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Published in:
IEEE Access

DOI (link to publication from Publisher):
[10.1109/ACCESS.2018.2849065](https://doi.org/10.1109/ACCESS.2018.2849065)

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Hossain, E., Perez, R., Nasiri, A., & Padmanaban, S. (2018). A Comprehensive Review on Constant Power Loads Compensation Techniques. *IEEE Access*, 6, 33285-33305.
<https://doi.org/10.1109/ACCESS.2018.2849065>

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Received April 20, 2018, accepted June 9, 2018, date of publication June 19, 2018, date of current version July 6, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2849065

A Comprehensive Review on Constant Power Loads Compensation Techniques

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ABSTRACT Microgrid, because of its advantages over conventional utility grids, is a prudent approach to implement renewable resource-based electricity generation. Despite its advantages, microgrid has to operate with a significant proportion of constant power loads that exhibit negative incremental impedance and thus cause serious instability in the system. In this paper, a comprehensive review is presented on accomplished research work on stabilization of dc and ac microgrid. After reviewing these, microgrid system stabilization techniques are classified with required discussions. As found out in this paper, the stabilization techniques can basically be classified as compensation done: 1) at feeder side; 2) by adding intermediate circuitry; and 3) at load side. Finally, after analyzing the merits and drawbacks of each generalized technique, several infographics are presented to highlight the key findings of this paper.

INDEX TERMS Constant power load, feeder side compensation, load side compensation, negative incremental impedance, stabilization of ac microgrid, stabilization of dc microgrid.

I. INTRODUCTION

The power sector is experiencing an unprecedented shift in the entire system including the generation, transmission, and distribution, fueled by extensive research into next-generation energy systems and depleting conventional fuel resources. Due to availability in nature and environment-friendly power generation, power sector specialists and professionals are preferring to adopt renewable energy resources, as the ace up their sleeve, to face the next generation energy crisis. To utilize renewable energy resources, microgrid systems have been already constructed and employed to provide electricity in grid-isolated areas, and to meet general demand in industrial setup. Microgrid - a localized group of electricity sources and loads - functions as a single controllable entity and is synchronized with the conventional utility grid to provide support in case of greater demand. According to the physical and economic conditions, it can be operated independently and can be isolated from the utility grid in case of any unwanted situation [1], [2].

In the next generation power system, microgrid is a preferable option due to a number of reasons. Firstly, most of the industries, professional organizations, and academic

institutions require reliable power backup because of the uncertain and interrupted nature of power supply from the utility grid. The available power backups such as private generation, energy storage systems, and diesel engines are very expensive. By adopting a microgrid system, it is possible to get rid of that, and experience a cost effective and reliable solution during power crisis. Apart from that, considering a wider picture, it is possible to save billions of dollars if a few hundred summer peak hours can be managed by load shifting or load shaving techniques. Besides these, reliability is one of the key justifications to adopt microgrid systems in larger scale. China has already introduced microgrid systems widely and experienced appreciable performance with sustainability. Since ‘energy security’ is one of the prime concerns in the power industry, microgrids can offer that much-desired fidelity to the entire system. It is also possible to solve cyber security problems by employing microgrid systems due to their smaller operating zones and easy control technique [3], [4].

In the utility grid system, a considerable amount of power is lost due to transmission. In microgrid applications, this transmission loss can be minimized significantly. Besides

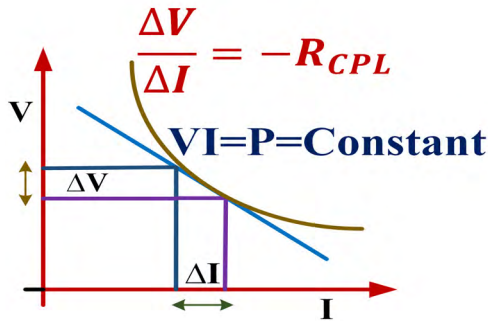


FIGURE 1. Negative impedance characteristic of CPL, the voltage decreases exponentially with increase in current [6].

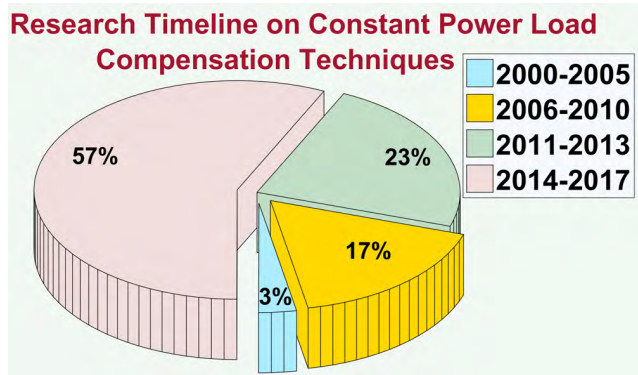


FIGURE 2. Research timeline based on the published research articles on Constant Power Load compensation techniques. It shows a trend of increased research in this field. More than half of the research works encountered for this study are published in 2014-2017 – marking this field as a very popular one in recent times.

that, it does not require investment on fuel to generate electricity, therefore overall costs can be minimized. The places where it is impossible to get utility grid connections can have the privilege of electricity regardless the transmission infrastructure by employing microgrid systems; hence it assures mass electrification [5]. With the advancement of technology, applications of power electronics devices are rising, thus increasing constant power loads (CPLs) at a tremendous rate which has huge effects on stability of power systems, especially in distributed power systems such as microgrids. Microgrids deal a lot with the increasing number of constant power loads (CPL) such as inverter-based loads. Constant power loads exhibit negative incremental impedance, and hence cause serious instability issues in the power system. Fig. 1 presents the negative incremental impedance characteristics of CPLs.

To compensate the CPL instability, a number of researches have been carried out around the world. Though researches regarding microgrid instability have been begun in early 1998-1999, with the growing industry of mass electrification, and eventually the microgrid technology, this issue has drawn attention of thousands of researchers around the world with passing time and increasing necessity. The research growth of Constant Power Load instability compensation is depicted in Fig. 2.

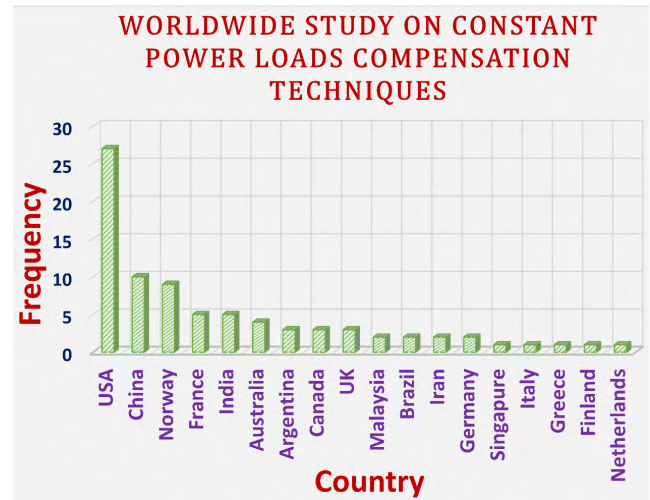


FIGURE 3. Country-based infographic on Constant Power Load instability compensation research around the world. USA leads this field and is clearly outrunning the others, with Norway projecting a solid chance to catch up China, which is currently in the second place.

From this illustration, it is evident that the research regarding the microgrid technology has considerably increased after 2010. To nullify any chance of misconception, it is necessary to mention that this comprehensive review is prepared based on research articles published up to May, 2016. Apart from that, though the United States of America is leading the microgrid technology and instability compensation research, China, Norway, France, and India are also contributing to this research in a significant manner. The country-based infographic for Constant Power Load instability compensation research in microgrid technology is illustrated in Fig. 3.

The contribution of this review article is delineated as follows. In section two, the generic as well as mathematical modeling of DC and AC microgrids are presented along with the simplified equivalent circuit diagrams. Section three, four, and five of this paper are dedicated to the investigations on cutting edge researches conducted on stabilizing DC and AC microgrids by the scientists, researchers, and professionals in recent time. In section six, after studying different techniques, we have classified three basic approaches to handle the instability problems and illustrated the subsections regarding the stabilization approaches. Besides that, several infographics are presented to delineate the review study from different aspects.

II. MODELING OF DC AND AC MICROGRIDS

According to the United States Department of Energy, a microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and it can be connected and disconnected from the grid to enable it to operate in both grid-connected or island mode. A microgrid is a small-scale power grid that can operate independently or in conjunction with the area’s main electrical grid. Any small-scale localized station with its own

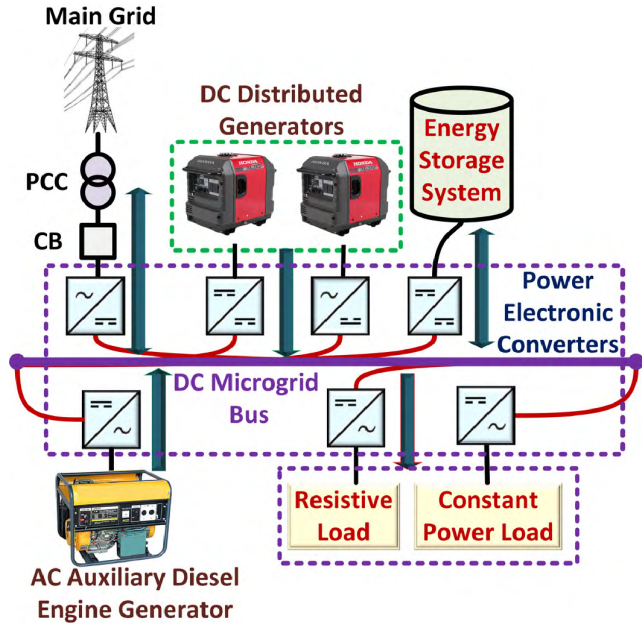


FIGURE 4. Generic modeling of DC microgrid system showing the constituent elements. The sources and the loads are connected to the microgrid bus through power converters configured to facilitate exchange of DC power with it, and the entire system links up to the main grid through the Point of Common Coupling (PCC).

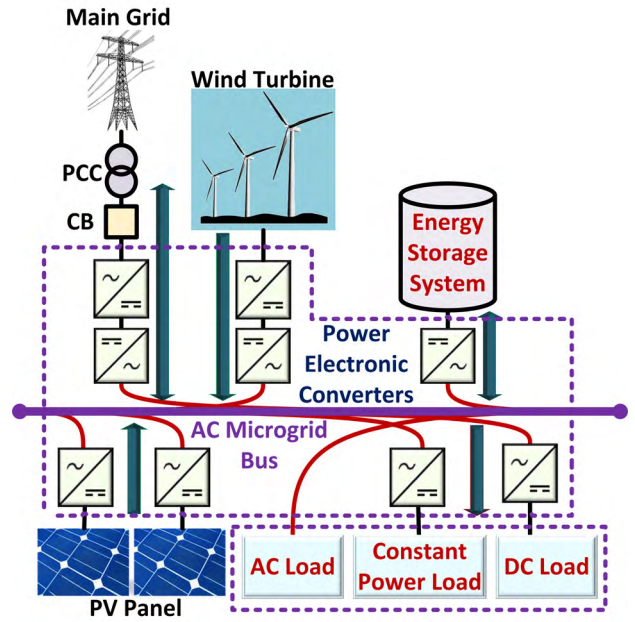


FIGURE 5. Generic modeling of AC microgrid system showing the constituent elements. The sources and the loads are connected to the microgrid bus through power converters configured to facilitate exchange of AC power with it, and the entire system links up to the main grid through the Point of Common Coupling (PCC).

power resources, loads, and definable boundaries qualifies as a microgrid. Based on the principle of power system the elements of microgrid can be operated both in AC and DC power systems. This section is dedicated to the modeling of DC and AC microgrid systems. At first, in Fig. 4 and Fig. 5, generic models of DC and AC microgrid systems are presented showing the constituent elements.

A detailed mathematical model of DC microgrid with constant power load (CPL) and constant voltage load (CVL) is shown in Fig. 6. The proportion of power shared between CPL and CVL for stability is changed to insure the desired stability condition. The transfer function of the system can be derived as shown in equation (1) [6].

$$\frac{V_o}{V_S} = \frac{1}{[(sL_{eq} + R_{eq})(sC_{eq} + \frac{1}{R_{CPL}} + \frac{1}{sL+R}) + 1]} \quad (1)$$

Where, V_0 = system input voltage, and V_S = system output voltage. The necessary conditions to maintain the system pole at the left half plane can be illustrated by,

$$a_0 = C_{eq}L_{eq}LR_{CPL} > 0 \quad (2)$$

$$a_1 = R_{eq}C_{eq}LR_{CPL} - L_{eq}L + C_{eq}L_{eq}RR_{CPL} > 0 \quad (3)$$

$$a_2 = L(R_{CPL} - R_{eq}) + L_{eq}(R_{CPL} - R) + C_{eq}R_{eq}RR_{CPL} > 0 \quad (4)$$

$$a_3 = R(R_{CPL} - R_{eq}) + R_{CPL}R_{eq} \quad (5)$$

$$b_1 = \frac{a_2a_1 - a_0a_3}{a_1} > 0 \quad (6)$$

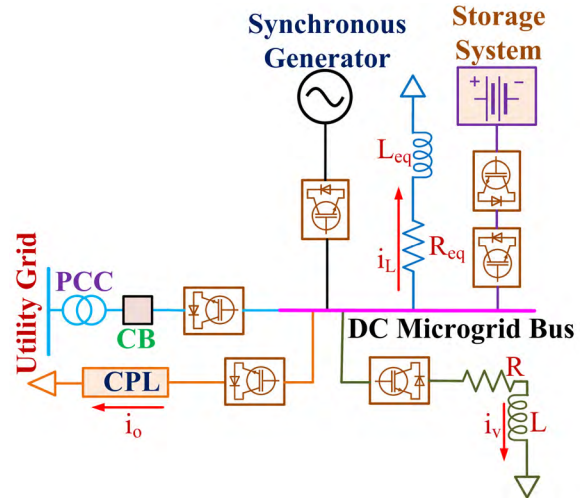


FIGURE 6. Mathematical model of DC microgrid for stability analysis. The CPL causes the bus voltage to be unbalanced.

From above stability conditions, two simple relations can be derived, which are,

$$\left\{ \begin{array}{l} R_{CPL} > \frac{RR_{eq}}{R + R_{eq}} \\ P_{CVL} + V_0^2 \frac{R_{eq}C_{eq}}{L_{eq}} > P_{CPL} \end{array} \right\} \quad (7)$$

From those conditions, we can conclude that, to be stable, the CPL power must be less than that of CVL and other system components combined. Power relation from the mathematical

model of DC microgrid is,

$$P_{CPL} > \frac{V^2 L_{eq} P_{CVL} + L_{eq} V^2 + L_{eq} V^2 + C_{eq} R_{eq} V^2 + L R_{eq} P_{CVL} + L R_{eq} P_{CVL}}{(L_{eq} V^2 + L R_{eq} P_{CVL})} \quad (8)$$

Where P_{CPL} is the power of constant power load and P_{CVL} is the power of constant voltage load. The power relation with reactive power compensation is shown in equation (9).

$$P_{CPL} > V^2 \frac{L L_{eq} + C_{eq} L L_{eq} + L_{eq} + R_{eq} + L_{eq} R + C_{eq} R R_{eq}}{L R_{eq} + L_{eq} R} \quad (9)$$

Since the proportion of constant power load is increasing in advanced power system applications, it is necessary to take care or handle the real and reactive power compensations independently for the sake of stability of microgrid. In particular cases, storage systems are used to provide high power density with quick charging and discharging time to maintain transient and steady state instability introduced by CPLs; hence point load compensation has to be adopted.

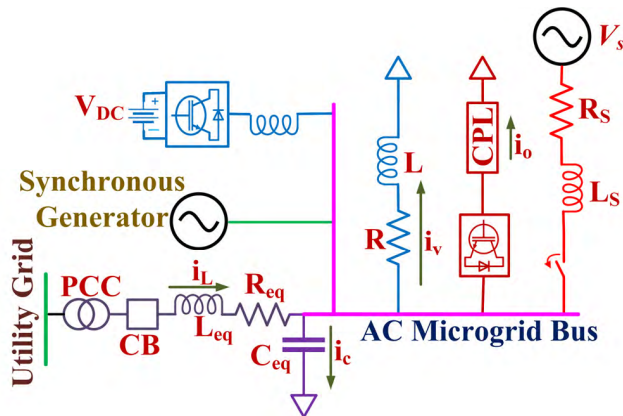


FIGURE 7. Mathematical model of AC microgrid for stability analysis. The CPL causes the bus voltage to be unbalanced. The R-L load, with i_v current flowing, represents CVL.

Then, a detailed mathematical model of AC microgrid with constant power load (CPL) and constant voltage load (CVL) is shown in Fig. 7. CVL is represented as an R-L load which is much more practical and simplified for using RMS value and unity power factor. This model represents microgrid as an arrangement where the V_o and stability margin vary with the change of R_{eq} , L_{eq} , and C_{eq} .

Simplified equivalent circuit of AC microgrid connected with conventional utility grid for further stability analysis is represented in Fig. 8. The equation (10) for governing rotor motion of a synchronous machine is based on the elementary principle in dynamics known as swing equation which states that accelerating torque is the product of the moment of inertia of the rotor times its angular acceleration.

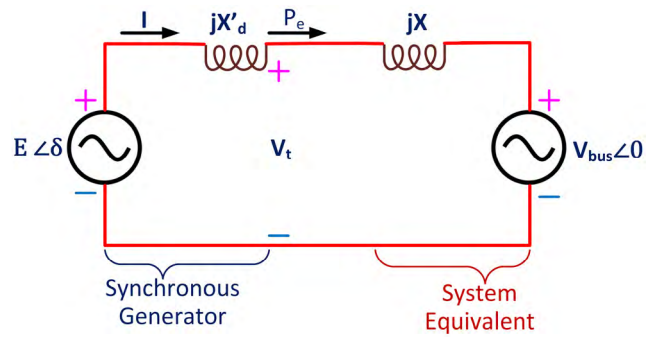


FIGURE 8. Simplified equivalent circuit of AC microgrid. The ‘Synchronous Generator’ part resembles the loads, while the ‘System Equivalent’ portion represents the rest of the system with loads.

This equation can be written for the synchronous generator in the following form [7]:

$$J \alpha_m(t) = J \frac{d^2 \delta}{dt^2}(t) = T_m(t) - T_e(t) = T_a(t) = J \frac{d \omega_m}{dt}(t) \quad (10)$$

Where, J is the total moment of inertia of the rotor masses. α_m is the rotor angular acceleration. δ is the angular displacement of the rotor with respect to stationary axis. ω_m is synchronous generator rotor speed. T_m is the mechanical torque, T_e is the net electrical torque and T_a is the net accelerating torque. Therefore, we can write equation (11) in per unit in the form,

$$\frac{2H}{\omega_s} \frac{d \omega}{dt}(t) = P_{mp} \cdot u(t) - P_{ep} \cdot u(t) \quad (11)$$

For a system with an electrical frequency of f Hertz the equation becomes,

$$\frac{H}{\pi f} \frac{d \omega}{dt}(t) = P_{mp} \cdot u(t) - P_{ep} \cdot u(t) \quad (12)$$

$$\frac{H}{\pi f} \frac{d \omega}{dt}(t) = P_{mp} \cdot u(t) - P_{ep} \cdot u(t) - D(\omega_s(t) - \omega_m(t)) \quad (13)$$

Where, P_m is the mechanical power input while P_e is the electrical power output, D is the Damping coefficient and H is the inertia constant. Now from the Fig. 8 we get,

$$I = \frac{E e^{j\delta} - V_t}{j X_g} \quad (14)$$

$$S = P + jQ = V_t I^* = \frac{E V_t (j \cos \delta - \sin \delta) - j V_t^2}{X_g} \quad (15)$$

Where, S is the complex power and X_g is the positive sequence synchronous reactance. Therefore, the delivered real and reactive power will be,

$$P = \text{Re } S = -\frac{E V_t}{X_g} \sin \delta \quad (16)$$

$$Q = \text{Im } S = \frac{V_t}{X_g} (E \cos \delta - V_t) \quad (17)$$

Which indicates real power increases when δ decreases. The above equations are derived by analyzing the operating

TABLE 1. Factors concerning microgrid stability.

Stability Region	Factors/Parameters and Their Influence on Microgrid Stability			
	Factors/Parameters	Stability Type	Influence on Stability	
Feeder Side	System Frequency (f)	S	High	
	Feeder Impedance (Z=R+jX)	S	Medium	
	d-axis Voltage (V _d)	S	Medium	
	q-axis Voltage (V _q)	S	High	
	d-axis Current (I _d)	S	Medium	
	q-axis Current (I _q)	S	High	
	Voltage/Generation Mismatch (ΔS)	T/S	High	
Intermediate Circuits	Filters	S	Medium	
	Microgrid Line Impedance (Z _L)	S	Medium	
	Voltage Source Converters(VSC)	T/S	Medium	
	Compensation Arrangement	Control flexibility	T/S	High
		Reactive power capability		
		Harmonics		
		Losses		
Time domain specification				
	Phase balancing ability			
Load Side	Constant Power Load (CPL)	T/S	High	
	Equivalent Resistance (R _{eq})	S	Low	
	Equivalent Inductance (L _{eq})	S	Medium	
	Equivalent Capacitance (C _{eq})	S	High	
	CVL Resistance (R _{CVL})	S	Low	
	CVL Inductance (L _{CVL})	S	Medium	
	Virtual Capacitance (C _B)	S	High	
	Virtual Inductance (L _B)	S	Low	
	d-axis Power (P)	S	Medium	
	q-axis Power (Q)	S	High	
	Nominal Voltage (V _N)	S	Medium	
	Distributed Generators Ratings	DC Voltage	T/S	Medium
Energy Storage System	Transformer Ratings	T/S	High	
	VSC Losses			
	Source Impedance			
	Filter Capacitance			
	Droop Coefficients			
	Sudden Change in Load			T
Energy Storage System	Voltage Level	T/S	Medium	
	Storage Capacity			
	Internal Impedance			
	Time domain specification			

Steady-State = S, Transient = T, High = High, Medium = Medium, Low = Low.

principle of synchronous generators. Active power is regulated via control of the voltage phase difference between synchronous generator and point of common coupling while reactive power can be regulated by controlling the voltage magnitude difference to alleviate the effect of the stability issues in the microgrid.

III. MICROGRID STABILITY

For a given initial operating condition, the ability to regain a state of operating equilibrium after being subjected to any

kind of physical disturbance is considered as the stability of microgrid. The stability of microgrid is dependent on the factors and parameters of the elements of microgrid, and varies accordingly. Table 1 precisely depicts the factors which affect the microgrid stability. From this table, it is evident that there are mainly three stability regions in the microgrid systems such as feeder side, intermediate circuitry, and load side. In the feeder side of a microgrid system, the stability depends on certain parameters such as system frequency, feeder impedance, d-axis voltage, q-axis

voltage, d-axis current, q-axis current, and voltage/generation mismatch. The influence of these parameters on the system stability is rated in this table, based on rigorous literature review. In the intermediate circuitry of a microgrid system, the stability depends on several parameters such as control flexibility, reactive power capability, harmonics, losses, time domain specification, phase balancing ability, etc. Then, in the load side of a microgrid system, the stability of a system depends on a number of parameters such as constant power load, equivalent resistance, equivalent inductance, equivalent capacitance, virtual inductance, virtual capacitance, d-axis power, q-axis power, nominal voltage, sudden changes in load, energy storage system, and so on. The ability of these parameters to influence the system stability is rated in this table based on comprehensive review of available literature.

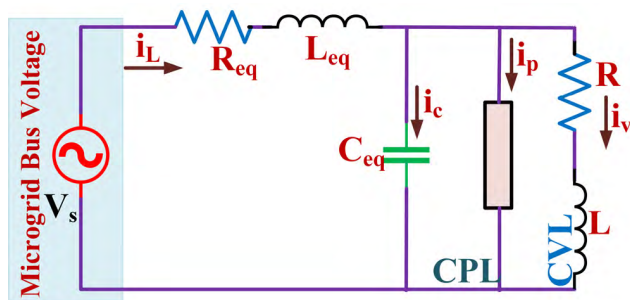


FIGURE 9. Schematic diagram of microgrid with CPL [6]. R_{eq} , L_{eq} , and C_{eq} represent the equivalent circuit for transmission lines connecting the microgrid bus to the loads.

A general microgrid with two distributed generators supplying a CPL is studied in [8]. It shows the dependence of stability on the proportion of CPL and constant impedance load (CIL). It also outlines simple methods of improving stability by changing the R/L value of distribution feeders, increasing capacitance by adding capacitors or by raising the bus voltage level showed in Fig. 9. However, modifying the distribution feeders is often not a feasible option and adding capacitance to stabilize a system is comparatively expensive. Similarly, increasing the bus voltage may not be an option since most of the protection devices only work at certain voltages and that cannot be changed. Thus, alternative methods are being investigated to provide stability for microgrids. The research works on CPLs in microgrid applications are categorized into two sections: DC microgrid applications, and AC microgrid applications. The majority of the work on control techniques for microgrid stabilization falls under the former category.

IV. REVIEW ON DC MICROGRID STABILITY

To ensure the required simplicity to comprehend the findings of the reviewed research articles, this comprehensive review categorizes all the published researches on DC microgrid stability into three sub-sections: Modeling and Analysis, Controller Intervention, Novel Techniques and Tools.

A. MODELING AND ANALYSIS

Su et al. [9] analyzed the factors which engendered major instability in a DC microgrid with multiple DC-DC converters. Khaligh [57] modeled an analog CPL which is shown in Fig. 10.

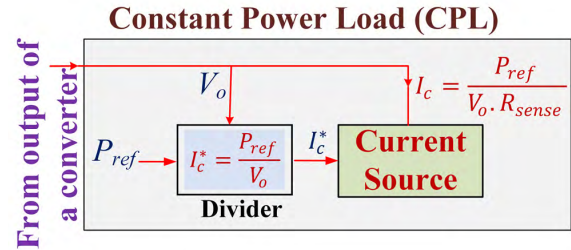


FIGURE 10. Model of analog CPL [10]. The divider divides the reference power, P_{ref} by V_o to generate the command current I_c^* , which is sent to the current source.

In the course of their research, they presented two stabilization methods for two operation modes: constant voltage source mode, and droop mode. On another occasion, Sanchez and Molinas [10] presented an approach to estimate the grid impedance by using two different techniques: the Kalman filtration method, and the recursive least squares method. After that, Liu et al. [11] and Khaligh et al. [12] worked on modeling and small-signal stability analysis of an islanded DC microgrid with dynamic loads. It is difficult to identify a system's stability characteristics for a large complicated system. Leonard [13] has proposed the Volterra Series to model nonlinear responses of constant power loads through Volterra kernel measurement by using a switch-mode power converter to synthesize large-signal perturbations to measure frequency domain Volterra kernels. Cupelli et al. [14] adopted the particle swarm optimization algorithm to find the best values of the parameters. Besides that, Islam and Anand [15] from IIT Kanpur focused on stability analysis of microgrid treating the converter interfaced loads as constant power loads. Eigenvalue analysis of highly nonlinear loads is shown by Zhao et al. [16]. To improve the stability scenario of DC microgrid system, several linear and nonlinear control techniques have already been adopted. A control design procedure based on linearization via state feedback, is proposed in [17] to mitigate CPL destabilization effects and to ensure medium voltage DC bus voltage stability. A control algorithm for a DC-DC boost converter with CPL is proposed to ensure stability and fast response of the system while making it robust to load variations in [18]. In [19], stability of equilibrium and an estimation of the region of attraction are investigated for cascaded system in the DC distribution power system based on Lyapunov linearization and Brayton-Moser's mixed potential theory.

The system state variables are shown in equation (18):

$$\begin{cases} x_1 = i_e - i_{eo} \\ x_2 = v_s - v_{so} \\ x_3 = v_{slf} - v_{so} \end{cases} \quad (18)$$

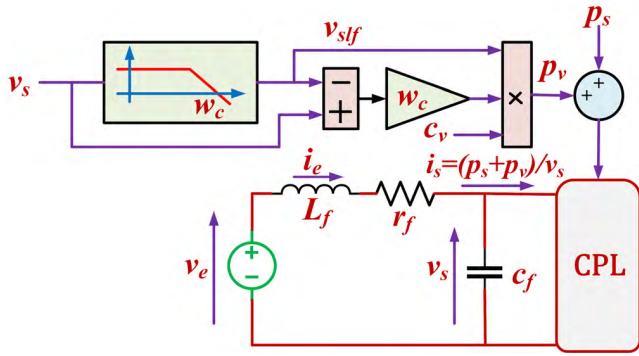


FIGURE 11. Model of a system with virtual capacitor current absorbed by the load [22].

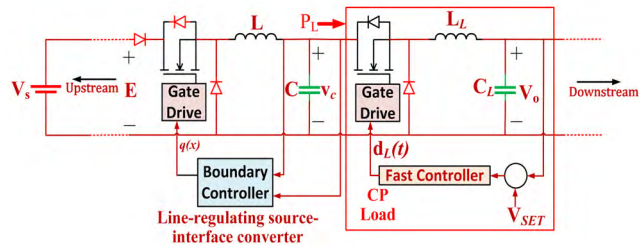


FIGURE 12. Circuit schematic showing a line-regulating source-interface converter on the left feeding a CPL on the right [23].

With

$$I_{eo} = \frac{p_{so}}{v_{so}} \quad (19)$$

$$v_{so} = \frac{V_e + \sqrt{V_e^2 - 4p_{so}r_f}}{2} \quad (20)$$

Coupling two systems together can allow the oscillating characteristics of the two systems to dampen each other out [20]. The systems may have slightly different characteristics, usually different inductances, or they may be identical but coupled with a small delay factor. Mathematical analysis for such two systems has been done to find the region of stability. Sanchez and Molinas [21] introduces a comprehensive analysis with the nonlinear tools for stability in operating systems influenced by interconnections of power electronics, and delivered by the discrete generation. Here, systems such as renewable as well as non-renewable energy sources can easily supply power to the microgrid, and their loads function as CPL. Hence, the inspection of Hopf bifurcation points is applied to prevent oscillations and instabilities in the operating system. A non-linear stabilization block is implemented in [22] to stabilize the system by increasing the dc-link capacitance. Model of the system with virtual capacitor current absorbed by the load, which has been used here is shown in Fig. 11. A designed boundary for DC-AC buck converters is examined in [23]. Fig. 12 shows a line-regulating source-interface converter used for CPL in [23].

Thus, the current through a general practical instantaneous CPL is given by equation (21), where V_{lim} represents the

voltage limit in volts.

$$i(t) = \begin{cases} 0, & \text{if } v(t) < V_{lim} \\ \frac{P_L}{v(t)}, & \text{if } v(t) > V_{lim} \end{cases} \quad (21)$$

When the switch is ON, the dynamics of the line-regulating source-interface buck converter, shown on the left side of Fig. 12, is governed by equation (22).

$$f_{ON}(x_1, x_2) = \begin{bmatrix} \frac{dx_1}{dt} \\ \frac{dx_2}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{L}(E - x_2) \\ \frac{1}{C}(x_1 - \frac{P_L}{x_2}) \end{bmatrix} \quad (22)$$

$$x_1 \geq 0, \quad x_2 > 0 \quad (23)$$

In [24], a compensator is designed by deriving the input impedance of CPL, and the output impedance of the filter. A model of a tightly regulated practical converter is presented in [25] which maintains the amount of added damping to stable the feeder converter. On another occasion, Awan *et al.* [26] addressed global stability analysis regarding electrical systems consisting of DC power supply, an actuator, and an LC Filter. In this case, they used Circle Criterion to study the global stability of the system. Jusoh [27] has presented an analysis of Constant Power Load instability of DC microgrids by using small signal analysis and passive damping method.

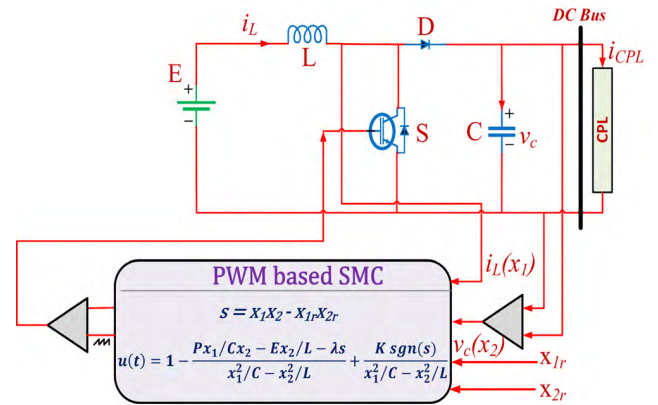


FIGURE 13. Implementation scheme of the proposed PWM-based SMC [29]. Inputs from the system will be used to control the switching operation through a control function.

B. CONTROLLER INTERVENTION

For building virtual resistance in the source side converter, a stabilizing method is proposed in [28]. Similarly, at [29], to limit the CPL instability in a certain level, Suresh Singh and Deepak Fulwani proposed a non-linear sliding surface which confirmed the constant power (Fig. 13). Maintaining this by using converters, the CPL's oscillating effect due to negative incremental impedance has been controlled considerably. Hence, DC microgrid stability has been maintained despite the continuously increasing proportion of CPL load in grid arrangement. After this, to investigate the

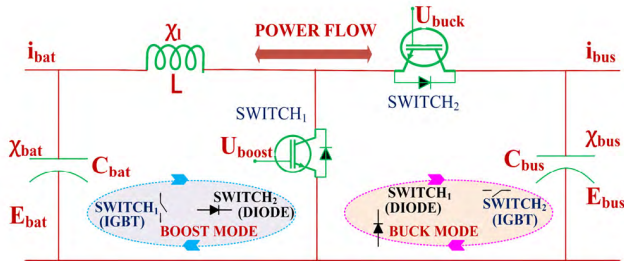


FIGURE 14. Equivalent circuit of DC/DC bidirectional converter (BDC). It is created neglecting equivalent series resistance of the capacitor and inductor, which in turn, makes the instabilities caused by CPL prominent [31].

CPL instability consequences with the increasing number of constant power loads, Gautam *et al.* [30] adopted a novel sliding mode controller and presented appreciable results. Besides that, Cupelli *et al.* [31] investigated the application of adaptive back-stepping to deal with the voltage stability of the DC microgrid. The state-space averaged model of the equivalent circuit of DC/DC bidirectional converter (BDC) from [31] (showed in Fig. 14) in charging mode is given by equation (24).

$$\left\{ \begin{array}{l} \dot{x}_1 = \frac{1}{L} [E_{bus} u_{buck} - x_{bat}] \\ \dot{x}_{bat} = \frac{1}{C} [x_1 - i_{bat}] \\ E_{bat} = x_{bat} \end{array} \right\} \quad (24)$$

A precise geometric control using circular switching surfaces is proposed for CPL-based electric vehicle’s power system by Anun *et al.* [32], [33]. For the particular case of DC microgrid, instead of over-linearizing, sliding mode control technique – with nonlinear modeling of the system– has been adopted by the researchers. By using a sliding mode controller, a sliding surface has been established to stabilize the voltage of the entire system [34]. A sliding-mode duty-ratio controller (SMDC) is introduced for DC/DC buck converters with CPL in [35]. Apart from that, for the automotive power systems, Srinivasan and Kwasinski [36] presented an autonomous control technique of a DC microgrid. Next, to manage the DC bus voltage stability appreciably, Stramosk and Pagano [37] designed a unique sliding mode controller. Linear and non-linear controllers can also be used, but the former cannot guarantee global stability of the desired equilibrium point, and the latter is very challenging in its design and changes with each system’s parameters. Stabilizing power can be generated and sent to the load power reference for slightly modifying the CPL behavior of the load. Using such a constrained optimization technique, a method to design the stabilizing system is proposed in [38]. Start-up and step response of an average current-controlled buck converter with CPL is analyzed in [39] based on phase portrait method through design criteria rules and proper current-limiting values. Modeling and analysis of DC microgrid done in different research works are tabulated in Table 2.

C. NOVEL TECHNIQUES AND TOOLS

Virtual impedance based compensation technique is analyzed for DC microgrid by Lu *et al.* [40]. Besides that, a review on DC microgrid control system is represented at [41]. Srinivasan and Kwasinski [42] presented a stability analysis of DC microgrid using the droop loop control technique. Cezar *et al.* [43] researched on stability of interconnected DC converters. In particular, this paper addressed the stability issues of DC networks with CPLs. Lu *et al.* [44] proposed a virtual resistance-based method to improve the stability status of DC microgrid by an impedance matching approach. A multi-converter with a centralized stabilizer for a DC microgrid is designed by Zadeh *et al.* [45]. Besides that, Ashourloo *et al.* [46] addressed stability problems of CPLs and proposed a simple active damping strategy to efficiently dampen the oscillations caused by CPLs. The transfer function for the cascade distributed power architecture used in this work (showed in Fig. 15) is given by equation (25).

$$V_{out}(s) = d(s) \cdot V_{in} \cdot \frac{1}{L_s C_s s^2 + (\frac{L_s}{R} + R_L C_s) s + (1 + \frac{R_L}{R})} \quad (25)$$

By implementing the proposed active damper, the equations of LRC loads are changed as follows:

$$L I_L(s) \cdot s = d(s) \cdot V_{in} - V_{out}(s) - R_L I_L(s) - \frac{k \cdot s}{s + \omega_c} \cdot V_{out}(s) \quad (26)$$

$$C V_{out}(s) \cdot s = I_L(s) - \frac{V_{out}(s)}{R} \quad (27)$$

Coupling two systems together can allow the oscillating characteristics of the two systems to dampen each other out [20], [47]. The systems may have slightly different characteristics, usually different inductances, or they may be identical but coupled with a small delay factor. Mathematical analysis for two systems has been done to find the region of stability. It is cumbersome to identify the system’s stability characteristics for a large complicated system. Active damping for boost converters with CPLs is provided through current mode control, which is described in [48]; and passive damping circuit is added with filter elements in [49] to stabilize the system. Various stabilization strategies such as load shedding, addition of resistive loads, and filters are explored in [50] to mitigate the stability issues in DC microgrids with instantaneous CPLs. Loop cancellation, a novel nonlinear feedback, is introduced in [51] to counter the effect of CPL by implementing different types of converters. This technique is shown in Fig. 16.

By implementing this nonlinear feedback loop, the equations (28-29) of the system are changed as follows:

$$i_L = \frac{1}{s \cdot L} \cdot (\frac{V_{FB}}{V_{Tr}} \cdot v_{in} - v_o) + \frac{V_{in}}{L \cdot V_{Tr}} \cdot \frac{K_{FB}}{v_o} \quad (28)$$

$$v_o = \frac{1}{s \cdot C} \cdot (i_L - \frac{v_o}{R_{Load}} - \frac{P_{CPL}}{v_o}) \quad (29)$$

TABLE 2. Modeling and analysis of DC microgrid.

Reference	University	Authors	Year	Stability Region	Analysis Method/ Control Technique	Simulation/ Experimental Platform	Domain	Design Approach
[9]	Central South University, Changsha, China	Zhangjie Liu et al	March, 2016	•	Constant Voltage Source mode, Droop mode	Simulink	T	
[10]	Norwegian University of Science and Technology, Trondheim, Norway	Santiago Sanchez et al	March, 2015	◆	Kalman filter, Recursive least squares method	OPAL-RT, Simulink	T & F	≈
[11]	College of Automation, Harbin Engineering University, China	Sheng Liu et al	June, 2015	◆	Small signal analysis	Simulink, PLECS	T	⊥
[12]	Illinois Inst. of Technol., Chicago	Alireza Khaligh et al	July, 2007	◆	Fixed frequency digital control, Continuous mode.	MATLAB	T	≈
[13]	Florid State University	Jesse Leonard	2015	•	Large signal perturbations, Frequency domain Volterra kernels	PLECS	T & F	⊥
[14]	Institute for Automation of Complex Power Systems, RWTH Aachen University, Germany	Marco Cupelli et al	October, 2014	•	Linearizing feedback, Synergetic Control	Opal-RT	T	
[15]	Institute of Technology, Kanpur, India	Shirazul Islam et al	2014	◆◆	Small signal analysis, Droop control	Simulink	T & F	
[16]	Institute of Electrical Engineering, Chinese Academy of Sciences, China	Fei Zhao et al	October, 2014	•	Small-signal Model, Lyapunov Stability Theory	N/A	F	⊥
[17]	University of Trieste Trieste, Trieste, Italy	Giorgio Sulligoi et al	2014	•	Linearization via state feedback	Simulink, RTDS	T & F	
[18]	Univ. of Nebraska-Lincoln, Lincoln, USA	Jianwu Zeng et al	August, 2014	•	Interconnection and Damping assignment passivity	Simulink	T	≈
[19]	Zhejiang University, China	Weijing Du et al	April, 2013	•	Lyapunov linearization	Computer Program, AP300	T & F	
[20]	Clarkson University, Potsdam, USA	Stanley R. Huddy et al	January, 2013	◆	Amplitude death methods	dde-biftool	T	≈
[21]	Norwegian University of Science and Technology, Trondheim, Norway	Santiago Sanchez et al	September, 2012	◆	Hopf bifurcation	N/A	F	≈
[22]	Institut National Polytechnique de Lorraine, France	Pierre Magne et al	June, 2012	•	Large signal study	Simulink	T	⊥
[23]	The University of Texas at Austin, Austin, USA	Chimaobi N. Onwuchekwa et al	August, 2010	◆	Large signal analysis	Simulink	T	⊥
[24]	University, Vandoeuvre-Lès-Nancy, France	Pisit Liutanakul et al	February, 2010	•	Oscillation compensation technique, Small signal analysis	Simulink	T & F	≈
[25]	Inst. of Technol., Chicago, IL	Amir M. Rahimi et al	July, 2009	•	Damping methods	CCM	F	≈
[26]	Nancy University, France	Ahmed-Bilal Awan et al	September, 2009	◆	Circle Criterion	Simulink	T & F	⊥
[27]	Univ. Teknologi Malaysia, Malaysia	A. B. Jusoh	November 2004	•	Small singal analysis, Passive Damping method	Simulink	T & F	≈

Feeder side = •; Intermediate Circuitry = ◆; Load side = ■; Time=T; Frequency=F; Linearized= ||; Nonlinear = ≈; Hybrid= ⊥

Introducing new variables, in terms of parameters, the power can be derived as,

$$P_1 = \frac{V_{in}}{L \cdot V_{Tr}} \cdot (K_{FB} - \frac{V_{Tr} \cdot L \cdot P_{CPL}}{V_{in}}) \quad (30)$$

Kwasinski and Onwuchekwa [52] outlined the typical strategies for mitigating the problems of CPL in DC microgrids. In this discussion, the effect of adding filters and

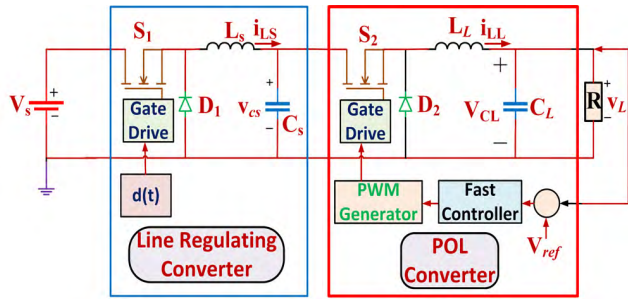


FIGURE 15. A cascade distributed power architecture [46], here a line regulating converter and a point of load (POL) converter is used one after the other. Here, V_s is the input voltage (V_{in}), and v_L is the output voltage (V_{out}).

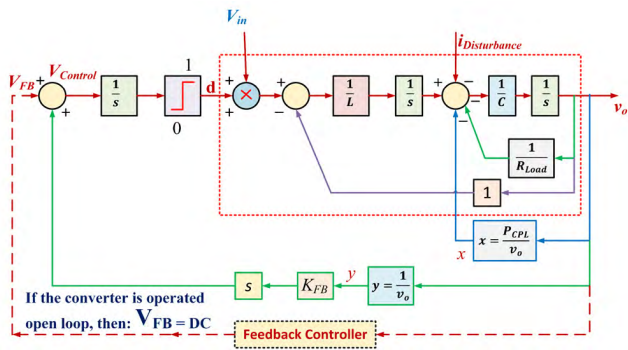


FIGURE 16. Block diagram representation of a buck converter with the loop-cancellation technique implemented [51].

capacitors was studied. But, this is an expensive system with the additional problem of capacitor failure which increases with rated voltage. Load shedding of CPLs can restore stability, but this is of little practical value since it only temporarily restores the system without increasing long-term capacity. A novel active-damping technique on DC/DC converters is shown in [53]. The mechanism of instability and oscillation along with some passive methods for compensating CPLs are explained and a novel method of compensating CPLs-based on the feedback linearization technique of nonlinear system have been proposed by Rahimi [54], which is a comprehensive overview of the stabilizing control methods for power electronic converters. A novel stabilizing control strategy to eliminate the destabilizing elements of CPL is described in [55] by reformulating the system dynamic equations. To stabilize the system, an input filter state feed-forward stabilizing controller is presented in [56]. Khaligh [57] has proposed a fixed frequency pulse adjustment digital control technique to mitigate the constant power load instability.

V. REVIEW ON AC MICROGRID STABILITY

To assure the required simplicity to comprehend the findings of a number of research articles, this comprehensive review categorizes all the published researches on AC microgrid stability into three sub-sections: Modeling and Analysis, Controller Intervention, Novel Techniques and Tools.

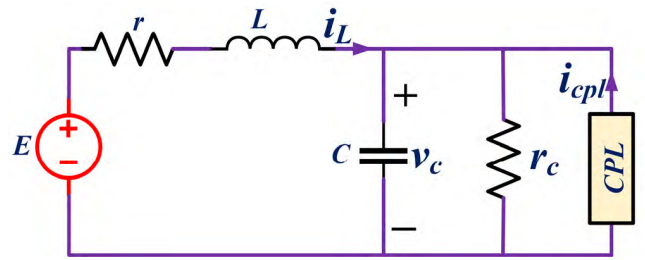


FIGURE 17. Linear RLC circuit with a CPL, where the RLC circuit is used as a filter, r_c is a resistive load which represents constant voltage loads (CVL) [59].

A. MODELING AND ANALYSIS

To improve the stability scenario of the AC microgrid system, several linear and nonlinear control techniques have already been adopted. Pre-planned switching events and fault events that lead to islanding of a distribution subsystem and formation of microgrid is analyzed in [58]. Considering linear and non-linear time invariant behavior described by a port-Hamiltonian model with constant dissipation and switching interconnected matrix, the condition of existence of equilibria for electrical system with external sources and CPLs is investigated in [59]. Fig. 17 shows a linear RLC circuit with a CPL, used for the investigation done in [59].

And the transfer function:

$$G(s) = \frac{Ls + r}{LCs^2 + (rC + \frac{L}{r_c})s + \frac{r}{r_c} + 1} \tag{31}$$

Because of higher power efficiency of active damping over passive damping, a summary and classification of existing active damping techniques is explored in [60]. Fig. 18 shows a CPL connected to a AC power system by their equivalent circuits, which has been used in [60]. Controller intervention of DC microgrid done in different research works are tabulated in Table 3.

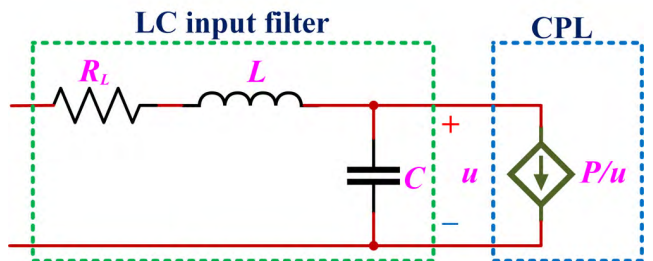


FIGURE 18. A CPL in AC power system with their equivalent circuit, an LC input filter is added before the CPL [60].

The operation of the cascaded system with linear methods can be described by equation (32).

$$\begin{cases} \frac{di}{dt} = -\frac{R_L}{L}i - \frac{1}{L}u + \frac{1}{L}V_{in} \\ \frac{du}{dt} = \frac{1}{C}i - \frac{P + P_{stab}}{Cu} \end{cases} \tag{32}$$

TABLE 3. Controller intervention of DC microgrid.

Reference	University	Authors	Year	Stability Region	Analysis Method/ Control Technique	Simulation/ Experiment Platform	Domain	Design Approach
[28]	Univ. of Sydney, Sydney, NSW, Australia	Mingfei Wu et al	July 2015	●	Virtual Resistance	Oscilloscope	T & F	≈
[29]	Indian Institute of Technology Jodhpur, Jodhpur 342 011, India	Suresh Singh et al	January 2015	●	Non-linear sliding surface	OPAL-RT, Simulink	T	⚡
[30]	Indian Institute of Technology Jodhpur, Rajasthan, India	A. R. Gautam et al	July 2015	●	Sliding mode controller	Simulink	T	⚡
[31]	Institute for Automation of Complex Power Systems, RWTH Aachen University, Germany	M. Cupelli et al	June 2015	●	Adaptive back-stepping	Simulink	T	≈
[32]	Univ. of British Columbia, Vancouver, BC, Canada	Anun M. et al	April 2014	◆	Geometric control using circular switching surfaces	MATLAB	T	⚡
[33]	University of British Columbia, Vancouver, BC, Canada	Matias Anun et al	September 2014	●	Sliding mode controller	MATLAB	T	⚡
[34]	Indian Institute of Technology Jodhpur, Rajasthan, INDIA	Suresh Singh et al	November 2014	●	Sliding-mode controller with a non-linear sliding surface	Simulink	T	⚡
[35]	Univ. of Nebraska-Lincoln, Lincoln, NE, USA	Yue Zhao et al	April 2014	●	Sliding-mode duty-ratio controller (SMDC)	Simulink	T	⚡
[36]	The University of Texas at Austin, USA	Mahesh Srinivasan et al	Decmber 2014	◆	Autonomous control technique	Oscilloscope	T	≈
[37]	Fed. Univ. of Santa Catarina, Florianopolis, Brazil	Vinicius Stramosk et al	October 2013	●	Sliding mode controller	PSIM simulator	T	⚡
[38]	University of Lorraine, GREEN Laboratory, France	Pierre Magne et al	June 2012	◆	Fault tolerant multi-agents stabilization system	MATLAB	T & F	≈
[39]	University of Aeronautics and Astronautics , Nanjing, China	Fanghua Zhang et al	January 2011	◆	Average current-controlled buck converter	Saber	T	≈

Feeder side = ●; Intermediate Circuitry = ◆; Load side = ■; Time=T; Frequency=F; Linearized= ||; Nonlinear = ≈; Hybrid= ⚡

Apart from that, a three phase AC system has been discussed in [61]. Instead of the conventional frame analysis, here, researchers have presented dq frame analysis for small signal stability. Romlie *et al.* [62], presented the stability of CPL-based microgrid system as a function of system parameters. Here, they used PSCAD simulation to investigate the stability issues for distributed power systems. After that, to identify the stability condition for AC microgrid arrangement, Liu *et al.* [63] have proposed a technique using Nyquist Stability Criterion with considerable results. A brief discussion on small-signal analysis methods for AC distributed power system and the utilities concerning the methods is presented in [64] with state-space modeling as well as their limitations. Heskes *et al.* [65] discussed on negative differential impedance load. They analyzed its effect on voltage stability in case of localized grid system. Next, in [66], an observer-based controller adopting input/output feedback linearization has been presented with adequate robustness analysis of the proposed technique for AC microgrid system regarding

parametric uncertainties. A brief examination on protection issues in AC microgrids and an analysis of each proposed method of protection issues concerning stability is represented in [67]. After that, Emadi [68] has modeled CPL load considering the negative incremental loading characteristics (shown in Fig. 19). In this course, he used generalized state space averaging method. By using this for AC distribution system, he has presented a detailed assessment in his paper. Small-signal transfer function of the circuit of Fig. 19 is expressed by equation (33).

$$\frac{\tilde{v}_o}{\tilde{v}_{ac}} = \frac{RR_{CPL}(\cos(\alpha) + s\frac{\sin(\alpha)}{\omega})}{As^3 + Bs^2 + Cs + D} \quad (33)$$

Where

$$A = \frac{L_{eq} \cdot C_{eq} \cdot RR_{CPL} \sin(\alpha)}{\omega} \quad (34)$$

$$B = \frac{L_{eq} + C_{eq}RR_{eq}}{\omega} RR_{CPL} \sin(\alpha) + L_{eq}C_{eq}RR_{CPL} \cos(\alpha) \quad (35)$$

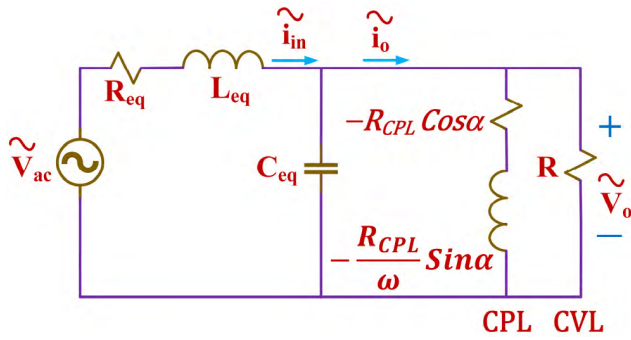


FIGURE 19. Small-signal equivalent circuit of a system with constant power loads (CPL) and constant voltage loads (CVL) connected to a conventional bus with controlled rectifiers [68].

$$C = R_{eq} \left(\frac{R_{CPL} \sin(\alpha)}{\omega} + C_{eq} R R_{CPL} \cos(\alpha) \right) + L_{eq} (R_{CPL} \cos(\alpha) - R) + \frac{R R_{CPL} \sin(\alpha)}{\omega} \quad (36)$$

$$D = R_{eq} (R_{CPL} \cos(\alpha) - R) + R R_{CPL} \cos(\alpha) \quad (37)$$

B. CONTROLLER INTERVENTION

A mix sensitivity based repetitive controller is proposed in [69] along with non-linear loads and PI regulator. To control a nonlinear system, sliding mode and Lyapunov Redesign control techniques are implemented along with PID controller to maintain constant terminal voltage of CPL via current injection method from storage in [6]. Novel techniques and tools for DC microgrid proposed in different research works are tabulated in Table 4. Modeling and analysis of AC microgrid done in different research works are shown in Table 5.

This paper suggests that load side stability management is the key to microgrid system stability and that is why we select load side compensation. Moreover, load side compensation is point load compensation – which means it can be accomplished in the exact point we desire. Microgrid loads can be categorized into several types including controllable loads, and critical loads. Controllable loads include electric vehicle charging stations, heat pumps etc.; data center, security systems etc. fall into the category of critical loads. Critical loads consisting of both constant power loads (CPLs) and constant voltage loads (CVLs) require proper attention for better performance. And to ensure that, managing those sensitive loads from the load side is the best way of compensation to maintain system stability. In microgrid applications, it is good practice to use load side compensation of CPL instabilities due to combination of CPLs and CVLs. In this practice, we can combine all CPLs in one single branch to handle their voltage collapse phenomena. Various power sharing control schemes and controllers are illustrated in [70]. Control structure of conventional *P/f* and *Q/V* droop control that is demonstrated here is shown in Fig. 20. The droop functions can be expressed as equation (38):

$$\begin{cases} \omega = \omega_0 - m_p \cdot (P - Q) \\ E_0 = E - n_Q \cdot (P + Q) \end{cases} \quad (38)$$

A framework for voltage source converter independent of any type of source with reduced computational complexity is presented for stability study of AC microgrid in [71]. Constant power mode operation of VSC that is demonstrated here is shown in Fig. 21.

The dynamics of a Class 2 load group can similarly be formulated as follows:

$$\begin{cases} p(x_{C2}) = \hat{f}_{x,C2}(i_{\sum C2}^{t,DQ}, v_{C2}^{t,DQ}, \omega_g, x_{C2}, \hat{\lambda}_{C2}) \\ p(i_{\sum C2}^{t,DQ}) = \hat{f}_{i,C2}(i_{\sum C2}^{t,DQ}, v_{C2}^{t,DQ}, \omega_g, x_{C2}, \hat{\lambda}_{C2}) \end{cases} \quad (39)$$

Where,

$$\begin{aligned} \hat{f}_{i,C2}(i_{\sum C2}^{t,DQ}, v_{C2}^{t,DQ}, \omega_g, x_{C2}, \hat{\lambda}_{C2}) \\ = n_{C2} \hat{f}_{i,C2} \left(\frac{i_{\sum C2}^{t,DQ}}{n_{C2}}, v_{C2}^{t,DQ}, \omega_g, x_{C2}, \hat{\lambda}_{C2} \right) \end{aligned} \quad (40)$$

A non-linear control strategy for controlling a DC/DC buck converter feeding a CPL is proposed in [72] and [73] combining a feedback controller with a feedforward strategy. A fully distributed control scheme without central controller or external information exchange for island AC microgrid with locally distributed generators is proposed in [74]. During faults, to maintain the active and the reactive power balance, a nonlinear distributed controller is presented in [75] using partial feedback linearization. Decentralized control methods with distributed generator feedback controller as well as the power controller gain and the eigenvalue trajectory is shown in [7]. In [76], feedback-based compensation techniques have been analyzed. Here, by taking a continuous feedback from the output, the reference level can be modified. From there, a virtual resistance-based damping technique has been introduced to mitigate the CPL instability in case of complex loading in microgrid. From the additional virtual resistor, the transfer function has been modified. The significance of this technique is it can assure the desired stability without any energy wastage (by cost). Besides the advantage, its limitation is that the improvement in the loading limit is not very appreciable. Yanjun Dong *et al.* worked with pulse width modulation rectifier to mitigate the constant power load instability. In their research, they introduced a simulation model for AC microgrid system loaded with CPL in [77]. Controller intervention of AC microgrid done in different research works are tabulated in Table 6.

C. NOVEL TECHNIQUES AND TOOLS

Karimipour and Salmasi [78] worked on Popov’s Stability criterion, one of the advanced nonlinear techniques, to handle CPL instability issues. Using this technique for AC system, they have accomplished stability analysis of the microgrid system. The CPL architecture in AC microgrid used there is shown in Fig. 22.

Here, state variables are introduced as $x_1 = i_{ld}, x_2 = i_{lq}, x_3 = i_{ld}, x_4 = i_{lq}, x_5 = V_d, x_6 = V_q, x_7 = I_{dc}$, and

TABLE 4. Novel techniques and tools for DC microgrid.

Reference	University	Authors	Year	Stability Region	Analysis Method/ Control Technique	Simulation/ Experiment Platform	Domain	Design Approach
[40]	Energy Systems Division, Argonne National Laboratory, Lemont, USA	Xiaonan Lu et al	November 2015	◆	Virtual impedance-based compensation technique	Simulink	T & F	≈
[41]	National Technical University of Athens, Zografou, Greece	C.N. Papadimitriou et al	May 2015	●	Review on DC microgrid control techniques	N/A	N/A	⚡
[42]	The University of Texas at Austin, Austin, USA	Maresh Srinivasan et al	June 2015	◆	Droop loop control technique	Simulink	T	
[43]	Stanford University, United States of America	Gustavo Cezar et al	December 2015	●	Converters driving techniques	PSIM	T	≈
[44]	University of Tennessee, Knoxville, TN, US	Xiaonan Lu et al	September 2014	◆	Virtual resistance-based method, impedance matching approach	Simulink	T	≈
[45]	Norwegian Univ. of Sci. & Technol., Trondheim, Norway	M. K. Zadeh et al	November 2013	◆	A multi-converter with a centralized stabilizer	Simulink	T	⚡
[46]	Sharif University of Technology, Tehran, Iran	M. Ashourloo et al	February 2013	●	Simple active damping strategy	Simulink	T & F	≈
[20]	Clarkson University, Potsdam, USA	Stanley R. Huddy et al	January 2013	●	Coupling two systems	MATLAB	T	⚡
[48]	National Semiconductor, Longmont	Yushan Li et al	January 2012	◆◆	Active damping for boost converters	Simplis simulations	T & F	⚡
[49]	Rensselaer Polytechnic Institute, Troy, USA	M. Cespedes et al	July 2011	●	Passive damping circuit	Oscilloscope	T & F	≈
[50]	The University of Texas at Austin, Austin, USA	A. Kwasinski et al	March 2011	◆	Load shedding, addition of resistive loads, filters	Simulink	T	⚡
[51]	Illinois Institute of Technology, Chicago, USA	A. M. Rahimi et al	February 2010	●	Loop cancellation, nonlinear feedback	Pspice	T & F	≈
[52]	The University of Texas at Austin, USA	Kwasinski, A et al	June 2010	◆	Adding filters and capacitors	Oscilloscope, Simulink	T	⚡
[53]	Illinois Inst. of Technol., Chicago, IL	A. M. Rahimi et al	May 2009	●	Active-damping technique	Pspice	T & F	≈
[54]	Illinois Institute of Technology	Rahimi, Amir M	2009	●	Feedback linearization technique	Pspice	T & F	
[55]	Univ. of Sheffield, Sheffield	J. Wang et al	November 2008	◆	Reformulating the system dynamic equations	Simulink	T	≈
[56]	The University of Manchester, UK	X. Liu et al	September 2008	◆	Input filter state feed-forward stabilizing controller	Simulink	T & F	⚡
[57]	Illinois Institute of Technology, USA	Alireza Khaligh	May 2006	●	Fixed frequency pulse adjustment technique	Simulink	T	≈

Feeder side = ●; Intermediate Circuitry = ◆; Load side = ■; Time=T; Frequency=F; Linearized= ||; Nonlinear = ≈; Hybrid= ⚡

$x_8 = v_c$. And the state space model is:

$$\left\{ \begin{array}{l} \dot{x}_1 = -R_t/L_t x_1 - 1/L_t x_5 + 1/L_t E_1 + \omega_0 x_2 \\ \dot{x}_2 = -R_t/L_t x_2 - 1/L_t x_6 + 1/L_t E_2 - \omega_0 x_1 \\ \dot{x}_3 = 1/L x_5 - R_L/L x_3 - \omega_0 x_4 \\ \dot{x}_4 = 1/L x_6 - R_L/L x_4 - \omega_0 x_3 \\ \dot{x}_5 = 1/C x_1 - 1/(RC) x_5 - 1/C x_3 - 3/(2C) m_1 x_7 + \omega_0 x_6 \\ \dot{x}_6 = 1/C x_2 - 1/(RC) x_6 - 1/C x_4 - \omega_0 x_5 \\ \dot{x}_7 = -r_f/L_f x_7 - 1/L_f x_8 + 3/(2L_f) m_1 x_5 \\ \dot{x}_8 = 1/C_f x_7 - P_{in}/C_f x_8 \end{array} \right\} \quad (41)$$

Next, Liu *et al.* [79] have researched on distributed power system (DPS). Through their research, using infinite norms input/output matrix, they have identified a stability criterion for DPS. It is evident that, due to the negative incremental load characteristics, the instability problem is intensified with the increasing proportion of constant power loads. Nadeem Jelani has worked to find out the nature of this relationship and investigated the previous works on this issue. A proposal for using distributed CPLs for asymmetrical fault ride through (FRT) instead of using a centralized STATCOM is presented in [80]. To solve the instability problem, the authors

TABLE 5. Modeling and analysis of AC microgrid.

Reference	University	Authors	Year	Stability Region	Analysis Method/ Control Technique	Simulation/ Experiment Platform	Domain	Design Approach
[58]	University of Vaasa, Finland	Aushiq Ali Memon et al	December 2015	•	Review of AC Microgrid protection issues	MATLAB, PSCAD	T & F	≈
[59]	Norwegian University of Science and Technology, Norway	S. Sanchez et al	July 2014	•	Port-Hamiltonian model	Simulink	T	≈
[60]	The University of Sydney, Darlington, NSW, Australia	WU, M. et al	July 2014	•	Active damping	MATLAB	T & F	≈
[61]	Virginia Tech, USA	Bo Wen et al	December 2014	◆	d-q frame analysis	MATLAB, Oscilloscope	T & F	≠
[62]	University of Nottingham, UK	F. Romlie et al	October 2013	•	State Space Modeling	MATLAB/ PSCAD	T & F	≈
[63]	Xi'an Jiaotong University Xi'an, China	Zeng Liu et al	February 2012	•	Nyquist Stability Criterion	Saber, MATLAB	T & F	≈
[64]	Rensselaer Polytech. Inst., Troy, NY, USA	S. Jian	November 2009	•	Small signal analysis, state-space modelling	Simulink	F	≠
[65]	Technical University of Eindhoven, the Netherlands	P. J. M. Heskes et al	June 2009	◆	Negative Differential Impedance	Simulink	F	≈
[66]	Instituto de Investigaciones en Ingeniería Eléctrica, Bolivia	Leon, A.E. et al	June 2008	•	Feedback linearization	Simulink	T	
[67]	Univ. of Toronto, Ont., Canada	F. Katiraei et al	February 2005	•	Negative incremental loading characteristics modelling	PSCAD/ EMTDC	T	≠
[68]	Illinois Inst. of Technol., Chicago, IL, USA	A. Emadi	October 2004	•	State space averaging method	Oscilloscope	T	≈

Feeder side = •; Intermediate Circuitry = ◆; Load side = ▣; Time=T; Frequency=F; Linearized= ||; Nonlinear = ≈; Hybrid= ≠

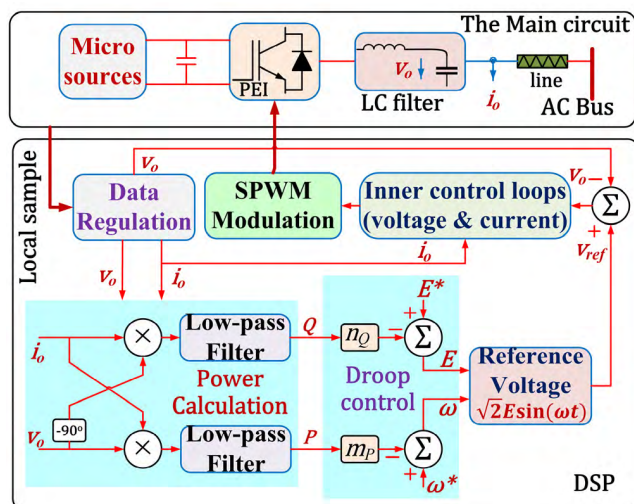


FIGURE 20. Control structure of conventional P/f and Q/V droop control [70].

introduced a STATCOM compensation technique in [81]. The novel techniques and tools for AC microgrid proposed in different research works are tabulated in Table 7.

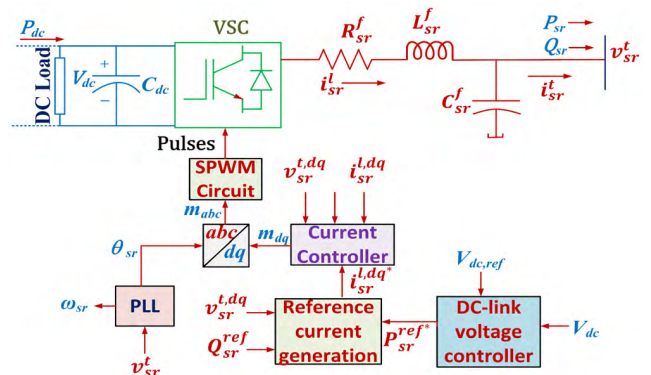


FIGURE 21. Source in constant power mode with controlled DC voltage [71]. The switching signal to the VSC is generated by the sinusoidal pulse width modulation (SPWM) circuit, which is controlled by signals (in dq-frame) from the phase-locked loop (PLL) and the current controller.

On another occasion, in [82], Immersion & Invariance control technique has been presented. Tools for large signal stability analysis by estimating the domain of attraction of the system operating point is presented in [83], which helps to design the system to optimize the criteria of the stability

TABLE 6. Controller intervention of AC microgrid.

Reference	University	Authors	Year	Stability Region	Analysis Method/ Control Technique	Simulation/ Experiment Platform	Domain	Design Approach
[69]	Delhi Technological University, Delhi	A. Trivedi et al	October 2016	•	Mix-sensitivity based approach with nonlinear loads	Simulink	F	⚡
[6]	University of Wisconsin-Milwaukee, USA	Eklas Hossain	August 2016	■	Sliding mode control, Active/Reactive current injection method	MATLAB/ Simulink	T & F	⚡
[70]	Central South University, Changsha, China	H. Han et al	January 2016	◆◆	Review of power sharing control strategies	N/A	N/A	⚡
[71]	Indian Institute of Technology Hyderabad, India	Manjunath. K. et al	April 2016	•	Framework for voltage source converter	MATLAB/ Simulink	T	≈
[73]	Universidad Nacional del Sur, Bahía Blanca, Argentina	J. A. Solsona et al	December 2015	•	DC/DC buck converter feeding a CPL	MATLAB	T	≈
[73]	Univ. Nac. del Sur, Bahía Blanca, Argentina	J. Solsona et al	August 2014	•	Feedback controller with a feedforward strategy	MATLAB	T	⚡
[74]	Zhejiang University, Hangzhou, China	H. Xin et al	March 2015	◆	Distributed control scheme	MATLAB	T	≈
[75]	Swinburne University of Technology, Hawthorn, VIC, Australia	M. A. Mahmud et al	December 2014	•	Nonlinear distributed controller, Partial feedback linearization	MATLAB	T & F	
[7]	Queensland University of Technology, Australia.	R. Majumder	August 2013	•	Distributed generator feedback controller, Eigenvalue trajectory	MATLAB	T & F	⚡
[76]	Nanyang Technological University, Singapore	Vilathgamuwa, D.M et al	November 2011	•	Feedback Compensation, virtual resistance-based damping technique	MATLAB/Simulink	T & F	⚡
[77]	Northwestern Polytechnical University, China	YanJun Dong et al	November 2008	◆	Pulse width modulation rectifier	MATLAB	T	≈

Feeder side = •; Intermediate Circuitry = ◆; Load side = ■; Time=T; Frequency=F; Linearized= ||; Nonlinear = ≈; Hybrid= ⚡

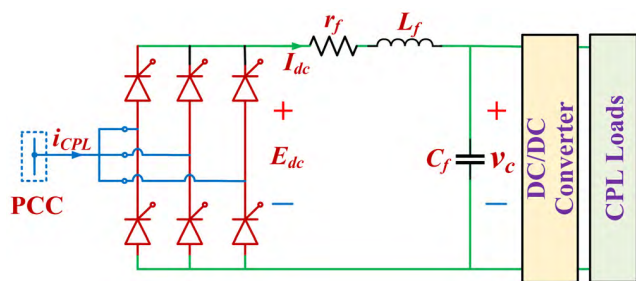


FIGURE 22. Typical architecture of CPL in an AC microgrid containing a rectifier, RLC filter and converter [78].

with CPLs. Acevedo and Molinas [84] worked on islanded mode operation of the microgrid system. To have appreciable operational performance, they introduced a four-wire-grid architecture to implement renewable energy resources in islanded mode operation. Next, Jelani and Molinas [85]

used discrete Fourier transformation. Besides that, they have implemented vector control techniques to develop a shunt filter as a constant power load compensator. After that, to analyze the CPL stability, single phase matrix control (commonly known as SPMC) technique has been illustrated in [86]. The rectifier system proposed here is shown in figure 23, whose output impedance is defined by equation (42).

$$Z_o = \frac{sL(1 + sRC_2)}{s^2LRC_1C_2 + s^2L(C_1 + C_2) + sRC_2 + 1} \quad (42)$$

Voltage gain of LC filter with passive damping network:

$$\frac{V_C}{V_S} = \frac{1 + sRC_2}{s^3LRC_1C_2 + s^2L(C_1 + C_2) + sRC_2 + 1} \quad (43)$$

And the transfer function:

$$H(s) = -R = -\frac{1}{K} = \frac{s^2L(C_1 + C_2) + 1}{s^3LC_1C_2 + sC_2} \quad (44)$$

TABLE 7. Novel techniques and tools of AC microgrid.

Reference	University	Authors	Year	Stability Region	Analysis Method/ Control Technique	Simulation/ Experiment Platform	Domain	Design Approach
[78]	Univ. of Tehran, Tehran, Iran	Karimipour, D. et al	July 2015	◆	Popov’s Stability criterion	Simulink	T	≈
[79]	Xi’an Jiaotong University, Xi’an, China	Zeng Liu et al	June 2015	●	Infinite norms input/output matrix	Simulink	T	≈
[80]	Norwegian University of Science and Technology, Trondheim, Norway	N. Jelani et al	March 2015	◆	Asymmetrical fault ride through (FRT)	PSCAD / EMTDC	T	≡
[81]	Norwegian University of Science and Technology (NTNU), Norway	Jelani, N. et al	April 2013	◆	STATCOM compensation technique	PSCAD / EMTDC	T	≡
[82]	Univ. of Santa Catarina, Florianopolis, Brazil	E. Lenz et al	2013	●	Immersion & Invariance control technique	MATLAB/ Simulink	T	≡
[83]	University of Lorraine, Nancy, France	D. Marx et al	April 2012	◆	Large signal stability analysis	MATLAB	T	≡
[84]	Norwegian University of Science and Technology, Trondheim, 7491 Norway	S. Sanchez Acevedo et al	2012	●	Four-wire-grid architecture method	Oscilloscope	T	≈
[85]	Norwegian Univ. of Sci. & Technol. (NTNU), Trondheim, Norway	N. Jelani et al	2012	●	Shunt filters with vector control technique	PSCAD/ EMTDC	T	≡
[86]	Universiti Teknologi Mara, 40450 Shah Alam, Malaysia	P. N. A. M. Yunus et al	2012	◆	Single phase matrix control (SPMC)	MATLAB/ Simulink	T & F	≈
[87]	Norwegian University of Science and Technology, Department of Electric Power Engineering, Trondheim, Norway	Jelani, N. et al	June 2011	●	Vector control techniques	PSCAD/ EMTDC	T & F	≈
[88]	Illinois Inst. of Technol., Chicago, IL, USA	Emadi, A. et al	July 2006	●	Large signal phase plane analysis	N/A	N/A	≡
[89]	Auburn Univ., AL, USA	R. L. Spyker et al	October 2000	●	Compensation with Capacitor	MATLAB	T	≈

Feeder side = ●; Intermediate Circuitry = ◆; Load side = ▣; Time=T; Frequency=F; Linearized= ||; Nonlinear = ≈; Hybrid= ≡

Jelani and Molinas [87] used vector control techniques to mitigate the CPL instability issues. Vector control technique is a technique in which a voltage source converter is used as a CPL load. By using this technique on distribution system, they have conducted phase margin analysis of the AC microgrid system. Besides that, in [88], a novel technique has been introduced to stabilize the CPL-based AC system. It covered the automotive system as well as the localized microgrid system. Here, large signal phase plane analysis and system level analysis have been presented. In [89] a numerical procedure is presented to calculate the time for a capacitor to supply a CPL through a DC-DC converter by observing the deviation in terminal voltage.

VI. CLASSIFICATION OF COMPENSATION TECHNIQUES

During the literature review for our research studies, we have noticed that all available techniques for CPL compensation can be classified into several groups of common criteria based on the location where the compensations are applied. The classifications are mentioned below.

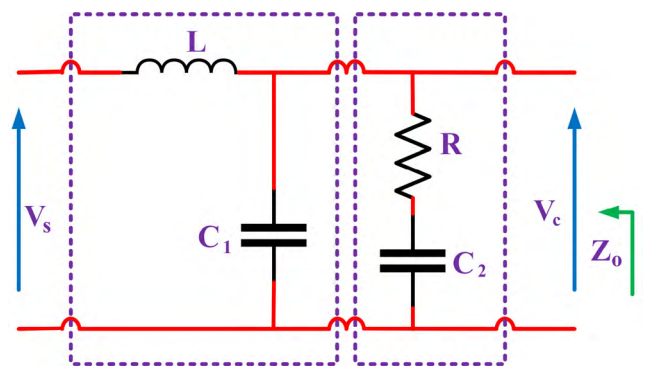


FIGURE 23. Rectifier system proposed in [86], it has a LC filter connected to a passive damping network created by R and C2.

- Feeder side compensation to make the system robust against CPL instability.
- Compensation by adding intermediate circuitry or elements between the feeder side and load to enhance system stability.

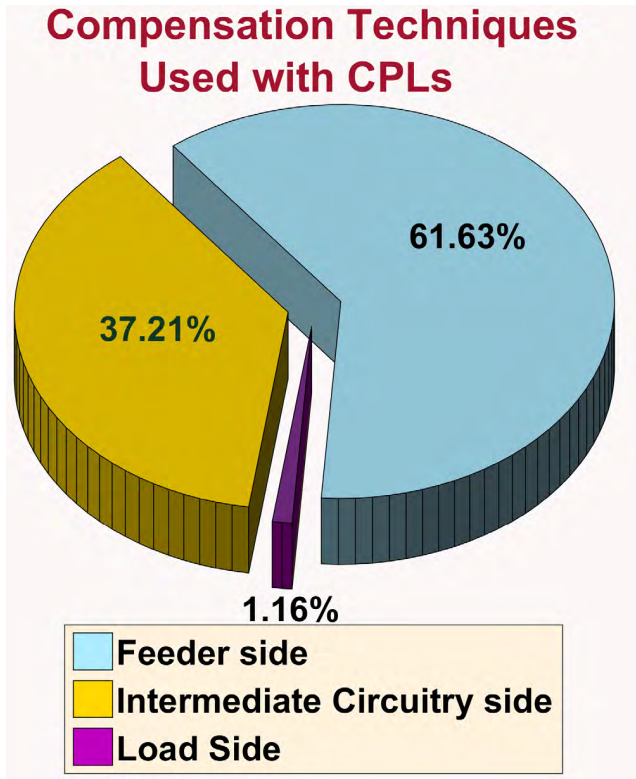


FIGURE 24. Usage of different compensation techniques according to the compensation side. Feeder side compensation is the most used one, while load side compensation appears to be the least popular.

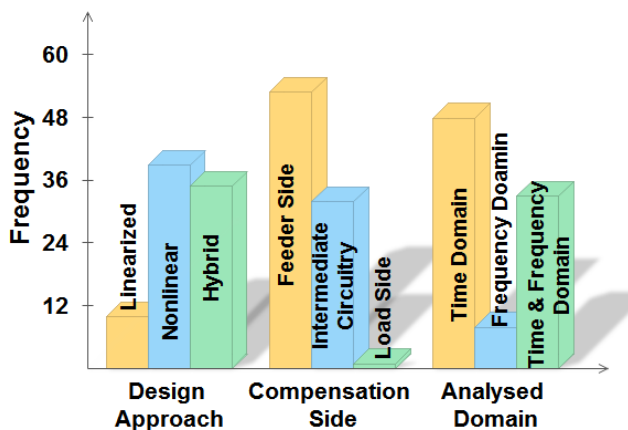


FIGURE 25. Comparing the use of different techniques for stable operation with CPL on various aspects. Nonlinear design approach can be seen as the most used one, with most of the compensation done at the feeder side, while the analysis is done in the time domain predominantly.

- Load side compensation so that the system does not experience the effect of constant power loads.

From the review analysis, we have the infographic shown in Fig. 24 that indicates the distribution of the techniques used to retain microgrid stability. It is evident that feeder side compensation techniques are mostly used for microgrid stability. Recently, the load side compensation technique has grown into the most robust technique for this purpose. Fig. 25 depicts the infographic on the frequency of generalized techniques

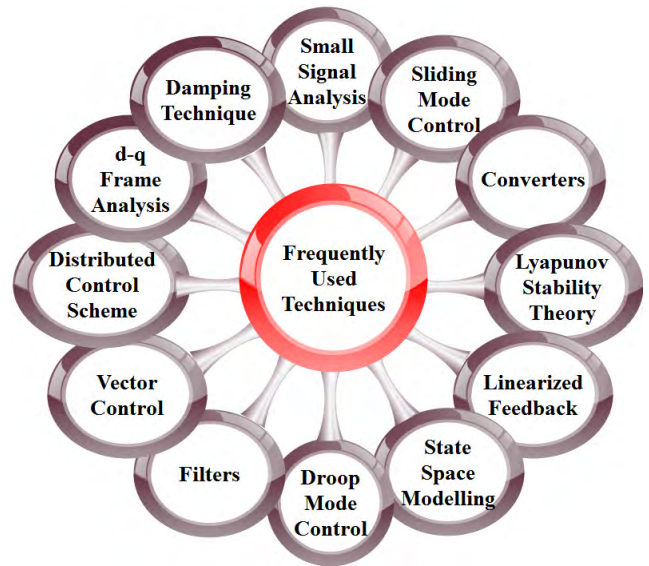


FIGURE 26. Frequently used techniques and tools to mitigate the instability due to CPL.

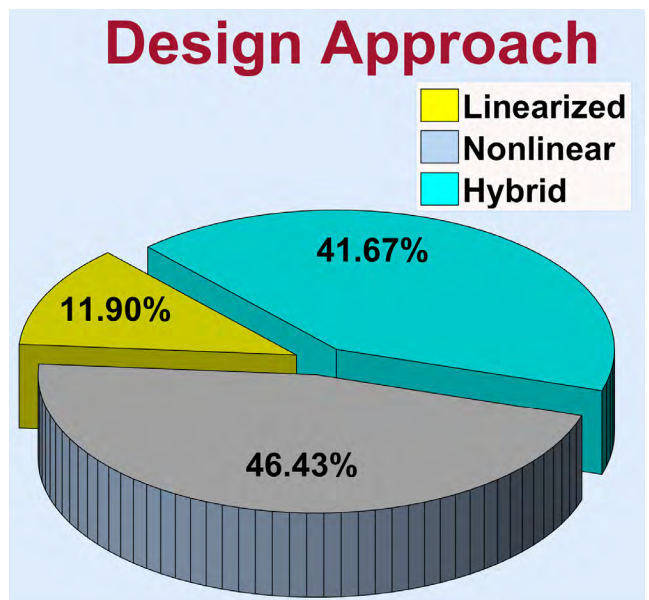


FIGURE 27. Design approach of the stability techniques concerning Constant Power Load. Nonlinear approach is the one that is adopted mostly, followed closely by the hybrid system.

to mitigate CPL instability. This infographic includes statistics on design approaches, compensation sides, and analyzed domain apropos of the overall research works. In the case of design approaches, it can be seen that nonlinear control techniques were majorly adopted to mitigate microgrid instability. Hybrid techniques combining both linear and nonlinear technique were also proposed by several researchers on this occasion.

Another infographic is shown in Fig. 26 that illustrates the frequency of the techniques employed to mitigate CPL instability. Then, the infographic on the frequency of

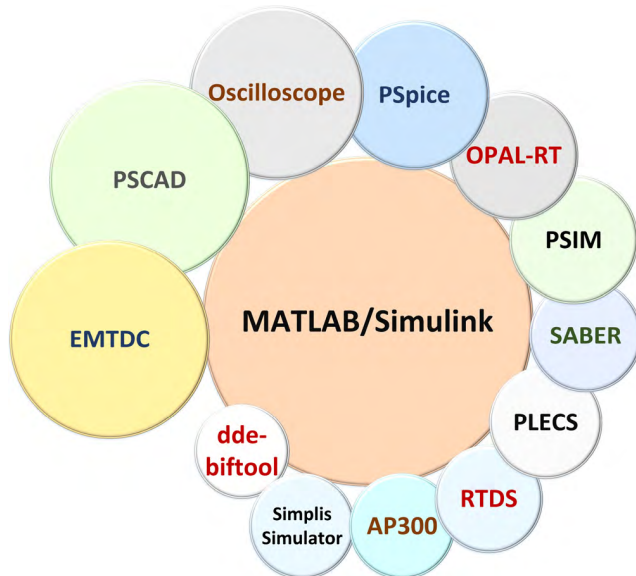


FIGURE 28. Used Simulation platforms or experimental environment for analysis and verification.

linearized, non-linearized, and hybrid techniques used on stability purpose is presented in Fig. 27. After that, Fig. 28 depicts the infographic on the frequently used platforms to analyze system stability. Based on application and compensation criteria, among the various techniques employed to mitigate the instability of microgrid with constant power load, damping techniques and small signal analysis are used most frequently along with various filters and feedback controllers. Sliding mode control techniques are also popular in compensating nonlinear systems with CPL. From this figure, it can be seen that MATLAB/Simulink based analyses are mainly adopted in the research purposes on this regard. Then, EMTDC, PSCAD, Oscilloscope, and PSpice are also frequently used to analyze system stability. Though not frequently, OPAL-RT, PSIM, SABER, PLECS, RTDS, AP300, and Simplis simulators are used on this purposes too in several occasions.

VII. CONCLUSION

In this paper, initially, the inclination towards microgrid system has been justified by discussing a number of advantages of it over the conventional utility grid system. Despite these advantages, the future of microgrid systems faces a potential challenge coming from instabilities due to the increasing proportion of CPL load. The research works conducted on stabilization of DC microgrid system have been reviewed thoroughly in this paper. Besides that, a comprehensive study has been conducted on the state of art researches on stabilization of AC microgrid system. After reviewing these, a generalized classification has been depicted on the stabilization of microgrid system with elaborated subsections of each. According to this classification, the stabilization techniques can basically be classified as: a) feeder side

compensation, b) compensation by adding intermediate circuitry, and c) load side compensation. Then, the merits and the drawbacks of each generalized technique have been analyzed to determine the suitable compensation technique to retain the stability of microgrid systems. Then, several infographics have been presented to present the findings of this review study from different aspects.

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