1

Introduction

The first commercial electric power system of Thomas Alva Edison, came into existence in 1882 at Pearl Street Station, New York, USA, to deliver electricity produced by central dc dynamos (110 V dc) over underground copper cable to nearby Wall Street offices of J.P. Morgan and New York Times. Due to low transmission voltage, Edison's dc power system had high losses, high cost of copper conductors due to high current, and small service area of maximum of 1-2 miles [Ford, 1997; Sulzberger, 2003b]. On the other hand, Westinghouse demonstrated first commercial ac power system of America in 1886, which could transmit electric power at a high voltage using transformers and had small losses and wider service area, vis a vis dc power system [Sulzberger, 2003a]. In 1888, began the so called "*War of the Currents*", i.e. ac vs. dc transmission or Westinghouse vs. Edison. In this war of currents, despite Edison's argument regarding safety of ac, ac power systems of Westinghouse prevailed [Sulzberger, 2003a]. The transformer which could step up or step down voltage, inherently efficient induction motor loads, and large three phase synchronous generators gave the core strength to ac power systems. After that in 1892, another ac power system to transmit power at 40 kV over 70 mile came into service, in California. And another in 1896, to deliver ac power from Niagra Fall to Buffalo, over a distance of 20 miles, to ac loads at 440 V and dc loads at 550 V using rotating converters [Sulzberger, 2003a; Ford, 1997; Sulzberger, 2003b].

Despite the widespread use of ac power produced by large centralized power stations, spanning entire 20^{th} century, dc power continued to show its presence at a few places e.g. Telecommunication power systems (48 V dc), control and protection application of power plants and substations (100-110 V), dc drives in railway traction and industrial drive systems etc. Then, developments in the power electronics technology infused a fresh life into dc power systems, by providing better control of dc power and making it possible to step up and step down the dc voltage. At this point, switching power converters begun to transform the existing dc power systems as they lead to reduced size, weight, cost, and improved reliability, efficiency, power quality and flexibility [Emadi and Ehsani, 2001]. Some of the examples of the switching power converter dominated system are more electric aircraft, MVDC ship board power system, electric vehicles and hybrid electric vehicles. Another application of dc technology came in the form of High Voltage Direct Current (HVDC) transmission, which connects two ac power systems through an asynchronous link.

With advancements in power electronics, control technology, and worldwide thrust to use more and more renewable energy, dc microgrids or dc distribution systems are treated as one of the preferred technologies to integrate renewable energy sources and storage units to feed local dc load. A dc microgrid may be connected to the existing power grid, and can operate in islanded or grid connected mode [Ito et al., 2004; Kakigano et al., 2010; Narasimharaju et al., 2010]. The schematic diagram of a typical dc microgrid is shown in Figure 1.1. With most of the renewable energy sources producing dc, rapidly increasing share of electronic loads operating on dc (data centers, laptops, mobile phones, home appliances and many more) and development of highly efficient loads (LED lighting and brushless dc drive based loads), the continued use of ac may not be an efficient choice [Chakraborty et al., 2015]. DC microgrids or dc distribution system offer higher efficiency (by avoiding multiple conversions), relatively less complexity of control (No reactive power and frequency control), and reduced size, weight and cost [Guerrero et al., 2014; Singh et al., 2014].

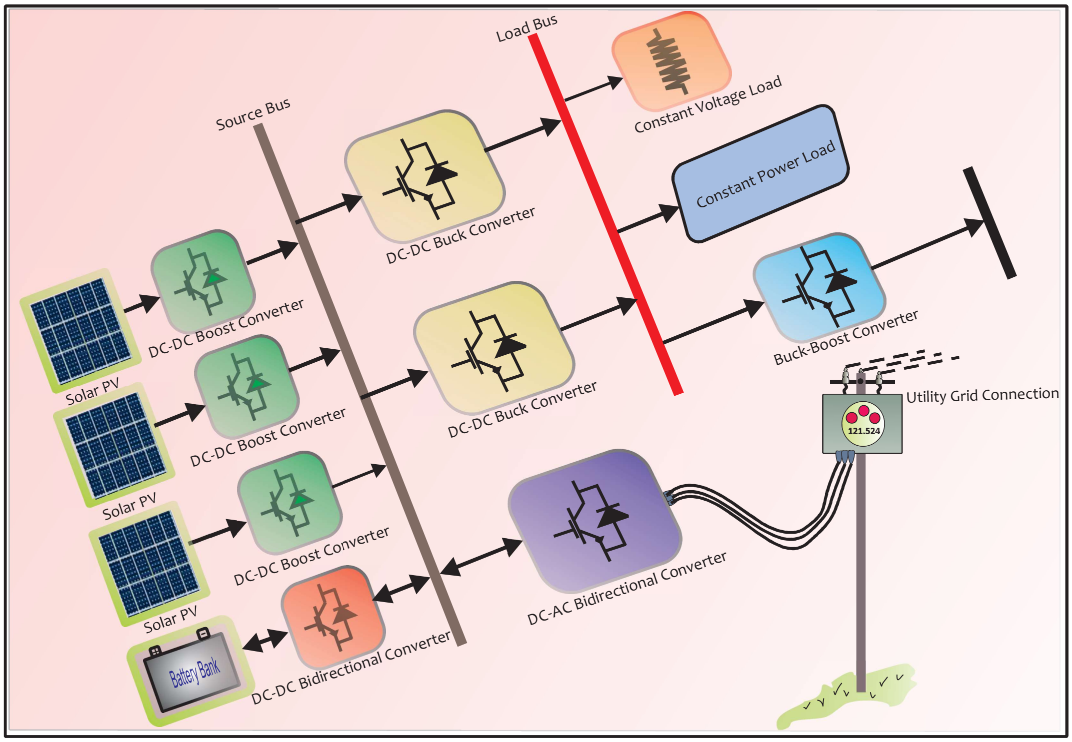


Figure 1.1 : Schematic diagram of a typical dc microgrid

Particularly, there has been a rising interest in the dc microgrids since the beginning of the first decade of 21^{st} century. This is also witnessed by the quantum of work contributed by the community, many pilot projects around the globe, development of different dc standards, and many special issues of learned journals dedicated to the topic [Diaz et al., 2015; Kwon et al., 2008; Marnay et al., 2015; Patterson, 2012; AalborgUniversity, 2015; Guerrero et al., 2014; Chakraborty et al., 2015; Romero Aguero, 2012]. Some of the developed dc standards are, $EMerge\ ALLIANCE^{TM}$'s 380 $V\ DC$ open standard for data/telcom center microgrid to facilitate use of dc and ac power, and 24 $V\ DC$ standard for indoor office and residential spaces to directly connect and use dc power from different renewable energy sources. Another 380 $V\ DC$ open standard is proposed by $REbus^{TM}$ pertaining to distribution of dc power in homes, offices etc. The choice of 380 $V\ DC$ performs better in terms of efficiency, space requirement and cost, as compared to single/three phase ac and 48 $V\ DC$ [AlLee and Tschudi, 2012].

The switching power converters with sophisticated control which had renewed interest in dc power systems, also brought in serious stability challenge [Shekel, 1976]. In a dc distribution system many loads such as speed controlled drives, electronic loads, and loads supplied by voltage regulator, are tightly regulated by their own converters, and this gives rise to CPL behaviour. These loads sink constant power from their source irrespective of their terminal voltage and introduces destabilizing effects into the dc distribution system. These destabilizing effects of CPLs may lead to significant oscillations in the dc bus voltage, reduced effective damping of the system, reduced stability margins, and voltage collapse [Belkhayat et al., 1995; Hodge et al., 2009; Emadi et al., 2006; Kwasinski and Onwuchekwa, 2011]. Several researchers have studied CPLs and their destabilizing effects in different vehicular dc distribution systems and renewable energy based dc microgrids [Emadi et al., 2006; Kwasinski and Onwuchekwa, 2011; Zhao et al., 2014a; Arcidiacono et al., 2009; LeSage et al., 2011]. Some passive and control based active compensation techniques have been reported by the community [Kwasinski and Onwuchekwa, 2011; Singer, 1990; Cespedes et al., 2011; Gao et al., 2014] and see the references therein. In the following section, sources of CPL, their behavior and effects are presented.

1.1 CONSTANT POWER LOADS: SOURCES, BEHAVIOUR AND EFFECTS

The renewable sources based DC Microgrids (DCMGs), transport power systems (surface, air, and water) and telecommunication power distribution systems usually consist of a large number of power converters in parallel, in cascade, stacking, load splitting, and source splitting configurations to ensure the desired design and operational objectives [Luo, 2005]. Such a power system is known as mutli-converter power electronic system or Distributed Power System (DPS) [Emadi and Ehsani, 2001; Luo, 2005]. Cascading of power electronic converter, a common feature of almost every converter dominated power system, helps in ensuring the desired point-of-load regulation. However, a tightly-regulated POLC behaves as a CPL and tend to destabilize its feeder system [Shekel, 1976; Kislovski, 1995; Olsson, 2002; Hodge et al., 2009]. A CPL exhibits a negative incremental impedance, i.e. the current drawn by it increases/decreases with a decrease/increase in its terminal voltage. The I-V characteristics of a typical ideal CPL is shown in Figure 1.2. However, the actual behavior of a tightly-regulated converter interfacing a load may not be that of an ideal CPL always, as it is largely influenced by the source and load side control bandwidth [Cupelli et al., 2015]. As shown in Figure 1.3, the common examples of CPL in a dc power system are tightly-regulated dc/dc converters supplying a load and dc/ac inverter drives. In Figures 1.3(a) and 1.3(c), the upstream/feeder system of the CPL is a controlled dc/dc converter, while in Figures 1.3(b) and 1.3(d) the feeder system is an input LC filter or uncontrolled rectifiers. The destabilizing behaviour of a CPL can be investigated using its small-signal model as follows [Rahimi and Emadi, 2009; Brombach et al., 2013].

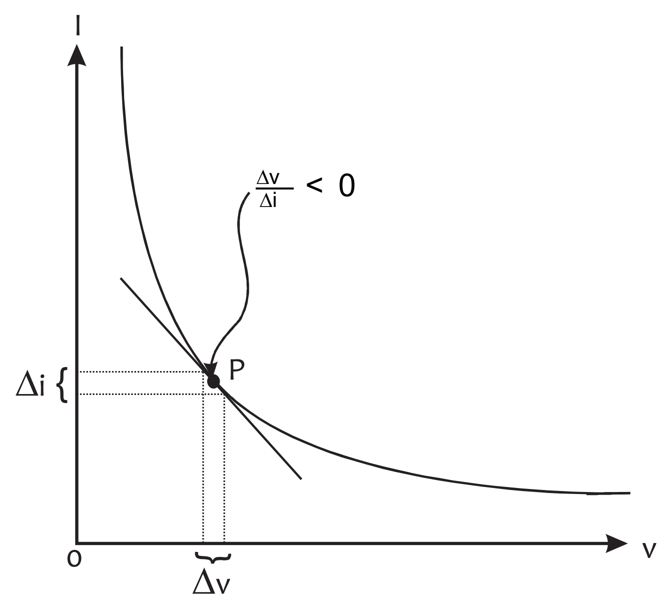


Figure 1.2 : I-V characteristics of a typical CPL

Mathematically, a CPL can be modeled as,

$$i_{CPL} = \frac{P}{v_{CPL}} \tag{1.1}$$

Where I_{CPL} is the current drawn by the CPL, v_{CPL} is the terminal voltage of the CPL, and P is the rated power of the CPL. The rate of change of current, for a given operating point

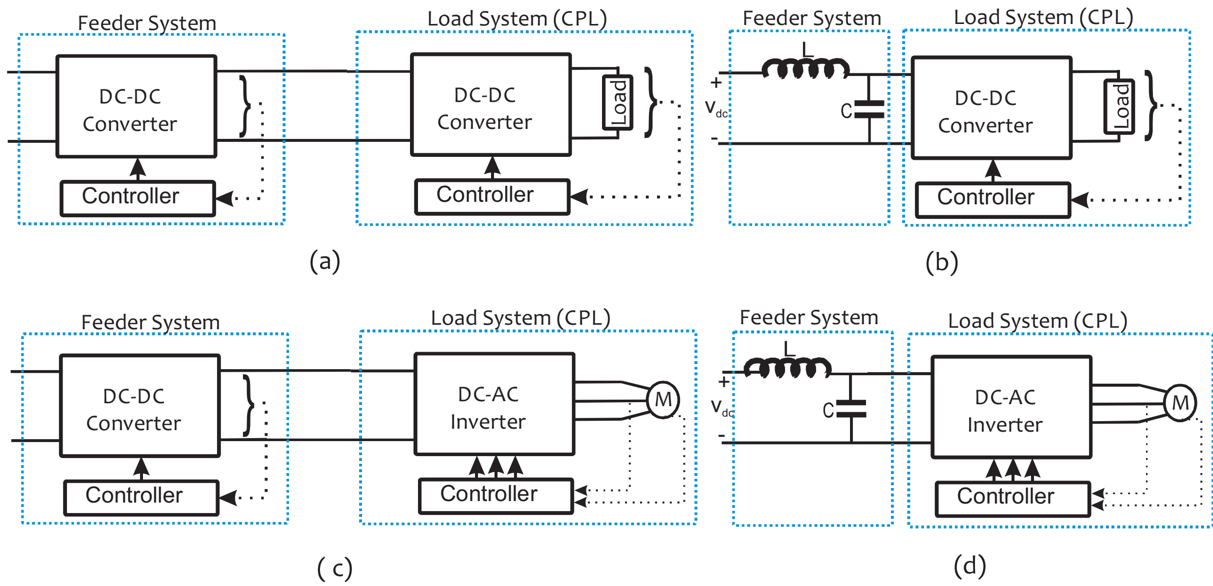


Figure 1.3 : CPL and feeder configurations; (a) A tightly regulated dc/dc voltage regulator with up-stream dc/dc converter, (b) A tightly regulated dc/dc voltage regulator with input LC filter/uncontrolled rectifier, (c) A tightly regulated inverter drive with upstream dc/dc converter, and (d) A tightly regulated inverter drive input LC filter/uncontrolled rectifier

($I = \frac{P}{V}$) using (1.1) is given by

$$\frac{\partial i_{CPL}}{\partial v_{CPL}} = -\frac{P}{V^2} \tag{1.2}$$

At the given operating point, the I-V curve of the CPL can be approximated by a straight line tangent to the curve given by

$$i_{CPL} = -\frac{P}{V^2}v + 2\frac{P}{V} \tag{1.3}$$

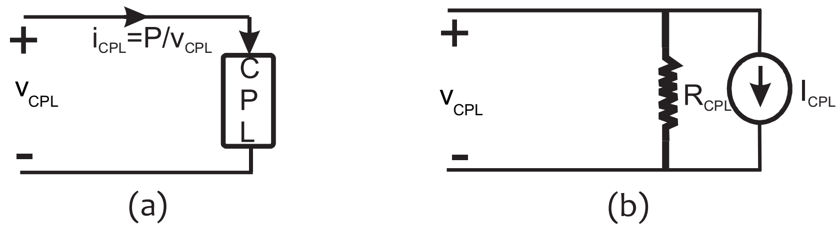
Figure 1.4(a) represents the large-signal model of a CPL given by (1.1). While (1.3), which gives a small-signal model of the CPL, can be represented as a negative resistance ($R_{CPL} = -\frac{P}{V^2}$) with a parallel constant current source ($I_{CPL} = 2\frac{P}{V}$) as shown in Figure 1.4(b). The constant current component in CPL's small-signal model does not affect the stability, however, negative resistance reduces the effective damping of the system and tends to destabilize the system. Such instabilities induced by CPLs are known as negative impedance/resistance instabilities. The major effects with the presence of a CPL in dc power system are as follows

1 Reduces the equivalent resistance of the system.
2 Causes high inrush current, as voltage build-up slowly from its initial value.
3 Reduces system damping and stability margins.
4 Causes limit cycle oscillation in the dc bus voltage and currents.
5 May lead to voltage collapse.

In the next section, an investigation of the small-signal stability of all basic dc/dc power converters in the presence of CPL will be presented.

1.2 SMALL-SIGNAL STABILITY OF BASIC DC/DC CONVERTERS WITH CPL

In this section, the small-signal stability of basic dc/dc converters with CPL is presented. The Figure 1.5 shows circuit diagrams of the four basic dc/dc converters loaded with CPL,



(a) (b)

Figure 1.4 : Large and small-signal models of a CPL

namely (a) dc/dc buck converter, (b) dc/dc boost converter, (c) dc/dc buck-boost converter, and (d) dc/dc bidirectional buck-boost converter.

1.2.1 Buck Converter

The nonlinear state-space averaged model of a dc/dc buck converter with CPL shown in Figure 1.5(a) and operating in Continuous Conduction Mode (CCM), is given by

$$L\frac{dx_1}{dt} = uE - x_2 \tag{1.4a}$$
$$C\frac{dx_2}{dt} = x_1 - \frac{P}{x_2} \tag{1.4b}$$
$$x_1 \geqslant 0, x_2 > \varepsilon$$

where x_1 is the moving average of the inductor current i_L, x_2 is the moving average of the capacitor voltage v_C, E is the input voltage, P is the rated power of the CPL, and $u \in \{0,1\}$ is the control input to the converter. L and C are the inductance and capacitance parameters of the converter. Replacing the input control signal with its fast average $u(t)$ (instantaneous duty cycle), (1.4) can be written as

$$L\frac{dx_1}{dt} = u(t)E - x_2 \tag{1.5a}$$
$$C\frac{dx_2}{dt} = x_1 - \frac{P}{x_2} \tag{1.5b}$$
$$x_1 \geqslant 0, x_2 > \varepsilon$$

For the system of (1.5) to be stable in a small-signal sense, its trajectory must asymptotically converge to the equilibrium point, when it is perturbed from the equilibrium point. In other words, the system is stable in the small signal sense if all eigenvalues of system matrix have negative real part. The equilibrium point $[x_1^*, x_2^*]$ of (1.5) is given by

$$[x_1^*, x_2^*] := \left[\frac{P}{u(t)E}, u(t)E\right] \tag{1.6}$$

The Jacobian matrix at the equilibrium point becomes

$$J = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & \frac{P}{Cu(t)^2E^2} \end{bmatrix} \tag{1.7}$$

The trace and determinant of the Jacobian matrix are $\tau = \frac{P}{Cu(t)^2E^2} > 0$ and $\Delta = \frac{1}{LC} > 0$. As the trace and determinant of the Jacobian matrix are positive, the equilibrium point of the system is unstable.

1.2.2 Boost Converter

The dynamic model of a dc/dc boost converter loaded with a CPL and operating in CCM as shown in Figure 1.5(b), is given by

$$L\frac{dx_1}{dt} = E - (1-u(t))x_2 \tag{1.8a}$$
$$C\frac{dx_2}{dt} = (1-u(t))x_1 - \frac{P}{x_2} \tag{1.8b}$$
$$x_1 \geqslant 0, x_2 > \varepsilon$$

The equilibrium point $[x_1^*, x_2^*]$ of (1.8) is given by

$$[x_1^*, x_2^*] := \left[\frac{P}{E}, \frac{E}{(1-u(t))}\right] \tag{1.9}$$

The Jacobian matrix at the equilibrium point becomes

$$J = \begin{bmatrix} 0 & -\frac{(1-u(t))}{L} \\ \frac{(1-u(t))}{C} & \frac{P(1-u(t))^2}{CE^2} \end{bmatrix} \tag{1.10}$$

The trace and determinant of the Jacobian matrix are $\tau = \frac{P(1-u(t))^2}{CE^2} > 0$ and $\Delta = \frac{(1-u(t))^2}{LC} > 0$. In this case also, the trace and determinant of the Jacobian matrix are positive, therefore the equilibrium point of the linearized system (1.8) is unstable.

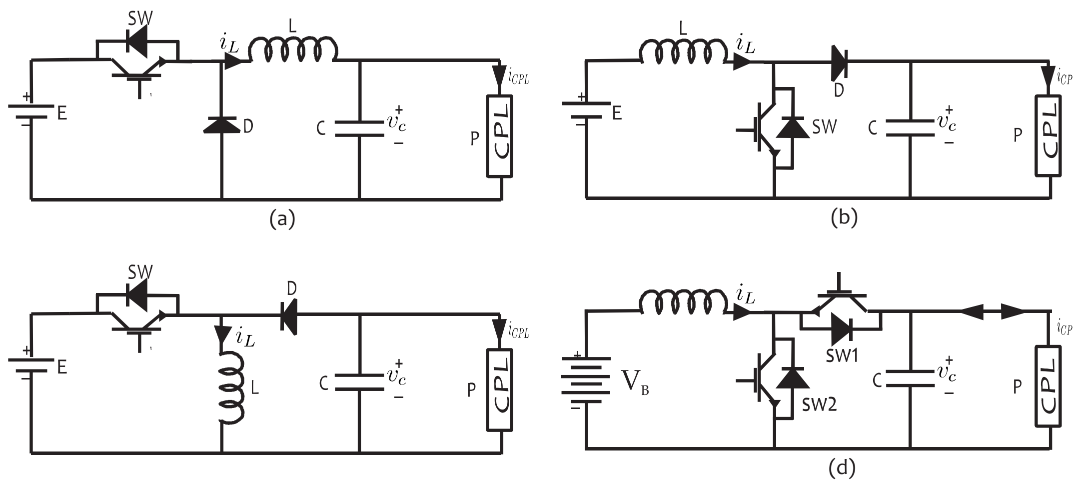


Figure 1.5 : DC/DC converters loaded with CPL: (a) Buck converter, (b) Boost Converter, (c) Buck-boost converter, and (d) Bidirectional buck-boost converter

1.2.3 Buck-Boost Converter

The nonlinear state-space averaged model of an inverted topology buck-boost converter with a CPL, shown in Figure 1.5(c), is given by

$$L\frac{dx_1}{dt} = u(t)E + (1-u(t))x_2 \tag{1.11a}$$
$$C\frac{dx_2}{dt} = -(1-u(t))x_1 - \frac{P}{x_2} \tag{1.11b}$$
$$x_1 \geqslant 0, x_2 < -\varepsilon$$

The equilibrium point $[x_1^*, x_2^*]$ of (1.11) is given by

$$[x_1^*, x_2^*] := \left[\frac{P}{u(t)E}, \frac{-u(t)}{(1-u(t))}E\right] \tag{1.12}$$

The Jacobian matrix at the equilibrium point (1.12) becomes

$$J = \begin{bmatrix} 0 & \frac{(1-u(t))}{L} \\ -\frac{(1-u(t))}{C} & \frac{P(1-u(t))^2}{Cu(t)^2E^2} \end{bmatrix} \tag{1.13}$$

The trace and determinant of the Jacobian matrix are $\tau = \frac{P(1-u(t))^2}{Cu(t)^2E^2} > 0$ and $\Delta = \frac{(1-u(t))^2}{LC} > 0$. Therefore, the equilibrium point of (1.11) is unstable.

1.2.4 Bidirectional Buck-Boost Converter

The state-space averaged model of a bidirectional dc/dc converter interfacing a battery storage in typical dc microgrid application and supplying a net CPL power P_n (resultant of power produced by Renewable Energy Sources (RESs) operating in Maximum Power Point Tracker (MPPT) and load demand), as shown in Figure 1.5(d), is given by.

$$L\frac{dx_1}{dt} = V_{bat} + u(t)x_2 \quad (1.14a)$$

$$C\frac{dx_2}{dt} = u(t)x_1 - \frac{P_n}{x_2} \quad (1.14b)$$

$$x_1 \geqslant 0, x_2 < \varepsilon$$

where V_{bat} is the nominal battery voltage. Assuming that the system on the right-side of the converter consists of both CPLs and Constant Power Sources (CPSs), the net load power P_n can be positive or negative. The equilibrium point $[x_1^*, x_2^*]$ of (1.14) is given by

$$[x_1^*, x_2^*] := \left[\frac{P_n}{V_{bat}}, \frac{V_{bat})}{u(t)}\right] \quad (1.15)$$

The Jacobian matrix at the equilibrium point 1.12 becomes

$$J = \begin{bmatrix} 0 & \frac{-u(t)}{L} \\ \frac{u(t)}{C} & \frac{P_n u(t)^2}{CV_{bat}^2} \end{bmatrix} \quad (1.16)$$

The trace and determinant of the Jacobian matrix are $\tau = \frac{P_n u(t)^2}{CV_{bat}^2}$ and $\Delta = \frac{u(t)^2}{LC} > 0$. When P_n is positive (discharging mode), the trace of the Jacobian is positive, this implies that the equilibrium point of (1.14) is unstable. On the other hand, when $P_n < 0$ (charging mode), the equilibrium point of the system is stable.

Remark 1.1. The use of ideal models of dc/dc converters in the above stability analysis is motivated by the fact that the absence of any dissipative element keeps the natural damping of the system to a minimum value. This leads to a worst case scenario from the stability point of view. As discussed above, all the basic open-loop dc/dc converters loaded with *CPL* and operating in *CCM* are unstable. Furthermore, in the absence of dissipative elements such as converter paracitics and Constant Voltage Loads (CVLs), there is no parameter which can contribute towards stabilization of the system. When both, *CVLs* and *CPLs* are present in the system, the system is unstable if amount of *CPL* is greater than *CVL* [Emadi et al., 2006].

In a closed-loop operation, the stability of dc/dc converters loaded with CPL depends on the mode of operation (CCM or Discontinuous Conduction Mode (DCM)) and control mode, Voltage Mode Control (VMC) or Current Mode Control (CMC). All the basic dc/dc converter loaded with a CPL and operating in CCM, are unstable under both VMC and CMC. The boost converter in DCM is stable under both VMC and CMC. The buck-boost converter in DCM is marginally stable under both VMC and CMC. And buck converter in DCM is stable under VMC and unstable under CCM. In open-loop, all basic dc/dc converters loaded with CPL and operating in DCM are stable, and in such cases the control design task is similar to that of dc/dc converters loaded with conventional CVL [Rahimi and Emadi, 2010].

1.3 STABILITY OF A DC MICROGRID WITH CPL

The power electronic converters are the basic building blocks of a renewable energy based DCMG. And it has been seen that, all the basic dc/dc converters loaded with CPL represents a nonlinear system and are unstable due to negative impedance characteristics of tightly-regulated POLCs. A dc microgrid with many RESs interfacing converters, energy storage interfacing converters, CPLs, and uncertainty associated with RESs, becomes a highly nonlinear system. It has been an established fact that Proportional-derivative-integral (PID) control techniques are insufficient to regulate dc bus voltage and to stabilize a dc distribution system in face of CPL and uncertainties. Under given situation, the designed control must have sufficient robustness to ensure stability and the performance of the system. In the following section, a review of different techniques to mitigate the destabilizing effects of the CPLs is presented, wherein the capability of each technique is critically examined, along with its limitations.

1.4 REVIEW OF LITERATURE

In this section a review of literature on mitigation of the destabilizing effects introduced by CPLs in dc distribution systems is presented. Techniques reported for mitigation of the destabilizing effects of CPLs are classified and the concept of each technique is described briefly, along with its merits and limitations.

The basic concept of CPL compensation involves increasing the effective system damping through some modifications at feeder/source level, load level or the use of some additional circuits [Mingfei and LU, 2014]. These modifications can be done in system hardware or in their control loops. The techniques based on hardware modifications are known as passive damping techniques and those based on modifications in the control structures are known as active damping techniques. The techniques based on some specialized control approaches, discussed separately here, are also usually considered under active damping. A broad classification of the CPL compensation techniques is shown in Figure 1.6. In the following subsections, different CPL compensation techniques are presented.

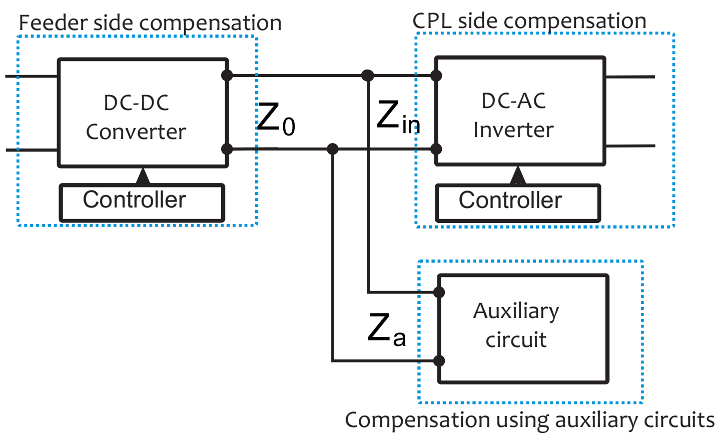


Figure 1.6 : Broad classification of CPL compensation techniques: (a) Feeder side compensation, (b) Load side compensation, (c) Compensation using auxiliary circuits

1.4.1 Passive Damping

In this technique, in order to compensate the negative incremental impedance effect of the CPLs, the system damping is increased by adding passive components (resistances, resistance-capacitance, and resistance-inductance) to the concerned system. This approach results in an increased size, cost, weight of the system. Furthermore, passive components lead to high power dissipation, particularly when resistance is used in parallel with filter capacitor, which is detrimental to the system efficiency. The application of the Loss Free Resistance (LFR) [Singer, 1990] can be used to reduce the power dissipation. The downside of LFR is that, it increases the system size, complexity, and cost.

In [Jusoh, 2004], the interaction of CPL's small-signal negative input resistance with input LC filter is analyzed and a passive damper consisting of series RC (resistance-capacitance) branch in parallel with filter capacitor is proposed to stabilize the system. Cespedes et. al. in [Cespedes et al., 2011] have proposed three different passive dampers to stabilize the input filter of a CPL, and presented an analytical theory to determine the required values of damper parameters. The design of the dc bus capacitor, to ensure the desired stability margins using impedance criteria under three droop control schemes, is presented in [Gao et al., 2014]. The test system considered consists of a dc aircraft power system having parallel sources driving a CPL. The influence of the converter paracitics (switch 'ON' resistance, inductor resistance, and diode resistance) in the presence of CPLs is analyzed in detail in [Khaligh, 2008] under both CCM and DCM operation. Furthermore, design recommendations are presented to avoid CPL induced instabilities in a dc distribution system, feeding a pure CPL and a combination of CPL with resistive loads.

1.4.2 Active Damping

The underlying concept of active damping is to create the damping effect of series/parallel resistances or dc bus capacitance through the modifications in the control structure of the feeder or load subsystem. In addition to this, an auxiliary circuit can also be connected at the load terminals, to inject a compensating current or to emulate variable impedance, so as to mitigate the CPL induced instabilities [Rahimi and Emadi, 2009; Mingfei and LU, 2014]. Next, the active damping techniques realized at feeder side, load side and through the auxiliary circuits will be discussed separately.

(a) Feeder side active damping

In this section, active damping methods implemented through the modifications in control loops of the feeder subsystem are summarized [Rahimi and Emadi, 2009; Rivetta et al., 2006; Li et al., 2012; Radwan and Mohamed, 2012b,a; Ahmadi and Ferdowsi, 2014; Wu and Lu, 2015; Shafiee et al., 2014; Cai et al., 2014; Lu et al., 2014; Xuhui et al., 2011; Ashourloo et al., 2013; Kuhn et al., 2007]. The compensation of the CPL effect at the upstream feeder level is applicable only when, the upstream feeder subsystem is a switched dc/dc or ac/dc converter. When the feeder subsystem of the CPL is an input LC (inductance-capacitance) filter or uncontrolled rectifier, CPL compensation at the feeder side is not possible. In active damping at the feeder side, the additional compensation loops modifies the output impedance Z_0 of the feeder converter, so as to satisfy the impedance stability criterion. The major advantage of this approach is that the system can be stabilized without compromising the load performance [Mingfei and LU, 2014; Smithson and Williamson, 2012].

An active damping technique which emulates a resistance in series with the converter inductor to stabilize the basic dc/dc converters loaded with a CPL is presented in [Rahimi and Emadi, 2009]. The measured inductor current is passed through a feedback coefficient R_{LA} and is subtracted from control voltage to emulate a resistance in series with the inductor, which increases the system damping (see Figure 1.7). Furthermore, the technique is extended to the isolated dc/dc converters loaded by a CPL. Through active damping, only a limited amount of the CPL can be compensated. In [Rivetta et al., 2006], the global behaviour of a dc/dc buck converter is analyzed using phase-plane analysis, wherein the system is controlled using current feedback loop with hysteresis and PI voltage controller. In [Li et al., 2012], it is shown that peak and valley current mode control can be used to stabilize a dc/dc boost converter loaded with a CPL. The stability of the system is analyzed in a small-signal sense. Furthermore, concept of load current feed forward is used to improve the transient response. Authors in [Radwan and Mohamed, 2012b], proposed an active damping of a bidirectional Voltage Source Converter (VSC) interfacing a DCMG, by injecting a damping signal in its outer, intermediate, and inner control loop (concept is shown in Figure 1.8). The stability of the compensation is analyzed in a small-signal sense, and sensitivity analysis of the compensation and voltage control dynamics is also presented. It has been shown that the intermediate loop dynamics provides best performance in terms of damping capabilities and its influence on the voltage

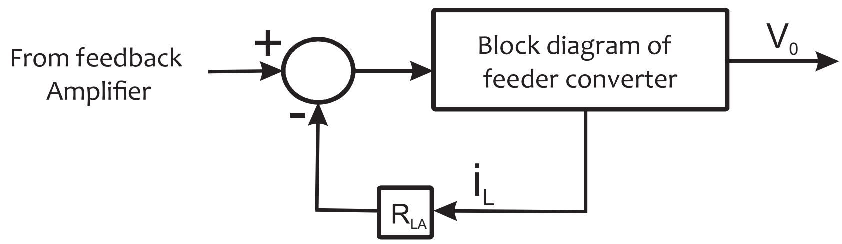


Figure 1.7 : Active damping of dc/dc converters

control loop. In [Radwan and Mohamed, 2012a], active compensators are proposed to reshape input admittance of a tightly regulated VSC in a hybrid ac/dc distribution system to stabilize the system, in the presence of interaction dynamics and negative impedance effect of the CPLs. In order to stabilize the feeder converters in a CPL dominated DCMG, two active compensators are proposed in [Ahmadi and Ferdowsi, 2014] using two approaches based on linear theory. In addition to stabilize the feeder converters, the active damping loops also improve the dynamic performance of the microgrid. Active damping control to emulate virtual resistance in a source dc/dc buck converter supplying power to paralleled CPLs, with their input filter is presented in [Wu and Lu, 2015] (Figure 1.9). The major disadvantages of the proposed method are that, in order to stabilize the system, the closed loop bandwidth of source converter should be greater than the resonant frequencies of the input LC filter, and resonant frequencies of the filters must be different.

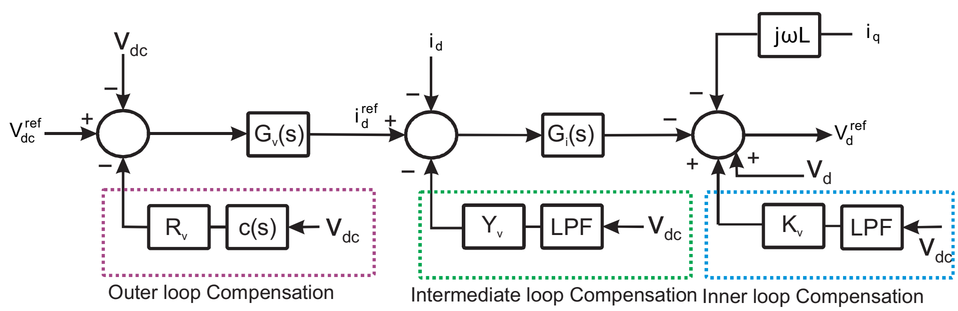


Figure 1.8 : Active damping of grid-connecting VSC in a dc microgrid

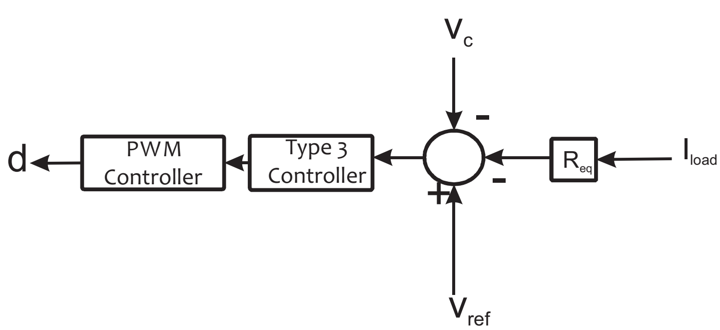


Figure 1.9 : Active damping of dc/dc a buck converter loaded with CPL

Shafiee et al in [Shafiee et al., 2014], have proposed a concept of dc Active Power Filter (APF) to stabilize a dc microgrid under load changes, and while connecting it to other dc microgrids. A small signal model of the system is derived to analyze the effect of CPLs and tie line impedance on the stability. To implement the active damping current loop, information of load current and current disturbance in tie line are used, and compensation gain is selected through root locus analysis. For more feeder side active damping methods, see [Cai et al., 2014; Lu et al., 2014; Xuhui et al., 2011; Ashourloo et al., 2013; Kuhn et al., 2007], and the references therein.

(b) CPL side active damping

Under the situations, when the feeder subsystem of a CPL is an input LC filter or an uncontrolled ac/dc rectifier (behaves as LC filter), the compensation of CPL from the feeder side is not possible, due to the absence of control loops associated with feeder subsystem [Glover and Sudhoff, 1998; Sudhoff et al., 1998; Liu et al., 2007; Liu and Forsyth, 2008; Liutanakul et al., 2010; Mohamed et al., 2012; Magne et al., 2012b, 2013, 2012a, 2014; Mosskull, 2014]. In such cases, there are two alternatives available for the CPL compensation: CPL side compensation and the use of an active shunt damper between feeder and load subsystems. Here, the active damping methods based on CPL side compensation will be summarized. In these methods, a compensating current or power is injected into the CPL control loops to modify its input impedance Z_{in}, such that Middlebrook's stability criteria is satisfied. The main drawback of this approach is that the additional compensating loop dynamics may interfere with the main control loop of CPL, and may deteriorate the load performance. On the other hand the approach is advantageous as CPL itself is utilized to mitigate the negative impedance instabilities.

In [Glover and Sudhoff, 1998; Sudhoff et al., 1998], a Nonlinear System Stabilizing Controller (NSSC) is proposed to mitigate the negative impedance instabilities as shown in Figure 1.10(a), where n is a real number. The controller is tested on a tightly regulated induction motor drive and a dc/dc converter with input LC filter, controlled through a nonlinear PI controller. It is shown that, the controller stabilizes the system while compromising the load performance significantly. A Negative Input Resistance Controller (NIRC) is proposed in [Liu et al., 2007] as shown in Figure 1.10(b), to stabilize a brush-less dc motor drive exhibiting a CPL behaviour. The compensator design using small-signal analysis and sensitivity analysis with motor performance is also presented. In order to further reduce the effect of the compensator on motor performance and to improve immunity to the input voltage disturbances, an improved version of NIRC, known as State Feedforward Stabilizing Controller (SFSC) (Figure 1.10(b)) is proposed in [Liu and Forsyth, 2008]. The controller takes input filter inductor current and input voltage as its inputs.

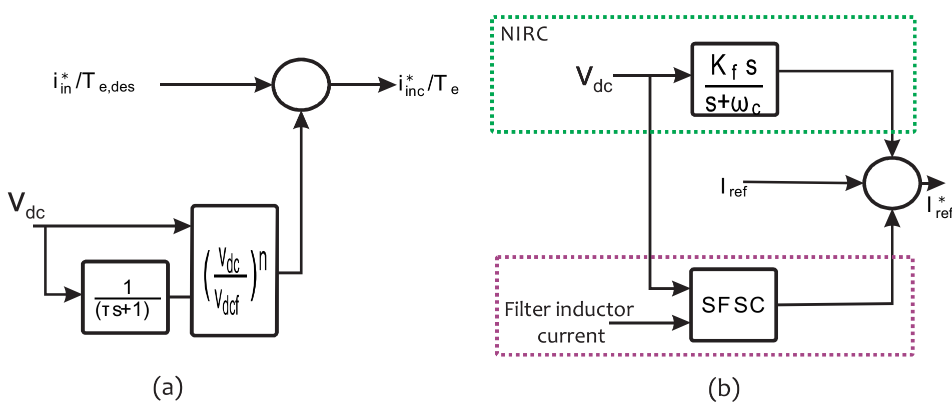


Figure 1.10 : (a) Nonlinear system stabilizing controller, (b) Negative input-resistance compensator (NIRC) and state feedforward stabilizing controller (SFSC)

In [Liutanakul et al., 2010], the local stability of a Permanent Magnet Synchronous

Motor (PMSM) inverter drive, tightly controlled using linear controllers, and with input LC filter is analyzed using Nyquist and bode plots. An additional compensating block consisting of a band-pass filter and a proportional controller is proposed to compensate for the input voltage oscillations and to reduce dc bus capacitor size. Compensating block parameters can be tuned to get an optimum motor performance and suppression of oscillations. Authors in [Mohamed et al., 2012], have proposed two Reference Voltage Based Active Compensators (RVCs) and its improved version to mitigate the negative impedance instabilities in a PMSM drive. It has been shown that, low-pass filter (RVC-1) and band-pass filter (improved version RVC-2) active compesnators stabilize the system without compromising the motor torque and speed performance. Second configuration RVC-2 is found to be more effective, with reduced interaction dynamics between compensator and motor-drive main control (see Figure 1.11). Magne et. al. in [Magne et al., 2012b], have presented a small-signal stability of a system consisting of a inverter motor-drive, dc/dc converter with resistive load, and a Bidirectional DC/DC Buck-boost Converter (BDC) interfacing a supercapacitor. A central stabilizing controller is proposed to ensure the system's global stability and to reduce the size of input filter components. The main drawbacks of the proposed scheme are, requirement of a large number of sensors and high control bandwidth. To reduce the number of sensors required, the authors proposed an observer in [Magne et al., 2013], to estimate the load voltages. In [Mosskull, 2014], the active stabilization of a CPL supplied through a LC input filter is formulated as linear H_∞ optimization problem with an objective to minimize the degradation of load performance while ensuring desired stability and robustness. It has been shown that the main CPL control bandwidth is limited by LC filter resonant frequency. Details about more CPL side active damping methods can be found in references [Magne et al., 2012a, 2014; Awan et al., 2009], and the references therein.

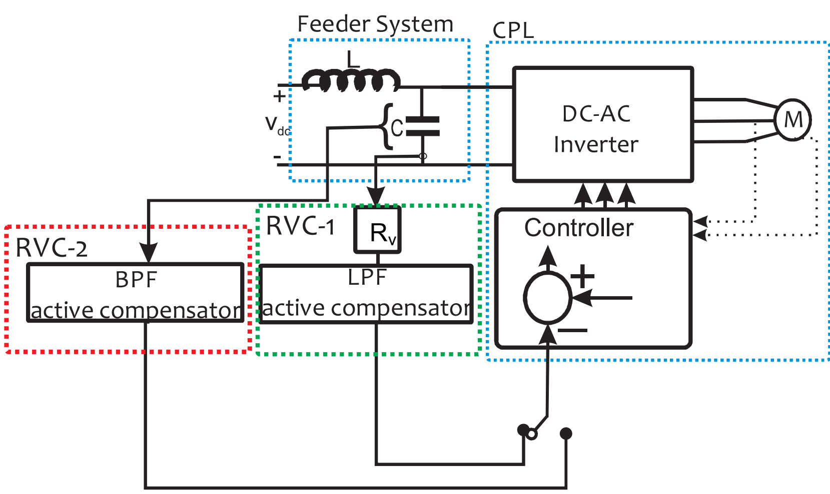


Figure 1.11 : Reference voltage based active compensators (RVC-1 and RVC-2)

(c) Active damping using auxiliary circuits

In this method, to mitigate the destabilizing effect of CPLs, an additional circuit is connected between feeder and load subsystems, leaving the feeder and load subsystems intact. This additional circuit is usually a dc/dc converter which is controlled to inject the desired compensating current in the entire operating range of the main system. This method, although eliminates the challenges of the above two approaches, results in increased cost and increases overall complexity of the system.

In [Inoue et al., 2012], a dc/dc BDC interfaced with storage capacitor is connected between CPL and its input LC filter, to eliminate the oscillations in the input voltage. The controller uses voltage and current variables, of the filter and the BDC, to place the poles of the overall dynamic system at the desired location. Furthermore, a second order observer is also proposed to reduce the number of sensors required. Authors in [Carmeli et al., 2012], have presented the placement of a suitably sized capacitor and a PI controlled BDC with storage at the terminals of a tightly controlled inverter drive with an input LC filter, to stabilize the dc bus voltage. The concept of auxiliary smart active damper is presented in [Pizniur et al., 2014], to stabilize a dc telcom power systems and data center dc microgrids. The active damper which emulates the RC damper characteristics, is realized through non-isolated BDC without any additional storage, and communicates with source and load subsystems in real time to determine the desired damping current required to stabilize the system under various input and load conditions. The inner loop of the damper is controlled in peak-current mode at a fixed frequency, while outer loop eliminates the deviation in the peak and average current of the inductor.

1.4.3 Feedback Linearization

Linearizing a nonlinear plant about an operating point ensures stability only in a small-signal sense. Feedback linearization is a nonlinear control approach used to compensate CPL effect in dc DPSs, wherein a nonlinear feedback is chosen to cancel the nonlinearities introduced in the system due to the presence of CPLs [Emadi and Ehsani, 2000]. Basically, this involves a nonlinear coordinate transformation which allows access to the system nonlinearities through input channel, such that the resultant system is linear [Ciezki and Ashton, 1998]. Consequently, control system can be designed using conventional linear control theory. In contrast to the active damping technique, feedback linearization can compensate any amount of CPL and stabilize the system in large-signal sense. The major drawback is its noise sensitivity due to the presence of differentiator and slower transient response compared to techniques which handle CPL nonlinearity as it is, such as sliding mode control and synergetic control [Cupelli et al., 2014].

Authors in [Ciezki and Ashton, 1998], used feedback linearization through nonlinear coordinate transformation to stabilize a dc/dc buck converter feeding a CPL. It is shown through Lyapunov analysis that the transformation results in an extension of local asymptotic stability. Stabilization of a dc/dc buck converter, driving a combination of resistive load and CPL is presented in [Emadi and Ehsani, 2000] and the large-signal stability of the system is proved using Lyapunov approach. Rahimi et. al. in [Rahimi et al., 2010], have proposed a loop cancellation technique to stabilize all the basic dc/dc converters feeding a resistive and a CPL load using suitable nonlinear feedback, which cancels nonlinearity introduced due to the presence of CPL. It is shown that the value of feedback gain to cancel CPL nonlinearity depend on input, load and the converter parameters. To overcome this problem, feedback gain value is chosen such that, under all operating conditions, the sign of the resultant nonlinear term is positive. This implies that the resultant nonlinear term can be represented by a positive equivalent resistance, which helps to increase the system damping. In [Solsona et al., 2015], a nonlinear coordinate transformation is applied to a dc/dc buck converter loaded with a pure CPL, to obtain its linear model. To obtain near exact linearization the converter parameters (L and C) to be entered in the controller are assumed to be equal to their actual values. Furthermore, a reduced order observer is proposed to estimate the CPL power and its derivative, to ensure the accuracy of linearization in the entire operating range, i.e., to improve the transient performance. A full order feedback controller is then designed for the linearized converter model. The sensitivity analysis of parameter mismatch on the performance of the observer and closed loop system is also presented.

A technique based on linearization via state feedback (LSF) is presented in [Sulligoi et al., 2014] to stabilize a medium voltage shipboard dc power system in the presence of CPLs. The method involves defining two functions, one to linearize the nonlinear system and another to realize the pole placement at desired location. A PD state feedback controller is proposed and sensitivity analysis of system parameter mismatch on the performance of the linearizing function is also presented.

1.4.4 Pulse Adjustment

The pulse-adjustment control [Khaligh et al., 2007, 2008], is a digital control technique in which the task of converter output voltage regulation is achieved by supplying high and low-power pulses to the converter. Depending on measured actual output voltage and the reference voltage, the controller chooses either high or low-power pulse. If $v_o < V_{ref}$, the controller generates switching pulse of duty ratio D_H (high duty ratio), until the desired voltage level is reached, otherwise switching duty ratio D_L (low duty ratio) is selected to regulate the output voltage to its reference value. The ratio $\frac{D_H}{D_L}$ presents a trade-off between output voltage ripple and the voltage regulation, and can be chosen to satisfy a particular application requirements. The selected value of the high pulse duty cycle D_H is such that the converter operates in DCM. The output voltage sampler and switch driver being synchronized, the technique ensures constant frequency switching of the converter. A block diagram of the pulse-adjustment technique is shown in Figure 1.12.

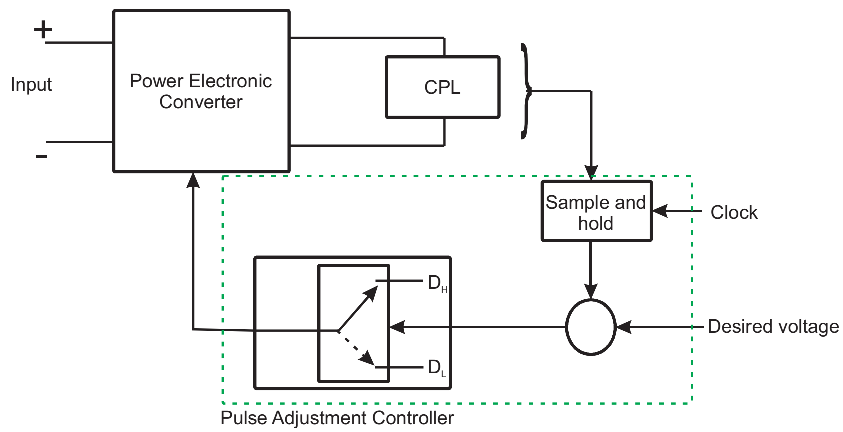


Figure 1.12 : Block diagram of Pulse-adjustment control technique

In [Khaligh et al., 2007], the pulse-adjustment technique is applied to stabilize a dc/dc buck-boost converter loaded with a CPL. A model of the converter with CPL and operating in DCM is derived, which is then used to analyze system stability, and to determine the output voltage variations during high and low-power pulses. Furthermore, a detailed sensitivity analysis of the output voltage variations and stable CPL power range, with respect to switching frequency, input voltage, reference voltage, and converter parameters (L and C) variations is presented. It is shown the output voltage contains undesirable disturbances under input voltage variations, if not filtered properly. The authors proposed modified pulse-adjustment technique in [Khaligh et al., 2008] with variable D_H, and applied to buck-boost converter to minimize the effect of the input voltage variations on the output voltage.

The technique of pulse-adjustment is inexpensive and simple to implement using digital tools, gives fast response, and does not require detailed small or large signal model of the converters. The main limitation is that it can stabilize the system in the limited range of the CPL power only.

1.4.5 Sliding Mode Control

Sliding Mode Control (SMC) is a robust nonlinear control technique which falls under Variable Structure System Control (VSSC) [Utkin, 1978]. In SMC, depending on the switching conditions a system can be considered as a set of subsystems, and each subsystem exhibits a fixed characteristics in a specified region of state space. An introduction to SMC is presented in Annexure A, for a quick reference to the readers. As shown in Figure 1.13, a SMC can be designed with continuous equivalent control law, discontinuous control law, or a combination of two. SMC has a wide control application in nonlinear systems due to its robustness and simple implementation.

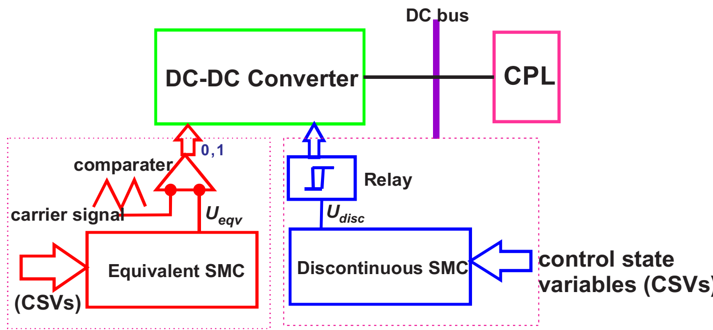


Figure 1.13 : Equivalent and Discontinuous SMC, shown in Red and blue colours respectively

Emadi et. al. in [Emadi et al., 2006], have presented a simple SMC for a dc/dc buck converter which ensures supply of constant power to the load. One of the limitation of proposed SMC is that it does not ensure the regulation of converter output voltage. Authors in [Zhao et al., 2014b], have proposed a sliding mode duty cycle ratio controller for buck converter feeding a CPL, to stabilize the dc bus voltage, in an application of medium voltage dc shipboard power system. The designed control law, in addition to equivalent control term, contains a switching term which provides robustness to line and load disturbances during reaching phase. A geometric control based on a circular switching surface for constant power load stabilization in buck and boost cascade topology interfaced with battery has been proposed in [Anun et al., 2015]. The authors have shown the minimum switching action of the controller for stabilization of CPLs with different bandwidth. A SMC using a washout filter for a bidirectional converter feeding a mixed load is proposed in [Tahim et al., 2011]

1.4.6 Synergetic Control

Synergetic control [Kondratiev et al., 2006; Santi et al., 2003] is a non-linear technique which encompasses dissipative structure algorithms. This control technique shares similarity with SMC and ensures constant frequency switching. The control design follows an analytical procedure using state space approach. The steps involved in control design through synergetic control are as follows,

(a) Plant modeling

In this step, a mathematical model of the dynamic system is described using differential equations of the following form,

$$\dot{x} = f(x,u,t) \tag{1.17}$$

where x is the state vector of dimension n, and u is the control vector of dimension m. Then, a macro variable $\psi(x)$ and control law are designed, such that the control law forces the system trajectory from an arbitrary initial condition, towards the predefined invariant manifold, $\psi(x) = 0$ and constrain it to manifold then on. The macro-variable can be any function of the state variables. The number of macro variables should be less than the number of control channels.

(b) Control law synthesis

To synthesize a control law, a dynamics governing the evolution of the macro-variable towards the manifold is defined. The required dynamic evolution of the macro-variable is given by

$$T\dot{\psi} + \psi = 0; \quad T > 0 \tag{1.18}$$

where T is a parameter of the above dynamics which controls the speed of convergence of trajectory toward the manifold. The control is obtained by solving (1.18) with (1.17) for u. The order of the system on the manifold is reduced to (n-m).

In [Kondratiev et al., 2004], authors have proposed synergetic controllers for dc voltage stabilization and dynamic current sharing between two buck converters with constant power load and operating in CCM, and for voltage regulation of a single buck converter with CPL, considering DCM operation of the converter. The authors extended this work and proposed a generalized synergetic control strategy in [Kondratiev and Dougal, 2006], for the dc voltage regulation and dynamic current sharing among m-number of paralleled buck converters feeding constant power load.

1.4.7 Passivity Based Control

Passivity Based Control (PBC) is a non-linear control approach for designing a static or dynamic controllers for a physical system described by the Euler-Lagrange equations [Guo et al., 2008; Sira-Ramirez and Ortega, 1995; Leyva et al., 2006]. The central idea behind PBC control design is to passivize the system by, 1) Defining a closed loop storage function to compensate the energy difference between the energy of the system and energy injected by the controller. This results in modification in the Potential Energy Function (PEF) only, in order to get the strict local minimum of PEF at the required equilibrium point. Basically, PBC works on the principle of energy conservation, i.e.

$$E_{supplied} = E_{stored} + E_{dissipated} \tag{1.19}$$

2) Modifying the energy dissipation function by damping injection in order to make equi-

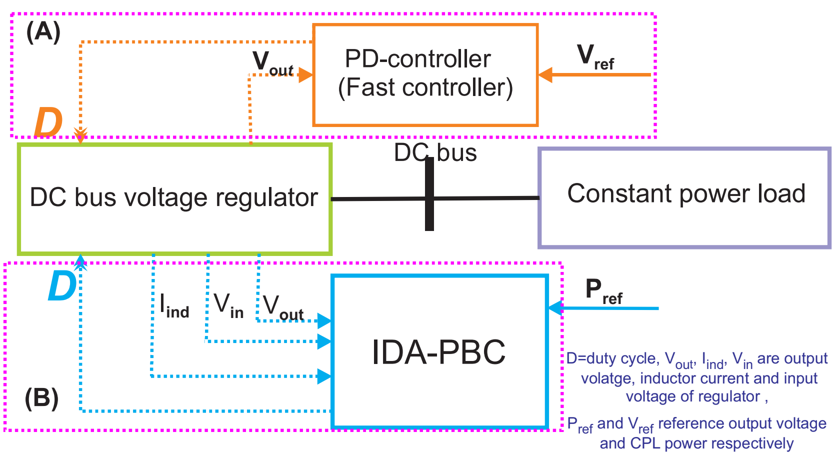


Figure 1.14 : Block diagram of passivity based control control techniques

librium point a globally asymptotically stable point. This is achieved by adding a virtual impedance matrix.

Some researchers have used Port Controlled Hamiltonian model, instead of Euler-Lagrange equations, to a nonlinear electrical dc power system and to implement Interconnection and Damping Assignment (IDA)-PBC. A PBC combined with IDA technique used for stability analysis and to design a linear PD (proportional-derivative) controller for a buck converter, and a nonlinear inverse quadratic PD controller for a boost, and buck-boost converters in a dc microgrid application, have been proposed in [Kwasinski and Onwuchekwa, 2011]. However, the PD controller poses noise susceptibility issue, therefore an appropriate filter is needed. Furthermore, IDA technique has been designed with fixed parameters (i.e. for specific operating point of CPL), which is not always the case in practical systems. To mitigate this problem, a complementary PI (proportional-integral) controller along with adaptive IDA-PBC technique for dc/dc boost converter is proposed in [Zeng et al., 2014]. A PBC with Immersion and Invariant controller has been proposed for dc bidirectional converter interfaced with a battery in [Lenz and Pagano, 2013]. This combined control ensures improved transient performance of the converter feeding a mixed load (CPL and resistive load). Two different PBC design approaches using PD and IDA controllers for dc bus regulator are shown in Figure 1.14.

1.4.8 Power Shaping Stabilization

In power shaping control strategy to mitigate the destabilizing effect of CPLs, the system differential equations are re-formulated in terms of rate of energy or instantaneous power. This basically results in a linear system, thus eliminates the nonlinearity introduced by the CPL. The power shaping control strategy is relatively easy in design and implementation, and results in the desired regulation of dc bus, while maintaining large-signal stability. The authors in [Wang and Howe, 2008], have proposed stabilization of a dc distribution system supplying constant power loads using power stabilization control strategy.

1.4.9 Coupling Based Techniques

An amplitude death solution or coupling based technique, is basically coupling induced stabilization of the equilibrium points of an unstable dynamic system [Huddy and Skufca, 2013; Konishi et al., 2014, 2015]. The sufficient strength of coupling and different natural frequencies of the systems being coupled, are the two main requirements for amplitude death. The technique originally belongs to nonlinear dynamical systems and has recently been applied for open-loop stabilization of the dc-dc converters in a dc microgrid in the presence of CPLs. Authors in [Huddy and Skufca, 2013], have proposed a heterogeneous and time-delay coupling to stabilize a dc/dc buck converter supplying a CPL. Konishi et. al. in [Konishi et al., 2014], have presented a bifurcation analysis of instability phenomenon of dc bus voltage in the presence of CPLs and proposed a delayed feedback control to stabilize the system. The concept of delayed feedback control has been further extended in [Konishi et al., 2015], to a networked system having multiple dc bus systems, connected through resistive links. The delayed-feedback control is applied to each unit, in a decentralized manner to stabilize the system. Moreover, it has been shown that stabilization is independent of the number of dc buses and the network topology. The block diagram of the techniques discussed in this section is shown in Figure 1.15.

The information on some other techniques to mitigate the destabilizing effects of CPLs can be found in references [Kim and Williamson, 2011; Hou et al., 2014; Xu et al., 2008]. A summary of the techniques discussed above, used to mitigate or reduce the destabilizing effect introduced by CPLs, is given in Table 1.1.

1.5 MOTIVATION

The passive damping technique to mitigate the destabilizing effects of CPLs is rarely used due to its poor efficiency and high cost. On the other hand, coupling based amplitude death and delayed-feedback control, which have been proposed for open-loop stabilization of power converters and dc bus, are not feasible for RESs based dc distribution systems because of large inter-source distances. To evaluate a particular CPL compensation technique, the amount of CPL it can compensate, robustness, speed of response, noise immunity and ability to

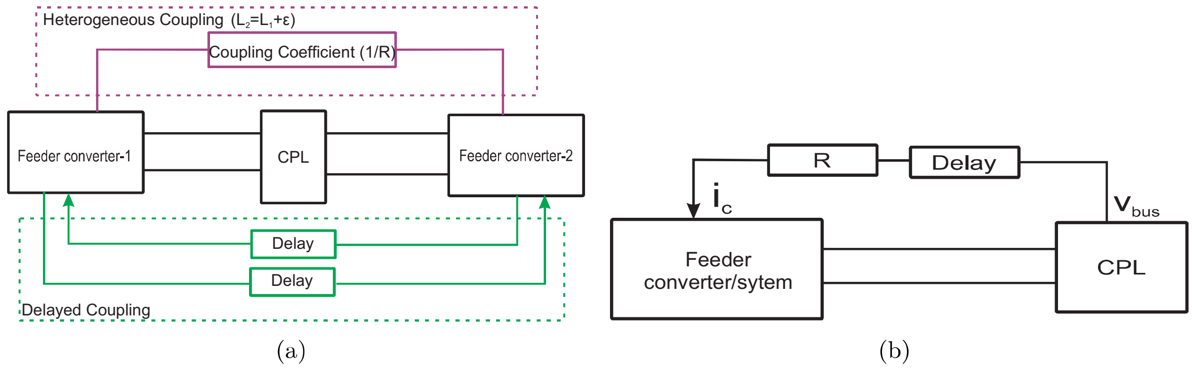


Figure 1.15 : Block diagram of coupling based techniques: (a) Heterogeneous and delayed coupling; (b) Delayed feedback control

ensure large-signal stability, are some of the most important parameters. The active damping technique, although widely applicable, is operating point dependent, and can compensate only a limited amount of CPL. Feedback linearization ensures compensation of any amount of CPL and large-signal stability, however, performs poorly with the requirement of robustness, speed of response and noise immunity. Power shaping stabilization, in which a linear model of the system is obtained by re-formulating it in term of instantaneous power, ensures better robustness and noise immunity, compared to that with feedback linearization, however, it requires current loop bandwidth to be sufficiently higher than that of voltage-squared loop. Pulse adjustment technique ensures robustness and fast response, however, it has limitations of poor line rejection, operates in DCM and ensures stability with a limited range of CPL. Passivity based control has poor noise immunity due to the presence of differentiator and is sluggish in response. Synergetic control which is similar to sliding mode control in many respects becomes problematic in DCM and is sensitive to high frequency noise. Furthermore, the dynamics of the macro-variable does not ensure finite time converge, thus reaching phase response is slow, because response becomes extremely slow in the vicinity of switching function.

In order to achieve the main operational requirements (dc bus voltage regulation and stability) in dc microgrids in the presence of CPLs, it is necessary to overcome aforementioned major limitations. With inevitable uncertainty associated with RESs supplying power to the microgrid and limited resources of power (particularly in island mode), the overall control of microgrid must be robust to ensure the performance and stability. It is an established fact that sliding mode control technique ensures invariance to matched uncertainties and variations in the system parameters, i.e., the controller is capable to ensure the required performance despite the model and actual plant mismatches. Through sliding mode control any amount of CPL can be compensated and system stability can be ensured in large-signal sense. In addition to this sliding mode control of dc/dc converter provides better steady-state and dynamic response, less EMI, and results in an inherent order reduction, compared to linear controllers [Ahmed, 2004]. Furthermore, in sliding mode control convergence speed can be controlled in reaching and sliding mode using parameters of the reaching dynamics and switching function respectively. This work proposes novel switching functions based sliding mode approach to mitigate the destabilizing effects of the CPLs in dc/dc power converters and the island dc microgrid under high penetration of CPL. Novel switching functions are used to design robust sliding mode controllers using nonlinear converter models. Limits on the CPL power are established analytically to ensure stable operation of the system. In the proposed work, different load profile e.g. a total load of CPL nature, mixed load (resistive and CPL), and composite load (constant resistance, constant current, and CPL) are considered, and it

Table 1.1 : Summary of different CPL compensation techniques for dc distribution systems

Stabilization Technique	Merits	Limitations
Passive Damping	Simple to implement. No modification, in source or load hardware.	High power dissipation. Modifies source or load hardware
Active Damping	No change in source or load hardware. Higher efficiency and reliability	Can compensate limited amount of CPL. May interfere with main control objectives. Switching frequency affects the effectiveness
Feedback linearization	Can compensate any amount of CPL. Can achieve stability in the large signal sense. Use of conventional linear control design techniques	Sensitive to noise in the output channel. Dynamic response is not comparable to that offered by nonlinear controls such as SMC and synergetic control
Pulse Adjustment	Fast dynamic response. Insensitive to system parameters. Inexpensive implementation. Reduced switching losses and EMI noise, due to DCM operation	Sensitivity to input variations. Stable in limited range of CPL.
Sliding mode control	Insensitive to matched uncertainties. Large-signal stability. Fast response	Variable frequency switching and chattering issue. Higher sensor requirement.
Synergetic control	Fixed frequency switching. Large-signal stability. Suitable for digital implementation.	Sensitive to high frequency noise. Higher sensor requirement. Oscillatory in DCM.
Passivity based control	Simple Implementation. Robust. Energy based modeling.	Sluggish transient response.
Power Shaping stabilization	Large-signal stability. Insensitive to parameter mismatch	Increased computation needs
Coupling based techniques	Low implementation cost	Limited to open-loop stabilization. Implementation issue, when sources are at different locations

is shown that in each case the proposed robust controller is capable to stabilize the system. Furthermore, it is verified that derived limits on the CPL power in the worst case, match with the already established limits. The performance of the proposed sliding mode controllers is validated through simulation studies and experiments using prototype individual dc/dc power converters and PV based islanded dc microgrid.

1.6 RESEARCH OBJECTIVES

The main objective of the research work presented in this thesis is to mitigate the destabilizing effects of CPLs, which includes significant oscillations in the dc bus voltage or voltage collapse, in dc distribution systems through robust control approach. The main objective is split into the following sub-objectives. A robust nonlinear sliding mode control scheme is proposed to mitigate the destabilizing effect of CPLs and to achieve regulation of dc bus voltage, under high penetration of CPL and uncertainties.

- Mitigation of the destabilizing effects of CPLs in a single converter dc distribution systems e.g., dc/dc boost, buck, buck-boost, bidirectional buck-boost converters through robust control approach. Figure 1.16 shows a typical placement and objective of different dc/dc converters in RESs based dc microgrids.
- Mitigation of the destabilizing effects of CPLs in a multi-converter islanded dc microgrid, consisting of many RES interfacing converters, storage unit interfacing converters and

supplying a composite load though a robust control approach.

- Design and realization of a PV based islanded dc microgrid, and robust control design to achieve dc bus voltage regulation and stability under various operating modes, under high penetration of CPL.

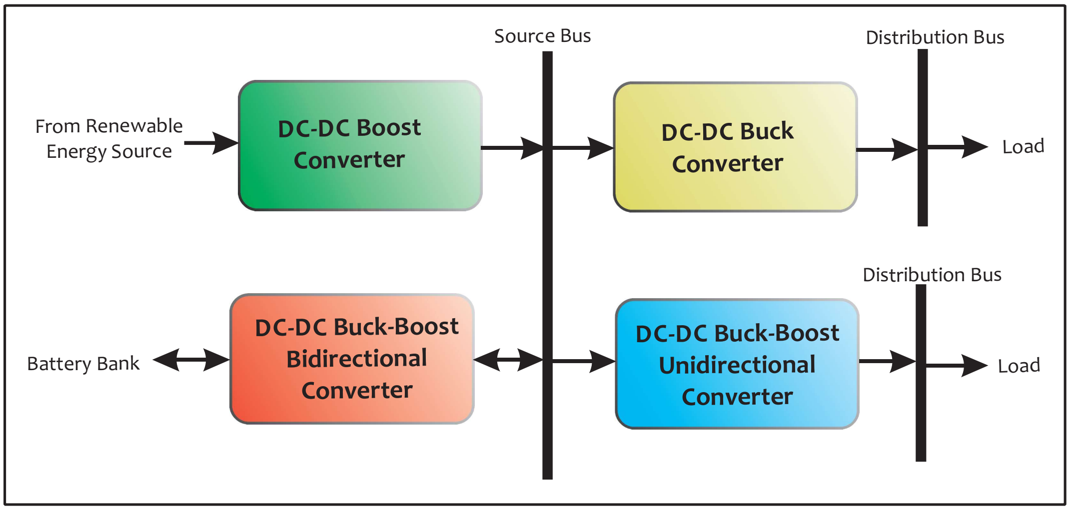


Figure 1.16 : DC/DC converters in RESs based dc microgrids

1.7 ORGANIZATION OF THE THESIS

The main purpose of this Thesis is to propose solutions to mitigate the destabilizing effects of CPLs in all basic non-isolated dc/dc converters and an islanded dc microgrid. This thesis is organized in 6 chapters and the content of each chapter is described briefly as follows.

Chapter 1: This chapter presents an introduction to dc distribution systems, CPL and its behaviour, stability of dc/dc converters and islanded dc microgrids with CPL, a brief review of the literature, the motivation behind the proposed work, and objectives and organization of the thesis.

Chapter 2: This chapter addresses mitigation of the destabilizing effects of CPLs in dc/dc boost converter using novel sliding mode controllers. The emulation of a dc programmable CPL using dc/dc boost converter, controlled by a novel sliding mode controller, is also presented in this chapter. Simulation studies and experimental results are presented to validate the proposed sliding mode controllers.

Chapter 3: This chapter addresses mitigation of the destabilizing effects of CPLs in a dc/dc buck converter feeding a mixed load. Discontinuous and PWM based sliding mode controllers, using novel nonlinear switching function are proposed to ensure the system stability and robustness under large variations in the supply and the load. A limit on the total load power is established to ensure the stable operation of the converter. The performance of the proposed controllers is validated through simulation studies and experimental results.

Chapter 4: This chapter addresses mitigation of the destabilizing effects of CPLs in an inverted topology dc/dc buck-boost converter and dc/dc bidirectional converter. A buck-boost converter has non-minimum phase structure which makes it unstable, even with resistive load. The presence of CPLs further aggravates the challenges in the stabilization of the buck-boost converter. Robust sliding mode controllers are proposed to ensure the stability and performance of both versions of the buck-boost converter. The real-time simulation studies are presented to validate the effectiveness and performance of the proposed sliding mode controllers.

Chapter 5: This chapter presents mitigation of the destabilizing effects of CPLs in a multi-converter islanded dc microgrid feeding a composite load. The second part of this chapter presents development of PV based islanded dc microgrid, and proposes a robust sliding mode control scheme to achieve mitigation of destabilizing effect of CPL under high penetration of CPLs and to achieve dc bus voltage regulation. A PV based dc microgrid is realized in the laboratory and is used to validate the performance in various operating modes, under high penetration of CPL.

Chapter 6: This chapter concludes the thesis and summarizes the major contributions. It also presents a few recommendations for future research.

1.8 PUBLICATIONS

The findings of the research work presented in this thesis have been submitted to various renowned peer reviewed journal and conferences. A list of publications, from this work, is as follows:

1 Suresh Singh, Deepak Fulwani, and Vinod Kumar, ”Robust Sliding Mode Control of DC/DC Boost Converter Feeding a Constant Power Load”, IET Power Electronics, Vol.8, No.7, pp.1230 - 1237, 2015.

2 Suresh Singh, Deepak Fulwani, and Vinod Kumar, ”Emulation of a power electronic dc power constant power load”, International Journal of Electronics (Taylor and Francis), major revision submitted (Paper ID: TETN-2015-0622.)

3 Suresh Singh, Aditya R. Gautam, Vinod Kumar, and Deepak Fulwani, ”Mitigating Destabilizing Effect of Constant Power Loads in DC/DC Buck Converter System-A DC Microgrid Application”, under review in International Journal of Control (Paper ID: TCON-2015-0548)

4 Suresh Singh, Nupur Rathore, and Deepak Fulwani, ”Mitigation of Negative Impedance Instabilities in a DC/DC Buck-Boost Converter with Composite Load”, under review in Journal of Power Electronics (Paper ID: JPE-15-02-057(0001))

5 Suresh Singh, Vinod Kumar, and Deepak Fulwani, ”Mitigation of Destabilizing Effect of CPLs in Island DC Microgrid using Nonlinear Control”, under review in IET Power Electronics (Paper ID: PEL-2015-0520)

6 Singh, S.; Fulwani, D., ”On design of a robust controller to mitigate CPL effect — A DC micro-grid application,” Industrial Technology (ICIT), 2014 IEEE International Conference on, Busan, Korea, pp.448-454, Feb. 26 2014-March 1 2014

7 Singh, Suresh; Fulwani, Deepak, ”Constant power loads: A solution using sliding mode control,” Industrial Electronics Society, IECON 2014 - 40th Annual Conference of the IEEE, Dallas, USA, pp.1989-1995, Oct. 29 2014-Nov. 1 2014

8 Singh, S.; Fulwani, D., ”Voltage regulation and stabilization of DC/DC buck converter under constant power loading,” Power Electronics, Drives and Energy Systems (PEDES), 2014 IEEE International Conference on, Mumbai, India, pp.1-6, 16-19 Dec. 2014

9 Suresh Singh, Deepak Fulwani, ”A PWM Based Sliding Mode Control for Negative Impedance Stabilization in DC Micro- grids”, 6th IEEE Power India International Conference (PIICON 14), New Delhi, India, pp.1-6, 5–7 Dec. 2014

10 Atul Agarwal, Koyinni Deekshitha, Suresh Singh, and Deepak Fulwani, ”Sliding mode

control of dc/dc bidirectional converter", DC Microgrids (ICDCM), 2015 IEEE First International Conference on, Atlanta, USA, pp.287-292, 7–10 Jun. 2015

11 Gautam, Aditya R. and Singh, Suresh and Fulwani, Deepak, "DC bus voltage regulation in the presence of constant power load using sliding mode controlled dc-dc Bi-directional converter interfaced storage unit", DC Microgrids (ICDCM), 2015 IEEE First International Conference on, Atlanta, USA, pp.257-262, 7–10 Jun. 2015

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