

Literature Review

The previous chapter consists of an introduction to the second order ripple. The distribution of SRCs in DC Microgrid has also been discussed. In this chapter various methodologies proposed in literature to regulate the SRCs in SSIs as well as in the DC Microgrid will be presented. The different methodologies proposed can be categorized as: passive decoupling based SRC control, active power decoupling based SRC control and software based programmable control of SRCs. The merits and challenges of using each of the methodologies will be discussed in detail.

2.1 EFFECTS OF SRCS ON THE SOURCES

The second order ripple currents have various detrimental effects on the sources and the interfacing converter components. In sources it leads to rise in temperature which in turn results in the reduction of power generation efficiency. In terms of energy storage, it causes the depletion of battery electrodes. Further, the oscillations in voltages and currents leads to stress in the switches, diodes and capacitors. This may lead to failure of the converter and hence affects the reliability of the designed system. The effects of SRCs are categorically explained below:

2.1.1 Fuel cell

The fuel cells (FCs) are used in distributed power generation. The fuel cells are considered to be an alternative to the traditional non-renewable sources of energy. However, the FCs have a slower dynamic response. The FC stacks dynamics do not get affected if the current drawn from it is modulated at high frequency. However, a low frequency oscillating current current leads to an interaction between the current drawn and the electro-chemical reaction as presented in Fontes *et al.* [2007]. Usually, the interactions between the ripple current and proton exchange membrane based fuel cell is analyzed (PEMFC). The fuel cells have slower dynamics which further degrades in presence of SRCs Palma *et al.* [2006]. The interaction of fuel cell with various other power electronic converter topologies is widely studied in literature Boscaino *et al.* [2014]; Haiping Xu *et al.* [2004]; Peng *et al.* [2004]. In Fontes *et al.* [2007], an interaction between the input capacitance and electrical response of PEMFC is analyzed. It shows that a larger value capacitor is required to absorb the oscillations in current drawn, so that the electrical dynamics of the FCs are not affected. An equivalent circuit is derived in Choi *et al.* [2004] to analyze the effect of low frequency ripples on FCs. The experimental results show that there is a 10% reduction in available power in case of low frequency current drawn. To regulate the SRC component, a power management unit (PMU) is proposed in Li *et al.* [2011]. This unit manages the oscillating power between the inverter fed ac load and the fuel cell. A hybrid system is proposed in Jin *et al.* [2009]. The system consists of a battery system and a fuel cell as source. The battery provides power during peak load and during ripple currents when ac load is driven from the FCs. A battery management system (BMS) is proposed so as to manage the power flow in different scenarios. Hence, to mitigate the SRCs from propagating to the FCs, an extra system has to be developed such as BMS or PMU. This increases the cost and complexity of the system.

2.1.2 Battery storage

The power generation in a microgrid depends on the availability of solar or wind energy. These sources are not intermittent in nature. As a result, different types of batteries are used to store the surplus energy. The batteries used are- Nickel Cadmium (Ni-Cd) batteries, Lead-acid batteries, Vented Lead acid (VLA) batteries, Valve Regulated Lead acid (VRLA) batteries, Sodium-Sulphur (Na-S) batteries, and Lithium ion batteries. Each of the batteries have different ability to cater to the ripple current demand. In Kim *et al.* [2012], a charge discharge based analysis is carried out to analyze the effects of ripple on the Li-ion batteries. The effects of SRCs are found to be minimal. Similarly, the Ni-Cd batteries are also not adversely affected due to the ripple currents as the impedance of these batteries remain almost constant in fully charged to discharged condition as mentioned in IEEE-1184 standards. However, these batteries are costlier. The Lead-acid batteries such as VRLA and VLA have heating issues when the ripple current is drawn from it. There is a reduction of efficiency and the battery life time degrades when the ripple current is drawn for a longer period of time as specified in the IEEE-519 standards. Different IEEE standards emphasize on limiting the ripple current drawn from the batteries. Different IEEE standards for battery usage are: IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications IEEE [2011], Recommended Practice for Installation Design and Installation of Large Stationary Generating Station and Substation Lead Storage Batteries IEEE [1974], IEEE Draft Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications IEEE [2010], IEEE [2020]. Hence, proper batteries must be selected or proper SRC level must be maintained so as to ensure minimal damage to battery electrodes and increase the lifetime of the batteries.

2.1.3 Photo-voltaic sources

The SRCs cause the junction temperature of the PV panels to rise. Any increase in the rise of temperature leads to a reduction of efficiency of the sources as specified in Kan *et al.* [2019]. Further any oscillations in the voltage and currents leads to improper function of the maximum point extraction algorithm. This further degrades the efficiency of power generation of the PV sources as shown in Lin *et al.* [2012]. To extract the maximum power from the PV sources, ripple based extremum seeking control is proposed in Brunton *et al.* [2010]. A ripple correlation control for maximum power extraction is proposed in Casadei *et al.* [2006]. A particle swarm optimization (PSO) based methodologies have also been used so as to extract maximum power during ripple in currents as in Ishaque *et al.* [2012]. The degradation of output power due to SRCs is analyzed in Sullivan *et al.* [2013]. The SSIs used in the micro-inverter also suffer from source second order ripple current. A comprehensive modeling of a SSI with consideration of the ripple currents is presented in Liu *et al.* [2014]. The variation of impedance of PV sources with voltage ripples is analyzed in Benavides and Chapman [2008]. Hence, presence of ripple in the current drawn from PV sources reduce the efficiency and various complex algorithm have to be used to extract maximum power. Instead the ripple current must be prevented from being drawn from it.

2.1.4 Wind Turbines

SHCs when drawn from a wind turbine (WTs) leads to ripple torque in it. These ripple in torque leads to mechanical stress in the turbine Bati and Luk [2015]. There are two types of WTs- Vertical Axis Wind Turbines (VAWT) and a Horizontal Axis Wind Turbines (HAWT) depending on the axes of rotation. The ripple in torque reduces life time of a VAWT compared to the HAWT Xia *et al.* [2011]. However, ripple in torque can be reduced by means of adequate speed control gears Parker *et al.* [2016]. Hence, SRCs must be regulated rather than allowing it to propagate to the WTs and cause ripple in torque.

2.1.5 Effect of SRCs on converter components

The SRCs affect the sources drastically and lead to a reduction in the operating life time. To mitigate the SRCs the converter components may be over sized Zhang *et al.* [2014]. If the converter is not designed considering the SRCs, then it may lead to failure of the equipment. The low frequency oscillations in voltage and current may lead to stress in the active switches or the capacitors which are used to absorb the ripple content. The capacitor being the weakest element of any circuit may lead to failure as shown in Zhong *et al.* [2016]. Use of a non-electrolytic capacitor leads to an increase of cost of the system. If SRCs are not mitigated, there may be oscillation in the voltage which leads to the problem of LED flickering. In Shagerdmootaab and Moallem [2015], authors presents a comprehensive study to reduce the size of capacitor in a ac-dc flyback converter connected to a LED with the aim to reduce the flickering due to SRCs. Similarly an adaptive control is proposed in He *et al.* [2017] to remove the electrolytic capacitor and drive the LEDs using a power factor correction circuit (PFC) and a bidirectional converter. The SRCs lead to oscillation at the dc terminals of the converter and affect the equipments connected to it as shown in Krein *et al.* [2012]. This affects the equipment life time at consumer end, and the power quality is also degraded.

2.2 SECOND ORDER RIPPLE MITIGATION METHODOLOGIES

Different methodologies have been proposed to mitigate the SRC propagating through a converter. The SRCs are mitigated by using a capacitor at the dc end. The capacitor provides the ripple power required during dc-ac conversion. However, the capacitor size required increases with the reduction in the SRC frequency value. To reduce the capacitor size, various active control methodologies have been proposed. In Gautam *et al.* [2020], authors present a comprehensive review of various SRC control strategies. The SRC control methodologies can be broadly categorized as: passive power decoupling methodologies, active power decoupling methodologies and control oriented methodologies. The description of different methodologies are as follows:

2.2.1 Passive Power Decoupling methodology

The passive power decoupling methodologies consists of increasing the size of the capacitors and inductors so as to regulate the SRCs as mentioned in Balog and Krein [2002]. However, as the frequency of operation is reduced, the size of passive component is to be increased as specified in Ale Ahmad *et al.* [2012]. This leads to an increase of the weight and size of the converter when inductor size is increased. On the other hand, increase in capacitor size increases the cost of the system. The bulkier electrolytic capacitors are needed to reduce the cost and absorb the ripple content. The electrolytic capacitors are not reliable Falck *et al.* [2018]. In Krein *et al.* [2012], authors derive the minimum capacitance required to mitigate the SRC content. In literature different methodologies have been proposed so as to reduce the capacitor requirement. In Chen *et al.* [2015], authors have proposed a capacitor less inverter so as to reduce the stress on the circuit components. Electrolytic capacitor elimination is also done in Chen and Hui [2012]. Hence, there is a need to reduce the capacitor size and improve reliability of the system. For capacitor size reduction various active power decoupling strategies proposed in literature are presented in the next subsection.

2.2.2 Active power decoupling methodologies

The active power decoupling circuit (APDC) consists of an extra circuitry through which the SRC is regulated. The circuit can either be connected in series or parallel to the dc-ac stage converter. The configuration of a series and parallel connection is shown in Figure 2.1 and Figure 2.2 respectively.

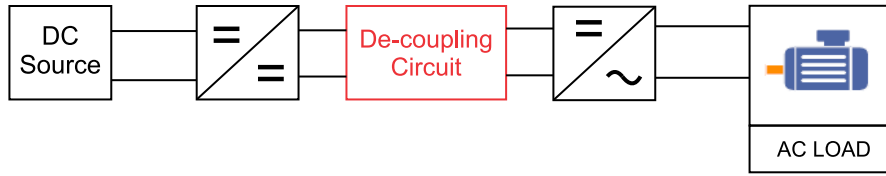


Figure 2.1 : Series interfacing of APDC

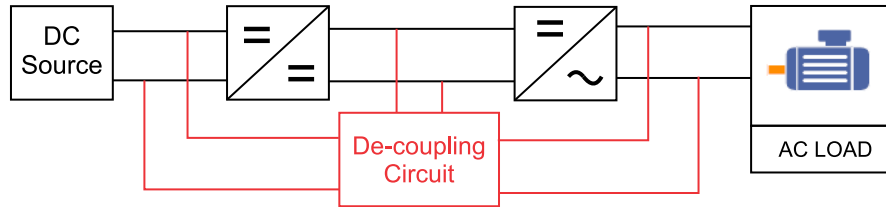


Figure 2.2 : Parallel interfacing of active power APDC

In Zhang and Jin [2014], the authors proposed an active power filter (APF) for the current source inverters (CSIs) as shown in Figure 2.3. The APF consists of a bidirectional buck-boost converter which stores the ripple energy to the passive component of the filter in one half and provides the ripple energy in the other half. The proposed control leads to a significant reduction in the second order ripple currents. Similarly, an active power buffer circuit is used to store and

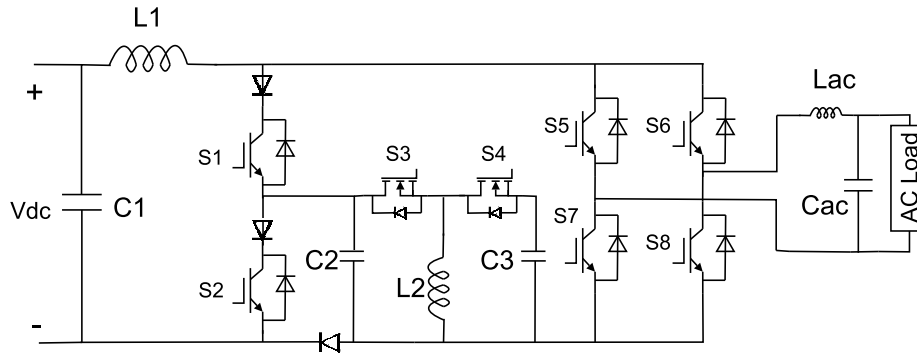


Figure 2.3 : Active power filter for CSIs

provide the ripple energy in Ohnuma *et al.* [2015]. The paper also proposes a control scheme to reduce the second order ripples while feeding a pure sinusoidal current to the grid interfaced to it. The buffer filter and control is implemented for a CSI. The filter and control were used to obtain 8.9% ripple with THD of 4.2%. The power factor of 99% was obtained with a efficiency of 95%. The implemented active buffer is shown in Figure 2.4 The ripple in source current are reflected on the dc side in a qZSI. To mitigate the ripples, either a bulky capacitor is to be installed or the size of impedance network is to be increased. This leads to an increase in the size and weight of the qZSI. In Ge *et al.* [2016a], the authors have proposed an active filter integrated with the qZSI. The resultant circuit is shown in Figure 2.5. The low frequency oscillations are mitigated at dc end. This leads to a reduction in size of the impedance network. Also, the size of capacitor for ripple energy absorption is smaller.

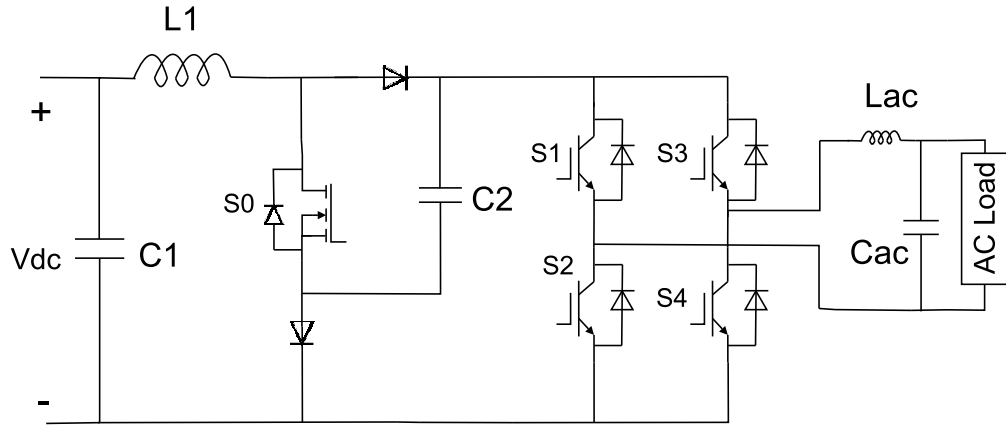


Figure 2.4 : Active power buffer for CSI

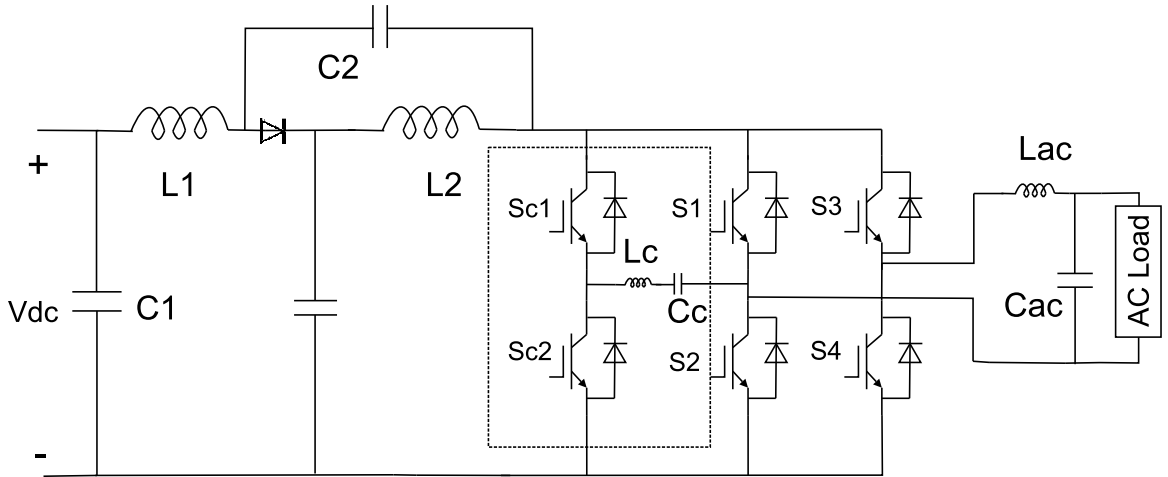


Figure 2.5 : Active filter for qZSIs

In Krein *et al.* [2012], the ripple current is reduced by considering the ripple energy demand due to the dc-ac conversion. A ripple port is implemented so as to provide the oscillating second order power. This approach has the effect of port requirement to a two quadrant converter, which is formulated with same switches at the dc side of the inverter. It leads to the reduction of converter size and cost. The proposed ripple control configuration is shown in Figure 2.6.

The lifetime of the electrolytic capacitor reduces due to extreme operating conditions such as high atmospheric temperature. In Shimizu *et al.* [2006], a high frequency flyback based utility interactive topology is proposed which is suitable for PV applications. The ripple filter circuit proposed facilitates usage of film capacitor of a smaller value compared to the conventional ones. The proposed configuration is shown in Figure 2.7.

In Hirao *et al.* [2005], two modulation techniques i.e. time shared magnetizing modulation (TMM) and sequential magnetizing modulation (SMM) has been proposed. These methodologies have been implemented on the flyback type single phase grid interactive inverters. The TMM has the advantage with respect to the conversion efficiency while the SMM has comparatively low conversion efficiency. The objective of a high conversion efficiency and low current distortion has

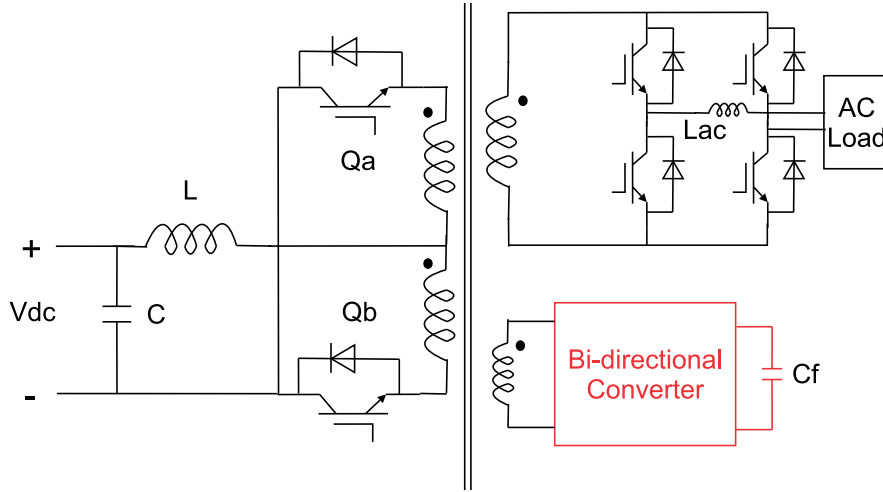


Figure 2.6 : High frequency flyback based utility interactive topology

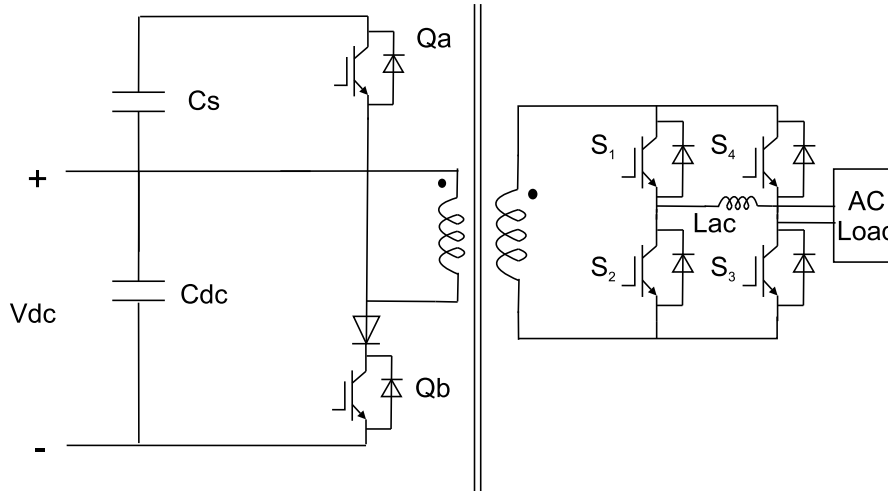


Figure 2.7 : Flyback type single phase grid interactive inverters

been achieved. The circuit is shown in Figure 2.7. In Tan *et al.* [2007], a flyback inverter for PV applications, shown in Figure 2.8, has been proposed. The capacitor idling methodology is used to derive a circuit topology from a single ended primary inductance converter to a two switch flyback converter. To improve the conversion efficiency, soft switching was implemented. Further, a peak current control was employed to sinusoidal current to the ac grid interfaced to the converter. A stacked switched capacitor (SCC) architecture is proposed in Chen *et al.* [2012], to improve the energy density of the ceramic and film capacitors. The energy density is to be made comparable with the electrolytic capacitors so as to replace them in the system. The SCC architecture can be used as energy buffer to mitigate the power oscillations during the dc-ac conversions. The work has further been extended in Afridi *et al.* [2014]. The SCC buffer is enhanced to achieve a higher energy density, and also high round trip efficiency with the desired dc bus ripples. A bidirectional ripple eliminator is proposed in Cao *et al.* [2015]. The eliminator consists of a bidirectional buck boost converter with the capacitor as the energy storage element. The voltage of the capacitor terminals can be regulated to be more or less than the dc bus from which the ripples are to be eliminated.

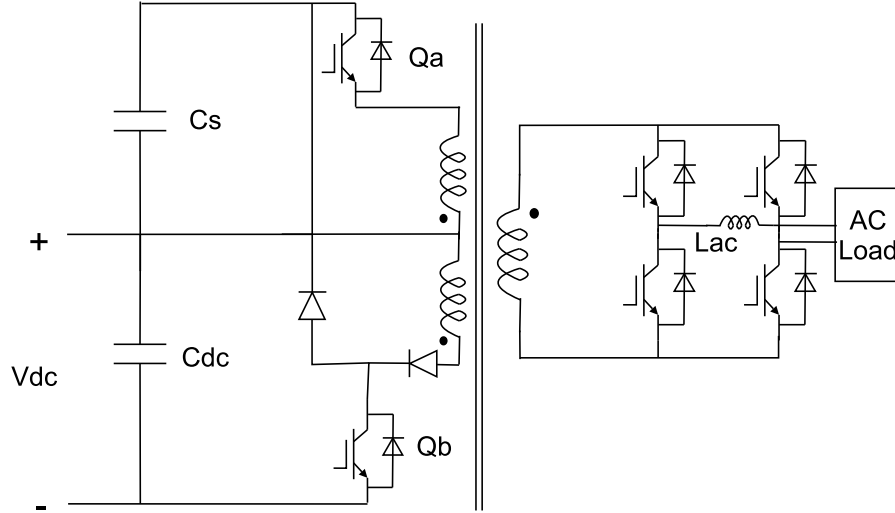


Figure 2.8 : Flyback inverter for PV applications

This helps in reducing the capacitor requirements in the filter. A rectification system with PFC also consists of the second order ripples in dc side voltage and source currents. In Li *et al.* [2015], a differential ac/dc rectifier is proposed with inductor current waveform control so as to regulate the ripple content. The usage of electrolytic is minimized by usage of the control proposed. Another control is proposed to compensate for oscillations by putting a voltage source in series with the dc bus line has been proposed in Wang *et al.* [2014]. This helps in compensating the dc bus voltage oscillations. A comprehensive analysis of static and dynamic impacts on system characteristics has been presented. An active power decoupling is proposed by using a neural filter. The ripple content in dc voltage is estimated and its ratio with average dc bus is found Wang and Wai [2019]. This is used to improve the neural SRC filtration method. To improve the system robustness, sliding mode control is used. To regulate the output impedance of the cascaded converters, an adaptive active capacitor converter (AACC) is proposed in Zhang *et al.* [2013]. The AACC acts as the equivalent capacitor and helps to reduce the output impedance of the source converters. This helps to avoid any interaction between the source and load impedance. Similarly, methods to manage output impedance for SRC regulation is proposed in this work.

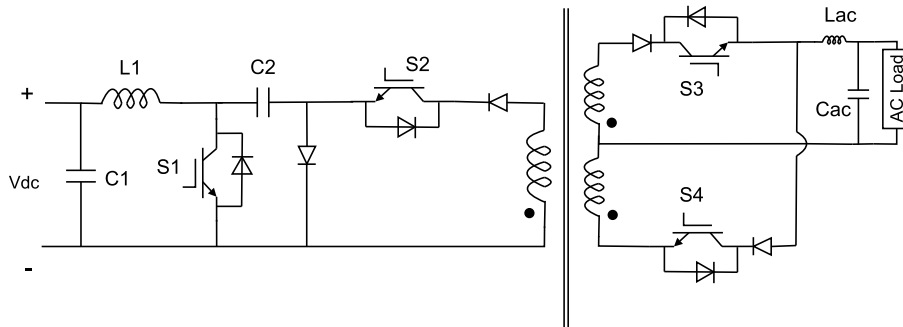


Figure 2.9 : Single phase pulse width modulation voltage source rectifier

A single phase pulse width modulation voltage source rectifier capable of feeding a pure sinusoidal current and achieving a zero ripple output current is proposed in Shimizu *et al.* [2000]. The proposed circuit configuration is shown in Figure 2.9.

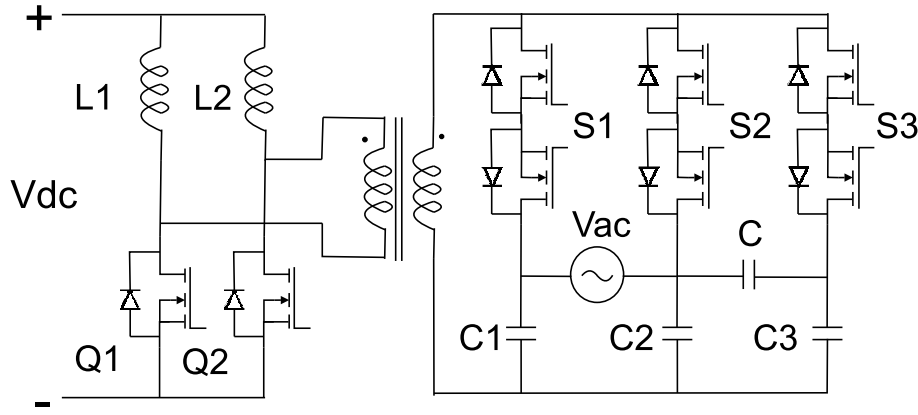


Figure 2.10 : Series interfacing of active power APDC

Two different control methodologies have been used which are referred as dc side inductor method and ac side inductor method. The proposed control is applicable for storage batteries that are connected to a common dc bus in parallel.

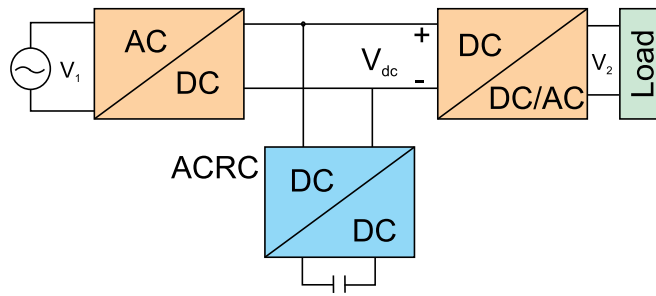


Figure 2.11 : ACRC proposed in Mellincovsky *et al.* [2018]

An active capacitor reduction circuit (ACRC) is proposed in Mellincovsky *et al.* [2018], to reduce the voltage ripples in the dc bus. This facilitates the usage of a smaller value capacitor to absorb the SRCs. The filter consists of a bi-directional converter controlled by a dual loop voltage and current control. The proposed ACRC is shown in Figure 2.11. A buck based charger is proposed in Nguyen and Lee [2018], to provide the charging and filtering capability for electric vehicle capability. This helps in reducing the size of the accessories of EV. Another buck converter based active power circuitary is proposed in Kong *et al.* [2018]. The filter is used for the modular multilevel converters (MMCs). The control configuration reduces the SRCs, the sub-module capacitor voltage is regulated with a smaller capacitor size.

It is applicable for high and medium voltage level MMCs. A doubly grounded inverter topology is proposed in Xia *et al.* [2017] to eliminate the common mode leakage currents and second order oscillations in voltages and source currents.

The proposed topology is applicable for the transformer-less PV applications. The configuration eliminates the capacitance coupled with the common ground currents of the inverter. The proposed methodology can be categorized as a active power decoupling scheme. The configuration is shown in Figure 2.12. The new circuit configuration is proposed in Ohnuma and Itoh [2014], which is capable of power factor correction and, power decoupling. The proposed control is applied to achieve the dc sode THD to be as low as 1.5% and ripples of about 6.3%.

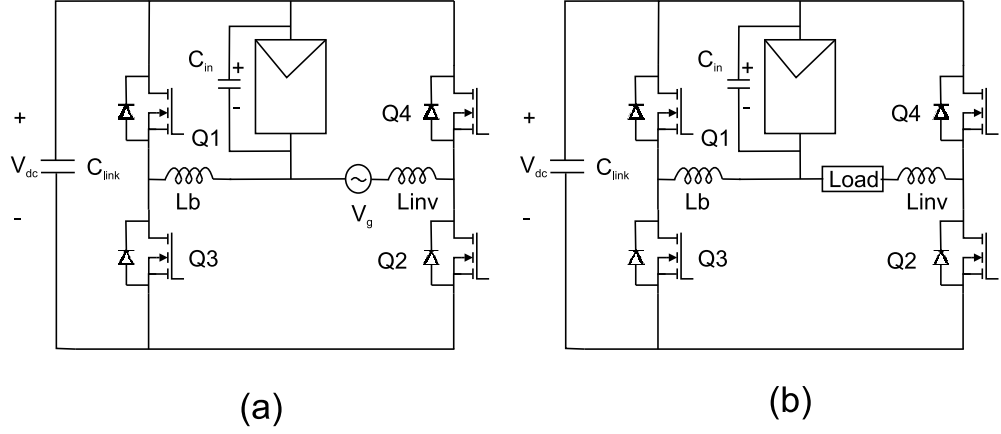


Figure 2.12 : Doubly ground inverter topology proposed in Xia *et al.* [2017]

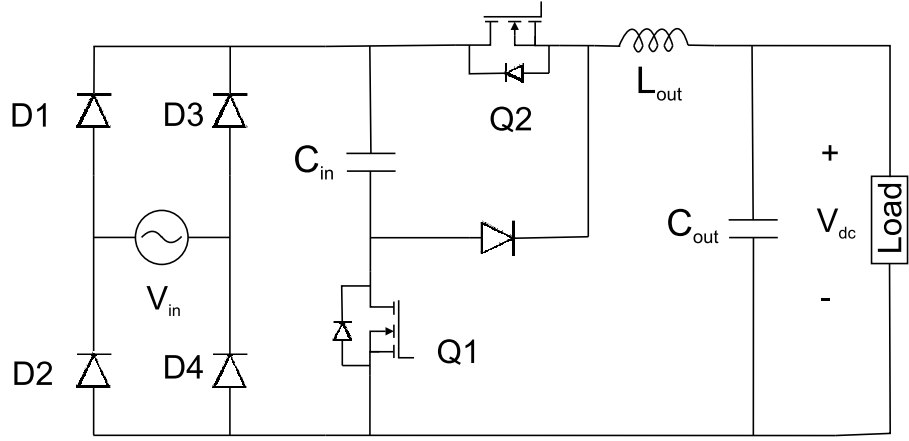


Figure 2.13 : Configuration proposed in Ohnuma and Itoh [2014]

The power factor correction of 99% was achieved with an efficiency of 96%. The control was implemented for a 750W system. The proposed configuration is shown in Figure 2.13. An active power decoupling scheme using dual buck converter and model predictive control is used in Xiao *et al.* [2018] to regulate the second order oscillations. The dual buck converters are controlled to operate at individual cycles. The configuration consists of the split capacitors. The proposed ripple regulation configuration is simple and reliable compared to traditional methodologies. In Zhu *et al.* [2016], an extra pair of switches are connected at the output of the single phase inverter terminals to confine the ripples to flow through the output capacitors. The proposed configuration provides sinusoidal power with ripple free dc at the inverter input terminals.

The control methodology is defined as the ripple confinement control. The configuration is shown in Figure 2.14. A similar configuration is proposed in Serban [2015]. The proposed configuration consists of additional active switch based on H bridge configuration. It requires two capacitors connected at the midpoint and the one end of the inverter legs. The proposed configuration is shown in Figure 2.15. To mitigate the second order oscillations in transformer-less grid connected micro-inverters, a doubly grounded buck-boost (Cuk) topology is proposed in Jamatia *et al.* [2018]. The control incorporated uses a large swing in the capacitor voltage of the

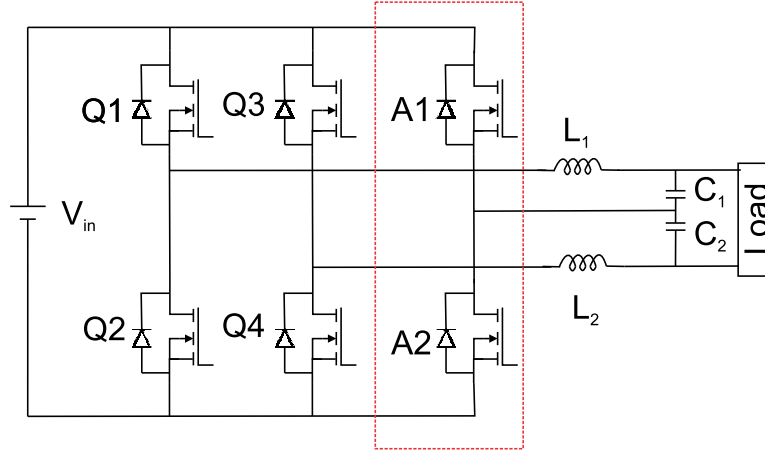


Figure 2.14 : SRC control configuration proposed in Zhu *et al.* [2016]

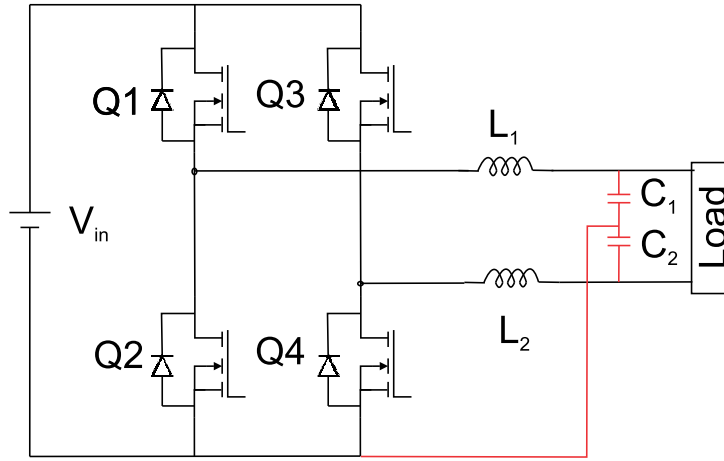


Figure 2.15 : Configuration proposed in Serban [2015]

terminal capacitor. It facilitates the usage of film capacitors instead of the less reliable electrolytic capacitors.

In Lyu *et al.* [2017], a combinational power decoupling method (CPD) is proposed to reduce the bus capacitance required to minimize voltage oscillations and improve the power density for a dc-ac power conversions. The configuration can be connected in parallel or series to the conversion stages. The analysis of decoupling for second order and instantaneous enitites is presented. A PFC with sinusoidal current output is presented in Ohnuma *et al.* [2015]. The active power decoupling is used to achieve a low voltage ripple of 8.8% and THD of 4.2%. The power factor of 99% and efficiency of 94.9% is achieved. The topology is shown in Figure 2.16. A bidirectional single phase matrix converter with centre tapped transformer is used for ripple regulation in Takaoka *et al.* [2018]. The matrix converter uses a pulse density modulation so as to achieve zero voltage switching. This will help in improving the efficiency of conversion. The switched of the full bridge inverter can also be switches in ZVS partially. The ripple reduction of 80% was achieved in charging mode and 76% was achieved at discharging mode. The control has been implemented for battery charging applications. The ac side THD is regulated to be less than 3%.

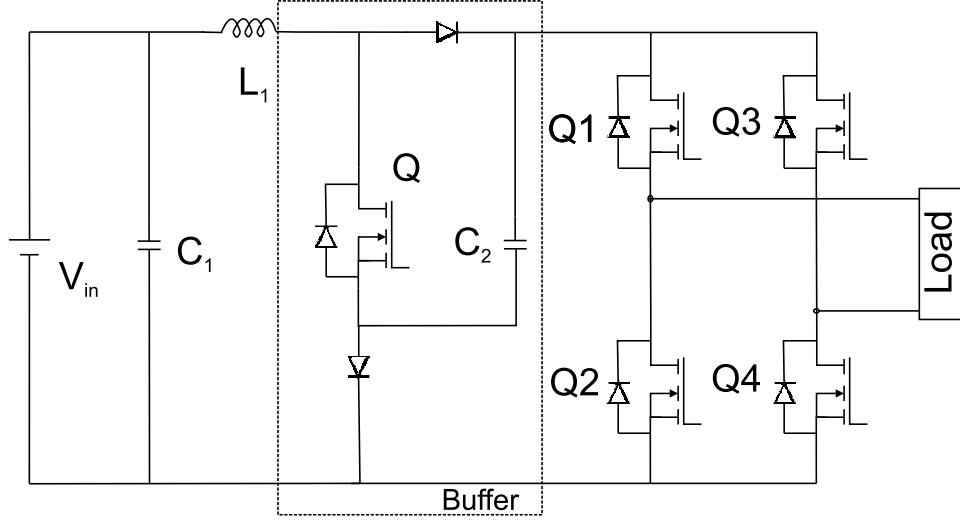


Figure 2.16 : Configuration proposed in Ohnuma *et al.* [2015]

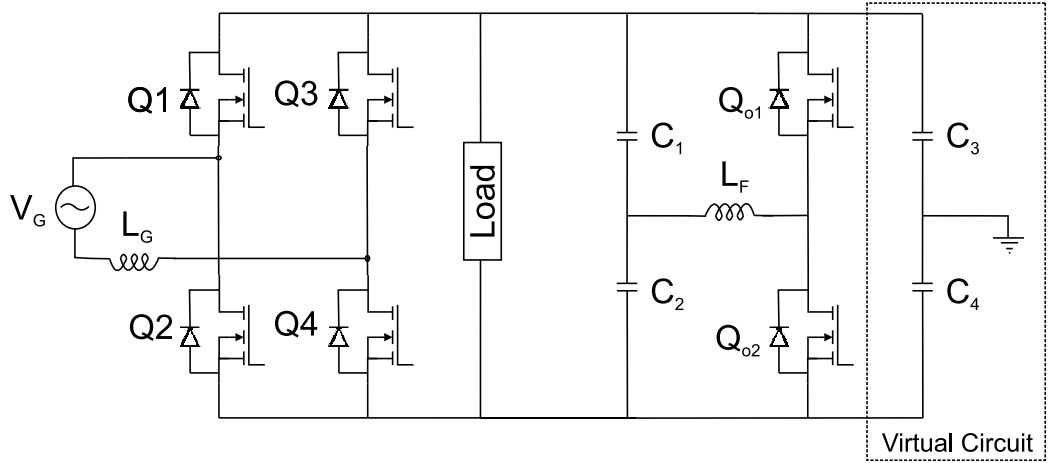


Figure 2.17 : Symmetrical half bridge configuration proposed in Tang *et al.* [2015]

In Cai *et al.* [2015], a SRC mitigation circuitry of four switch three port dc-dc-ac converter is proposed with applications to DC Microgrids. The topology consist of three interfaces of ports that can be connected to capacitor, dc or ac ports. In comparison with the H bridge inverter, the proposed control do not require any extra switches or devices. The control algorithm has also been presented. An active control circuit based on the symmetrical half bridge is proposed in Tang *et al.* [2015]. The small signal analysis of the proposed configuration is presented. In terms of control, one of the voltage control loop is designed to operate in stationary frame and the other loop operates in synchronous frame. The bandwidth is regulated to achieve acceptable voltage fluctuations during the load variations.

The proposed configuration is shown in Figure 2.17. Similarly, a half bridge configuration with two capacitors in series is used instaad of a single bulky capacitor to mitigate the second order ripples in Yao *et al.* [2017]. A slight mismatched between the dc component and oscillations in power can be mitigated. The ripple is regulated as per IEEE 1547 standards. The proposed

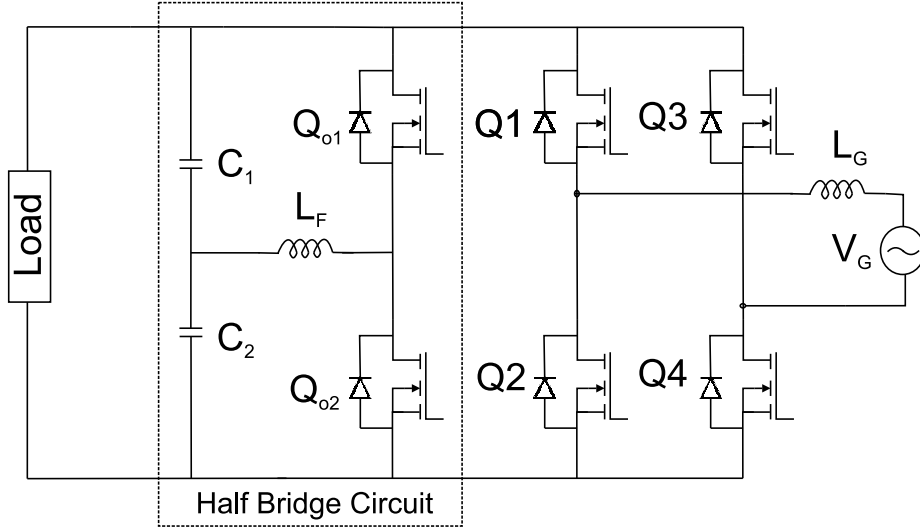


Figure 2.18 : Half bridge split capacitor proposed in Yao *et al.* [2017]

configuration is shown in Figure 2.18.

2.3 CONTROL BASED SRC MITIGATION METHODOLOGIES

In literature, different control based methodologies have been proposed to reduce the second order ripple content. In Shi *et al.* [2016], a load current feed-forward methodology has been proposed for SRC control in a two stage converter. The proposed control regulates the dc bus voltage to swing at twice the ac supply frequency. This forces the dc bus capacitor to supply the ripple power demanded during dc-ac conversions. The control is designed to have minimal impact on the stability and the dynamics of the system. The control loop implemented is shown in Figure 2.19. In the figure, G_v is the voltage controller, G_d is the delay in the sample and hold circuit of the controller, and V_{in} is the input supply voltage. The load current disturbance is fed to the voltage control loop with the objective of deriving the control law which cancels the SRCs. A band pass filter is incorporated to filter out the load disturbance at some desired frequency. The ripple current is reduced from 27% to about 1.8% for a 2.5kW load system. The proposed control law can further be implemented for various other forms of isolated and non-isolated family of converters.

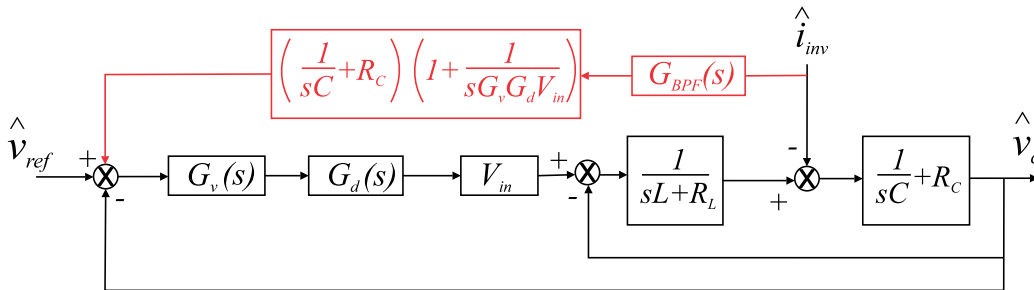


Figure 2.19 : Load current feed-forward methodology

In Yang *et al.* [2014] an feed-forward control scheme is proposed for ripple control in the LED driver circuit. The driver circuit consists of a power factor correction circuit and a bi-directional converter (BDC). The BDC is responsible for absorption of the ripple components.

S.no	Type	Topology/Method	Reference	Connection	Application
1)	Rectifier	Current Source Inverter	Ohnuma <i>et al.</i> [2015]; Zhang and Jin [2014]	Parallel	PV sources
2)	Rectifier	q-Z source inverter	Ge <i>et al.</i> [2016a]	Parallel	PV
3)	Inverter	Push-pull	Krein <i>et al.</i> [2012]	Parallel	Fuel Cell
4)	Inverter	Flyback	Shimizu <i>et al.</i> [2006]	Parallel	Fuel Cell
5)	Inverter	Flyback	Hirao <i>et al.</i> [2005]	Parallel	PV sources
6)	Inverter	Flyback	Tan <i>et al.</i> [2007]	Series	PV, Fuel Cell
7)	Inverter	Dual-Boost	Shimizu <i>et al.</i> [2000]	Series	PV sources
8)	Inverter	Stacked Switched Capacitor	Afridi <i>et al.</i> [2014]	Parallel	Capacitor Reduction
9)	Rectification	Differential Rectifier	Li <i>et al.</i> [2015]	Parallel	Power factor Correction
10)	Inverter	Switched Capacitor	Zhang <i>et al.</i> [2013]	Series	DC Microgrid
11)	Bidirectional converter	ACRC	Mellincovsky <i>et al.</i> [2018]	Parallel	AC-DC converters
12)	Rectifier	Buck converter	Kong <i>et al.</i> [2018]	Parallel	Modular converters
13)	Rectifier	Buck Converter	Nguyen and Lee [2018]	Series	Electric vehicle charging
14)	Rectifier	PFC	Ohnuma and Itoh [2014]	Series	Improve power factor
15)	Inverter	Cuk derived	Jamatia <i>et al.</i> [2018]	Series	Grid connected microinverters
16)	Inverter	Full bridge-Matrix converter	Takaoka <i>et al.</i> [2018]	Parallel	Battery charge-discharge
17)	Inverter	Combinational power decoupling	Lyu <i>et al.</i> [2017]	Parallel	DC-AC conversion
18)	Inverter	No separate circuit	Cai <i>et al.</i> [2015]	Parallel	DC Microgrid
19)	Rectifier	Symmetric Half bridge	Tang <i>et al.</i> [2015]	Parallel	AC-DC conversions
20)	Rectifier	Half bridge split cap.	Yao <i>et al.</i> [2017]	Parallel	AC-DC conversions

Table 2.1 : Summary of active control methodologies

The control loop implemented is shown in Figure 2.20. The reference current is phase shifted by negative ninety degrees and multiplied with k_1 , which is a positive constant and is used to regulate the reference value within the saw-tooth signal range. The maximum range of saw-tooth signal is V_m . The proposed control facilitates the use of non-electrolytic capacitors for ac-dc led drivers. A

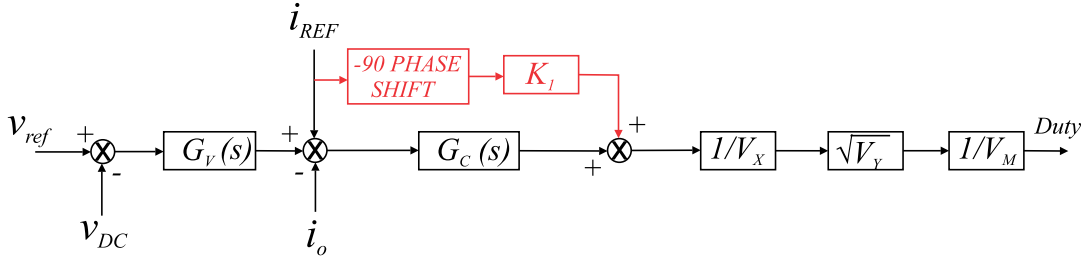


Figure 2.20 : An feed-forward control scheme Yang *et al.* [2014]

resonant controller based dual loop control is proposed in ZhengWei *et al.* [2012]. The resonant controller G_R is used to filter out the component of signal with some desired frequency. Hence, if the ripple occurs at twice the ac supply frequency, the G_R is tuned at that frequency. The output of voltage control G_v is fed to G_R . This generates the current reference, which is fed to the current controller G_i . The constant T_{PWM} is the gain of PWM generator. The T_{dv} is control to output voltage transfer function and T_{di} is control to inductor current transfer function. The ripple is reduced from 25% to 5% for a 1500W load.

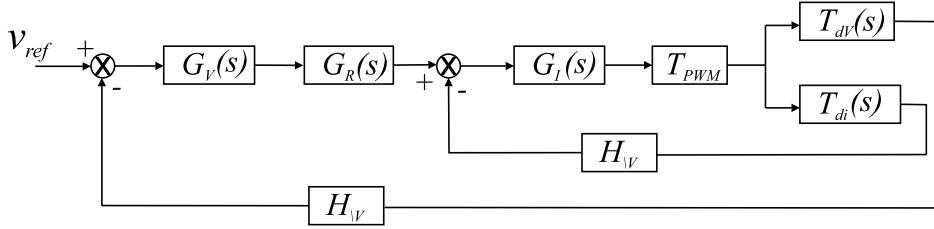


Figure 2.21 : Resonant controller based dual loop control ZhengWei *et al.* [2012]

A virtual resistance based control is proposed in Zhu *et al.* [2015]. In this control methodology, either the current from inductor or diode is fed back to the control loop. A constant parameter R_v regulates the impedance in the inductor branch. However, this control has effect on all frequencies instead of just $2f_{ac}$. This results in degradation of dynamics of the converter.

In Zhang *et al.* [2014] authors have proposed a band-pass filter incorporated inductor current feed back scheme (BPFICF) to control the SRCs. In this scheme, the impedance of inductor branch is increased virtually at twice the ac supply frequency ($2f_{ac}$). The current can be fed back to the control loop either from the inductor branch or from the capacitor branch, as shown in Figure 2.23. The magnitude of impedance to be added is R_v . The transfer function for a bandpass filter is

$$G_{bpf} = \frac{s/Qw_f}{(s/w_f)^2 + s/Q + 1} \quad (2.1)$$

where, Q is the quality factor and $w_f = 2\pi(2f_{ac})$. The peak of the BPF can be varied by changing the R_v and the frequency at which it occurs can be manipulated by changing w_f . Further, for diode current feedback $K = 1 - \frac{V_{in}}{V_{bus}}$ and for inductor current feedback $K = 1$. The dynamics are better than the VRS scheme.

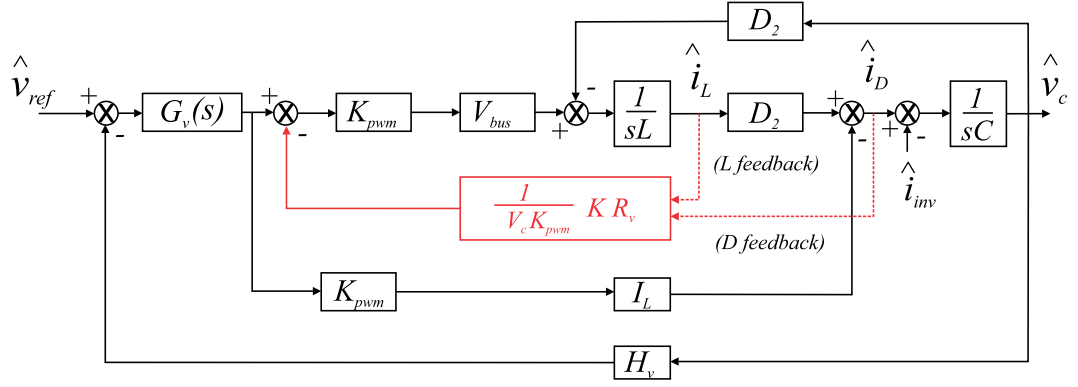


Figure 2.22 : Virtual resistance scheme

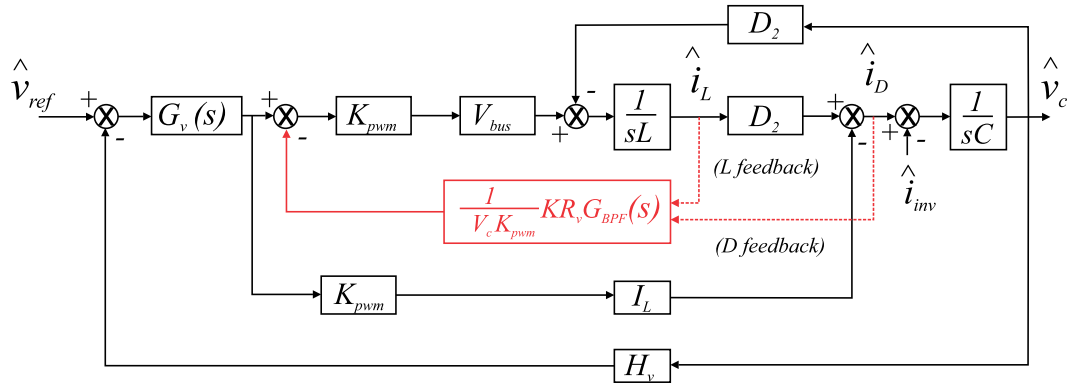


Figure 2.23 : Band pass filter inductor current feedback scheme

To further improve the dynamics a parallel impedance is also added in combination with a series virtual impedance. The scheme is define as Notch-Filter-Inserted Load-Current Feedforward Scheme (NF-LCFFS) Zhang *et al.* [2018a]. For this, the current through the capacitor is fed to the control loop through a notch filter. The notch filter is tuned to have notch at $2f_{ac}$.

The transfer function for a notch filter G_n is,

$$G_n = \frac{(s/w_f)^2 + 1}{(s/w_f)^2 + (s/Qw_f) + 1} \quad (2.2)$$

where, Q is the quality factor and $w_f = 2\pi(2f_{ac})$ as for the G_{bpf} case. The inner band pass filter loop remains same as for the previous case. However, the dynamics obtained is better than the previous control methodology. The control loops are shown in Figure 2.24. The values of $K_1=(1-D)$ and $K_2=1$ for diode current feedback and $K_1=1$ and $K_2=1/D$ for inductor current feedback, where $D=1-V_{in}/V_{bus}$. The bandpass filter can further be removed to get a configuration as shown in Figure 2.25. The inductor current or diode current is fed by a block which causes the resistive impedance to increase. The value R_v is the magnitude of the impedance. This control methodology is analogous to the VRS scheme described earlier. This control improved dynamics compared to the VRS scheme however, it is not as good as the NF-LCFFS scheme. The inverter current can also fed to the control for a two stage dc-ac conversion applications. The scheme is called Notch-Filter Cascading Voltage Regulator Plus Load-Current-Feedforward Scheme (NF-VR+LCFFS). The series impedance control is based on virtual resistance scheme and the parallel impedance is the

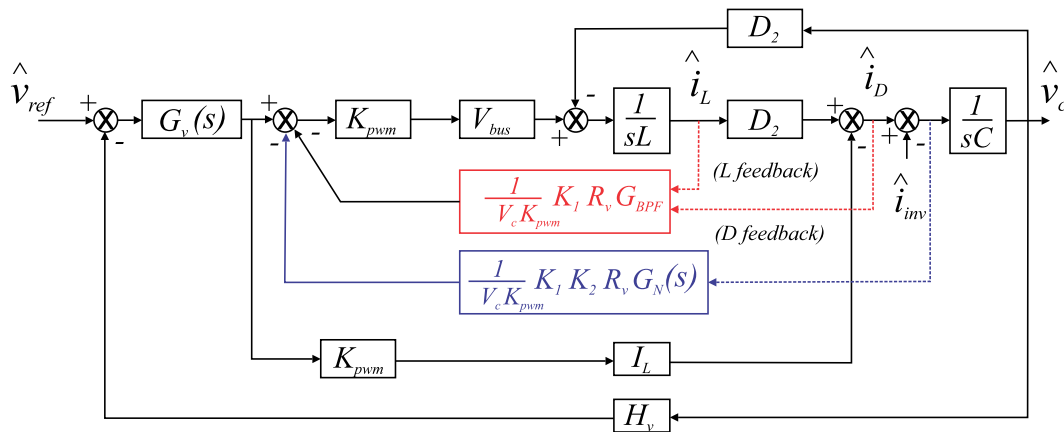


Figure 2.24 : BPFICF with parallel impedance loop

notch filter fed load current scheme. The proposed control methodology is shown in Figure 2.26. The term $D_2=(1-D)$, where D is the duty ratio of the converter.

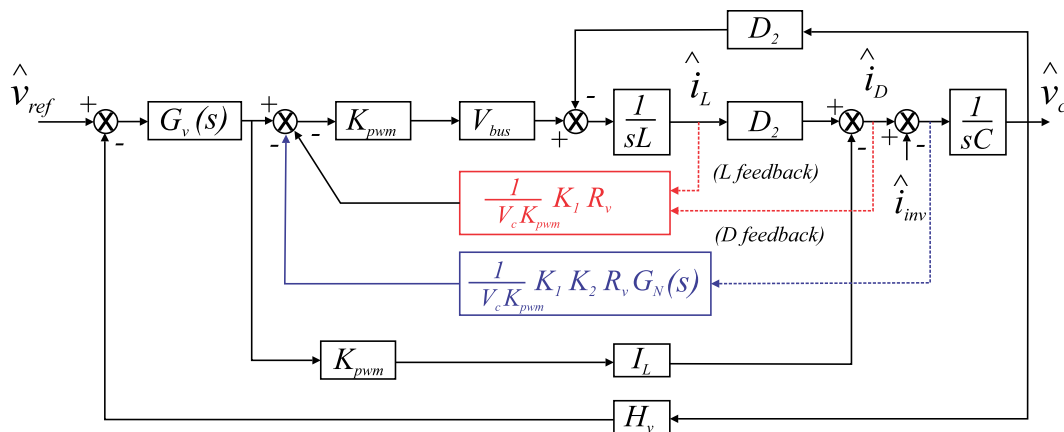


Figure 2.25 : Notch-Filter-Inserted Load-Current Feedforward Scheme (NF-LCFFS)

2.4 SINGLE STAGE INVERTERS WITH NANOGRID APPLICATIONS

The single stage inverters are capable of boosting the input dc voltage and dc-ac conversion in a single stage. It does not require any separate intermediate boost converter to step up the input dc voltage. The boosting is achieved by shoot through mechanism. During shoot through the inverter terminals are shorted. No power is transferred from the source to the load during shoot through. The SSIs consist of a impedance network of inductors and capacitors. The Z-source inverters (ZSI) were proposed in Fang Zheng Peng [2003a]; Peng *et al.* [2003]. The ZSI consists of two inductors and two capacitors connected in cross fashion. The ZSIs have found applications in PV applications, electric vehicles and nanogrids. The ZSIs have poor input current profile and there is voltage stress in the capacitors. As a result a quasi-Z source inverter is proposed in Li *et al.* [2009]; Liu *et al.* [2014]. The qZSI are used for low and moderate power applications. The different applications of qZSI have been specified in Guo *et al.* [2013]; Nguyen *et al.* [2012]; Sun *et al.* [2014]. Further, to reduce the voltage and current oscillations due to dc-ac conversions different solutions have been proposed. An ac equivalent model of a qZSI is derived in Sun *et al.* [2014]; Zhou *et al.* [2013] to analyze the low frequency ripple in the voltage and source currents. The designing of the

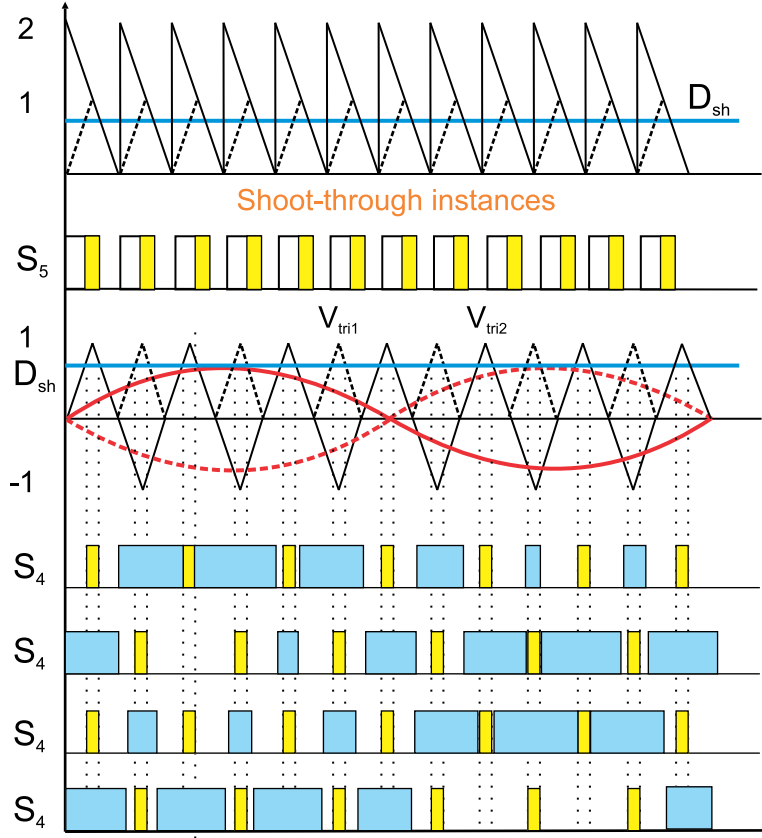
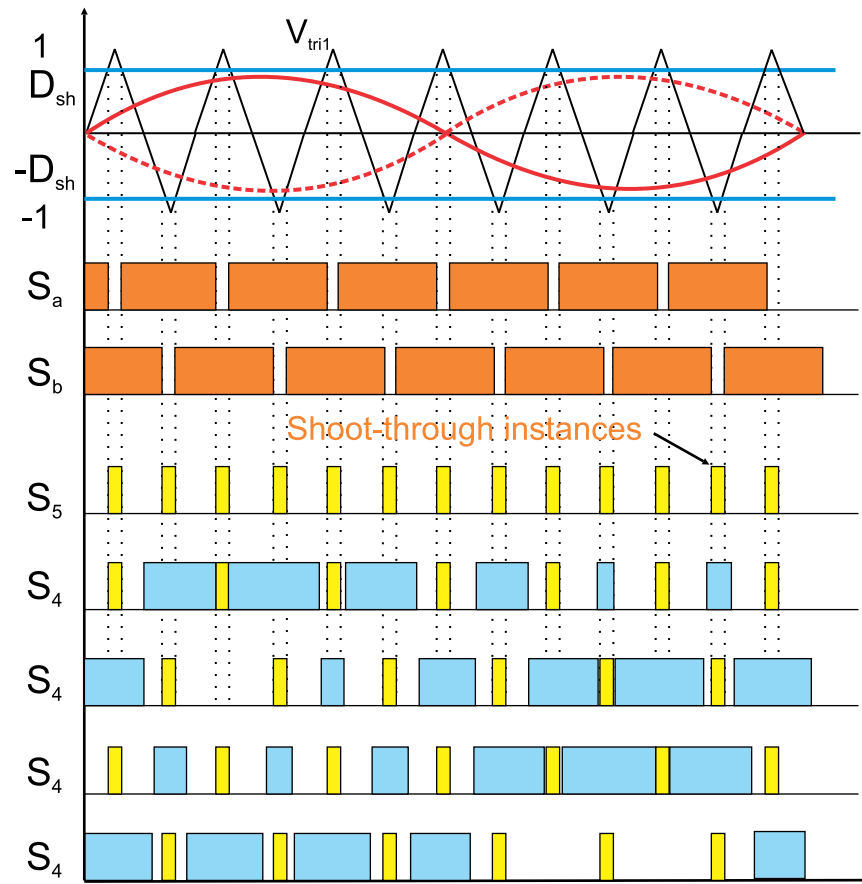


Figure 2.28 : PWM strategy proposed in Nguyen *et al.* [2019]

the required voltage gain Nguyen *et al.* [2015c]. However, in fuel cell and PV applications a high voltage gain is needed. In order to reduce the size, weight and cost of the SSIs, the Switched Boost Inverters (SBIs) have been proposed in Adda *et al.* [2013]; Nag and Mishra [2014]. The SBIs have lesser number of components compared to the qZSIs however, an extra active switch is used in the circuitry. The SBIs have the disadvantage of discontinuous source currents due to a diode in the input end. The voltage boost of SBI is lesser than the qZSIs. To overcome these drawbacks, various other topologies of quasi-SBIs have been proposed in literature Nguyen *et al.* [2015a]. The qSBIs are either of embedded type or the dc link type. An embedded type qSBI consist of an inductor at the input terminals. An Inverse Watkins-Johnson Topology-Based Inverter topology is proposed for dc and ac power applications in Mishra *et al.* [2012].

2.4.1 Control of SSIs

The SSIs also suffer from the second order oscillation in the source current and the capacitor voltages like in the traditional VSIs and CSIs. These SRCs have detrimental effects on the sources and electrolytic capacitors as discussed earlier. In literature different control based and impedance shaping methodologies have been used to mitigate the SRC propagation to the source. An improved pulse width strategy is proposed in Zhang *et al.* [2018c] to achieve maximum voltage boost and to improve the efficiency. In this methodology, the shoot through duty of one leg is regulated to control the average value of the dc link capacitor. This leads to a reduction in switching frequency of inverter switches by one-third. This reduces the switching losses, and hence, the efficiency is improved. A simple boost modified space vector modulation is proposed in Abdelhakim *et al.* [2017], to reduce the number of switch commutations during a switching cycle in a three-phase ZSI. The proposed methodology simplifies gate signal generation process



by usage of only three reference signals. A hybrid pulse width modulation strategy is presented in Liu *et al.* [2016]. The proposed PWM methodology combines the pulse width modulation and pulse amplitude modulation (PAM). The PWM is designed to operate when the output ac voltage is less than the input dc voltage, else the PAM operates. A constant boost control is proposed in Miaosen Shen *et al.* [2006] to reduce the voltage and current ripples and improve the voltage gain. A PWM scheme is proposed in Nguyen *et al.* [2019], to improve the modulation index for the SBIs. The proposed PWM methodology leads to lesser second order ripples in capacitor voltages, and inductor currents, reduction of stress on the switches, with increased efficiency and modulation index value. The conventional PWM generation methodology is shown in Figure 2.27. The shoot through duty D_{sh} is compared with a repeating sequence. The shoot through signal is generated at twice the frequency of the repeating sequences used for inverter pulses. The sinusoidal signal is the modulating signal, with some modulation index less than unity. The shoot through instances are shown in yellow while the sine PWM is shown in blue in the figure. To improve the modulation index range, another PWM generation strategy is proposed in Nguyen *et al.* [2019]. In this, a repeating sequence has maximum value of two and other has maximum value of unity. The shoot through duty is compared with these repeating sequences to generate the shoot through signals as shown in Figure 2.28. These instances are then added with the SPWM signal to obtain the voltage boosting. In Ravindranath *et al.* [2013], the shoot through is compared in the negative side and positive side of the repeating sequence. Using this, the signals S_a and S_b are generated. These signals are passed through a NAND gate to obtain the desired shoot through signal, as shown in Figure 2.29. To obtain ripple cancellation, the shoot through can be made to consist of some second order signal which is related with the second order component in the source current. This

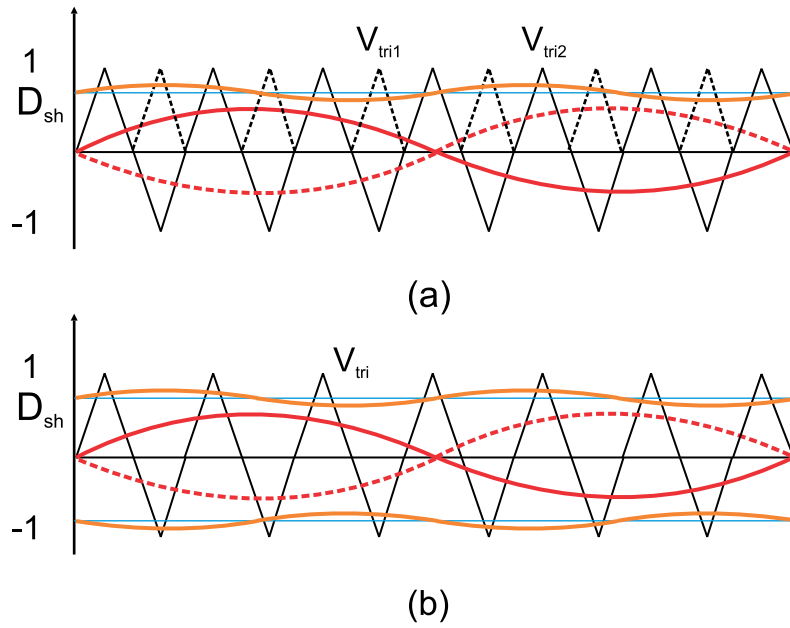


Figure 2.30 : PWM strategy proposed in Yu *et al.* [2011a]

methodology makes the dc bus capacitor to provide the oscillating power and mitigates the ripple in source currents. The shoot through duty on both ends can be made to oscillate with a 180° phase to generate the desired signal as proposed in Yu *et al.* [2011a]. The waveforms for PWM is shown in Figure 2.30.

2.5 CONTROL OF MICROGRIDS

Until now a control for SRC mitigation for SSIs has been presented. In this subsection, the control of DC Microgrids is presented. The control can be broadly classified as centralized, decentralized and distributed control. These methodologies are defines as under:

2.5.1 Centralized control

In centralized control, the voltage and current measurements are sent to a central nodes. The data from each node is processed and corresponding references are generated for individual nodes. The centralized control has the advantage of easier control and implementation Tsikalakis and Hatziaargyriou [2008]. However, it suffers from a single point failure, i.e. if the central control does not functions in the desired way, the microgrid may become unstable of failure may occur. Hence, it is applicable for a small scale microgrid system Kim *et al.* [2010]. A centralized control scheme is shown in Figure 2.31a.

2.5.2 Decentralized control

The decentralized control scheme does not requires communication among the interfaced nodes of the DC Microgrid. The desired global operating conditions are obtained by only local information of the node. A simple example of decentralized control is droop control. In this, the voltage reference of a node is reduced if it is more loaded. This helps in load distribution between the nodes. An example of decentralized control is shown in Figure 2.31b.

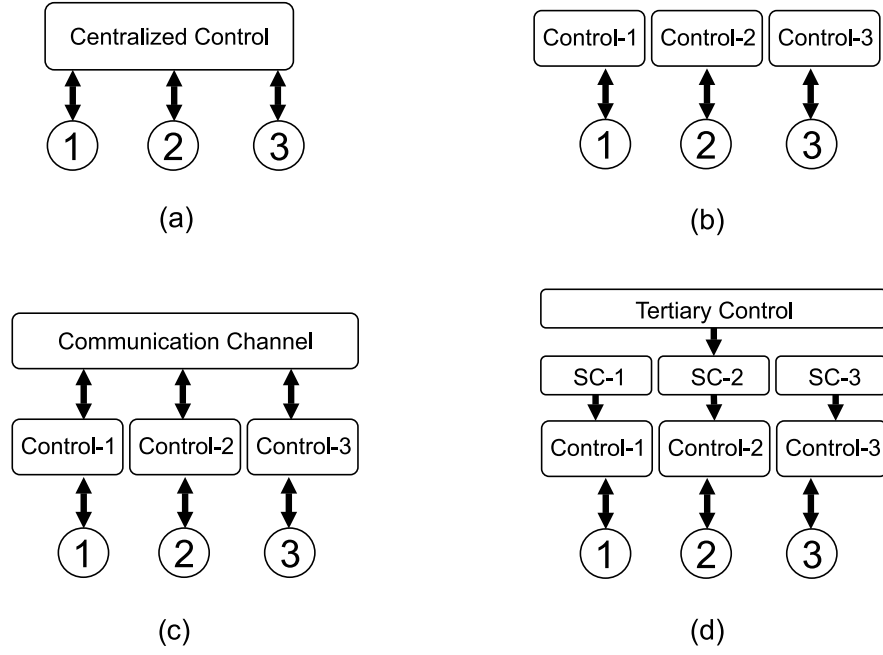


Figure 2.31 : Concept of centralized and decentralized control

2.5.3 Distributed control

To improve the reliability and performance of the microgrid different control schemes are used thereby integrating the management part with the decentralized control. Different communication technologies such as- WiFi, Zigbee etc Niyato *et al.* [2011] are used with distributed algorithms such as consensus based control, gossip algorithm etc Katiraei *et al.* [2008]; Lexuan Meng *et al.* [2014]; McArthur *et al.* [2007]; Nasirian *et al.* [2014]. The decentralized control with communication is shown in Figure 2.31c. However, maintaining the co-ordination between the controllers at different nodes still remains a challenge. An example of distributed control is shown in Figure 2.31d. An example of distributed control is the hierarchical control of microgrids. In hierarchical control consists of a primary control that operates at a node, a secondary control which receives the communication data and estimates the references for the primary control and finally the tertiary control which controls a cluster of microgrids. The load distribution in a large scale microgrid is done by the tertiary control. It generates the reference for the secondary control. The configuration of control is shown in Figure 2.32. The figure shows and overview of tasks performed by an individual controller.

Primary control

The primary control layer operates to regulate the local voltage and current as desired. It receives the reference from upper layers of the hierarchical control. In literature, different forms of primary control has been proposed. The droop control manages the voltage reference at a node depending on the loading condition of that node. Different control methodology has been proposed in literature. The traditional droop control are used to achieve load sharing without any need of data transfer between the nodes Dragičević *et al.* [2016a,b]. The droop control is easy to implement as only local values are needed. In Rajagopalan *et al.* [1996a], a master slave control is proposed to achieve load sharing. One of the nodes are considered to be master and other nodes follow the parameters of the master node. To improve fault tolerance and detection, a circular chain control configuration is proposed in Tsai-Fu Wu *et al.* [2000]. To improve the performance of the microgrid under heavy loading condition, various non-linear droop control methodologies

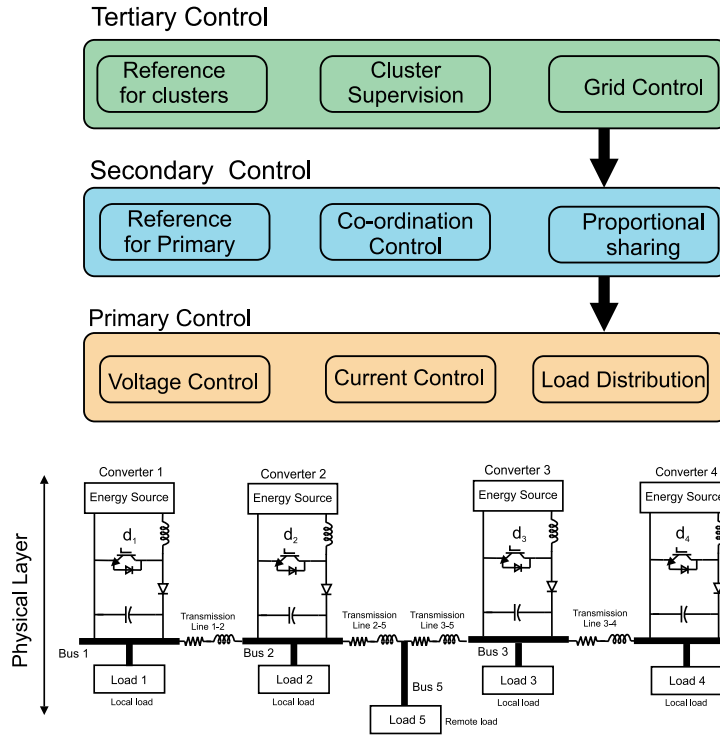


Figure 2.32 : Control hierarchy for microgrids

have also been proposed. An efficiency based virtual resistance is designed in Meng *et al.* [2015] for load sharing. A multi-agent system-based real-time load in an electric ship is proposed in Farasat *et al.* [2015]; Feng *et al.* [2012]. A similar non-linear droop is proposed in Feng *et al.* [2012]. The dc bus signaling based control for selection of mode of operation has been presented in Gu *et al.* [2014]; Sun *et al.* [2011]. The mode of operations are: grid-connected, islanding with battery discharging, islanding and grid-connected rectification.

Secondary control

The primary droop control results in a poor voltage regulation when the load is varied from no load to full load. The secondary control is responsible to generate adequate voltage reference shift to improve the voltage regulation. The secondary control is used to achieve proportional load sharing, synchronization of different nodes and a good voltage regulation Sun *et al.* [2011]. In Lu *et al.* [2014], a low bandwidth communication is used to facilitate the voltage and current data transfer between neighboring nodes. These values are compared with local values and adequate voltage and current reference shifts are generated to achieve proportional load sharing. A distributed team oriented load sharing based secondary control is proposed to achieve a good voltage regulation and minimization of circulating currents between the nodes in Moayedi *et al.* [2015]. The current sharing among nodes is further improved in Dam and Lee [2018]. The proposed control uses slope-adjusting approaches to adjust the droop coefficients depending on the commanded signal from the secondary control. The secondary control for AC Microgrids is presented in Shafiee *et al.* [2012]. It regulates the frequency deviations due to load variations. Distributed control for reactive power sharing and maintaining voltage stability is proposed in Schiffer *et al.* [2016]. A distributed averaging based secondary control for islanded microgrid is formulated in Simpson-Porco *et al.* [2015]. A linear matrix inequality based control is proposed in Tucci *et al.* [2018] to facilitate smooth plug and play control in the microgrids. The proposed control operated in all to all communication mode or minimal communication modes with the condition

that the network should have atleast a spanning tree as shown in Figure 2.33. The node in red shows that it may be disconnected from the microgrid so as to operated in islanded mode. Hence, plug and play feature must also be addressed.

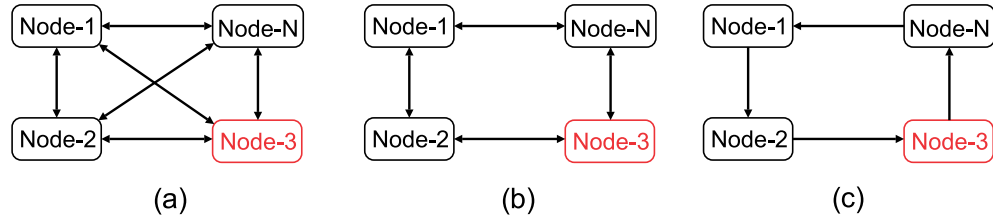


Figure 2.33 : Communication: (a) All to All (b) Neighboring (c) Sparse

Tertiary Control

The function of the tertiary control is to manage power flow between the cluster of microgrids and to minimize the operating cost. The tertiary control is necessary to improve the reliability of the microgrid. It also ensures proper co-ordination between the energy storage and generation units Geng-yin *et al.* [2004]; Xiao-Ping Zhang [2004]. In terms of power flow controls, the Newton Raphson method and its extended versions are used for computations in dc-ac system. Similar power calculations can be performed for DC Microgrid applications with the availability of terminal voltage measurements as in Haileselassie and Uhlen [2012]; Li *et al.* [2014]. Further, the economic load dispatch is focused in research works of Palma-Behnke *et al.* [2013]; Vaccaro *et al.* [2011]. Various parallel computation algorithms have also been proposed to optimize the performance of the microgrid system Mondal *et al.* [2017]; Shi *et al.* [2015]. The tertiary control is shown in Figure 2.34. The connection with dotted lines show that the node can be removed or added to the network.

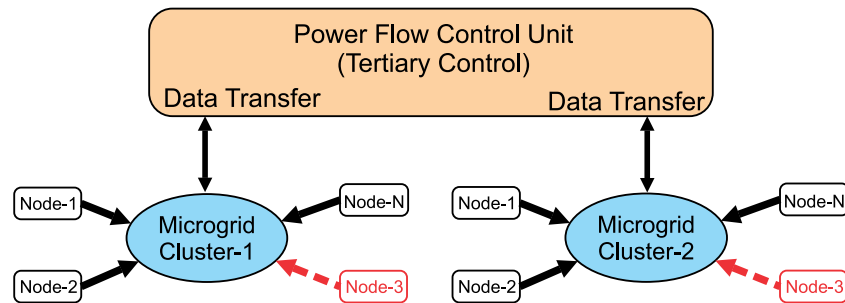


Figure 2.34 : Tertiary Control

Ripple Management in microgrids

A dc-ac conversion leads to the second order oscillations in the dc bus voltage and source currents. The dc bus voltage is controlled to be within the desired voltage regulation limits. As a result of this, the SRCs are visible in the source currents. In a microgrid environment, in presence of primary and secondary control, the SRC is shared as per the proportional sharing of the load among the interfaced nodes. However, the source with a higher power rating may not have a high SRC bearing capability. Also, the ripple filter can be installed at a node, and all the ripples must be propagated to this node. In literature, some of the ripple sharing methodologies have been proposed. In Hamzeh *et al.* [2015], the authors have proposed an oscillatory and dc load is shared as per the rating of the converter. The current control consists of a dc and oscillatory current control block and a multi loop voltage control is employed to regulate the dc bus voltage. A SRC suppression methodology is proposed in Liu *et al.* [2020a]. The proposed control uses a notch filter

and resonance regulators in the control loop. The bandwidth of the voltage control loop is below twice the ac supply frequency. This will lead to degradation of dynamics. Further, in Hamzeh *et al.* [2016], a power oscillations damping control is proposed to regulate the SRCs. The proposed control uses a dynamic droop to actively damp the oscillations due to dc-ac conversions. The small signal analysis and pole placement is used to design the virtual impedance control. The control has been verified for a hybrid system consisting of a fuel cell, a super capacitor and a photo-voltaic system.

2.6 SUMMARY AND OPEN ISSUES

In this chapter, different methodologies which have been proposed in literature to mitigate the SRCs in source currents, have been presented. The methodologies consist of the active and passive control methodologies. Increasing the passive components to reduce SRCs leads to an increase of the size, weight and cost of the system. Increase of capacitance will lead to decrease in reliability of the system as the low cost electrolytic capacitors has smaller life span compared to the non-electrolytic capacitors. The non-electrolytic capacitors are costlier than the electrolytic ones. To reduce the capacitance required, various active and passive filters have been proposed. The active filters consists of a series or parallel arrangement of filters. It consists of a capacitor or inductor as the ripple energy storage element. The interfacing filter circuit is either a buck, boost or buck-boost circuit. The filters usually absorb the second order ripple energy in one cycle and release the energy on the other cycle. The disadvantage of using the active filters is that it leads to an increase of component count, which in turn increases the cost of the system. DC Microgrids also suffer from SRCs when the ac load is connected to the dc bus. The SRCs propagate to the nodes depending on the line impedance. In absence of any control, the SRCs get divided such that the node with lesser impedance gets more share of SRCs. If a droop control is implemented to achieve load sharing, then also, the SRCs gets divided as per the droop constant. However, the sources which are interfaced to the dc bus have different capability of cater to the SRC demand. As discussed earlier, the temperature of the PV and lead acid batteries increase when SRCs is drawn from it for a long duration. On the other hand, the Li-ion batteries have a comparatively lesser rise in temperature. However, the Li-ion is more costly compared to the lead acid batteries. Hence, the source installed at a node may have higher rating but the impact of SRC on it can be severe. This leads to a reduction in the lifespan of sources. Similarly, the SRC filter circuit may not be installed at all the nodes of the microgrid. So, there is a need of diverting all the SRCs from load, to a specific node which has a ripple filter circuit installed. This leads to an improved energy density in the ripple filter circuit.

The virtual impedance methodologies which have been proposed in literature consists of the linear controllers whose performance may degrade in case of modeling or operating condition uncertainties. The virtual impedance designed is of constant magnitude, while the SRC content keeps on varying as per the ac loading condition. An increased impedance with less ac load leads to degradation of dynamics. Hence, the impedance shaping must be dynamic in nature. Further, the virtual control such as NFLCFFS and NF-VRLCFFS require feedback of the load current in the control loop. In the distributed control architecture like DC Microgrid, feeding the load current, which are spread through out the network, is not feasible. It will increase the complexity of the system as the data exchange will increase and a larger communication bandwidth has to be incorporated. Further, the control designed must not affect the dynamics of the system under all loading conditions, and must not be affected due to uncertainties present in the system.

In the next chapter, a SMC based SRC control for qZSI and eqSBI is presented. The proposed control maintains the desired output ac voltage while mitigating the SRCs within the desired limits. The choice of qZSI and eqSBI covers a range of other SSI topology. This makes the proposed control

S.no	Reference	Type	Explanation	Application
1)	Shi <i>et al.</i> [2016]	LCFF	Load current feed forward through a band pass filter	DC-AC conversion
2)	Yang <i>et al.</i> [2014]	Feed forward scheme	Inductor current feed forward with a phase shift to regulate a bi-directional converter used in PFCs	LED drivers, PFC
3)	ZhengWei <i>et al.</i> [2012]	Resonant based control	Resonant control is used after the voltage controller in dual loop control	Two stage dc-ac conversion
4)	Zhu <i>et al.</i> [2015]	Virtual resistance control	Increase the virtual resistance at all frequency to regulate SRCs. Degrades dynamics	Two stage dc-ac conversions
5)	Zhang <i>et al.</i> [2014]	BPFICF	Band pass filter incorporated inductor current feedback control	DC-DC-AC conversion
6)	Zhang <i>et al.</i> [2018b]	NFLCFFS	Notch-Filter load current feed forward scheme to improve the dynamics	DC-DC-AC
7)	Zhang <i>et al.</i> [2018b]	NF+VR+LCFFS	The capacitor current is fed through a notch filter and a virtual resistance loop is also incorporated	DC-DC-AC
8)	Ravindranath <i>et al.</i> [2013]	Shoot through PWM Logic	Generate the shoot through signals for SSIs with improved modulation	qSBI, SBI
9)	Nguyen <i>et al.</i> [2019]	Improved PWM	Novel repeating sequences to improve the modulation index	qSBI
10)	Yu <i>et al.</i> [2011a]	Phase difference shoot through	The shoot through signal consists of controlled ripple component with opposite phase	ZSI, qZSI

Table 2.2 : Summary of Control methodologies

applicable to other SSI topologies.