CHAPTER-VII

CONCLUDING REMARKS AND RECOMMENDATIONS

In this exposition, a new Pulse-position pulse-width modulation (PPPWM) concept [12] of control strategy for PWM class of control system and the associated theoretical developments together with numerical design procedures have been presented.

PPPWM control strategy presented in this thesis retains all the advantages of PWM control such as efficiency and implementation in digital form and provides, at the same time, higher degree of freedom, thus improving the system performance compared to PWM. PPPWM is, therefore, more general in nature and PWM has been shown to be a subset of PPPWM. It is based on the concept of ensuring equivalence, at sampling instants, of states produced by PPPWM signal to those produced by linear discrete control signal. This concept results in a situation that does not vitiate the linear system performance at sampling instants. Consequently, transformation equations have been derived to obtain different types of PPPWM signals such as Unipolar and Bipolar ones from linear discrete control signals for exact state equivalence at sampling instants. It has been shown that these transformation equations are complex and are not
always suitable for real time implementation of systems having order higher than two due to the additional computational time required. However, most of the practical servo systems can be approximated by a second order dynamics with a reasonable degree of accuracy. Hence PPPWM with exact state equivalence can easily be implemented in real time for most of the servo systems. A design example has been presented to illustrate the practical application of PPPWM control concept to such systems for exact state equivalence.

For higher order systems, to make the PPPWM transformation equations simple for implementation, different types of PPPWM signals such as first order, second order etc have been developed by approximate equivalence of states at sampling instants. The state error due to approximation of state equivalence has, therefore, been derived and intersample ripple has also been analysed. The design procedure, thus, has been made iterative to choose the lowest order PPPWM that meets the ripple and output error specifications. It has been shown that there is an improvement in error approximately by a factor of a hundred from first order to second order PPPWM and further improvement beyond second order is not as significant. Hence for most of the systems second order approximation has been shown to meet the required error specification.
The closed loop system stability of PPPWM system has been analysed using Lyapunov's direct method and a condition for asymptotic stability has been developed following Lyapunov's function used by Murphy and Wu [8] and the procedures of Yedavalli [25]. Different types of PPPWMs are modelled for stability analysis using nonlinear state space formulation through modification of the state space theoretical procedure, which is significant from engineering design point of view. The effect of modulation has been characterised by an equivalent perturbation of the nominal state transition matrix. The upper bound of perturbation matrix for each type of PPPWM has been derived. Explicit conditions for asymptotic stability have been derived on the upper bound of perturbation matrix. These conditions have also been extended to verify the relative stability of the loop.

Finally, a closed form analytical expression has been developed to estimate the steady state gain characteristics of the PPPWM system for step input commands. A comparison in this respect has been made between first order and second order PPPWMs. A detailed procedure for the design of a state feedback gain vector to place the eigenvalues of the modulation free nominal system at a desired set of locations has been presented and gain has been optimised to achieve asymptotic stability in the presence of modulation. Then a systematic design procedure
has been suggested for the design of the complete loop taking in to account the selection of the type of PPPWM, ripple bound, steady state error and asymptotic stability in order to satisfy both static and dynamic performance specifications. An example has also been worked out to illustrate various steps of design procedure and the responses have been presented.

The thesis has thus provided a new generalised control signal modulation strategy named PPPWM for PWM class of sampled-data control systems with a superior performance and the author hopes that this will be of great help to practising engineers in designing systems where PWM systems are presently being used.

**suggestions for future research**

Feasible fruitful areas for further research which came to mind while performing the research for this thesis are the following,

(i) Formulation of PPPWM signals for nonlinear time varying plant
(ii) Analysis of ripple amplitude for time varying plant

(iii) Extension of stability analysis and limit cycle amplitude determination under excited condition

(iv) Finding technique for integrated robust PPPWM control system design.