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Review of Permanent Magnet Synchronous Motor Fed by Multilevel Inverter

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Abstract This paper presents a review of Permanent Magnet Synchronous Motor (PMSM) drive based on a three-phase Modular Multilevel Inverter (MMLI) compared to conventional two level inverter. Many techniques is applied to control speed and currents of PMSM drive system such as, Fuzzy logic control, PI control and sliding mode control(SMC). In this paper, a cascaded SMC compared with PI controller is utilized for PMSM control technique. A cascaded Maximum Torque per Ampere (MTPA) and Maximum Torque per Voltage (MTPV) algorithms also discussed in this review to control the drive through the field-weakening region to increase the speed beyond the base speed. The control algorithm is based on field-oriented control with Pulse width modulation technique. Lyapunov stability theorem is used to prove the stability of the sliding surfaces.

Keywords: Three-phase MMLI, SPWM, IPMSM, MTPA, FW and MTPV, PMSM, THD, Lyapunov stability theorem.

1 Introduction

Inverter is a power electronic device that converts DC power into AC power at desired output voltage and frequency. Multilevel Converters nowadays have become an interesting area in the field of industrial applications. Conventional power electronic converters are able to produce an output voltage that switches between two voltage levels only. Multilevel Inverter generates a desired output voltage from several DC voltage levels at its input. The input side voltage levels are usually obtained from renewable energy sources, capacitor voltage sources, fuel cells etc. The different multilevel inverter topologies are, Cascaded H-bridges converter, Diode clamped inverter, and Flying capacitor multilevel inverter. Multilevel inverters nowadays are used for medium voltage and high power applications. The different field of applications include its use as UPS, High voltage DC transmission, Variable Frequency Drives, in pumps, conveyors etc. The disadvantages of MLI are the need for isolated power supplies, design complexity and switching control circuits.

Multilevel inverters (MLIs) are extensively utilized in industry and academic research to achieve high-efficiency, reliability...etc. The mechanism of Modular Multilevel Inverters (MMLI) has been utilized to diminish the problem of semiconductor device rating limitation; in addition, it is connected in series to fulfill HV. To fulfill the higher rating voltages, the conformable submodules with low-voltage ratings are connected in cascade. The MMLI approach has many advantages like boost converters ratings, simple in installation and maintenance, and in case of the cascaded submodule failure, the MMLIs operate at minimized ratings. Consequently, an MMLI become prevalent in industrial applications and academic research for HV, high power applications. In recent years, many power converters were utilized in a wide range of industrial applications like pumps, compressors, fans, mills, crushers, conveyors, transportation, cement mills, paper mills. The (MLI) topology is an appropriate solution for HV, high-power applications.

Recently Modular Multilevel Inverters (MMLIs) become more widespread in medium and high power applications because they are distinguished by curtailment switching losses, costless, minimal Total Harmonic Distortion (THD) and high voltage

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capability…etc. A comprehensive survey of multilevel topologies, controls, and their applications is presented in [1-4]. In [5] a Sinusoidal Pulse Width Modulation (SPWM) technique is employed to diminish the THD in load voltage where the switches state is determined by comparing the reference signals with the saw tooth signals. In [6], the PWM technique is used to trigger the diode clamped MLI to fed the PMSM. In [7], the gating signals generation of the MLI has been done using the PWM techniques. In [8, 9], the PWM technique is applied to produce gate signals of the MLI switches to reduce the THD of the output voltage, consequently improve the voltage magnitude.

Permanent Magnet Synchronous Motor (PMSM) drive systems have received a greet solicitude in recent years, due to the advantages of PMSMs such as; high efficiency, high power density and its capability of speed, torque and position control [10]. Hence, PMSM-based drive systems have been used in wide range of applications such as Electric vehicles, railway trains, aerospace and other applications [11]. The PMSM-based drive system consists of three main parts; the controller, the converter, and the PMSM. The rule of the controller is to adjust the converter output voltage to obtain the required speed of the PMSM. Variety techniques have been used for PMSM speed control [12]. Classical PI-controller is profusely used in electric drives because of their simple control pattern, its facility of construction, implementation and reasonably priced. Nevertheless, in a large PMSM system PI-controllers present poor transient response for confrontation of load changes challenges [13-15]. In addition, PI-controllers require gain-tuning method, which add some complexity to the control design process. Hence, different control strategies have been applied to improve the performance of the PMSM drive system. For instance, a combination of fuzzy logic controller with PI-controller is utilized to the PMSM control system for improving the dynamic performance of the PI-controller [16]. In this method, the PI- controller is used during steady state operation whilst the Fuzzy controller is used during overshoot and internal or external disturbance. However, such hybrid controllers have the complexity problem [17]. Model Predictive Control (MPC) is used to adequate system performance because of its appropriate advantages such as, swift dynamic response, stability, simplicity of design, and good susceptibility of remedy limitation of fluctuation and controlled variables [18].

Sliding Mode Controller (SMC) has been utilized in electric machine drives. Because it exhibit manifold properties such as weak allergy to variable fluctuation, load changes removal and fast dynamic response. SMC is prepared to regulate the speed of PMSM to improve the tracking precision in addition to reduce the chattering problem [19, 20]. Total sliding mode controller is used to regulate the position of the PMSM, an observer is used to detect the uncertainty in the system [21]. In this paper, cascaded integral SMC is destined to promote the FOC fulfillment of the PMSM drive.

Permanent Magnet Synchronous Motors (PMSM) have an enormous solicitude in variable speed drives in latest years due to plenty of qualities such as high torque/ flux density, high efficiency, small size…etc. Extra solicitude must be taken into consideration when the PMSM drive is designed for MTPA and FW operation [22]. The traditional two-level inverter has many problems when it is used with PMSM drives such as high dv/dt, high blocking voltage across each device...etc.[1]. In [23], the MLI is utilized to eliminate the problems appeared with the 2-level inverter and produces many features such as low blocking voltage, minimum THD, low dv/dt, low switching losses and high capacity. In [24], the Field Oriented Control (FOC) is utilized to control the torque and speed of the IPMSM drive for MTPA region using a diode clamped MLI. An FW strategy is utilized for high-speed operation, especially beyond base speed this strategy based on controlling the d-axis current using A PI controller [25]. Some studies discuss the performance of the IPM synchronous motor drives fed by three-phase MLI. In [26], a Direct Torque Control (DTC) is utilized for MTPA and FW control of IPMSM, whereas two PI-controllers are utilized for torque and linkage flux control, a conventional Voltage Source Inverter (VSI) is utilized. In [27], medium-voltage, high-power motor drives without using a step-up transformer is discussed, where a nine-level medium voltage MMLI motor drive is utilized. In [28], a PMSM is supplied by a 3-level and 5-level diode clamped multilevel inverter, a lot of modulation techniques, such SPWM, third harmonic injection PWM, Space Vector PWM...etc. is employed. In [29] a high-performance PI controller for an IPMSM drive is developed. The PI is tunned online using the artificial neural network (ANN), this drive is used for MTPA and FW. In [30], a 3-level NPC inverter is utilized to feed a PMSM, where PI-controllers are utilized for speed regulation and Model Predictive Control (MPC) to regulate the d-q current components, where good steady-state and transient conditions results are obtained. In [31], the PMSM is utilized for EV due to inherent features such as the high power density, the low maintenance cost and the high reliability. IPMSMs are profusely utilized in Electric Vehicle (EV) drives because they offer good flux-weakening profile. Also, EV drive systems necessitate private stipulations, such as high power and torque density and superb dynamic performance while meeting the inverter voltage and current constraints [32]. In [33], The V-shape rotor of IPMSM is utilized in the Toyota Prius 2004. In [34], the MLI is compared with the 2-level inverter, the cascaded PI-controllers is utilized to control speed, flux and torque of the EV drive which shows improved MLI performance based on lower THD and better dynamic response during MTPA and FW regions. In [35] voltage regulation feedback algorithm with deadbeat current control, using the conventional 2-level inverter for FW control of

IPMSM.

2 Control of PMSM

Field-orientation control is commonly applied in the PMSM control system. This leads to a cascade control structure with an interior current control loop and an exterior speed control loop, so the PMSM is controlled similarly to the performance of Direct Current (DC) motors.

In [13], Shihua Li and Zhigang Liu, an adaptive control scheme for the PMSM is investigated considering the variation of inertia in the load. Speed and currents are controlled using PI- controllers. SVM-VSI is implemented in this method. The Extended-State-Observer (ESO)-based control method, is utilized to verify the fulfillment of the closed-loop system. This work fulfills a superior speed response in the subsistence varying the inertia. In [36], S. P. Sing et al. Investigated the fuzzy logic controller for the speed control of FOC PMSM. The Fuzzy Logic controller performance is also compared to a PI controller during no-load, full load, and varying load operation. The fuzzy logic controller produced higher efficiency and better dynamic response than the traditional method over a wide range of load variations. In [37], Atheer H. Abosh et al. developed a modified DTC-SVM strategy for PMSM, torque, and flux loops that are controlled using PI-Controllers. This method provides suppressed current harmonics. In addition, it keeps the merits of fast dynamic torque response. In [38], Wei Xie et al. developed and implemented the finite control set model predictive torque control (FCS-MPTC) with a deadbeat (DB) solution for PMSM drives using the two-level VSI to minimize the torque ripple associated with DTC method. In [39], Matthias Preindl and Silverio Bolognani have implemented the model predictive speed control for MTPA of PMSM – VSI drive. This method overcomes limitations of cascaded linear controllers, where the MPC controls speed and currents. The MTPA tracking is obtained and leads to high efficiency in this algorithm. In [40], Xiaoyu Lang et al. Designed a novel Direct Predictive Speed and Current (DPSC) controller for PMSM drive this controller applied to combined speed and current instead of PI controller. This method improves system dynamic performance. In addition, this method provided excellent robustness against inductance and inertia variation. In [41], T. Yuvaraja and K. Ramya established a FOC with PWM to control the PMSM using the original VSI, this inverter is supplied by photovoltaic source; also speed and current are controlled using PI-controllers. In addition, they used the hysteresis current control technique to limit the maximum current. It is also less sensitive to load variations. In [42], Xudong Liu et al. utilized the SMC for speed and current control of the PMSM using the traditional VSI. The SMC is applied to eliminate the intermediate variables in the controller. . The SVPWM technique is applied to generate the gating pulses for the switches. Besides, the Lypnouve stability theorem is applied to confirm the system stability. This method avoided the cascading of controllers where a single SMC controller controls the speed and current. In addition, this method proved that the controller has robust speed tracking under various conditions. In [43], Xiao gang Lin et al. the Deadbeat Direct Torque and Flux Control (DB-DTFC) using VSI is developed instead of DTC because it provides insufficiently small electromagnetic torque ripples, unsmooth dynamic response, heavy computation burden and relatively weak robustness to motor parameters variation. The 2-level inverters produce high output current/voltage THD and high switching losses. Furthermore, high dv/dt, derivative causes high stress on the semiconductor devices. In [44], Yong-ting Deng et al. investigated a combination of adaptive SMC with the sliding mode disturbance observer for current control of PMSM drive. Where the uncertainties of PMSM are compensated for by utilizing the adaptive SMC. The sliding mode disturbance observer estimates the external disturbances. Lyapunov stability theorem is utilized to prove the stability of the system. The SVPWM technique is utilized to generate the switching pulses of the 2-level VSI. This system is inherent for PMSM applications during external load disturbance and parameter variations. In [45], Donglai Liang et al. suggested an adaptive algorithm for online tuning the SMC coefficients of STA-SMO for sensor less control of PMSM. The SVPWM technique is used to generate switching pulses of the VSI. This scheme provided considerable features, such as high-power density, high efficiency, fast dynamic response, and the position estimation error under wide-speed range sensor less operation is reduced. In [46], Hyeon-Gyu Choi and Jung-Ik Ha, designed an expansion method of the operating speed of the PMSM drive using a series capacitor with the output of VSI. Where the maximum output voltage of the VSI limits the operating speed. This method increased the output voltage of VSI, besides the operating speed is increased. In [47], the PMSM is supplied by a sinusoidal supply, SPWM-VSI, and MLI. From the comparative study, the MLI provided torque ripple, and the harmonic content of the stator output

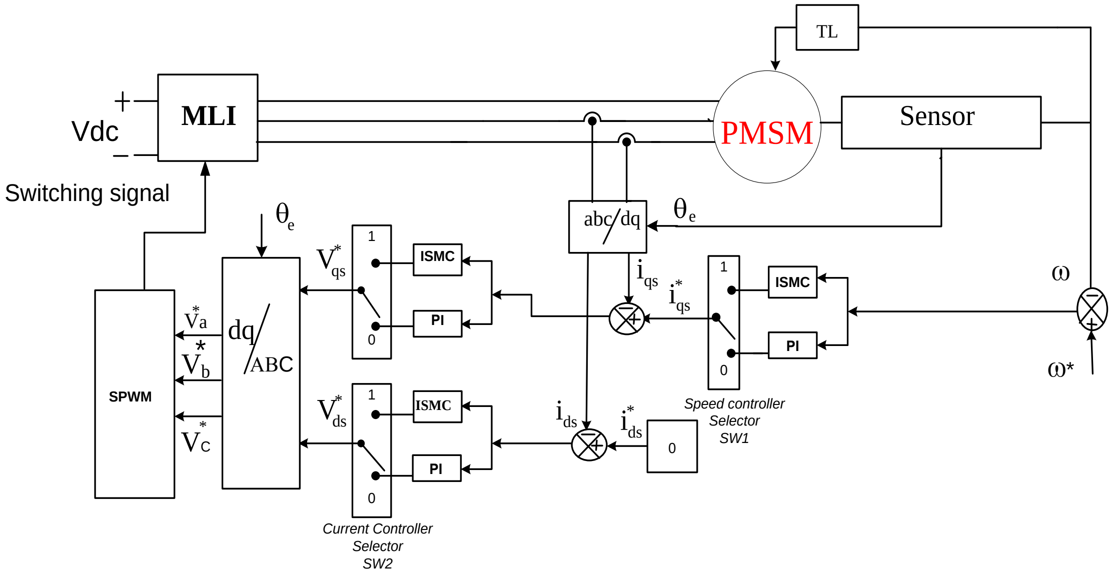

Fig. 1 Configuration of MLI fed PMSM drive system

current is less than the SPWM inverter. In [48], the Finite-Control-Set Model Predictive Control (FCS-MPC) with a three-level NPC is developed to feed the PMSM. To improve this method, they applied the multi-objective (MO) algorithm optimization and computation delay compensation. This structure is more robust than the others are. In [49], Adaptive Neuro-Fuzzy Inference System (ANFIS) based nine-level diode clamped MLI fed PMSM. Level shifted multi carrier PWM pattern is employed to generate the pulses of the nine-level diode clamped inverter. This scheme provided minimum THD in phase, line voltage, and currents. In [50], Jose Jacob, Chitra A, implemented FOC of SVM for asymmetrical seven-level MLI for PMSM drive. In this scheme, speed and currents are regulated by using PI-controllers. This method observed more accurate, tracking the reference speed and the load torque and providing smooth transitions during load variation.

3 Control of IPMSM

In [51], A. A. Hassan et al. investigated the adaptive SMC to control speed and the electromagnetic torque of IPMSM based on DTC. The dynamic performance of the IPMSM is improved utilizing the CSMC with the traditional VSI. This method minimized the large torque and current ripples associated with the DTC. The cascaded SMC overcome the chattering and reaching phase problems. This system has a fast transient response and robust in the face of uncertainties. In [52], A. A. Hassan et al. investigated a novel DTC of a sensor less IPMSM using an SMC technique using SVPWM VSI. The active flux concept is applied to estimate the position and speed of the IPMSM online. The SMC is employed for torque/flux control to overcome the problems associated with the classical DTC such as; torque and current ripples. Also, speed is regulated using a PI controller. This combination of SMC and SVPWM provided minimum torque and flux ripples and delivered high-resolution voltage control. This method provided a high performance of the IPMSM scheme at standstill, low and high speeds including load disturbance and parameter variation.

In [53], C.-K. Lin et al. investigated a chattering-free non-linear sliding-mode controller for IPM based on SVPWM VSI drive. This method provided satisfactory performance, including fast transient response, good load disturbance rejection, and good tracking response. Besides, this method also reduced the chattering phenomenon. In [54], Zhaowei Qiao et al. achieved the sensor less control of IPMSM based on SVPWM VSI. This method proposed a novel sliding-mode observer (SMO). The SMO can effectively estimate rotor speed and position. This method is improved estimation accuracy, also achieved good static and dynamic performance. In [55], Lianchao Sheng et al. achieved a sensor-less control strategy of IPMSM based on a new sliding mode observer (SMO) using SVPWM-VSI. The fuzzy control technique is utilized to adjust the sliding mode gain. The Phase-Locked Loop (PLL) technique is used to increase the robustness of the observer and reduce the error caused by chattering in the traditional SMO. This method provided a good dynamic response capability, high observation accuracy, and robustness.

In [56], Kahyun Lee et al. investigated a voltage boost of the VSI using a series capacitor to fed the IPMSM. The capacitor network between the inverter and the motor is introduced for voltage boosting to overcome the problems associated with the conventional VSI such as, reduced torque capability at high speeds besides the maximum output power is limited due to the voltage limitation of the conventional VSI which limited by the DC link. This method improves the torque and power capability at high speeds, compared to the conventional VSI, where the rated speed increases by 70% compared to the conventional VSI. Hence, the rated power increases, also, by 70%.

4 Control of IPMSM using MLIs

The VSI allows the motor to output power over a wide operating range by supplying balanced three-phase ac voltages with variable frequency and amplitude. Nonetheless, it has limitations in increasing the power capability of the motor because the line-to-line voltages synthesized by VSI are limited below the dc-link voltage. In traditional IPMSM driving using VSI, the stator is connected directly to the VSI, limiting the stator voltage to the same value as the inverter voltage. The limited voltage, which is supplied to the IPMSM, causes the torque capability to fall below the rated torque at high speeds. In [57], Zheng Wang et al. the DTC with the SVM technique is applied to the T-type NPC 3-level inverter to improve the dynamic fulfillment of the double stator winding PMSM. Speed and currents are controlled using PI controllers. Under fault conditions, the torque ripple is suppressed in addition to the copper loss. In [58], Gilbert Foo et al. designed a three-level simplified NPC inverter for DTC and flux control relinquish the current control technique instead of the stator flux and torque directly and independently adjustment for IPMSM. The SVM technique is employed to generate the reference voltage vector for control purposes while balancing the neutral point voltage. This algorithm provided an excellent dynamic performance that can be expected from the motor drive, making it attractive for low and MV applications. In [59], G. Sree Lakshmi et al. applied a three-level DCMLI to fed IPMSM. In this work, SPWM and SVPWM techniques are studied with different modulation index. The THD of the SVPWM in voltage and current is better than SPWM techniques; also, Speed and torque response is better. In [60], Deepu Mohan et al. investigated a novel duty cycle based DTC for IPMSM based on a three-level NPC MLI. This method is simpler than other types of DTC-NPC. This method diminished the effects of drooping flux phenomena presented in the three-level DTC-NPC drives during low-speed operations. In addition, it reduces both torque and flux ripples when operated at low switching frequencies. In [61], Deepu Mohan et al. investigated a three-level DTC using NPC for IPMSM with constant switching frequency. In this method, the influence of the torque variation rate is cancelled by the torque error regulating the PI-controller, which regulates the duty cycle of the vectors of the applied voltage. This method reducing torque ripples and improve the IPMSM dynamic performance under all operating conditions. In [24], G. Sree Lakshmi et al. applied FOC of three-level and five-level diode clamped MLI for IPMSM. The SVPWM is utilized to generate the inverter switching pulses, two PI controllers are applied to regulate the speed and currents of IPMSM. Five levels of MLI produced IPMSM dynamic performance better than the three-level inverter. In [62], Sree Lakshmi Gundebommu applied five and seven-level diode clamped MLI for IPMSM. This drive is controlled by the FOC method, the Carrier-Based SVPWM technique is utilized for generating inverter switching pulses. This scheme is used for high power applications.

The Integral SMC is applied to control speed and currents of the PMSM compared with PI controller, as shown in Fig.1. Where speed response of PMSM with SMC and PI controllers are shown in fig.3 and fig.4 respectively.

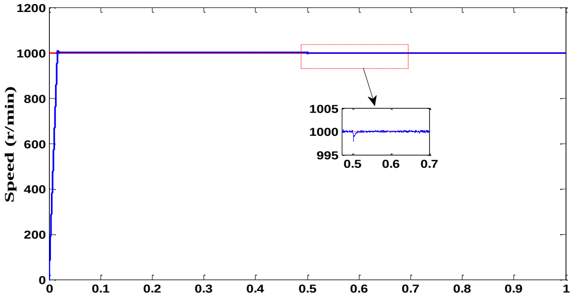

Fig. 3 Response of PMSM drive using SMC under load disturbance.

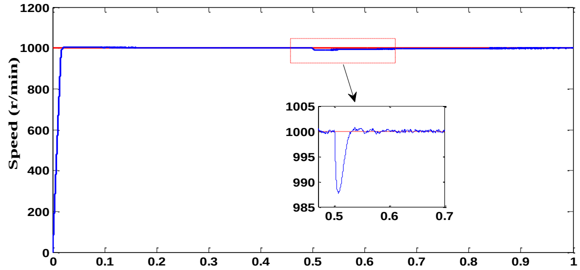

Fig. 4 Response of PMSM drive using PI under load disturbance

5 Flux-weakening Control of IPMSM.

In [63], M. Nasir Uddin and M. Azizur Rahman, applied an fuzzy logic controller for high-speed operation of the IPMSM using the 2-level VSI with PWM. This control scheme is used to control the IPMSM in MTPA and FW regions. A complete drive has been implemented in real-time using a DSP board Ds1102. The FLC provided robust performance for speed control, efficient industrial drive applications. In [26], Gilbert Foo et al. investigated a less sensor DTC based on SVM of VSI to control the IPMSM during the FW region. Two PI controllers are utilized to achieve the linkage flux and the PI controller regulates torque speed. At low speeds, the rotor position is extracted by adopting a high-frequency signal injection technique. This method handled full-load over the entire speed range. This method is presented to confirm the veracity of the wide speed. In [64], Ping-Yi Lin et al. investigated an infinite method for MTPA and MTPV control of the IPMSM drive system. In this method, SVPWM technique is applied to produce switching signals of VSI for FW control of IPMSM drive. In addition, the digital signal processing controller is applied for the infinite speed of the IPMSM drive. This method achieved both, MTPA and MTPV control of IPMSM. In [65], Lindita Dhamo et al. designed a robust control strategy based SMC to reduce the settling time without overshoot of the IPMSM drive system in the MTPA region. The 2-level VSI gating pulses are produced using the SVPWM technique. This control structure provided a faster transient response and low sensitivity to system uncertainties. In[66], Garin M. Schoonhoven et al. designed a robust nonlinear control technique for MTPA and FW IPMSM. In this scheme, the stability of the drive is demonstrated by the Lyapunov stability criterion. Thus, the MTPA and FW schemes are utilized to control the d-axis stator current below and above the base speed, respectively. The system nonlinearities are also scrutinized through the online estimation of the motor parameters.

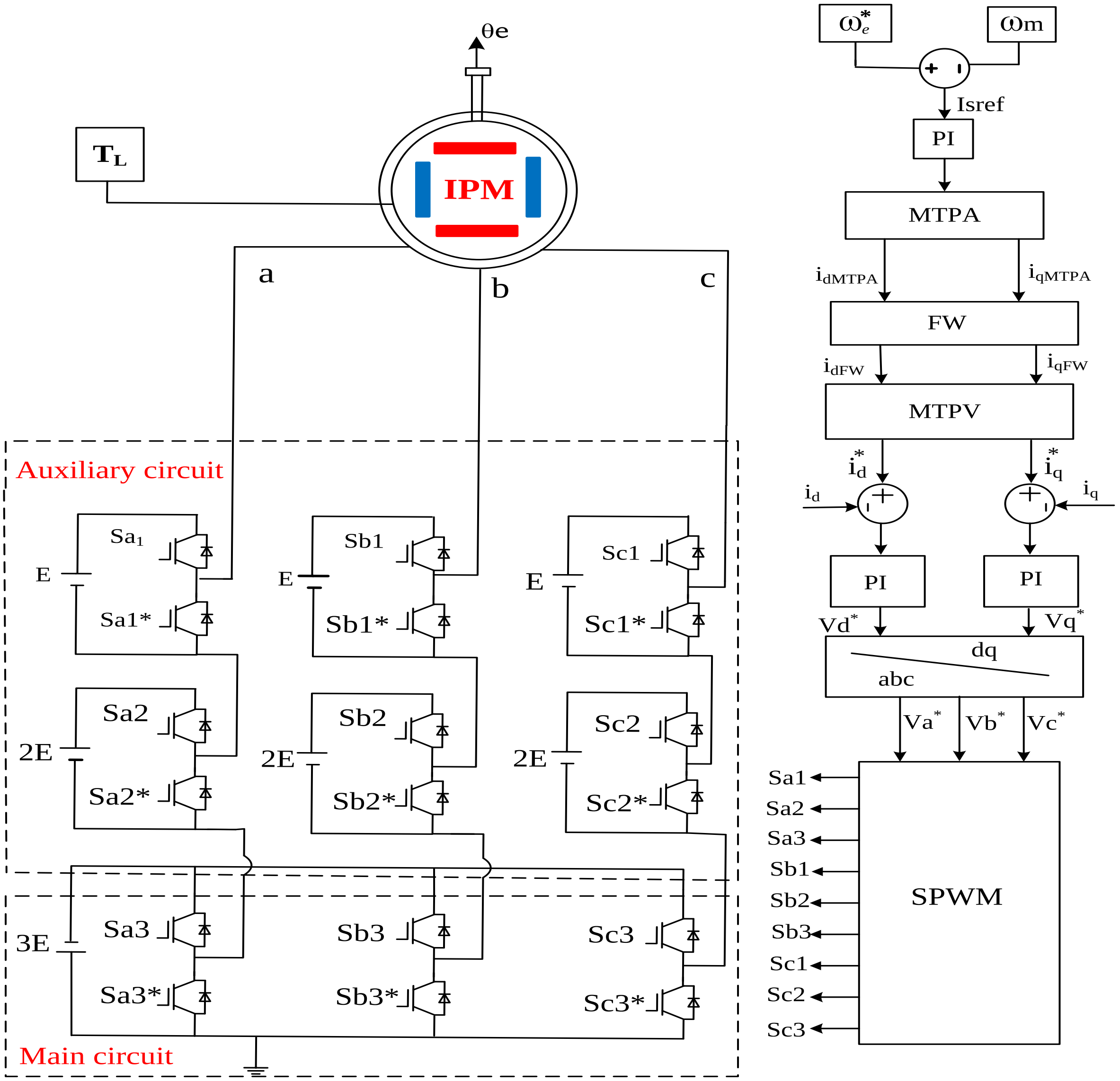

Fig. 2 Block diagram of IPMSM fed by MMLI for FW operation.

This scheme provided a faster transient response and high sensitivity to system uncertainties. In [67], Xuecong Xu et al. investigated MPC speed control for MTPA of IPMSM drive using VSI. In this scheme, a cost function is utilized to optimize the switching states for the IPMSM control; also, dynamical adjusting weight factors are designed to realize speed tracking and guarantee the currents operating points lay on the MTPA trajectory. This method produced many features such as excellent dynamical performance, and the control strategy has good robustness for load variation. But the insufficiency of this control strategy fails to consider the quantization error and dead-time which exist in the real system. Thus, improvement is needed in future work. In [68], Huimin Wang et al. designed a new control scheme based on feedforward control and fuzzy-PI feedback control strategy for MTPA and FW control of IPMSM drive using the PWM technique to generate gating pulses for 2-level VSI. This scheme provided excellent performances of drive system, like robust robustness to parameter perturbation, better dynamic performance in the flux-weakening region. In [69], Yaman Zbede, developed a new FW control method for an integrated PMSM vehicle drive using the PWM technique for VSI drive. In this method, to produce the demagnetizing current reference, the DC-link and the rotor speed is adopted as a feedback signal. An MTPA strategy is presented in this work. In this method, stable and satisfactory operation at speeds below the rated speed, also in the FW region, including different loading conditions, is produced. In [70], Essam E. M. Mohamed, designed hybrid feed-forward/feedback flux-weakening algorithm for MTPA and FW regions of IPMSM. The deadbeat (DB) current control is employed to diminish the problems associated with cascaded PI control loops for speed and current control using SVM to generate switching pulses of 2-level VSI. This algorithm provided improved d-q current component track and reduced torque ripples compared with the conventional feed-forward optimal current profile. In [71], Sithumini Ekanayake et al. performed a direct torque and flux control (DTFC) of IPMSM. Two PI control loops are used to control speed and currents SVPWM for a 2-level VSI drive system. In this method, the DTC and flux controlled for Maximum torque per voltage operation (MTPV). This scheme provided extended motor speed to the deep FW region without violating the maximum load angle condition. In [72], Shuai Dong et al. designed a Z-source inverter for FW control of IPMSM drive with adjustable DC-link voltage to increase speed beyond base speed and enhance the system capacity. This system indicated good dynamic characteristics and achieved high efficiency.

Fig .2 shows the MTPA and FW control of IPMSM using MMLI, this method exhibit more simple, cheap, compared with the relevant techniques.

7 Conclusion

This paper presents a review of SPMSM and IPMSM utilizing mmli compared with the conventional VSI and MLI drive system. This review demonstrates the various control scheme for SPMSM and IPMSM such as, PI-controller, SMC, ANN, and MPC. The MMLI presents many advantages over the conventional two level inverter; such MMLI used lowest average number of active components per pole levels, the MMLI produce currents with minimum THD which is 3.56 at switching frequency of 10 KHz. This result obeys the IEEE 519 standards, the SMC presents the preferable dynamic performance with the lowest overshoot and settling time compared with the relevant schemes, as shown in Table 1.

Table 1 . Performance comparison of PMSM drive under load disturbance

Control scheme	Settling time (s)	Max dip speed (r/min)
PI	0.033	13
SMC	0.012	1.8

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