Robust Control Techniques for Virtual Impedance Shaping to Mitigate and Share the Double Line Frequency Ripple in Microgrids

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Discussion and conclusion

The second-order ripple currents have various detrimental effects on the sources. They cause a temperature rise in the sources, energy storages, and converter components. The rise in operating temperature of sources like the photo-voltaic leads to a reduction in the power generated. The SRCs cause oscillations in the maximum power points in PVs which further affects the efficiency of power generation. In terms of battery storages, it leads to degradation of electrodes. The electrode degradation deteriorates the life span of the batteries. To reduce the SRCs, the converter components size and rating has to be increased. A larger capacitor has to be incorporated to provide the second-order oscillatory power demand. An increase in capacitors leads to an increase in the size and weight of the system. Usually, the electrolytic capacitors are used as they cost less, however, they have a comparatively low lifetime compared to the other microgrid components. Hence, the usage of electrolytic capacitors degrades the reliability of the system. In a distributed power generation system like DC Microgrid, a node consists of an interconnection of the source and interfacing converter. The interfacing converter consists of a buck, boost, or a buck-boost converter. These are connected to the dc bus through an interconnecting cable. The SRCs propagate to the node which consists of the interfacing converter with has less output impedance at twice the AC supply frequency, hence a node may get more loaded with the SRCs. This leads to unequal distribution of SRCs throughout the microgrid. This may further lead to failure of the source and hence affect the reliability of the microgrid. To address above issues due to SRCs, different active and passive SRC control methodologies are used. The active control methodology is more beneficial compared to the passive control methodology due to lesser capacitance requirement. However, active methodology increases the component count and leads to increase of overall cost of the system. To mitigate SRCs, different virtual impedance based control methodologies are proposed in literature. However, these methodologies are not robust against parametric and modeling uncertainties. It may lead to degradation of the converter dynamics.

In this thesis, various robust control methodologies have been proposed to mitigate or regulate the SRCs. The proposed methodologies add a virtual impedance in series with the input inductor branch. The controller is designed to increase impedance at twice the ac supply frequency. As a result, the SRC gets reduced, and the voltage and currents are maintained within desired limits. The proposed impedance shaping techniques have the benefit of uncertainty mitigation. The SRCs are regulated even in uncertain operating conditions. The proposed impedance shaping control technique has been applied to the single-stage qZSI, eqSBIs, and to the DC Microgrid system. In DC Microgrid, the control is integrated with the consensus-based secondary control, and robust integral sliding mode based secondary control. Further, a robust secondary control methodology is proposed to facilitate desired operation in presence of uncertainties. The analysis of impedance variation has been presented, and the control techniques have been proved to be stable using the Lyapunov's stability criteria. The proposed control methodologies leads to robustness of overall microgrid system due to SMC and ISMC. The SMC mitigates the uncertainties once the trajectories reach the designed sliding surface. Hence, the control is robust during the sliding motion. To achieve disturbance rejection from beginning, the ISMC is incorporated. In ISMC the system trajectories start from the sliding manifold right from the beginning, and hence the reaching phase is eliminated. The implementation of ISMC facilitates integration of classical control with a non-linear ISM control to improve overall response of the system. In this chapter, the research work will be concluded, and recommendations for future research in this field will be discussed.

The thesis begins with an introduction to SRCs. The cause of SRC generation is discussed for SSIs and DC Microgrids. The proposed control techniques are discussed briefly. A literature review of various methods adopted in literature to deal with SRC mitigation is presented. Among the methodology, the passive power decoupling method is discussed. It consists of increasing the passive components like capacitors and inductors to reduce the SRC propagation to the source. In literature, various active power decoupling circuits have been proposed to reduce the capacitor requirement. Different circuit topology has been described briefly. The main challenge of adding an active power decoupling circuit is that it increases the system's complexity and size. Further, more components are to be integrated with the system, which increases the component count and cost. The ripple filters must also be controlled to have a high energy density. Further, different virtual impedance-based control strategies have been discussed. Methods like BPFICF, VRS, NFLCFFS, NF-VRLCFFS, etc. have been discussed. The main issue with these SRC mitigation methods is that the dynamics degradation may occur in uncertain operating conditions. Further, some of the control methodologies require feedback of load current in the control loop. This makes such methods inapplicable for DC Microgrids as communicating the load current data may require additional load estimation and a reliable communication system. Finally, various distributed control methods used for DC Microgrid control are described. Some linear control based SRC distribution techniques proposed in the literature has also been discussed. In this work, the robust control strategies for SRC mitigation in SSIs and DC Microgrid have been discussed.

The single stage inverters consists of the impedance network to facilitate the boosting of the input DC voltage during the shoot through stage. The impedances are designed at a frequency which is much higher than the second order ripple frequency $2f_{ac}$. Due to less impedance at $2f_{ac}$, the SRCs propagate to the source and affects it. An increase in impedance network components will increase the weight and size of the SSIs. A sliding mode based control is proposed to virtually increase the impedance for the single-stage qZSI and eqSBI. The proposed method is robust against modeling and parametric uncertainties. The current error is the difference between the actual current and the low pass filtered inductor current. The time constant of the low pass filter must be less than the time period of the oscillation so as to give a dc current reference. The effect of varying the low pass filter time constant on SRC has been analyzed. The simulation and experimental results verify that the ripple gets reduced from 2A to 0.7A in qZSI and from 2A to 0.2A in EqSBI.

The dynamics of the single stage inverters with dual loop control degrades in presence of uncertainties. The uncertainties consist of the matched and the unmatched uncertainties. The matched uncertainties can be mitigated by designing the appropriate control law. The designed control must not amplify the unmatched uncertainty. To improve the dynamics and mitigate the SRCs in SSIs, an integration of the dual loop control with ISMC is proposed. The proposed control method is robust and mitigates the uncertainties from beginning. The dual-loop control consists of the outer voltage control loop and the inner current control loop. The inner loop is designed to have faster dynamics compared to the outer voltage control loop. An ISMC loop is designed so as to mitigate the SRCs. The control law of ISMC is non-linear and reduces the SRCs, making the converter more robust. The ISMC improves the dynamic of the SSIs in uncertain conditions. The only condition required is that the uncertainty must be a known bounded uncertainty. The shoot-through control law is obtained by the addition of the dual-loop control law and the ISMC control law. The proposed control has been implemented on both qZSI and eqSBI converters. These two topologies have been chosen as their operation is similar to a wide range of other SSI topologies. The proposed control mitigates the ripples irrespective of load changes and uncertainties.

The SRCs get unevenly distributed in the distributed power generation environment due to unequal connecting cable impedance, and converter output impedances. This leads to the more SRC propagation to some nodes. An impedance shaping strategy is proposed to regulate SRCs in the DC Microgrids. A linear control based virtual impedance is designed, which has the effect of regulating the SRC propagating to the source of a node in the microgrid. The controller consists of a dual lop control with a virtual impedance loop. A low bandwidth communication is incorporated so as to facilitate the per-unit current exchange between the nodes to facilitate the proportional dc load sharing. The SRC reference to a node is provided, and accordingly, the virtual impedance is increased or decreased to manage the SRC content. The advantage of the proposed control is that the ripple filter can be installed at a node in microgrid, and SRC from all other nodes can be propagated to this filter node. Hence, the energy density of the SRC filter can be improved. The proposed control has been implemented on a two-node microgrid, and experimental results verify that the SRC sharing is possible and the dc component of load current is shared proportionally among the interfaced converter.

A DC Microgrid control consists of interconnection of several nodes, regulated by hierarchical control. The hierarchical control requires data exchange between the neighboring nodes. An erroneous data exchange may lead to oscillations in voltage or instability of microgrids. Further, accurate modeling of converter components and control is needed. In order to make the DC Microgrid control robust, a SMC based primary and and ISMC based secondary control solution for DC Microgrid application is proposed. As discussed in earlier chapters, any uncertainty in communicated data will lead to a faulty reference generated from the secondary control. This reference, when fed to primary control, may lead to failure of the system. To mitigate the uncertainties, an ISMC based secondary control is proposed. The control cancels out the bounded known disturbance in the communicated data without the addition of any lag due to low pass filters which are used conventionally to remove low-frequency oscillations. In addition to this, a dynamic sliding surface is proposed for the primary control of a node. The surface varies with the variation of voltage and current error of the node. The proposed SMC primary control facilitates plug and play operations in the microgrid. Hence, a robust primary and secondary control has been proposed, which can handle the uncertainties due to modeling and communication uncertainties. The simulation and experimental results show that proportional sharing is achieved in less than 100ms. The proportional sharing is maintained irrespective of load variations from 0.5 p.u. to 1 p.u of the rating of converters. A good dc bus voltage regulation and proportional load sharing is achieved, during plug-in and out of high and low loaded nodes.

The control algorithm of a node must be capable of maintaining desired DC bus voltage along with SRC mitigation. The control must further, be able to be integrated with consensus based secondary controllers to achieve proportional load sharing among the neighboring nodes. An adaptive output impedance shaping methodology is proposed to manage the SRC propagation to the source at a node. The sliding surface proposed is dynamic and varies with voltage and current errors. The surface can be designed to maintain some desired voltage regulation on the dc bus. The current error terms can be designed so as to regulate the SRC content. The proposed control is designed using locally known parameters. The proposed primary control is integrated with the dynamic consensus-based secondary control. The consensus-based control drives the connected node to achieve proportional dc component sharing. The ρ component is regulated to increase or decrease the SRC propagation to a node. The stability of the proposed controller is analyzed considering multiple source nodes using Lyapunov's approach. A DC Microgrid consisting of parallel-connected dc-dc boost converters, dc load, and inverter load is simulated to verify the proposed control strategy. From experimentation, it has been verified that the dynamic parameter α maintains the dc bus voltage within $\pm$ 5% of rated voltage. The ripple reduction has been achieved, such that for an increase of ρ from 0.2 to 1, the SRC gets reduced from 0.4A to 0.1A for 1A dc component. The proposed control maintains proportional load sharing during both ac and dc load variations and, the dc bus voltage is kept within the desired regulation limits.

8.1 FUTURE WORK AND SOME OPEN PROBLEMS

The community has made significant progress in proposing the solutions to the SRC control, however, many problems still need attention. The SRC control methodology consists of an active power methodologies, however in distributed power generation, optimal location of active filter will lead to an improved power density of the installed filter. In terms of virtual impedance shaping methodologies, the different methods usually consist of linear controllers which are not robust against uncertain operating conditions. The controller leads to reduction of SRCs, however, the virtual impedance designed is not dynamic, this leads to a degradation in the dynamics of the system. Further, these virtual impedance methodologies, are usually applied on the two-stage inverters and are not integrated with any other control as in the case of DC Microgrids, where the control is to be integrated with the hierarchical secondary or tertiary controllers. Ensuring the stability of the system in presence of uncertainties is yet to be addressed. The uncertainties can either occur in modeling or communicating uncertainties.

In this section, some recommendations for future works and open problems in the field of virtual impedance shaping will be discussed.

- **Applications to other SSI topologies** The robust impedance shaping control techniques can be designed for various other SSI topologies such as SLZSI, TZSI, etc. All the SSIs will suffer from SRCs due to the dc-ac conversion. The derived control must not affect the dynamics of the SSIs.

- **Improve modulation index** Another work can be done in the field of control of SSIs. The shoot-through generation logic can be improved to obtain fewer ripples in the output side. The modulation index must be increased to reduce the switching ripples.

- **Implementation in ac-dc conversions** The robust SRC controllers can be designed for ac-dc conversion as it too suffers from second-order voltage and sources current oscillations at the dc side. The aim of the control to be designed must be to reduce the capacitance required so as to avoid the usage of any electrolytic capacitors.

- **Applications to ac microgrids** The present work can be extended to the ac microgrids. In microgrid, active and reactive power sharing must be achieved by appropriately controlling the voltage and frequency values. The ac microgrid also consists of the hierarchical control, which is susceptible to failure in uncertain operating conditions. Hence, a robust control mechanism can be designed to ensure the desired operation in the presence of uncertainties.

- **Improve the hierarchical control** The robust control can be extended for tertiary control also as they are at the higher level of control layer and any ambiguous reference generation from tertiary control can lead to the overall failure of the microgrid.

- **Application to three-phase topologies** The control used in this work can be extended for three-phase inverter and single-stage systems. In the three phase system, the oscillations occur when there is a load imbalance or when some fault occurs.

- **Minimize capacitance** Further, an analysis of the amount of capacitance required at the dc bus to mitigate the oscillations on the dc bus due to ac load can be performed.

- **Optimal placement of SRC filters** The present work diverts the SRCs to some node, which consists of some SRC filter. Another interesting implementation of the work can be an optimal placement of the SRC filter in the microgrid system such that, the SRCs can be diverted to this node with minimal control effort.

- **Impact analysis** The effect of the designed control on the lifetime of the sources can be also be addressed. By means of this, one must be able to select an appropriate impedance shaping technique for some specific application.

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