CHAPTER 2

LITERATURE SURVEY

2.1 CONCEPT OF MULTILEVEL INVERTERS

Leon et al (1999) presented a transformer less multilevel converter as an application for high-power and/or high-voltage electric motor drives. The cascade inverter is a natural fit for large automotive all-electric drives because it uses several levels of DC voltage sources, which would be available from batteries or fuel cells. The back-to-back diode-clamped converter is ideal where a source of AC voltage is available, such as in a hybrid electric vehicle. Simulation and experimental results showed the superiority of these two converters over two-level pulse width modulation-based drives.

Byung-Moon Han et al (2002) described a static synchronous series compensator (SSSC) based on three-level multi-bridge pulse width modulation inverter. The dynamic characteristic of proposed SSSC was analyzed by simulation with EMTP and experiment with a scaled hardware model, assuming that the SSSC is inserted in the transmission line of one-machine-infinite-bus power system. The proposed SSSC can be directly inserted in the transmission line without coupling transformers, and has flexibility in expanding the operation voltage to increase the number of bridges in series connection.

John Chiasson et al (2003) applied the mathematical theory of resultants to compute the switching angles in a multilevel converter so that it produces the required fundamental voltage while at the same time cancels out unwanted order harmonics. Experimental results were given for the three DC source case. It was shown that for a range of the modulation index the switching angles can be chosen to produce the desired fundamental while at the same time the fifth and seventh harmonics are identically zero.

Zhou et al (2007) proposed a cascaded H-bridge multilevel inverter based active power filter with a novel direct power control which can be directly connected to medium/high voltage power line without using the bulky transformer or passive filter. Simulations on a 4160 V/1.2MVA system and experimental results on a 208 V/6 kVA laboratory prototype were presented to validate the proposed active power filter design.

Zhong Du et al (2009) presented a cascaded H-bridge multilevel inverter that can be implemented using only a single DC power source and capacitors. Standard cascaded multilevel inverters require n DC sources for 2n+1 levels. Without requiring transformers, the scheme proposed here allows the use of a single DC power source (e.g., a battery or a fuel cell stack) with the remaining n−1 DC sources being capacitors, which is referred to as hybrid cascaded H-bridge multilevel inverter (HCMLI). It was shown that the inverter can simultaneously maintain the DC voltage level of the capacitors and choose a fundamental frequency switching pattern to produce a nearly sinusoidal output. HCMLI using only a single DC source for each phase is promising for high-power motor drive applications as it significantly decreases the number of required DC power supplies, provides high-quality output power due to its high number of output levels, and results in high conversion efficiency and low thermal stress as it uses a fundamental frequency switching scheme.

Feel-soon Kang (2009) proposed a modified multilevel PWM inverter to increase the number of output voltage levels and to improve the system characteristic of a prior 11-level shaped PWM inverter scheme. In appearance, it consists of three full-bridge modules and a cascade transformer; therefore, the configuration of the proposed multilevel PWM inverter is equal to that of the prior one. Only the turn-ratio of one transformer and its corresponding switching function are different from each other. Based on the difference, the proposed multilevel PWM inverter has two promising advantages. First, output voltage levels increase almost two-fold. Consequently, it can generate more sinusoidal output voltage waves. Second, due to a suitable switching pattern, it lightens power imposed on the transformer, which is used for compensating output voltages with chopped pulses between step levels.

Reza-Salehi et al (2010) applied a new approach called the "bacterial foraging algorithm" (BFA) which eliminates and optimizes the harmonics in a multilevel inverter. This method has higher speed, precision, and convergence power compared with the genetic algorithm (GA), a famous evolutionary algorithm. The proposed technique can be expanded in any number of levels. The purpose of optimization is to remove some low order harmonics, as well as to ensure the fundamental harmonic retained at the desired value. As a case study, a 13-level inverter was chosen. The comparison results by MATLAB software between the two optimization methods (BFA and GA) have shown the effectiveness and superiority of BFA over GA where convergence is desired to achieve global optimum.

Banaei et al (2011) presented a new group for multilevel converter that operates as symmetric and asymmetric state. The proposed multilevel converter generates DC voltage levels similar to other topologies with less number of semiconductor switches. It results in the reduction of the number of switches, losses, installation area, and converter cost. To verify the voltage injection capabilities of the proposed inverter, the proposed topology was used in dynamic voltage restorer (DVR) to restore load voltage. The operation and performance of the proposed multilevel converters were verified by simulation using SIMULINK/MATLAB and experimental results.

Banaei et al (2012) proposed a novel cascaded transformer multilevel inverter. Each basic unit of the inverter includes two DC sources, single phase transformers and semiconductor switches. This inverter, which operates as symmetric and asymmetric, can output more number of voltage levels in the same number of the switching devices. Besides, the number of gate driving circuits is reduced, which leads to circuit size reduction and lower power consumption in the driving circuits. Theoretical analysis, simulation results using MATLAB/SIMULINK and experimental results were provided to verify the operation of the suggested inverter.

Javad Gholinezhad et al (2013) reported the analysis of cascaded H-bridge multilevel inverter in DTC-SVM (Direct Torque Control-Space Vector Modulation) based induction motor drive for FCEV (Fuel Cell Electric Vehicle). Cascaded H-bridge multilevel inverter uses multiple series units of H-bridge power cells to achieve medium-voltage operation and low harmonic distortion. In FCEV, a fuel cell stack is used as the major source of electric power moreover the battery and/or ultra-capacitor is used to assist the fuel cell. The drive control strategy is based on DTC-SVM technique. In this scheme, first, stator voltage vector was calculated and then realized by SVM method. Contribution of multilevel inverter to the DTC-SVM scheme achieves high performance motor drive. Simulations are carried out in Matlab-Simulink. Five-level and nine-level inverters were applied in 3HP FCEV induction motor drive for analysis the multilevel inverter.

Zedong Zheng et al (2014) proposed a hybrid cascaded multilevel converter which involves both battery energy management and motor drives is proposed for EV. Simulation and experiments were implemented to verify the performance of the proposed converter. In this topology, each battery cell can be controlled to be connected into the circuit or to be bypassed by a half-bridge converter. All half bridges were cascaded to output a staircase shape DC voltage. Then, an H-bridge converter was used to change the direction of the DC bus voltages to make up AC voltages. The outputs of the converter were multilevel voltages with less harmonics and lower *dv/dt*, which is helpful to improve the performance of the motor drives. By separate control according to the SOC of each cell, the energy utilization ratio of the batteries can be improved.

2.2 FAULT DIAGNOSIS OF MULTILEVEL INVERTERS

Debaprasad Kastha et al (1994) described a systematic investigation into the various fault modes of a voltage-fed PWM inverter system for induction motor drives. After identifying all the fault modes, a preliminary mathematical analysis has been made for the key fault types, namely, input supply single line to ground fault, rectifier diode short circuit, inverter transistor base drive open, and inverter transistor short-circuit conditions. The predicted fault performances were then substantiated by simulation study. The study has been used to determine stresses in power circuit components and to evaluate satisfactory post-fault steady-state operating regions. The results are equally useful for better protection system design and easy fault diagnosis.

Frede Blaabjerg et al (1997) proposed a new topology for a low-cost three-phase pulse width modulation (PWM) VSI inverter where a true phase current information exists with the use of only one current sensor in the DC link. The proposed topology also has the benefits of full protection of the inverter such as short circuits in the DC link, output phase faults, and output earth faults. By the use of space vector modulation in a double-sided implementation, the PWM-pulses were adjusted so true information about the phase current exists even at very low speed. The DC link current was sampled twice during one switching period, and it was proposed to sample in the center of the PWM-pulses to obtain a real average phase current. The effects of blanking-time and over modulation were also discussed. The strategy was implemented in a 16-bit microcontroller, and the test results showed the technique is useful in the whole speed range.

Mendes et al (1998) described the use of the Park's Vector Approach for diagnosing voltage source inverter faults, like output single-phasing and the occurrence of either a short-circuit or an open circuit of the controlled power switches. Power switches faults, either an open-circuit or a short circuit, were characterized by distinctive patterns of the three-phase motor current Park's Vector representation, whose angular orientation is associated with the faulty power switch. The location of the faulty power switch was obtained using an auxiliary sectogram. The rules for the location of the open-circuited and short-circuited controlled power switches are opposite, mirroring the different behavior of the DC component in the motor line currents Park's Vector, which implies a rotation of 180° in the numbering of the sectogram.

Brian et al (2004) compared the many fault tolerant three phase AC motor drive topologies that have been proposed to provide output capacity for the inverter faults of switch short or open-circuits, phase-leg short-circuits, and single-phase open-circuits. The output voltage and current space in terms of components was identified for each topology and fault. These quantities were then used to normalize the power capacity of each system during a fault to a standard inverter during normal operation. Silicon overrating cost factor was adopted as a metric to compare the relative switching device costs of the topologies compared to a standard three-phase inverter.

Alian Chen et al (2004) proposed a new topology with fault tolerant ability to improve the reliability of multilevel converters, which is based on the analysis of different power devices failure modes. With the proposed scheme, the function of the power stage can be maintained even part of it fails. The fault tolerant ability is resulted from the inherent redundant nature of the multi switching- states topology and control signals modification. Furthermore, the topology balances the voltage levels automatically except for achieving fault-tolerance. The validity of the proposed scheme was confirmed by experiments in a five level inverter prototype.

Ho-In Son et al (2004) proposed the simple fault diagnose method and the neutral-point voltage control method that can protect a system from the unbalancing voltage of the DC-link capacitors when the of switching element faults in the 3-level inverter occur that is very efficient in AC motor drives of the high voltage and high power applications. Many multi-level inverter faults have been detected using the over voltage and the over current in their systems. However, the fault detection of the switching elements is very difficult because the voltage and current according to each switching fault decrease more than the normal operation. The DC-link unbalancing voltage when the 3-level inverter faults occur causes a serious problem in safety and reliability of system. In this work, through experimental results, the superiority of the proposed method was also demonstrated.

Xiaomin Kou et al (2004) presented a unique design for flying capacitor type multilevel inverters with fault-tolerant features. When a single-switch fault per phase occurs, the new design can still provide the same number of converting levels by shorting the fault power semiconductors and reconfiguring the gate controls. The most attractive point of the proposed design is that it can undertake the single-switch fault per phase without sacrificing power converting quality. Future more, if multiple faults occur in different phases and each phase have only one fault switch, the proposed design can still conditionally provide consistent voltage converting levels. Computer simulation and lab results were presented to validate the proposed controls.

Alian Chen et al (2005) proposed a new topology with fault-tolerant ability that improves the reliability of multilevel converters. This new topology is developed through analysis of different power device's failure modes. With the proposed scheme, the function of the power stage can be maintained even part of it fails. Its fault-tolerant ability results from the redundant nature of the multi switching-state topology and from control signal modification. Furthermore, it balances the voltage levels automatically without any assistance from other circuits. The validity of the proposed scheme was confirmed by experiments in a five-level single-phase inverter prototype.

Demba Diallo et al (2005) studied the feasibility of fault detection and diagnosis in a three-phase inverter feeding an induction motor. The proposed approach was a sensor-based technique using the mains current measurement. A localization domain made with seven patterns was built with the stator Concordia mean current vector. A probabilistic approach for the definition of the boundaries increases the robustness of the method against the uncertainties due to measurements and to the PWM. In high-power equipment where it is crucial to detect and diagnose the inverter faulty switch, this simple algorithm compares the patterns and generates a Boolean indicating the faulty device. In low-power applications (less than 1 kW) where only fault detection is required, a radial basis function (RBF) evolving architecture neural network is used to build the healthy operation area. Simulated experimental results on 0.3 and 1.5 kW induction motor drives show the feasibility of the proposed approach.

Mingyao Ma et al (2007) presented fault-tolerance potential of multilevel inverters with redundant switching states such as the cascaded multilevel inverters and capacitor self-voltage balancing inverters. The failure situations of the multilevel inverters were classified into two types according to the relationship between output voltage levels and switching states. The gate signals can be reconfigured according to the failure modes when some of the power devices fail. The reconfiguration method was discussed for phase disposition PWM strategy (PDPWM) and phase shifted PWM strategy (PSPWM).

Baocheng Wang et al (2009) proposed a new fault-tolerant control method for cascaded multilevel inverter. This method utilized the specialties of cascaded multilevel inverter, and needn't change the topology of the system. The only thing to do is changing the drive wave of the inverter. So the reliability of the system is improved.

Pablo Barriuso et al (2009) proposed a reconfiguration system based on bidirectional electronic valves for three-phase cascaded H-bridge inverters. Once a fault is detected in any of the insulated gate bipolar transistors of any H-bridge, the control was capable to reconfigure the hardware keeping the higher power bridges in operation. In this way, the faulty phase can continue working at the same voltage level by adjusting its gating signals. Some simulations and experiments with a 27-level inverter, to show the operation of the system under a faulty condition, were displayed in this work.

Pablo Lezana et al (2010) reported a survey on faults that can appear in multilevel (ML) inverters, which have a high number of components. This is a subject of increasing importance in high-power inverters. First, methods to identify a fault were classified and briefly described for each topology. In addition, a number of strategies and hardware modifications that allow for operation in faulty conditions were also presented. As a result of the analyzed works, it can be concluded that ML inverters can significantly increase their availability and are able to operate even with some faulty components.

Jun Li et al (2012) analyzed the operation of three-level inverters under device failure conditions and proposed the fault-tolerant strategies to enable continuous operating of the inverters and drive systems under single and multiple device open- and short-failure conditions. Therefore, the reliability and robustness of the electrical drives are greatly improved. Moreover, the proposed solution adds no additional components to standard inverters; thus, the cost for robust operation of drives is lower.

Frederic Richardeau et al (2013) discussed that multilevel converters have many power devices and drivers. Thus, a direct reliability calculation based only on the first failure occurrence on one of the components clearly leads them to be devalued compared to two-level converters. In this work, a general and theoretical methodology was used to calculate reliability laws and failure rates and applied to compare two-, three-, and five-level topologies was proposed. Results showed that the fault handling of three- and five-level three-phase topologies permits a great increase in reliability over a “relatively” short time duration, in addition to other benefits.

Ui-Min Choi et al (2014) proposed a new diagnosis method of an open-switch fault and fault-tolerant control strategy for T-type three-level inverter systems. The location of the faulty switch can be identified by the average of the normalized phase current and the change of the neutral-point voltage. The proposed fault tolerant strategy was explained by dividing into two cases: the faulty condition of half-bridge switches and neutral-point switches. The performance of the T-type inverter system improves considerably by the proposed fault-tolerant algorithm when a switch fails. The proposed method does not require additional components and complex calculations. Simulation and experimental results were reported to understand the feasibility of the proposed fault diagnosis and fault-tolerant control strategy.

Behrooz Mirafzal (2014) presented a survey of fault tolerant techniques for three phase voltage source inverters. Inverters play key roles in motor drives, flexible power transmissions, and recently grid-tied renewable energy generation units. Therefore, availability and reliability of inverters have become increasingly important. Following early stage fault detections in inverters, remedial actions can extend normal operation of inverters and, in some cases, derate the system to prevent unexpected shutdowns. A remedial action typically contains a combination of hardware and software reconfigurations. The main purpose of this paper was to provide an instructive survey of existing fault-tolerance (remedial) techniques for three-phase, two-level, and multilevel inverters.

2.3 APPLICATIONS OF SIGNAL PROCESSING TECHNIQUES FOR FAULT DIAGNOSIS

Shoji Hayashi et al (2002) developed a machine fault diagnostic system using FFT spectrum analysis and neural networks. Generally it is very difficult to diagnose a machine fault using conventional techniques based on mathematical models because of system complexity and the existence of nonlinear factors. In this work, the time series data obtained from the machine is converted into spectral data using FFT algorithm and given as an input to neural networks. Neural network has learning and memory capability. Hence the proposed fault diagnostic system satisfactorily works in real time.

Surin Khomfoi et al (2007a) developed a fault diagnostic system in a multilevel-inverter using the features extracted from Fast Fourier Transform technique and a neural network. FFT algorithm was used to extract the harmonic order magnitude as an important feature. Five multilayer perceptron (MLP) networks were used to identify the type and location of occurring faults from inverter output voltage measurement. The classification performance of the proposed network between normal and abnormal condition was about 90%, and the classification performance among fault features was about 85%. Thus, by utilizing the proposed neural network fault diagnostic system, a better understanding about fault behaviors, diagnostics, and detections of a multilevel inverter drive system can be accomplished.

Surin Khomfoi et al (2007b) proposed a fault diagnostic and reconfiguration method for a cascaded H-bridge multilevel inverter drive (MLID) using FFT algorithm and artificial-intelligence-based techniques. Output phase voltages of the MLID were used as diagnostic signals to detect faults and their locations. FFT algorithm was used to extract the harmonic order magnitude as an important feature. Multilayer perceptron networks were used to identify the type and location of occurring faults. The principal component analysis was utilized in the feature extraction process to reduce the NN input size. A lower dimensional input space will also usually reduce the time necessary to train an NN, and the reduced noise can improve the mapping performance. The genetic algorithm was also applied to select the valuable principal components. The proposed network was evaluated with simulation test set and experimental test set. The overall classification performance of the proposed network was more than 95%. A reconfiguration technique was also proposed. The proposed fault diagnostic system requires about six cycles to clear an open-circuit or short-circuit fault.

Saleh et al (2007) presented an experimental testing of a wavelet packet transform (WPT)-based technique for protecting and controlling three-phase voltage-source (VS) pulse-width modulated (PWM) inverters under extreme load conditions. The proposed technique was based on a two-level multi resolution analysis (MRA) applied on output currents of a PWM inverter. The MRA aims to extract certain signatures, which are the second level highest frequency sub band coefficients. These coefficients take a nonzero value for any signal that is short-duration, non-periodic and non-stationary with impulse-super imposed high frequencies. Such a signal perfectly matches a current arising from any typical fault occurring in either the inverter legs or on the load side. The extreme load conditions including inverter open-leg, motor starting currents and different faults in motor stator windings were studied and realized that the proposed method show accurate, fast, and effective response to all disturbances including fault currents.

Pablo Lezana et al (2009) presented a method to detect faulty cells in a cascaded multicell converter requiring just one voltage measurement per output phase. The method was based on high-frequency harmonic analysis obtained from FFT signal processing technique, using a dynamic prediction of their behavior, avoiding erroneous detection on transients while keeping the precision under real fault events. Once the faulty cell was detected, it can be bypassed allowing the converter to keep working according to any reconfiguration techniques. Experimental results confirm accurate and fast fault detection, with a good rejection to normal operation transients.

Khan et al (2009) presented the practical implementation of a novel fault diagnostic and protection scheme for the interior permanent-magnet (IPM) synchronous motors using wavelet packet transform (WPT) and artificial neural network. In the proposed technique, the line currents of different faulted and normal conditions of the IPM motor were preprocessed by the WPT. The second level WPT coefficients of line currents were used as inputs of a three-layer feed forward neural network. The proposed protection technique was successfully simulated and experimentally tested on the line-fed and inverter-fed IPM motors. The Texas Instrument 32-bit floating-point digital signal processor TMS320C31 was used for the real-time implementation of the proposed protection algorithm. Test results showed satisfactory performances of the proposed diagnostic and protection technique in terms of speed, accuracy, and reliability.

Vinothkumar et al (2013) presented a new fault diagnosis technique based on discrete wavelet transforms for H-bridge multilevel inverter drives. For demonstrating the proposed method, one H-Bridge open circuit faults were considered in the H-Bridge multilevel inverter. The 30V prototype system was developed and controlled by Renesas processor. LabVIEW based data acquisition system was used to acquire the real time inverter output voltage and current signals. The mean, maximum, and the standard deviation values of the voltage and current signals were analyzed. The experimental results were shown to illustrate the effectiveness of the proposed wavelet transform based method of fault diagnosis.

Jorge et al (2013) proposed a novel diagnostic algorithm that allows the real-time detection and localization of multiple power switch open-circuit faults in inverter-fed AC motor drives. The proposed method was quite simple and just requires the measured motor phase currents and their corresponding reference signals, already available from the main control system, therefore avoiding the use of additional sensors and hardware.

Jianghan Zhang et al (2014) proposed a simple method for single switch and double switches open-circuit fault diagnosis in pulse width modulated voltage-source inverters (PWM VSIs) for vector controlled induction motor drives, which also applies to secondary open-circuit fault diagnosis. An open-circuit fault of power switches introduces the repetitive current distortions, whose period is identical to that of the three-phase currents. The current distortions appear at faulty stages and disappear at healthy stages. The stage is determined by recalculating the current vector rotating angle. The d- and q-axis current repetitive distortions were applied to the detection of faulty switches due to its simplicity and fair robustness, while the faulty stages were used for the identification of faulty switches.

Kavitha et al (2014) discussed the fault tolerance capability of three phase induction motor fed by multilevel inverters. In this work, an analytical tool to quickly analyze and predict the performance of multilevel inverter fed induction motors under fault conditions was proposed. Wavelet based fault detection is superior than other spectral methods to depict fault classification in multilevel inverters. Haar wavelet based fault classification in multilevel inverter fed induction motor were tabulated in this work which can be used as reference for diagnosing fault in five level inverters.

Jiangbiao He et al (2014) introduced an on-line diagnosis method for open-circuit switch faults that could happen in one of the most promising multilevel converters: Active Neutral-Point-Clamped (ANPC) converter. This diagnostic method was implemented based on the comprehensive information of pole voltages, phase currents, and switching states of ANPC inverters. Compared with the existing diagnostic methods in the literature, the presented method in this paper has lower cost and shorter detection time (less than one fundamental cycle). Simulation results verified the effectiveness and robustness of the introduced fault diagnosis method.

Marjan Alavi et al (2014) introduced a fault detection and isolation (FDI) method for faulty metal–oxide–semiconductor field-effect transistors in a three-phase pulse width-modulated (PWM) voltage source inverter. Short-circuit switch faults are the leading cause of failure in power converters. It is extremely vital to detect them in the early stages to prevent unwanted shutdown and catastrophic failures in motor drives and power generation systems. For a healthy inverter, the projection of the state transitions in the voltage space results in a cubic pattern. Each short-circuit switch fault uniquely changes the voltage-space pattern that allows isolating the faulty switch. The fault detection time is only within one PWM carrier period, which is significantly faster than current-based conventional methods.

2.4 APPLICATIONS OF SOFT COMPUTING TECHNIQUES FOR FAULT DIAGNOSIS

Bernieri et al (1994) investigated the possibilities offered by neural networks for system identification and fault diagnosis problems in dynamic systems. In particular, an original "neural" procedure was illustrated and its sensitivity and response time enable it to be used in on-line fault diagnosis applications. For fault diagnosis problems, neural networks lend themselves well to recognizing anomalous situations because of the intrinsic capacity to classify and generalize.

Fiorenzo Filippetti et al (2000) presented a review of the developments in the field of diagnosis of electrical machines and drives based on artificial intelligence (AI). It covers the application of expert systems, artificial neural networks (ANNs), and fuzzy logic systems that can be integrated into each other and also with more traditional techniques. The application of genetic algorithms was considered as well. In general, a diagnostic procedure started from a fault tree developed on the basis of the physical behaviour of the electrical system under consideration. The fault tree navigation was performed by an expert system inference engine leading to the choice of suitable diagnostic indexes, referred to a particular fault, and relevant to build an input data set for specific AI (NNs, fuzzy logic, or neurofuzzy) systems. The proposed methodology was applied to an induction machine, utilizing as input signals the instantaneous voltages and currents. In addition, the supply converter was also considered to incorporate in the diagnostic procedure of the most typical failures of power electronic components.

Said Barkati et al (2008) described two evolutionary algorithms for the optimized harmonic stepped–waveform technique. Genetic algorithms and particle swarm optimization were applied to compute the switching angles in a three-phase seven-level inverter to produce the required fundamental voltage while, at the same time, specified harmonics were eliminated. This combination provides a very effective method for the harmonic elimination technique for different structures of seven-level inverters.

Salankayana et al (2012) presented an artificial neural network based fault identification system for a five-level cascaded H-Bridge multi-level inverter. A Radial Basis Function (RBF) neural network was trained using radial basis function training algorithm to identify the location of the switch that is misfired at an instant prior to its actual firing time. The proposed fault diagnostic system identified the fault with a greater accuracy.

Farid Kadri et al (2013) studied the feasibility of fault detection and diagnosis in a three-phase inverter feeding an induction motor. The proposed approach was a neural network classification applied to the fault diagnosis of a field oriented drive of induction motor. Multilayer perception (MLP) networks were used to identify the type and location of occurring fault using the stator Concordia mean current vector. In the case of a single fault occurrence, a localization domain made with seven patterns was built. With the possibility of occurrence of two faults simultaneously, there are twenty-two different patterns. Simulated experimental results on 1.5-kW induction motor drives show the effectiveness of the proposed approach with a classification performance over than 95%.