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Discussion and Conclusion

The electronic equipment market is seeing an exponential growth. With their rise, arises the issue of efficient power utility and power quality. Converters are used at the front-end for harmonics-free rectification and voltage regulation. These converters are needed to be as efficient as possible at all loads. Typically, they are designed to be efficient around their rated operating point, however, they operate at much lower load for majority of the time. Therefore, there is a need to make them efficient at all operating conditions, especially at lower loads. In this Thesis, a novel concept of Event-triggered Sliding mode Control has been used to improve efficiency of power converters by reducing switching actions. The concept has been verified for power converters at the front end of an electronic equipment including PFC and DC-DC converters cascaded in a two-stage AC-DC-DC converter. Moreover, for the single-stage power factor correction application a new non-linear controller has been proposed. The proposed controller mitigates harmonics in the input current while providing the desired dynamic performance of the system at the line-load transients. This proposed solution has then been extended for the a modular three-phase AC-DC converters. Furthermore, the concept of Integral Sliding mode has been proposed for PFC application to eliminate the finite reaching phase in classical SMC and make system robust from the initial point. Additionally, the attribute of ISM to compensate for the parametric variation has been explored for Z-source converters. ISMC mitigates the effect of asymmetry due to parameter variation and thus, allows use of reduced order model to design controller for voltage regulation. The stability and the performance of different non-linear controllers have been investigated. The proposed theoretical developments have been validated through the simulation and experimentation. In this Chapter, the findings of the work and associated challenges and recommendations to carry forward the future research will be discussed.

The Thesis begins with discussing the explosive growth in the consumer electronics market and how this rise has raised the two major concerns of energy efficiency and grid power quality. The need to maintain efficiency at all operating conditions and the obstacles in achieving the same has been studied, especially at light load conditions wherein switching losses are dominating. The advantages of load adaptive switching pattern to address the unnecessary switching losses has been established. It is then followed by an extensive literature review covering the existing control schemes for both DC-DC and AC-DC converters. The presently available control schemes aims at either dynamically changing the control parameter or the hardware structure however, these techniques involve various challenges. In this Thesis, a novel concept of Event-triggered Sliding mode control (ETSMC) has been used for power converters. ETSMC leverages system dynamics and eliminates unnecessary switching actions to improve efficiency, especially at low loads. The conclusion of the work is as follows.

The concept of ETSMC has been used for an Isolated Half-bridge converter for voltage regulation DC-DC stage. The basic concept of the "action on demand" was applied to restrict the redundant switchings while maintaining the system performance. Moreover, Hysteresis based SMC has been established as a special case of ETSMC. Using memory less event triggering, the performance of HM-SMC can be emulated. The proposed scheme improves efficiency upto 16% at lower loads. The adaptive nature of the proposed controller also improves the dynamic performance.

The effectiveness of the strategy has been demonstrated under line and load transients.

The cumulative effect of the appliances in degrading the grid current quality is a graving issue. The concept of Sliding mode based loss free resistor to for harmonics free rectification has been discussed and then on in light of the IEC 61000-3-2 guidelines, the need for load adaptive boundary conditions has been established in second work. Adopted Event-triggered SMC for PFC application adapts the band size depending on the load condition, thus leverages the flexibility in wave shaping to reduce switching actions. Furthermore, expediency of the proposed scheme over HM-SMC has also been demonstrated and validated through simulation and experimentation.

The concept of SLFR forms an inherent choice for input current shaping and is ideal for a pre-regulator stage in a two-stage AC-DC-DC converter. A novel Adaptive SLFR (ASLFR) has been proposed in third work which presents itself as an effective single-stage PFC solution. The scheme gives a voltage regulation feature to the pre-regulator PFC, proposed using the existing SLFR technique in Chapter 3. The effectiveness of the adopted novel scheme over the existing SLFR based controller and the most commonly adopted dual-loop PI control for single-stage PFC solution has been demonstrated. For a 50 % load change, the PI controller takes 150 ms for voltage recovery with about -13 % undershoot, on the other hand the proposed controller recovers the voltage within a single cycle with effectively no undershoot. The quality of input current for the proposed controller is better than the SLFR based work at higher loads and is quite high as compared to the PI one. Then on, Event triggered implementation of the scheme was discussed. The ETSMC allowed for the flexible wave shaping of the input current, while regulating the output voltage. The harmonic content was always within the prescribed limits for Class D regulations for a reduced switching actions.

Furthermore, the proposed concept of ASLFR was extended to three-phase AC-DC application. An effective single-stage solution for three-phase PFC in high power equipment like EV chargers has been provided using Ćuk rectifier modules. The presented solution reduces the number of conversion stages while offering nearly unity power factor and fast dynamic transient. A comparative study established the expediency of the proposed solution over the existing control schemes in terms of input current quality. Results establish that the proposed system gives excellent power factor correction and tight voltage regulation. A power factor of 0.997 is achieved when system operates at nominal 1 kW load. Moreover, the system meets the harmonic regulations as per IEC 61000-3-2 class A limits, at all load levels.

The classical control methodologies have been widely used in the industry due to their ease of design and analysis. However, these linear control guarantee stability in vicinity of the operating point. The non-linear controls are preferred for the system having the frequent large line-load transients and uncertainty in the system parameters. The integral sliding mode (ISM) based control amalgamates these linear and non-linear control to achieve the best of both worlds. Furthermore, it ensure the robustness of the system against matched uncertainties arising due to external disturbances or parameter variations from the very beginning, by eliminating the reaching phase. The concept has been proposed for PFC and Z-source converter applications. Widely popular PID-controller associated in the dual-loop control has been adopted as the nominal control for the ISM based control. For Boost PFC, with the nominal PI controller alone, the %THD is 9.6%. The THD increases to 14.75% with external disturbance in input channel. However, the harmonics are eliminated and %THD is brought to 8.27% using proposed ISM based controller. Furthermore, for the parametric variations also ISM was able to compensate for the reduction in inductance unlike nominal PI controller by restricting %THD to 9.26%. The transient behaviour for the controller was also analysed. In the second section, effect of asymmetry on system response, due to unmodeled dynamics of elements, for a Z-source converter is studied. Proposed control is able to maintain the system performance while the nominal controller is effected and provides a highly oscillatory capacitor voltage. Similarly, the effectiveness of the ISM based control against external disturbances and with load variation is established.

Recommendations for Future Work and Some Open Problems The Event-triggered Sliding mode control is proposed for power converters in the Thesis. The scheme leverages system dynamics to efficiently utilize the resources. In a microgrid, power converters form an interface between several distributed sources, energy storage units and loads. Thus, in order to achieve highly reliable and efficient network the control algorithms must be improved to minimize the requirement of communication and therefore switching from centralized to decentralized control.

The present work, however, can be explored further in different aspects. For this, the recommendations for future research are as follows

- The present work focuses on an individual converter, however, it can be extended to investigate the performance of the proposed control techniques in the network of converters or a Microgrid. In a network, event-triggered control can ensure that the attention is provided to a particular converter only when the "need" arises thus reducing the burden on computational resources.

- The present work employs Event-triggered SMC which involves continuous monitoring of the states. The concept of the Self-triggered control would make a good future work. Self-triggered control uses system model to predict the future instances of triggering and thus eliminates the need for continuous or periodic system monitoring.

- The present work has proposed a generic implementation of Adaptive Sliding mode based LFR for PFC application. It has been explored for single-phase as well as three-phase converters. This work can be extended for other converter configurations like bridge-less or semi-bridge-less topologies.

- In the present work, studies have been made to understand the effect of system variation in Z-source converter for the voltage regulation application. The work can be extended for the power factor application of Z-source converters.

- The concept of ISMC could be explored for those control problems in which the nominal classical control performs well for the designated task. However, the sensitivity of the system trajectory with respect to uncertainties, starting from the initial time moment is a concern. Therefore, instead of developing new control strategies, the existing nominal control could be used with ISMC to ensure exact (with respect to the matched uncertainties/disturbances) tracking of the nominal trajectory designed for nominal systems.