torque ripples influenced by the SVM strategies in a TPFS inverter-fed PMSM drive for reducing the high-frequency torque harmonics should be provided. In addition, the capacitor voltage fluctuations strongly impact the linear modulation range of the TPFS inverter, which has not been mentioned previously. If the capacitor voltage fluctuations are not considered, the TPFS inverter-fed PMSM drive may operate in the over-modulation zone with an improper DC bus voltage, thus producing abundant low-frequency torque harmonics. Meanwhile, the linear modulation range also deteriorates as a result of the DC offset of the two capacitor voltages, which should be eliminated. However, the capacitor voltage offset suppression method in [13] and [14] utilizes a second-order low pass filter (LPF) to extract the DC offset component, which is not applicable to TPFS inverter-fed PMSM drives under low-speed conditions due to the reduced stability margin of the control loop caused by the limited bandwidth of the LPF. Thus, an improved capacitor voltage offset suppression method applicable to TPFS inverter-fed PMSM drives is required to eliminate the low-frequency torque ripple caused by the limited linear modulation range.

II. CONTROL OF TPSS INVERTER

With the parameters of the proposed TPFS inverter-fed PMSM drive listed in Table II, the minimum required DC voltage VDCmin for linear modulation is depicted in Fig. 2 and Fig. 3. Clearly, the VDCmin calculated using is related to the electromagnetic torque Te, the capacitor voltage offset ΔVDC and the rotor speed ωm. In general, with increasing Te, the capacitor voltage fluctuation more severely deteriorates the linear modulation range. Consequently, VDCmin increases with increasing Te, as shown in Fig. 2. Similarly, the capacitor voltage offset ΔVDC limits the full use of the DC bus voltage, which also deteriorates the linear modulation range of the TPFS inverter-fed PMSM drive. From Fig. 2 and Fig. 3, VDCmin increases linearly with increasing rotor speed ωm in the high rotor speed zone mainly because the stator voltage magnitude increases linearly with ωm, as depicted. Nevertheless, when the rotational speed ωm is low, the capacitor voltage fluctuation is also aggravated. Consequently, as shown in Fig. 2 and Fig. 3, a high value of VDCmin is required in the low rotational speed zone. Taking capacitor voltage fluctuations into account, which is not seen in the conventional over-modulation judgment. The proposed analysis provides sufficient insight into the linear modulation range of the TPFS inverter-fed PMSM drive, where the effects of the capacitor voltage fluctuations and offset are revealed.

Therefore, the low frequency torque ripples caused by the over-modulation can be avoided by selecting an appropriate DC link voltage. As described above, the linear modulation range of the TPFS inverter-fed PMSM drive is deteriorated by the capacitor voltage offset. In practice, the dynamic behaviors of the PMSM, such as accelerating and decelerating, inject the DC component into the phase current, which produces the DC offset of the capacitor voltages. Thus, active control methods for suppressing the capacitor voltage offset are required to reduce torque ripples caused by the over-modulation. In [11] and [14], a close-loop control method in grid-connected applications is proposed for capacitor voltage offset suppression. The method utilizes a 2nd-order LPF to extract the DC component of the capacitor voltage offset and injects the compensated current component into the faulty phase, as shown in Fig. 2. With a PI regulator to eliminate the steady error, the open-loop transfer function is expressed as

\[
G(s) = \frac{K_p + K_i}{s} \cdot \frac{\omega_n^2}{s^2 + 2\xi\omega_n + \omega_n^2} \cdot \frac{1}{Cs}
\]

where \(\omega_n\) is the bandwidth of the LPF. However, due to the wide rotor speed range of the PMSM, the method in [12] and [13] is not applicable to the TPFS inverter-fed PMSM drive. As shown in Fig. 2, the low bandwidths of the LPF and PI regulator severely deteriorate the stability margin of the control loop in the low speed zone, where the reliability of the TPFS inverter-fed PMSM drive is threatened.

Fig. 2. Control Structure of TPSS inverter.

Instead of the LPF, an adaptive notch filter together with a proportional regulator is proposed in this study to extract the capacitor voltage offset. Due to the integral characteristic of the capacitors, the proportional controller also results in zero steady-state error. The resonant frequency of the adaptive notch filter is obtained by the speed sensor of the PMSM drive, and the entire control scheme is shown in Fig. 2. Based on the adaptive filter, the open-loop transfer function of the capacitor voltage offset suppression loop is expressed as

\[
G(s) = G_p(s) \cdot G_n(s) \cdot G_{eff}(s)
\]

\[
= \frac{K}{s^2 + 2\xi\omega_n + \omega_n^2} \cdot \frac{1}{Cs}
\]

(2)
A Fuzzy Controlled Four Switch Inverter based PMSM Driving Converter with Reduction in Torque Ripples

III. FUZZY CONTROL

The controller of the MERS circuit topology controls the duty ratio of the IGBTs switching states. The duty ratio of the controller is dynamically controlled by PI controller with an error input achieved by comparison of ‘iac’ (Input current RMS value) with MERS output DC voltage amplitude. The control structure block diagram is given below.

Fig. 3. Control block diagram of MERS.

In the control structure it can be clearly observed that the PI or Fuzzy controllers [6] generate Duty ratio which is compared to a triangular wave with a specific frequency (very much higher than the input frequency) generating a pulse given to both the IGBTs simultaneously. The proportional and integral gain values are taken as $K_p = 0.012$, $K_i = 10^{-5}$ respectively. The fuzzy structure is designed with seven input and seven output membership functions with a total of 49 rules according to the rule base shown below Fig.4.

Fig. 4. 49 Rule table for fuzzy structure.

The duty ratio output generation with control of output voltage amplitude of the lamp will be discussed in next section.

IV. SIMULINK MODELING AND RESULTS

Simulation results of this paper is as shown in bellow Figs.5 to 9.

Fig. 5. TPSS inverter with PMSM.

Fig. 6. PI controller control structure.

Fig. 7. Fuzzy controller control structure.

Fig. 8. Speed settling comparison with PI (Blue) and fuzzy (Green) control.

Fig. 9. Fuzzy Rule base.
V. CONCLUSION
The replacement of the PI controller with fuzzy is improvising the speed characteristics with TPSS inverter topology. The voltage of the fuzzy controller is settling faster resulting in speed parameter of the PMSM to stabilize faster to the response of the inverter. The digitalized PWM is adapted with the fuzzy controller with dynamic state operation and controlling of power electronic devices with specific sector selection.

VI. REFERENCES