ABSTRACT

This thesis is concerned with the existence and evolution of subharmonics when ferroresonance occurs in a power system. The existence problem is addressed using two basic approaches: (i) unearthing the hidden solutions in the unstable segments in the fundamental solution continuation path and (ii) detection of isolated solutions by continuation of steady states obtained from temporal bifurcation diagram. To the author's knowledge these approaches have not been applied by the early investigators. Further analysis of subharmonic solutions and stability are carried out using a hybrid approach and tools of nonlinear dynamics. The hybrid approach is the unification of conventional time domain and continuation approaches.

In the course of investigation of hidden solutions, abnormal solutions such as subharmonic, quasi-periodic and banded chaotic are encountered. The bifurcations that occur include period doubling (flip), period halving (reverse bifurcation), cyclic fold, pitchfork and Neimark-Sacker. Practically, analysis of hidden subharmonic is relevant when a normally operating system "drifts" to an unstable region due to varying system conditions. Once in the unstable region, it can "lock" into a subharmonic or quasi-periodic or chaotic ferroresonant state. Isolated subharmonics can occur for varying system conditions following a switching operation. The motivation for investigating the isolated subharmonics

is the reported case of “locking” into a subharmonic ferroresonance solution following a switching operation.

In the earlier part of the thesis investigations related to the hidden subharmonics in the unstable flip segment, due to successive period doubling bifurcations, are reported. The reported case of ferroresonance in the 1100 kV transmission network of Bonneville Power Administration (BPA), U.S.A, is considered for analysis. The network is modelled by a circuit with transformer represented in detail and rest of system represented by a Thévenin equivalent. The more realistic and accurate model of transformer core loss is adopted. The core loss is modelled by a third order power series in voltage. A state variable model for the network is developed by topological approach. Time domain simulations are carried out using fourth order Runge-Kutta (RK4) method. The results obtained are validated using EMTP / MicroTran. Using the tools mentioned earlier, the results obtained reveal that range of stable subharmonic solutions decreases with increase in core saturation and are at a lower value of the bifurcation parameter. Also, the inclusion of nonlinearity in core loss results in less susceptibility of solution to “jump” phenomenon and initial conditions.

While tracing the evolution of the hidden solutions, quasi-periodic behaviour and intermittency are encountered for a two phase open configuration. These abnormal solutions can culminate in chaotic ferroresonance. The results obtained reveal that the two phase open configuration is distinguishably different from that of the single phase open in many respects. In particular, quasiperiodicity and crisis induced intermittency that ultimately lead to chaos are relevant to this configuration. Also, composite route to chaos involving both period doubling and Neimark-Sacker bifurcations are a possibility.

The later part of the thesis deals with isolated subharmonic ferroresonant behaviour. Typical single phase open configuration is considered for analysis. Isolated subharmonics do not occur as a natural evolution following period doubling bifurcation. Detection of isolated subharmonic solutions requires computation of appropriate initial conditions. Methods of obtaining initial conditions for bifurcation analysis can be broadly classified as frequency methods and temporal methods. A class of temporal methods is proposed to obtain the subharmonic initial conditions and it is referred to here as “temporal bifurcation diagram” approach. Starting with initial conditions provided by temporal bifurcation diagram, a continuation procedure predicts multiple subharmonic solutions. Analysis of isolated subharmonic solutions reveals that in general they form a closed loop. Further, odd symmetric subharmonic solutions give rise to supercritical pitchfork bifurcations. The hybrid analysis reveals the existence of banded chaotic solutions.

The occurrence of isolated subharmonic solutions in practical systems is considered next. Two reported cases of ferroresonance involving the network of BPA are considered for analysis. The system corresponding to first case is 1100 kV transmission system. The second case involves the 525 kV transmission system of BPA between Big Eddy and John Day stations. The analysis also includes, the effect of core loss nonlinearity on isolated subharmonics (for 1100 kV system) and the sensitivity of isolated subharmonics with respect to length of de-energised line (for 525 kV system). Temporal bifurcation diagrams are used to obtain the subharmonic initial steady states. The coexistence of different subharmonic solutions is obtained by the continuation technique. The results reveal that the inclusion of nonlinearity in core loss results in elimination of nearly all subharmonic oscillations. Higher capacitance to ground of the de-energised line widens the range of subharmonic solutions. Supercritical and subcritical pitchfork bifurcations are likely to occur in odd subharmonic solution paths.

Finally, the effect of a metal oxide arrester on the isolated subharmonic behaviour of a transformer connected in parallel is analysed. The arrester is modelled by a nonlinear resistance. The sensitivity of subharmonic solutions with respect to arrester parameters, core loss, transformer saturation, source capacitance and the amplitude of the exciting source is examined. The hybrid analysis unearths the higher order banded chaotic solutions, namely, 9-band, 11-band and 21-band. To the author’s knowledge higher order banded chaos in ferroresonance problems have not been reported in literature as of this writing. The analysis also reveals that the presence of MOV eliminates the isolated subharmonic ferroresonant solutions for lower saturation index. For the higher saturation index, the MOV shrinks the region of stable and unstable subharmonic solutions.