Chapter 6

Conclusions and Future Work

This thesis has involved a detailed study of high performance PWM methods for three phase voltage source inverters and it was developed in two stages.

The first stage of the thesis involved a detailed analysis of linear modulation range waveform quality and semiconductor device switching loss characteristics of modern PWM methods. The rigorous analysis and detailed graphical illustrations of multivariable modulator functions provided improved insight to modulator behavior. The study provided simple analytical methods and tools for modulator design. Simple techniques for generating the modulation waves of the high performance PWM methods were described. Most importantly, the study aided the development of the high performance GDPWM method with on-line performance optimization capability. In addition, the thorough analysis established the basic knowledge for the second and dominant portion of this thesis.

The second stage of the thesis involved the overmodulation region performance study of AC drives employing the modern PWM methods. First the voltage linearity limits were investigated and then the overmodulation characteristics were studied. The overmodulation region fundamental component voltage gain characteristics, and the per carrier cycle modulator phase and magnitude error characteristics were rigorously analyzed. As the overmodulation characteristics of modern modulators were clearly understood, the following step involved the study of AC drive behavior employing such modulators. The overmodulation region steady state and dynamic performance of AC motor drives and utility interfaces was thoroughly investigated. Both voltage feedforward drives and closed loop current controlled drives were considered. Strong correlation between theory, computer simulations, and laboratory tests was obtained. The overmodulation studies of this thesis illustrated the steady state and dynamic performance issues of various modulators and aided the modulator selection and design procedure. Furthermore, control algorithms with superior overmodulation region performance were developed and verified. As a result, it was shown improved inverter utilization and superior overmodulation region performance could be obtained by only moderate software modifications to the state of the art PWM-VSI drives.

6.1 Conclusions

The most significant contributions and conclusions of this thesis can be itemized in the following paragraphs.

Modern modulation methods were separated into two groups; the continuous PWM and discontinuous PWM methods. A thorough investigation indicated the equivalency of various modulation methods, and an attempt to unify the modern modulation methods successfully reduced their count to less than a handful. Employing the magnitude rules, modulation signals of all the modern modulators could be easily generated by means of software/hardware. The difficulties encountered in learning the behavior of large number of modulation methods, and selecting and implementing one among them, are greatly overcome with these classifications and generalizations.

The analytical modulator waveform quality and switching loss formulas, and the graphic illustration of these multivariable functions significantly simplify the modulator design stage of drives employing modern PWM methods. These formulas and graphics provide substantial amount of information on the modulator behavior. Therefore, they are invaluable PWM learning tools.

The waveform quality and switching loss comparisons indicated near zero modulation index region CPWM methods are superior to DPWM methods. However, in the remainder of the voltage linearity region the opposite is true.

A high performance GDPWM method with on-line controllable characteristics was developed and its characteristics analytically investigated. Simple to implement, GDPWM could be closed loop controlled to maintain high drive performance as opposed to the conventional modulators with predefined and operating point dependent performance characteristics. With GDPWM, reduced switching losses, wide voltage linearity range, and high waveform quality could be obtained in a wide operating range. Since the near zero modulation index range performance of SVPWM/SPWM is superior to GDPWM, a simple modulation algorithm which selects SPWM or SVPWM in the lower modulation index range, and GDPWM in the remainder of the voltage linearity region, was established and tested in the laboratory. As the GDPWM control variable, the modulator phase angle was controlled in a manner to minimize the switching losses.

When combining several modulation methods in a modulation algorithm, the modulation indices at which the transitions occur could be accurately calculated (based on a selected performance criteria) by employing the analytical HDF and SLF functions.

The overmodulation region fundamental component voltage gain characteristics of modern PWM methods were analytically investigated. Comparisons indicated DPWM1 has significantly higher gain than the remainder of the modulators. The overmodulation region waveform quality investigation indicated DPWM methods are superior to CPWM methods until approximately 0.95 modulation index. Beyond this limit, the waveform distortion rapidly increases with both modulator groups. With the voltage feedforward drives requiring high fundamental component voltage gain, and high waveform quality, the DPWM1 method was illustrated to be the most appropriate modulation method for such drives. Employing DPWM1 (as an operating point of GDPWM), and including a voltage gain compensator (inverse gain compensation by means of polynomial approximation) and a DC bus voltage disturbance rejection controller (by on-line scaling the modulation index with the inverse of the normalized DC bus voltage), the overmodulation region performance of a voltage feedforward drive could be substantially enhanced. The laboratory experiments illustrated the superiority of this approach.

The influence of inverter blanking time and minimum pulse width control on the modulator linearity was studied in detail. It was shown that both have substantial effect on the waveform quality and voltage linearity. It was illustrated DPWM methods perform poorly near zero modulation index and both effects exacerbate the performance substantially. However, the maximum linear modulation index of DPWM methods is higher than the CPWM methods and it is less influenced by the blanking time and MPW.

When current controlled PWM-VSI drives operate in the overmodulation region, the modulator and current controller exhibit strong interactions and oscillatory drive performance may result. The degree of instability was shown to strongly depend on the modulator phase error characteristics. The phase error characteristics of all modern PWM methods were calculated and their influence on the dynamic overmodulation performance of AC a drive was studied.

The investigation revealed the minimum voltage magnitude error dynamic overmodulation attribute (one-step-optimal) of SVPWM method, indicating a significant implementation advantage compared to the two methods reported to achieve rapid current regulation.

Due to its lagging phase error characteristics, the DPWM2 method forces strong current regulator dynamics, and leads to poor drive dynamic performance. Therefore, its utilization in the dynamic overmodulation range is prohibitive.

In a motor drive, motion quality is more important than rapid current control. For intermediate dynamic overmodulation performance SVPWM provides satisfactory performance. For high dynamic overmodulation performance a modulator phase error regulation method was adapted from the direct digital PWM technique to enhance the performance of the triangle intersection PWM methods.

Current controller antiwindup limiters maintain the modulator phase error at a small value such that the dynamic overmodulation oscillations are suppressed and overcurrent fault conditions are avoided. However, they limit the voltage utilization and delay the controller response. The practical voltage utilization limit with antiwindups is 0.95 modulation index.

Higher current controller gains result in larger phase errors, and larger oscillations. Therefore, the dynamic overmodulation performance issues of high bandwidth current controllers are significant. When designing a modulator for such drives, the dynamic overmodulation performance must be taken into account.

The steady state overmodulation performance of current controlled drives is inferior to voltage feedforward drives due to the influence of the feedback current harmonic components. Current controlled drives with antiwindups provide approximately a maximum steady state voltage utilization of 0.95. Although their operating range is narrower than the voltage feedforward drives, current controlled drives manipulate dynamic conditions more rapidly and safer.

Current controlled drives can employ SPWM/SVPWM near zero modulation index, and GDPWM until the maximum linear modulation index. In the overmodulation region, SVPWM or the phase error regulation methods may be selected for superior performance. Implementing such an algorithm on a modern digital control platform is a viable task.

The theoretical current controller dynamic overmodulation studies were supported by computer simulations and laboratory experiments and a strong correlation was obtained.

As a result, this thesis increases our knowledge about the PWM-VSI drives, and develops high performance modulation and control algorithms for superior drive performance. As the heart of the drive, the pulse width modulator was thoroughly studied, and well understood. The study aided the development of control methods yielding improved inverter utilization, lower waveform distortion, higher energy efficiency, and superior dynamic performance. To be discussed in the next section, however, several important performance issues of PWM-VSI drives remain to be addressed.

6.2 Future Work

There exists a large variety of PWM-VSI drive types and applications. This thesis could only focus on several of the many fundamental drive performance issues and resulted in several contributions to the field. However, substantial amount of effort is needed to overcome the remaining difficulties and perfect the PWM-VSI drives. Several issues relating to the subject of this thesis and PWM-VSI drives which need immediate attention can be summarized in the following.

The linear and overmodulation region performance of three-level and higher level PWM-VSI drives require a detailed analysis and performance enhancement. The approach followed in this thesis for analyzing the modern modulation methods developed for the conventional two level inverter can be extended to three and higher level inverters in a straightforward manner. The steady state and dynamic overmodulation performance of multilevel inverters with various modulators can also be investigated with the same approach.

The modulation methods described and/or reviewed in this thesis are a few intelligently programmed modulators and many more can be developed. One such modulator could have a periodically varying carrier frequency. For example, the carrier frequency can be a linear function of the zero sequence signal of the SVPWM method ($f_c = a \times V_0 + b$). In the proposed method, the carrier frequency variation increases with the modulation index because the zero sequence signal V_0 is proportional to the modulation index. Thus, at high modulation index the carrier frequency significantly varies in space and at low modulation index it is practically fixed. Since at high modulation index the SVPWM harmonics become large and significantly vary in space (see Figures 3.15 and 3.16), employing the proposed scheme with SVPWM is advantageous. Varying the carrier frequency in this manner could reduce the harmonic distortion and spread the harmonic spectrum in a relatively wide frequency range. As a result, the audible noise could be reduced and/or the EMI performance could be enhanced. Although similar methods were reported in the literature [72], the proposed method has substantially simpler structure and can be easily implemented. Note that the method in [72] employs a large two dimensional table ($f_c = f(M_i, \theta)$), while the proposed method effectively employs a simple inverse model of the SVPWM harmonic distortion function. In the proposed method, selecting the two coefficients (a and b) appropriately is sufficient. Performance analysis and design of the proposed modulator requires appreciable effort.

The overmodulation performance of voltage feedforward controlled open loop drives could be substantially improved with a proper modulator choice and control method. This thesis established the fundamental design guideline for such drives. In this thesis current controlled drives have been investigated with greater effort. However, the current controlled system exhibits a highly nonlinear structure (due to voltage limits, antiwindup, motor dynamics etc.) and the results obtained in this thesis suggest further study is required in order to establish very high performance current controlled drives.

The current controlled drive overmodulation study of this thesis assumed the flux producing current reference (I^*_{de}) is constant. This assumption is valid within the base speed range of most drives, and only drives with field weakening capability reduce I^*_{de} with increasing speed. With this assumption, this thesis investigated the capability of the modulator and current controller regardless of the reference signals. However, with the induction machine rotor electrical time constant being large, the dynamic overmodulation performance could be further enhanced by modifying the flux current reference during a dynamic overmodulation transient. Assuming the rotor flux remains constant during the current controller transients, the flux producing current can be temporarily reduced (dynamic field weakening). With the flux current reference reduced, more voltage becomes available for torque current and the dynamics can be more rapidly manipulated. The method reported in [35] reduces I^*_{de} in proportion to the torque producing current error ($I^*_{deNEW} = I^*_{de} - K * (I^*_{qe} - I_{qe})$). However, a direct calculation of I^*_{de} based on the dynamic requirements may be possible. Therefore, a detailed study is required in order to determine the profile of I^*_{de} during dynamic overmodulation transients.

The GDPWM modulator phase angle also may be utilized as a control parameter to create the required dynamic field weakening condition. However, relations between the modulator phase angle and the field weakening level must be established. Alternatively a heuristically designed closed loop PI controller may regulate the phase angle. This subject also requires investigation and controller development and design.

The d and q channel antiwindups of the SFCR limit the current controller overshoot and delays. This performance is obtained at the expense of reduced voltage utilization. As a result relatively slow, however, controlled performance is obtained. On the other hand, during abrupt and long lasting transients (longer than the fundamental period associated with the electrical angular speed/frequency of the drive) it may be beneficial to operate the drive near or at the six-step operating mode so that the dynamics can be manipulated rapidly. Since the conventional SFCR structure with antiwindups does strongly limit the voltage utilization (to at most 95 %) and significantly high (prohibitive) controller gains are necessary to obtain full voltage utilization, a controller modification or a different controller type may be required for superior dynamic response. Perhaps, during dynamic overmodulation transients, a predictive controller with an accurate motor model could be utilized to calculate the feasible voltage vectors and guide the motor through the commanded motion trajectory with minimum disturbance and safely. Since the six-step mode yields 5 % higher voltage utilization than the SFCR with antiwindup, during long lasting transients this voltage margin may be sufficient to manipulate the transients in a substantially shorter time. A hybrid controller employing SFCR inside the inverter hexagon and a predictive controller in the overmodulation region could be designed to provide an overall superior drive performance. Designing such a control system requires a substantial effort.

A novel approach to enhance the overmodulation performance of high dynamic performance drives is to change the controller structure as the overmodulation region is approached. SFCR can be operated until roughly 90 % of the six-step voltage and a seamless transition to the DTC method [43, 190, 195] (in particular [43, 195]) enables the drive to perform satisfactorily until the six-step mode. The DTC method has been widely employed in high power traction drives which require performance in a wide operating range from zero voltage level to the six-step mode. Such drives employ field weakening above the drive base speed and fully utilize the inverter voltage by transitioning to the six-step operating mode and rapidly accelerate to very high speed levels. With an accurate motor model, the DTC method predicts the phase and magnitude of the motor EMF and precisely controls the stator flux to rapidly accelerate/decelerate the motor (utilizing all the available voltage) without unwanted overcurrent transients. Graceful transition to the six-step mode and back is easily achieved with DTC. Therefore, the high modulation region performance of DTC is superior to SFCR. Combining these two methods, a high performance variable structure control algorithm can be obtained. Seamless transition from SFCR to DTC and back can be easily achieved provided that the state variables of both controllers are precisely computed and updated. Since both controllers employ the same motor model (motor fundamental model), updating the inactive controller variables should not involve substantial computations. Therefore, this approach appears to be viable and the design and implementation of such a controller is an emerging research/development subject.

Additional issues involving SFCR or DTC controlled drives operating in the overmodulation range are the DC power source stability issues as well as the motor torque oscillations at/near six-step. Widening the overmodulation range of a drive implies increasing the loading of the DC power source. In particular, in soft DC bus applications (a diode rectifier with small capacitors forms a soft DC power supply), the DC bus can have negative impedance instability and increasing the voltage utilization may result in a DC bus overvoltage/undervoltage fault condition, rendering the drive unreliable. Therefore, in such applications voltage utilization must be intentionally limited. In certain applications the six-step operating mode may result in unacceptably large torque ripple (the dominant harmonic occurs at six-times the inverter output frequency). In such applications voltage utilization must also be limited to an acceptable value.

Most overmodulation studies assume an inverter model with fixed or relatively stiff DC voltage source. Detailed system level studies which involve the DC power source and load (motor) dynamics are required in order to design reliable inverter drives.

Since the soft switching resonant converter technology is rapidly developing and becoming an alternative to the conventional hard switching PWM-VSI drives, the modulation methods and modulator performance limits of such drives are gaining importance [45]. Since modulation methods involving such converters may employ fundamentally different approaches than PWM, and the modulator nonlinearities may be more significant than PWM-VSI drives, the performance study of such drives is more involved and requires significant attention.

Finally, the question remains on whether a high performance current regulated drive with wide steady state and dynamic performance (from zero modulation index until the six-step mode) could be developed. With the steady state and dynamic performance requirements contradicting (as illustrated in the previous chapter), an intelligent method with superior performance must be developed. This issue remains to be one of the most challenging tasks regarding SFCR controlled PWM-VSI drives.

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