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Review on Advanced Control Technologies for Bidirectional DC/DC Converters in DC Microgrids

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***Abstract*—DC microgrids encounter the challenges of constant power loads (CPLs) and pulsed power loads (PPLs), which impose the requirements of fast dynamics, large stability margin, high robustness that cannot be easily addressed by conventional linear control methods. This necessitates the implementation of advanced control technologies in order to significantly improve the robustness, dynamic performance, stability and flexibility of the system. This paper presents an overview of advanced control technologies for bidirectional dc/dc converters in DC microgrids. First, the stability issue caused by CPLs and the power balance issue caused by PPLs are discussed, which motivate the utilization of advanced control technologies for addressing these issues. Next, typical advanced control technologies including model predictive control, backstepping control, sliding mode control, passivity-based control, disturbance estimation techniques, intelligent control and nonlinear modeling approaches are reviewed. Then the applications of advanced control technologies in bidirectional DC/DC converters are presented for the stabilization of CPLs and accommodation of PPLs. Finally, advanced control techniques are explored in other high gain non-isolated (e.g., interleaved, multilevel, cascaded) and isolated converters (e.g., dual active bridge) for high power applications.**

***Index Terms*— Advanced control, bidirectional DC/DC converter, DC microgrid, constant power load, pulsed power load**

I. INTRODUCTION

In recent years, due to the wide utilization of DC power sources, such as solar PV, fuel cell (FC) and various energy storage systems (e.g., batteries, supercapacitors, etc), as well as the high penetration of DC loads, like light-emitting diodes, computation devices and motor drive systems, DC microgrids are gaining increasing attention. Moreover, DC microgrids do not have the issues of synchronization, reactive power flow, harmonics, etc, as their AC counterparts. DC microgrids have been widely applied in renewable energy systems, remote households, data centers, more electric aircraft, electric vehicles and electric ships, etc [1], [2].

Bidirectional DC/DC converters are the fundamental building blocks of DC microgrids. They are widely utilized as the interface between energy sources and the DC microgrids, or between two DC microgrids with different bus voltage levels. They provide power flow control and voltage/current regulation to ensure stable, reliable and efficient operation of DC microgrids. However, several challenges are encountered regarding the control of bidirectional DC/DC converters in DC microgrids.

The first challenge is known as the constant power load (CPL) instability problem in DC microgrids with tightly regulated power electronic loads [3]. Power electronic converters are extensively utilized in DC microgrids for power conversion and motor drives. It is widely acknowledged that tightly regulated power electronic loads tend to draw constant power and thus exhibit negative incremental impedance characteristics [4]. CPLs decrease the system damping and may even cause instability. Numerous control strategies have been proposed for stabilizing DC/DC converters loaded by CPLs, like virtual resistors [5], [6], virtual capacitors [7], virtual impedance [8], pole placement methods [4], loop cancellation approaches [9], etc. However, due to the nonlinearity of CPLs, these small signal model based linear control methods can only ensure small signal stability near the operating point. When large disturbances happen, these linear control methods may become ineffective and the system may be unstable. Therefore, advanced control technologies should be implemented to stabilize the system in a large signal sense.

The second challenge is caused by the pulsed power load (PPL) issue, which commonly occurs in onboard microgrids like more electric aircraft [10], electric ship [11] and electric vehicles [12]. PPLs draw a large amount of power in a very short period of time. Due to the pulse behavior with high power characteristics of the PPLs, they can move the microgrid far away from the stationary operating point. As a result, large voltage sags may happen and the system may even become unstable because conventional linear control methods may not be able to ensure the system stability in a large operating range. To accommodate the high power and fast dynamics requirement of PPL, energy storage systems (ESSs) with high

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power density, fast dynamics are required to make up the lack of fast transient output power of the main energy source (e.g., the conventional synchronous generator) [13]. In this context, supercapacitors (SCs) and flywheels are the two most popular types [11] [12]. ESSs are integrated into a microgrid with interface converters and the accommodation problem of PPL is converted to the management of ESSs and the fast control of the interface converter. There are various strategies available, like instantaneous power control [14], limit-based voltage control [15], profile-based control [16], continuous average current control [17], adaptive current voltage control [13] and power filter-based control [18]. However, these linear control methods cannot easily guarantee optimal performance, system stability and fast dynamics, which may be addressed by advanced control technologies.

In DC microgrids, the most widely used DC/DC converters are the classical buck, boost and buck/boost converters. However, in some applications, high step-up/step-down ratio is required for the interface DC/DC converters [19]. For example, in practical renewable energy systems, the output voltages of RESs and ESSs are low and not easily compatible with the required voltage levels of DC microgrids. For the classical converters, their step ratios are constrained by the effect of power switches and the equivalent series resistance of inductors and capacitors. To address this issue, numerous high gain DC/DC converter topologies have been proposed. They can be broadly divided as isolated [20] [21] and no isolated converters [22], [23]. Advanced control technologies could also play a role to improve their performances.

Advanced control technologies, including sliding mode control (SMC), model predictive control (MPC), passivity-based control (PBC), backstepping, intelligent control, etc, have the advantages of robustness, stability, optimality, flexibility and others. Therefore, they can significantly improve the performance of bidirectional DC/DC converters compared with the conventional linear control methods. This paper aims to provide an overview of advanced control technologies in bidirectional DC/DC converters in DC microgrids, mainly for the stabilization of CPLs and the accommodation of PPLs. Motivations of using the advanced control in DC microgrids are provided in Section II. Section III presents an overview of advanced control technologies, including MPC, backstepping, SMC, PBC, disturbance estimation techniques, intelligent control and nonlinear modeling approaches. Section IV demonstrates the applications of these advanced control technologies for bidirectional DC/DC converters in CPLs and PPLs. The applications of advanced control technologies in other DC/DC converter topologies are presented in Section V, including both non-isolated and isolated DC/DC converters for high power applications. Conclusion and future trends are illustrated in Section VI.

II. MOTIVATION OF USING ADVANCED CONTROL IN DC MICROGRIDS

Fig. 1 shows a typical DC microgrid with various sources, e.g., renewable energy sources (RESs), energy storage systems (ESSs) and fuel cells (FCs), as well as various loads. Two typical loads are CPLs and PPLs, whose dynamics cause critical issues in the stable and reliable operation of DC microgrids. Mitigating the issues caused by such loads using advanced control techniques are the main focus of this paper.

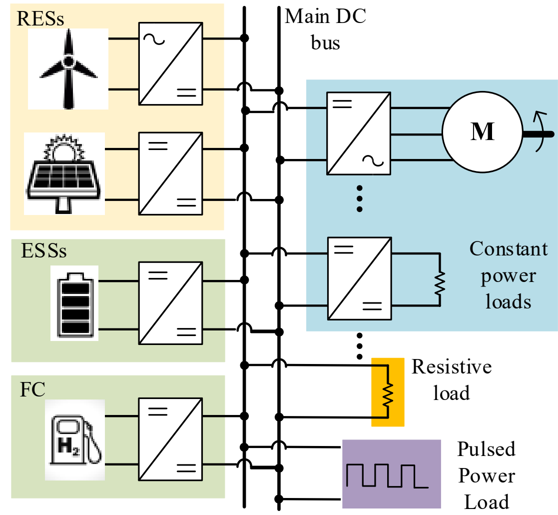

Fig. 1. A typical DC microgrid with various sources and loads.

A. Constant power load issue

Power electronic converter loads, when tightly controlled, behave as CPLs. CPLs are extensively integrated in a DC microgrid. Typical examples of CPLs are DC/DC converter feeding resistive loads and DC/AC inverter driven electric motors. The latter example is shown in Fig. 2 as a demonstration. It is a DC/AC inverter, which drives an electric motor with a rotating load that has a one-to-one torque-speed characteristic. Because of this behavior, for every speed value, there is a corresponding torque value. As a result, for a constant speed ω, torque T is constant, and power $P = \omega T$ is constant. So, if the controller tightly regulates the motor speed, then by assuming a constant efficiency for the drive system, the input power of the DC/AC inverter is constant. Consequently, the DC/AC inverter presents a CPL characteristic of the system.

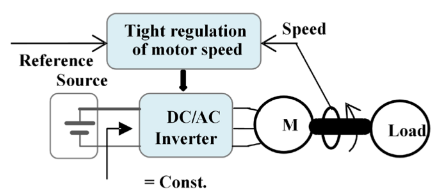

Fig. 2. An example of a CPL.

The CPL has negative impedance characteristics, as illustrated in Fig. 3. This negative impedance feature will pose negative impact on system performance. In particular, when the CPL is connected in cascade with a source converter, their impedances may form underdamped or even unstable oscillation.

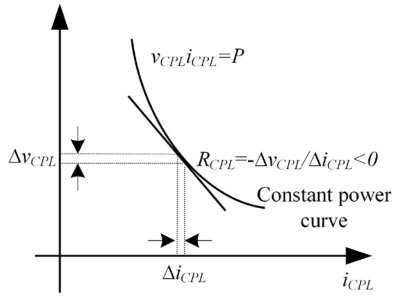

Fig. 3. Voltage-current characteristics of constant power loads.

Numerous strategies have been proposed for the DC/DC power electronic converters loaded by CPLs. Passive damping strategies, such as adding the necessary capacitor or resistor [24] or designing LC filters [25] are simple and effective. However, they are often costly and limited by the physical constraints. Many active damping methods are proposed as energy efficient alternatives to stabilize the system by modifying the control loops to emulate the passive elements, such as virtual resistor [6], virtual capacitor [7], virtual impedance [8]. These active damping methods are equivalent to injecting stabilizing power into the CPL to increase damping, which may in turn lead to the compromise of load performance. To avoid the compromise of load performance, a stabilizing method is proposed in [5] by modifying the control loop of the source converter to emulate a virtual resistor. However, the original converter control loop is still modified and thus the system dynamic response is affected. Moreover, since all these active damping methods are based on small signal models, they can only ensure small signal stability near the operating point. Therefore, the results are only local and when a large disturbance happens, these linear control methods may become ineffective and the system may be unstable. Taking into consideration the nonlinearity of converters and the negative impedance characteristics of CPLs, advanced control technologies should be implemented to stabilize the system in a large signal sense.

B. Pulsed power load issue

PPLs are important loads in on-board DC microgrids (naval power system, aircraft power system, etc), such as de-icing systems, radars, sonars, electromagnetic weapons, free electron lasers, etc. They consume a large amount of energy within a very short period. The PPLs have pulse behavior with high power characteristics, e.g., in aircraft power system, peak power may possibly last for 20-200ms and the peak-to-average power ratio can be more than 5-to-1 across a time scale of 50-500ms [10]; in a ship power system, a PPL might consume 15 MJ energy within 2 seconds [11]. There are two factors that lead to issues of PPLs. The first is the capacity limit, as the main energy source (e.g., the synchronous generator, fuel cell) is usually designed to supply the average loads that are online in most of the time rather than satisfy the peak power with only a short duration due to economic considerations. The second is the ramp rate constraint, as it is almost impossible for the main energy source to supply the PPL demand instantaneously due to their slow ramp rates. If PPLs demands are not satisfied, challenging issues may occur during the operation of the system, such as voltage drop, tripping of equipment due to undervoltage, and even a blackout of the whole microgrids.

To accommodate PPLs, one solution is to do load management so that some uncritical loads are shed during peak power period of PPL to make total load remain constant. However, it will cause interrupted or degraded services, and the ramp rate requirement of the conventional generator cannot satisfy PPLs. Installation of an energy storage system (ESS) is a promising solution that has attracted great attention in real applications.

Battery energy storage systems are widely utilized as slow energy sources in pulsed power load applications [13]. Considering high power and fast dynamics requirement of PPLs, ESSs with high power density and fast dynamics are required, and SCs [11] and flywheels [12] are the two most popular types. Hybrid battery/SC system is also a promising solution as it provides high power density, high energy density and fast dynamics at the same time [17].

There are two topologies for the integration of ESSs for pulsed load applications [13]. Passive topology is to connect ESS directly with the main power supply. This configuration is simple, but the power flow is uncontrollable. Active topology is to connect ESS through power electronic converters so that power flow can be actively controlled, and it is not necessary to match the terminal voltages of ESS with the bus voltage, giving flexible choices on the size of ESSs. Therefore, ESSs are usually connected to the bus through interface converters. There are two requirements to be satisfied for the accommodation of PPLs, one is the management of the ESS, or the coordination of the main energy source and ESS, and the other is the fast dynamic response capability of the interface converter of the ESS to accommodate the immediate load variation.

In existing works, several methods have been developed to accommodate PPLs through the management of the ESS. Instantaneous power control (IPC) method is developed in [14] by using the instantaneous power of the load and DC bus voltage to generate the reference charging current of ESS with a hysteresis voltage protection loop to monitor the status of ESS. Limit based voltage control method proposed in [15] is to regulate the bus voltage and charge the ESS as fast as possible subject to the practical limitation of the converter, but it's rather disruptive. In [17], a continuous average current control (CACC) technique is proposed where the output current of the ESS converter is kept relatively constant by summing the averaged PPL current and the steady-state load current so that current prompt change by PLLs are avoided. As an improvement work of CACC, an adaptive current-voltage control (ACVC) technique is proposed in [13] based on moving average current and voltage measurement with a voltage compensator to ensure constant current output considering the transient performance during PPL variation. To minimize the disruption caused by the charging process, a generalized profile based control is proposed in [16] by identifying the optimal charging profile. Ref. [12] develops a controller for a flywheel system to mitigate PPLs where the charging rate is controlled by regulating the terminal voltage of flywheel and the discharging current is a reference value from the outer loop. Ref. [18] develops a control scheme based on the power filter theory where the fast dynamic component of load power is supplied by SC and the average load demand is supplied by the main energy source. An extended droop controller is proposed in [26] to achieve decentralized dynamic power sharing of a hybrid battery/SC system for PPLs where SC only responds to fast fluctuations and battery supplies smooth power at steady state. Ref. [27] proposes two coordinated control strategies for a micro gas turbine (MGT) and SC hybrid power system for PPLs. One is the PI based control and the other strategy is based on the output characteristics of MGT to achieve fast and balanced power allocation. In [28], a series-configured hybrid energy storage system is coordinated to address multiple pulsed loads and a rolling charge algorithm is developed to do the charging dispatch of the ESSs to extend their operating time. However, all these methods are for the management of ESS and linear control techniques are utilized for the control of the ESS interface converter, which cannot easily satisfy the high performance and fast dynamics required by PPLs.

III. ADVANCED CONTROL TECHNOLOGIES IN BIDIRECTIONAL DC/DC CONVERTERS

In this section, different advanced control technologies are reviewed with their basic operation principles.

A. Model predictive control

As a powerful technique for optimized control tracking with constraints, MPC has attracted much attention in power converter and motor drive systems [29]. The main idea of the MPC is to use a dynamical model of the system to predict its future response and relate it to the sequence of future control input actions. For the MPC application in the power converter, at each step of designing the MPC controller, a sequence of future inputs is computed, and only the first array of the future control inputs is applied.

The basic operation principle of MPC can be described by solving the optimization below in a receding horizon

$$\min J = \sum_{l=k+1}^{k+N} \left\{ \left(\left\| y_r(l) - y(l) \right\|_Q^2 + \left\| u(l) - u(l-1) \right\|_R^2 \right) \right\} \quad (1a)$$

$$s.t.\ \ g(x(l), u(l)) \le 0, l = k+1, k+2, ..., k+N \quad (1b)$$

$$x(k+1) = Ax(k) + Bu(k) \quad (1c)$$

$$y(k) = Cx(k) \quad (1d)$$

where (1c) and (1d) describe the system model with state vector x, input vector u, output vector y; (1b) represents the constraints on state and control vector.

Eq. (1) is based on discrete MPC. The principle of continuous MPC is similar with the discrete one while it is based on a continuous-time model, given by

$$\min J = \int_0^T \left(\left\| y_r(t+\tau) - y(t+\tau) \right\|_Q^2 + \left\| u(t+\tau) \right\|_R^2 \right) d\tau \quad (2a)$$

$$s.t.\ \ g(x(t+\tau), u(t+\tau)) \le 0 \quad (2b)$$

$$\dot{x} = Ax + Bu \quad (2c)$$

$$y = Cx \quad (2d)$$

From its operation principle, MPC can achieve optimized performance and it's easy to incorporate constraints. Considering the high computation cost in online optimization, explicit MPC schemes are developed by solving the optimal control problem explicitly offline to get the control inputs [30]. But on the other hand, explicit MPC may not easily deal with the constraints.

B. Backstepping control

Backstepping technique is one of the most effective nonlinear control design tools for solving stabilization and tracking problems [31]. This approach is applicable for the systems with special structures (for instance, strict feedback) in which the virtual control input of each dynamic is the virtual output of another one in a cascaded form, starting from the system real output and finishing with the real control input.

As DC/DC converters are second order systems, a standard second order system with the backstepping design procedure is briefly introduced here.

Consider the second order system given by

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_1 &= v \end{aligned} \quad (3)$$

Do the coordinate transformation

$$\begin{aligned} z_1 &= x_1 - x_{1r} \\ z_2 &= x_2 - \alpha \end{aligned} \quad (4)$$

where α is the virtual control signal obtained by considering Lyapunov function $V_1 = 0.5z_1^2$ at the first step, as

$$\alpha = -c_1 z_1 \quad (5)$$

Then consider the Lyapunov function $V_2 = 0.5z_1^2 + 0.5z_2^2$, the final control law is designed as

$$v = -z_1 - c_2 z_2 + \frac{\partial \alpha}{\partial x_1} x_2 + \frac{\partial \alpha}{\partial x_r} \dot{x}_r + \ddot{x}_r \quad (6)$$

which can ensure $\dot{V}_2 < 0$ with the designed control gains c_1 and c_2.

It can be observed from the design procedure that the stability of the closed-loop system with the backstepping controller is guaranteed from the recursive design procedure.

C. Sliding mode control

SMC is a widely used nonlinear controller due to its robustness and simplicity. The main idea of the SMC is to define a virtual surface, called sliding surface, on which the system trajectory converges to the equilibrium point [32]. To keep the state trajectory on the sliding surface, a switching control input is applied.

Here the basic principle of SMC is demonstrated. For a system with state vector x and reference vector x_r,, the tracking error is described by

$$\tilde{x} = x - x_r \quad (7)$$

Then a sliding mode controller can be designed as

$$u = \frac{1}{2}\left[1 + sign(s)\right] \quad (8)$$

where s is the sliding surface to be designed; $s = c^T \tilde{x}$ is a simple example with the positive coefficient c.

Define a Lyapunov function as $V(s) = 0.5s^2$. The controller in (8) is designed such that the derivative of V(s) is always negative when $s \neq 0$.

Boundary control and hysteresis control methods are also used in converter control. They adopt similar concept with SMC, and can be seen in a broader category of SMC.

D. Passivity-based control

PBC has emerged as one of the most effective practical nonlinear control techniques due to its simplicity and easy implementation. It exploits the physical structure of the system and is based on energy conservation of the system, i.e., if a system is passive, it is stable [33]. To stabilize systems, PBC is to reshape the dissipated energy of the system by injecting a virtual resistance matrix to damp the system and to ensure the closed loop system to be passive [34]. There are two steps, i.e., energy shaping and damping injection.

For a standard PBC design procedure [33], the system model can be written in an Euler-Lagrange representation as

$$M\dot{x}+(J+R(x))x=Gu \tag{9}$$

where x and u are state vector and control vector. Matrices M, J, G and $R(x)$ are derived from the system model.

Energy shaping step: Eq. (9) is reshaped as

$$M\dot{e}+(J+R(x))e=Gu-\left(M\dot{x}_r+(J+R(x))x_r\right) \tag{10}$$

where $e=x-x_r$, x_r is the set point of x.

Damping injection step: A virtual damping matrix R_d is added, which yields

$$\begin{aligned}&M\dot{e}+(J+R_i(x))e\\&=Gu-\left(M\dot{x}_r+(J+R(x))x_r-R_de\right)\end{aligned} \tag{11}$$

where $R_i(x)=R(x)+R_d$

Then a stabilizing control law can be identified by solving the right side of (11) to zero.

The main advantage of PBC is that passivity is always preserved in any interconnections, which means, once all the subsystems are ensured passive, their interconnected system is also passive and stable.

E. Disturbance estimation techniques and attenuation controllers

Disturbances and uncertainties widely exist in power electronics systems and bring about adverse impacts like inaccuracy or even instability. There are various methods in literature for uncertainty/disturbance estimation including nonlinear disturbance observer (NDO), extended state observer (ESO), generalized proportional integral observer (GPIO), higher order sliding mode observer (HOSMO), as reviewed in [35]. Kalman filter technique [36] is another group of methods that provides a stochastic filtering framework for the estimation of uncertainties and disturbances.

Take the NDO as an example [37]. For a system given by

$$\dot{x}=f(x)+g_1(x)u+g_2(x)d \tag{12}$$

where x, u and d represent the state, control input and unknown disturbance, respectively. $f(x)$, $g_1(x)$ and $g_2(x)$ are smooth functions of x.

Then an NDO is designed

$$\begin{aligned}&\dot{z}=-l(x)g_2(x)z-l(x)\left[g_2(x)p(x)+f(x)+g_1(x)u\right]\\&\hat{d}=z+p(x)\end{aligned} \tag{13}$$

where z is the internal state and p is a nonlinear function to be designed and the gain $l(x)$ is given by $l(x)=\partial p(x)/\partial x$. It is proved that the NDO asymptotically estimates the disturbances with a properly designed nonlinear gain $l(x)$ [37].

It is proved that the disturbance observers can be designed independently of the baseline closed-loop controller [35]. Thus disturbance estimation techniques are widely employed with other nonlinear methods (MPC, backstepping, PBC, SMC, etc) to provide a feedforward compensation to compensate the uncertainties/disturbances of systems.

Based on the disturbance estimation techniques, various attenuation methods are developed, like disturbance observer based control (DOBC) and active disturbance rejection control (ADRC) [35]. A general framework is developed to design the disturbance observer based composite controller, which consists of two parts as

$$u=u_f+u_d \tag{14}$$

where u_f is generated by a normal feedback controller based on the measurements and u_d is the compensator for the disturbance/uncertainties estimated by the disturbance observer. The former is to guarantee tracking performance and stability, and the latter is to achieve accuracy, which is also known as the *separation principle*.

F. Intelligent control

There are various intelligent control methods, including heuristic, fuzzy, neural network, reinforcement learning, etc. The main advantage of intelligent controllers is that they do not need an exact model representation, and parameters of intelligent controllers can be tuned online. More precisely, an objective or cost function depending on parameters of intelligent controllers is considered and it is minimized online to tune the controller gains. Let's start from a traditional PI or PID controller, which is tuned based on some predefined operating conditions. If the operating point varies a lot, the traditional controllers will not have a desirable performance. By implementing optimization algorithms, the online tuning of the traditional controllers is achieved so that the desirable performance can be guaranteed at all times.

G. Nonlinear modeling approaches

There are several advanced control techniques that can transform a nonlinear system into a linear one, which facilitates the design of a stabilizing controller. Here we introduce the widely used feedback linearization technique and the Takagi-Sugeno (TS) fuzzy modeling method.

Feedback linearization technique is to transform a nonlinear system into a controllable linear system [38]. Then the stabilization problem for the nonlinear system is reduced to the stabilization problem for the controllable linear system [39], which can be achieved by designing a state feedback control law or other nonlinear control methods described above (e.g., backstepping, MPC, estimation approach, etc).

In the TS fuzzy or polytopic-linear parameter varying (LPV) method, a nonlinear system can be represented by a set of linear sub-systems, which are aggregated to approximately represent the original system. It is proved that the stability analysis of nonlinear systems based on TS fuzzy or polytopic-LPV models can be realized by investigating the stability of the individual

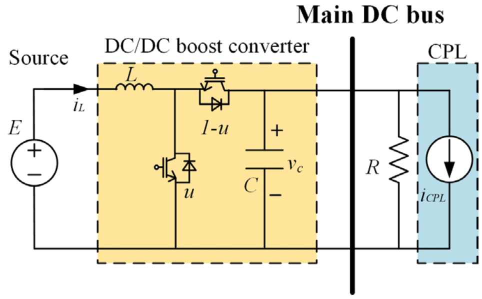

Fig.4. A bidirectional DC/DC boost converter feeding CPLs.

sub-linear systems. Thereby, the TS fuzzy and polytopic-LPV controllers facilitate deploying linear control theories to globally stabilize nonlinear systems. Moreover, the design procedure can be performed by using linear matrix inequality (LMI) technique, which is known as an effective numerical optimization method.

IV. Advanced Control Technologies in Bidirectional DC/DC Converters for CPLs and PPLs

In this section, the advanced control techniques discussed above are applied to deal with the CPL and PPL issues.

A. Application of advanced control to constant power load issue

To better demonstrate how the advanced control technologies are applied in bidirectional DC/DC converters with CPLs, a bidirectional DC/DC boost converter feeding CPLs is studied as an example. Fig. 4 shows the model of the system under study.

The system model in Fig. 4 is given as

$$\begin{cases} L\dfrac{di_L}{dt} = E-(1-u)v_C \\ C\dfrac{dv_C}{dt} = (1-u)i_L - \dfrac{v_C}{R} - \dfrac{P_{CPL}}{v_C} \end{cases} \tag{14}$$

where E, i_L and v_C are the input voltage, inductor current and capacitor voltage of the bidirectional boost converter; u is the duty ratio of the switch, which represents the control input signal. As can be observed, there is a nonlinear term P_{CPL}/v_C.

The control objective is to achieve fast and accurate regulation of DC bus voltage v_C to its reference value V_{Cref} even under large disturbances of CPLs.

Conventional double loop PI controller is widely adopted to control the boost converter. It is often used as a benchmark method to be compared with advanced control methods. It is based on the linearized model in frequency domain. Following the procedure in [26], [40], the voltage loop PI control gains are designed as (15) and the current loop PI control gains are designed as (16).

$$\begin{cases} k_{vp} = \dfrac{\omega_v C}{1-D} \\ k_{vi} = k_{vp}\eta\omega_v \end{cases} \tag{15}$$

$$\begin{cases} k_{ip} = \dfrac{\omega_i L}{V_{Cref}} \\ k_{ii} = k_{ip}\eta\omega_i \end{cases} \tag{16}$$

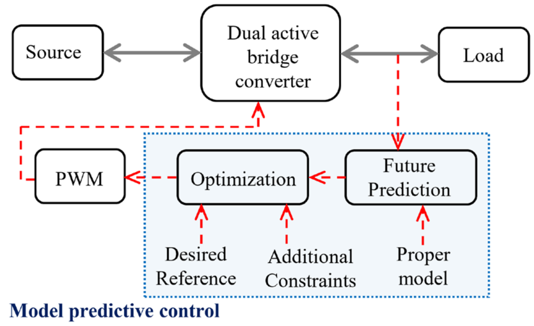

Fig.5. The model predictive control implementation to stabilize CPLs.

where D is the steady state duty ratio of u, V_{Cref} is the reference value of capacitor voltage v_C, η is a small value between 1/10-1/5, ω_v and ω_i are the control bandwidths of voltage and current control loops with ω_v designed as around 1/10 of ω_i, and ω_i is around 1/10 of the sampling frequency.

However, as discussed before, linear controllers can only stabilize the system around a specific operating point based on the linearized small signal model and the system may go unstable when large variations of CPLs happen. Therefore, advanced control methods are applied.

1) Model predictive control

Several MPC methods are applied for stabilizing DC/DC converters feeding constant power loads. A real-time hybrid MPC is proposed in [41] for a boost converter with CPLs. In [42] and [43], composite offset-free MPC controllers are proposed by utilizing continuous MPC and higher order sliding mode observer (HOSMO) for buck converter and boost converter systems with CPLs, respectively; the controller is calculated offline. In [44], an explicit nonlinear MPC strategy is proposed for a boost converter feeding CPL and nonlinearities are handled by fuzzy modeling. Here we take the offset-MPC in [42] and [43] as an example.

First, the tracking error should be defined and predicted. Considering the bilinear model of the boost converter and the nonlinear term caused by CPL in (14), directly managing the voltage tracking error is not very convenient and we use the feedback linearization technique in Section III.G to transform the system into the linear form as

$$\begin{cases} \dot{x}_1 = x_2 + d_1 \\ \dot{x}_2 = v + d_2 \end{cases} \tag{17}$$

by defining x_1=0.5Cv_C^2+0.5Cv_C^2 and x_2=Ei_L - v_C^2/R_0. R_0 is the nominal resistive load.

Then the tracking error is defined by $x_1 - x_1^*$ and the baseline MPC controller is designed by solving the receding optimization problem explicitly based on (2) by considering the nominal system $\dot{x}_1 = x_2, \dot{x}_2 = v$ and $y = x_1$.

To achieve offset-free tracking, an HOSMO [37] is designed to estimate the unknown load variations and model uncertainties d_1 and d_2.

The final control law can be integrated together with the nominal controller and observer, as demonstrated in Fig. 5.

Except for designing a nonlinear controller for bidirectional DC/DC converter, stabilizing current injection techniques can also be utilized to stabilize DC systems by using an energy

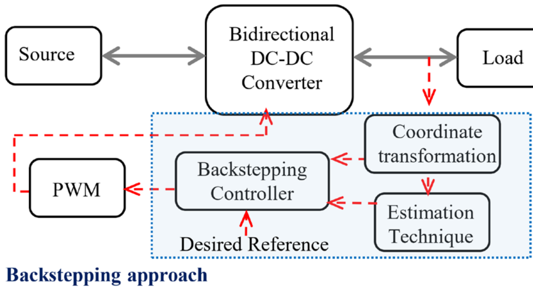

Fig.6. The backstepping control implementation to stabilize CPLs.

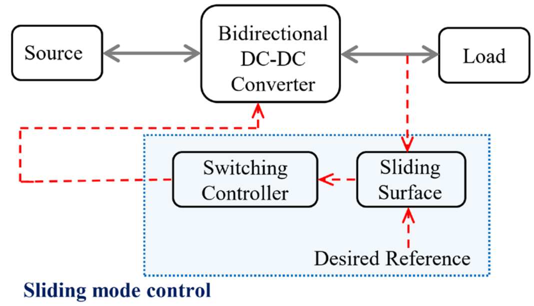

Fig.7. The sliding mode control implementation to stabilize CPLs.

storage system to inject a stabilizing current to the DC bus. In this case, a TS fuzzy model based online MPC scheme is proposed to optimally stabilize the system through adaptively modifying the ESS injection current [45]–[47].

For the MPC methods in DC/DC converters, online MPC is more flexible and straightforward to handle various constraints but the computational burden is higher. Offline MPC or say explicit MPC is to solve the optimal control law offline and thus it has little computation burden. Both MPCs have the advantage in achieving optimized performance with smooth transients. A disadvantage of classical MPC is its reliance on model accuracy, which may lead to tracking error if there are uncertainties and disturbances. This is compensated by combining MPC with various estimation techniques, like extended Kalman Filter (EKF), DOBC, etc, to get the off-set free, as implemented in Fig. 5 and [42], [43].

2) Backstepping

Composite backstepping controllers are developed for stabilizing DC/DC converter systems with CPLs [48]–[51]. The basic ideas of these methods are the same, i.e., an observer is designed for accurate tracking against disturbances/uncertainties and a backstepping controller is designed for large signal stabilization through the recursive Lyapunov design procedure. The main difference is the estimation techniques in estimating the CPL disturbances and model uncertainties. Here we briefly introduce [51] as an example.

Based on feedback linearization in Section III.G, the boost converter model in (14) is transformed into standard form in (17). Using the NDO technique in (13) with $p(x)$ designed as $p(x)= lx$, the lumped disturbances d_1 and d_2 can be estimated. Then the intermediate control law can be designed by following the backstepping recursive design procedure in (3)-(6) with the Lyapunov function V_1 and V_2 selected as $V_1 = 0.5z_1^2 + 0.5\tilde{d}_1^2$ and $V_2 = V_1 + 0.5z_2^2 + 0.5\tilde{d}_1^2$ considering uncertainties and disturbances. The final controller is designed by transforming back of the feedback linearization. Fig. 6 shows the structure of the backstepping controller for the system under study.

As can be observed, the backstepping method provides a straightforward way to design a controller with large signal stability; as long as the converter model can be transformed into standard form for backstepping design, this method provides a good solution with guaranteed large signal stability. To deal with model uncertainties, adaptive backstepping techniques or the composite solutions consisting of a standard backstepping method and an estimation technique are developed. Thus the backstepping approach achieves fast dynamics, accurate tracking, simple design implementation with large signal stability.

3) Sliding mode control

Various SMC techniques have been implemented in DC/DC converter systems to stabilize constant power loads with robustness to uncertainties and easy implementation by directly manipulating on/off state. Different sliding mode surface can be selected to get good performance. In [52], a washout filter based SMC is proposed for stabilizing boost converter with CPL. In [53], [54], the sliding mode surface is selected as a linear combination of voltage and current tracking errors to stabilize a boost converter with CPLs. The implementation of SMC for the system under study is presented in Fig. 7 with eq. (7)-(8).

The conventional SMC has the disadvantage of switching frequency variation, which may complicate the design of the filters and also cause severe noise [55]. To overcome this, fixed switching frequency strategies are proposed to get a duty ratio based on SMC block and applied to a PWM modulator. Then a PWM block should be added in Fig. 7 after the equivalent control signal is calculated by the SMC block for the PWM-based SMC. In [56], a sliding mode duty ratio controller is proposed with a fixed switching frequency to stabilize the buck converter system where an equivalent control law is calculated and a variable control term is added to handle the uncertainties. The suggested approach is compared with the conventional SMC method and showed that the developed SMC is more robust against the system uncertainties and is less sensitive to perturbations at the steady-state phase. The fixed switching frequency SMC is further improved in [57] by designing a digital SMC that assures the current limitation. In [58], a robust PWM-based SMC is proposed to stabilize a boost converter system with CPL where a nonlinear polynomial sliding surface is considered to design the duty cycle of the boost converter within the range [0,1] explicitly. A fixed time terminal sliding mode controller with a finite-time observer is proposed in [59] to stabilize on board DC/DC converter feeding uncertain CPLs to achieve fast dynamics with guaranteed stability.

From the above works, SMC provides a simple and robust approach to stabilize CPLs.

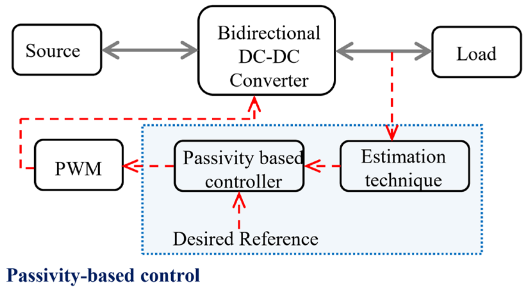

Fig.8. The passivity-based control implementation to stabilize CPLs.

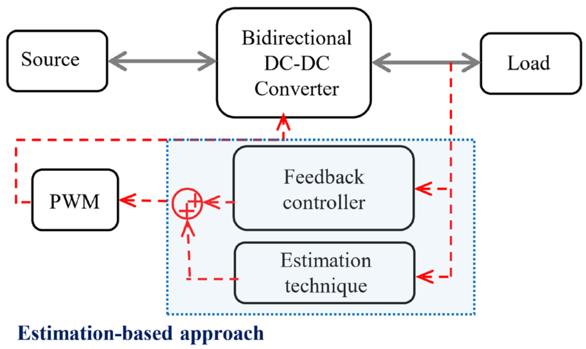

Fig.9. The estimation/observer based control implementation to stabilize CPLs.

4) Passivity based control

Many passivity based controllers are designed for stabilizing DC/DC converters feeding CPLs. In [60], a PBC is proposed for a buck converter with CPLs but the uncertainties are not handled. In [61], an interconnection and damping assignment PBC with a complementary PI controller is proposed for a boost converter with CPLs where a virtual circuit is injected to add system damping and a complementary PI controller is to eliminate steady-state error. An improved interconnection and damping assignment PBC is proposed with an adaptive interconnection matrix to guarantee passivity of both boost and buck converter systems with CPLs [62]. An adaptive passivity-based controller is proposed in [63] for stabilizing buck converter with CPLs where an NDO is designed to improve the robustness against disturbances and PBC is applied to guarantee system stability. In [64], an adaptive energy shaping algorithm is proposed by combining PBC and immersion and invariance (I&I) estimation technique to guarantee large signal stability and tracking accuracy; the algorithm is applied in buck and boost converter systems with CPLs.

Fig. 8 demonstrates the application of the PBC for a boost converter system with CPLs [64]. For the boost converter system in (14), following the standard PBC procedure in (9)-(11), the system can be written in Euler-Lagrange representation in (9) with $x=[x_1 \quad x_2]^T=[\frac{1}{E}\sqrt{\frac{L}{C}}i \quad \frac{v}{E}]^T$. The injected damping in (11) is $R_a = \mathrm{diag}(R_{a1}, R_{a2})$ and a stabilizing control law is designed by setting eq. (11) to zero, i.e., $Gu-\left(M\dot{x}_d+(J+R(x))x_d-R_d e\right)=0$. To deal with the unknown load power, an observer can be designed based on I&I, NDO or other estimation techniques.

As can be observed, PBC is designed directly from the physical structure; and once the passivity of all subsystems is ensured, the passivity of the whole system is ensured, which allows flexible plug and play of the distributed generators into microgrids.

5) Disturbance estimation techniques and attenuation controllers

As is shown in previous subsections, the disturbance estimation techniques are employed with the MPC [42] [43], SMC [59], backstepping [48]–[51], PBC [63] [64] to compensate uncertainties/disturbances of systems and achieves accurate tracking. Following the separation principle in (14) in Section III.E, the control diagram of the estimation-based control technique can be described in Fig. 9.

6) Intelligent control

The heuristic, fuzzy, and neural network approaches have been utilized to stabilize the DC microgrids with CPLs. In [65], an intelligent controller is designed based on non-integer fractional order theory and the fuzzy techniques. By using a cost function on the DC bus voltage error and the controller input, the gains of the fractional PID controller are tuned online. In [66], a neural network-based intelligent controller is suggested for a hybrid AC/DC microgrid feeding CPLs. The neural network is utilized to keep the power in a PV cell at the maximum power point, regulate the torques of a permanent magnet synchronous generator, and tune the parameters of a PI controller to manipulate the converters of the microgrid. In [67], the neural network approach is used to estimate the unknown terms and dynamics online and then an adaptive nonlinear controller is designed based on the Lyapunov stability theory. Fig. 10 demonstrates the principle of an intelligent controller where the gain of the PID controller is tuned online using an optimization algorithm [65].

As can be observed, the intelligent controllers can achieve desirable performance over a wide operating range and they do not need an exact model representation.

7) Nonlinear modeling methods

Feedback linearization technique is widely applied to transform a nonlinear model into a standard linear form. The system model in (14) can be transformed into the model in (17) by utilizing feedback linearization technique, as presented in Section IV.A.1. Thus, this technique is combined with other controllers to stabilize CPLs, eg. MPC [43], backstepping [48]–[51], SMC [59].

The design of TS fuzzy and LPV controllers is straightforward and simple. In [68] and [69], a TS fuzzy controller is designed by extending the linear pole placement and robust non-fragile control theories to nonlinear DC microgrids with DC/DC converters and CPLs. By using the pole placement approach, the eigenvalues of the sub-linear closed-loop systems are placed in a specific region to enhance the transient and steady-state performances, which approximately characterize the nonlinear closed-loop system behavior. The robust non-fragile controller is resilient against the system uncertainty and unknown parameter variations, as well as the digitalized approximation of a continuous-time control law. Also, in [70], by means of polytopic-LPV technique, a reset switching controller is presented to stabilize CPLs. The values of the dynamic reset controller states are promptly changed with the objective of improving the transient performance response.

Therefore, all these methods provide good solutions to achieve fast dynamics and accurate tracking with large signal stability. Among them, MPC could easily manage state/input constraints and could provide optimized performance with smooth transients. To achieve accurate tracking, MPC, backstepping and PBC need to be combined with estimation techniques, while SMC is simpler without the need of combining with an observer. The design of backstepping for Lyapunov stability is straightforward as long as the system is transformed to the standard form, the intermediate controller is obtained following the standard procedure and then transfer back to stabilize the original system. Passivity based controller exploits physical structure and allows plug and play of the converters for multiple systems with guaranteed large signal stability. Intelligent controller is preferred when the model is unknown. Therefore, these methods can be selected based on different requirements.

B. Application of advanced control to pulsed power load issue

As discussed in Section II.B, two requirements should be satisfied to accommodate PPLs, one is the coordination of the ESS and the main energy source, and the other is the fast response capability of the interface converter against the rapid and large load change. The conventional works only consider the coordination to get the reference current of ESS and the interface converter of ESS is controlled by linear control techniques, which cannot easily satisfy the high performance and fast dynamics required by PPLs. The advanced control strategies that consider both coordination and fast dynamics are reviewed first, and then the advanced control strategies for interface converters to achieve fast dynamics are discussed.

1) Coordination

Various advanced control strategies are applied for the coordination of the ESS and main energy source for the accommodation of PPLs. In [71], an energy management scheme is developed based on heuristics and model predictive control to optimize the power allocation between the generator and ESS under PPL conditions. In [72], a nonlinear model predictive controller is proposed to minimize the effectiveness of unknown PPL, where a novel nonlinear power observer is proposed to estimate the unknown PPL and a model predictive scheme is utilized to optimally determine the injected current of ESS to stabilize the overall DC microgrid considering

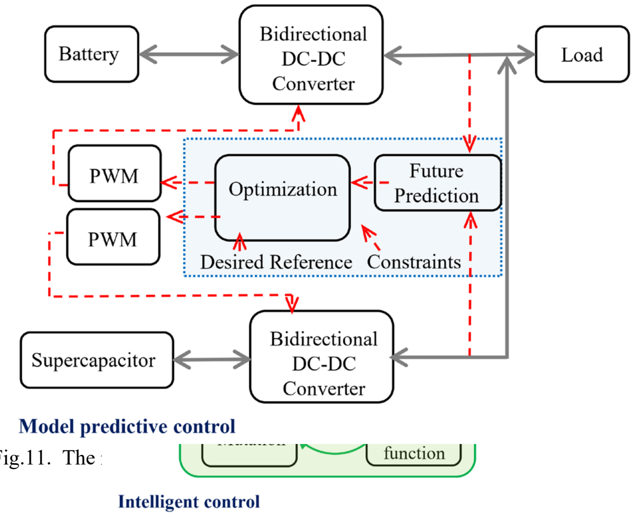

Fig.11. The

Fig.10. The intelligent control implementation to stabilize CPLs.

constraint of the main DC source and the ESS. Ref. [73] proposes a novel model predictive controller for the power allocation of a hybrid battery/SC system with the guaranteed hard constraints on the state variables and control signals; then the SC can be recharged as fast as possible and the dynamics of PPLs are assured. A feedback linearization technique is proposed in [11] to achieve fast and smooth ESS based on the different ramp rates of generation and charging power to provide generating references for the generator and ESS. In [74], an adaptive critic design (ACD) based cooperative control is proposed for a synchronous generator (SG) and an SC to achieve near optimal control under disturbances and model uncertainties; the charging current references of SC and SG are generated by using interactive learning of two neural networks for cost-to-go function and optimal control respectively; then PI controller or hysteresis-based controller is implemented for current tracking. As an improvement of [74], a two-player zero-sum game based cooperative control is proposed in [75] for onboard PPL; one player is the optimal controller and the other player is the disturbance; an online learning neural network is developed to solve the optimal control problem under disturbance; the proposed controller does not require the exact system model, initial control conditions and predetermined control references. In [76], a supervisory control strategy is proposed to manage the power flow and coordinate the system and an SMC strategy is proposed to track the power reference synthesized by the supervisory controller. An adaptive SMC with hysteresis control strategy is proposed for the coordination and control of a hybrid energy storage system [77]. In [78] a composite finite-time control scheme is proposed for a hybrid SC/FC system that an integral droop/proportional droop is combined with a finite-time controller and a finite-time observer for SC/FC converter, respectively so that SC only compensates fast fluctuations and FC supplies smooth power at steady state.

2) Fast response capability against PPL

To deal with PPLs which draw a large amount of power in a very short period of time, the interface converter should have fast dynamic response and stability over a wide operating range. There are many advanced control strategies that achieve fast dynamics with large disturbance rejection capability, though they are not specifically designed for PPL applications, they can still be applied for PPLs. Therefore, the advanced control methods with observers, e.g., MPC [42] [43], SMC [59], backstepping [48]–[51], as discussed in Section IV.A to address the CPL issue, can also address PPLs; and there are also many other works that provide good solutions:

A continuous MPC method with an observer is proposed in [79] for a DC/DC boost converter to achieve reduced time horizon and fast voltage dynamic response with a peak-constrained inductor current. An explicit MPC strategy is proposed for the inner loop control of a boost converter to achieve optimized fast dynamics with input constraints [80]. In [81], a composite finite control set MPC method with an observer is proposed to achieve a rapid dynamic response and offset-free tracking with input constraints. An explicit MPC method with an EKF is proposed in [30] to regulate the voltage under a wide operating range with improved dynamics.

A backstepping controller is proposed for an FC/SC system so that SC can track fast reference in the presence of load variation [82]. A backstepping approach is proposed with ESO to achieve decentralized active disturbance rejection control of interacting boost converters [83].

A continuous nonsingular terminal SMC strategy is proposed in [84] for a DC-DC boost converter to achieve fast transient responses, strong suppression ability against time-varying disturbances and small steady state oscillations of output voltage. A second-order SMC method is proposed in [85] to stabilize a synchronous buck converter with a fast step-load and start-up transient response, and is robust against parameter uncertainties.

In [86], a dynamic evolution control strategy is proposed to integrate an SC into an FC system. In [87], an artificial neural network is applied to calculate the optimal prediction horizon and then a finite control set MPC is utilized to control boost converter to ensure the performance with the reduced computational burden. An adaptive fuzzy neural network based SMC is proposed in [88] to achieve robust voltage regulation of DC/DC boost converter against various uncertainties.

An ADRC method is proposed in [89] for a bidirectional buck-boost converter control in a flywheel ESS to achieve high performance against model uncertainties and unknown disturbances. An optimized active disturbance rejection method with a reduced order generalized proportional integral observer (GPIO) is proposed in [90] for a buck converter to achieve optimized performance even with large disturbances. In [91], an equivalent input disturbance observer (EIDO) based method is proposed for voltage regulation of a buck converter against model uncertainties and output disturbances.

It can be observed from above that MPC, SMC, backstepping, intelligent and estimation/observer-based control provide fast dynamics against large disturbances to accommodate PPLs. As the applications of these advanced methods for PPLs follow the similar operation principle demonstrated in Section III, the advantages and disadvantages are similar with that discussed in Section IV.A, and the design procedure can follow the procedures demonstrated in Fig. 5-Fig. 10.

V. APPLICABILITY OF ADVANCED CONTROL IN OTHER DC/DC CONVERTER TOPOLOGIES

In the above sections, the bidirectional DC/DC converters are the classical buck, boost and buck/boost converters, which have been most widely applied due to their simplicity. However, they have limitations in high power applications, which require high step-up/step-down ratio and high power rating. To address this issue, numerous high gain DC/DC converter topologies have been proposed. They can be broadly divided as isolated and no isolated converters. In this section, the application of advanced control in these converters are reviewed.

A. Advanced control applications in other non-isolated DC/DC converters

Transformer based isolated converters can achieve a high voltage ratio easily. But considering the requirement of weight, volume and cost, if isolation is not necessary, non-isolated converters provide a more attractive choice. There are many non-isolated converter topologies in literature [19], e.g. switched capacitor [92], coupled inductor [93], voltage multiplier [94], multilevel [20], interleaved [21], or combination of some of the above structures [95], [96], etc. Although most of the topologies are derived from the classical converters, the control implementation of these topologies is more difficult due to more complex topologies and higher order converter models. Most of the non-isolated converters are controlled by PI controllers, but to further improve the performance and achieve robustness against uncertainties and disturbances, advanced control techniques can provide significantly better performance.

Voltage lifting techniques like switched capacitors, coupled inductors, switched inductors and voltage multiplies, provide effective high gains and help to develop various converter topologies. For the control of switched-capacitor DC-DC converters, there are output voltage ripples caused by alternatively turning on and off the switches and output leakage voltage caused by the reverse-recovery currents of transistors and diodes [97]. To address these issues, hysteresis control methods are widely used due to their advantage in stability and fast transient response compared with conventional PI control methods. Ref [98] proposes a modified hysteresis modulation based SMC for a hybrid converter (a boost converter combined with switched capacitors) to improve the dynamic performance and achieve accurate voltage regulation with guaranteed stability and easy implementation. In [99], an adaptive current mode controller is proposed for a hybrid converter by combining the indirect current control with an adaptive law to estimate the inverse of load resistance to calculate the inductor current reference, thus it achieves fast dynamics with accurate output voltage regulation against load variation. A deadbeat current controller is proposed in [100] for coupled inductor boost converter to enhance dynamic performance. In [101], a double integral SMC is proposed for a four quadrant quasi-z-source converter, providing eliminated steady-state regulation error and stable operation under the large variations of input voltage and load.

Quadratic converters are derived from boost converters to achieve high gain with a single switch. In [102], a robust controller is designed for a quadratic boost converter to achieve accurate voltage regulation with parameter variation and operating condition changing, where the inner current loop is based on SMC and the outer loop is derived based on Nyquist based robust loop shaping approach. In [103], the model of a quadratic converter is developed based on Hammerstein approach and a robust control technique is employed to achieve stable and accurate regulation against parameter uncertainties and load variations.

Cascaded converters increase the overall voltage gain and reduce the required voltage rating of switches by connecting *N*-conventional converters in cascade, then the voltage rating of the components is also reduced. But there are synchronization issues of converters in cascading and the stability issues caused by the interaction [104]. Ref. [105] developed a general model of N-stage cascaded converters with a single active switch. Based on this model, various control methods used in classical converters can be developed. A modified MPC is proposed for a cascaded modular DC/DC converter for the input voltage sharing and output voltage sharing.

Multi-level converters have advantages of lower component voltage rating, higher effective switching frequency, smaller filter size and higher power density compared with standard classical converters. However, balancing the flying capacitor voltage is a challenge. A second-order SMC is proposed for a three-level buck converter [106]. The proposed controller achieves fast start up with small overshoots, fast dynamics and accurate tracking against load disturbances and parameter uncertainties, and the flying capacitor voltage is balanced as well. In [107], two robust control laws are implemented for a ladder multilevel converter for voltage regulation, one is based on H_∞ mixed sensitivity control law and the other is based on μ robust control law.

Interleaved converters are widely studied in recent years, with the low current ripple and high-power application due to the phase interleaving and modular design. In [108], a nonlinear controller based on the flatness principle is proposed for a multiphase interleaved converter to achieve fast dynamics of power regulation with asymptotic stability. Ref. [109] proposes an advanced robust controller for a two phase interleaved converter consisting of a flatness controller and an ADRC, so that output voltage is accurately controlled and power among each phase is balanced accurately even with parameter variations. A robust dual loop voltage controller is proposed in [110] for a floating interleaved boost converter, where the SMC is for the inner current loop to achieve fast dynamics and the ADRC is introduced for the voltage control loop to enhance robustness against uncertainties. An SMC method with NDO is proposed in [111] for an interleaved boost converter feeding CPLs to ensure accurate tracking and large signal stability of CPLs. In [112], a tanh-function based super-twisting SMC is proposed for a floating interleaved buck-boost converter with suppressed noise. A dual loop control with a flatness controller for voltage regulation and a SMC for current regulation is proposed in [113] for a double dual-interleaving boost converter, which ensures good robustness against uncertainties and good performance against load variations. A PI + SMC is employed for a floating interleaved boost converter with high performance [114]. In [115], an ADRC is proposed for a floating interleaved boost converter to achieve uncompromised

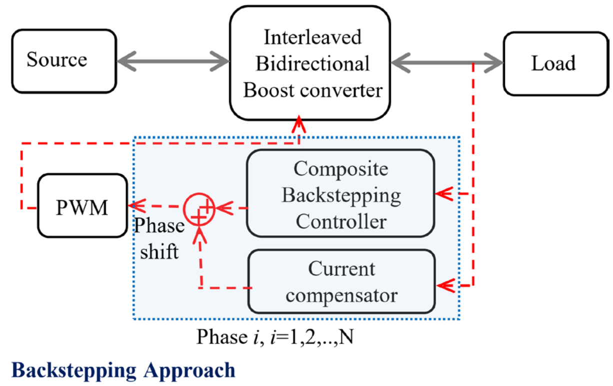

Fig.12. The backstepping implementation for interleaved converter system with CPLs.

performance with switch fault, external disturbances and parameter uncertainties. A robust MPC is proposed to achieve output voltage regulation with uncertainties [116]. Ref. [117] develops a generalized model for nonisolated multiphase DC-DC converter and an optimal controller is designed to achieve accurate voltage regulation with uncertainties. In [118], a backstepping controller with a finite-time observer is proposed for stabilizing an interleaved double dual boost converter feeding CPLs where the finite-time observer is to estimate CPL disturbances and the backstepping controller is for stabilization.

There are various topologies of non-isolated converters, and various advanced control technologies can be applied, including MPC, backstepping, SMC, intelligent control, observer-based control, as discussed above. The implementation of the advanced control technologies in these topologies can also follow the procedure introduced in Section IV.A. Fig. 12 shows an application example of backstepping control for an interleaved boost converter in [118]. The procedure of designing the composite backstepping controller is similar as that in Fig. 6 in Section IV.A.2: the model is first transformed into the standard form, then a disturbance observer is designed to estimate disturbances to achieve accurate tracking and a backstepping controller is designed for stabilization; the difference is a current compensator, which is added to ensure current balance considering the interleaved structure. Therefore, the demonstrations in Fig. 5 - Fig. 10 in Section IV.A can provide a guideline for advanced control technologies to be applied to various non-isolated converters to further enhance their performance.

B. Advanced control applications in isolated DC/DC converters

Transformer isolated converters are often utilized to comply with safety standards, provide voltage step up/down capability and reduce the common mode noise. They have wide applications in automotive powertrains [22], [23], more electric aircraft distribution systems [119], [120], naval shipboard microgrids [121], [122], power electronics transformers [123], nanogrids [124] and median voltage DC applications [125] etc.

Typical isolated DC/DC converters such as flyback, forward, Ćuk, Dual-Active-Bridge (DAB), *LLC* resonant have been widely applied in practical industry scenarios and there are many other isolated DC/DC topologies have also been reported in the literatures [126], [127]. Compared with the non-isolated DC-DC converters, literature on the topic of the advanced

Table I Comparison of advanced control technologies for DC/DC converters and their applications

Control methods	Advantages	Disadvantages	Application examples
Model predictive control	-Optimized transient performance with constraints -Multi-objective optimization with constraints -Fast dynamics -Accurate tracking with estimation based techniques	-High computation burden -Need to know detailed model	CPL[41-47], PPL[30,71-73,79-81], Non-isolated [105,116], Isolated [121,133-136]
Backstepping	-Fast dynamics -Straightforward implementation with large signal stability -Accurate tracking with estimation based techniques	-Need to transform the model into standard form	CPL[48-51], PPL[82,83], Non-isolated [118]
Sliding mode control	-Fast dynamics -Simple implementation -Robustness -Large signal stability	-Chattering problem	CPL[52-59], PPL[76,77,84,85], Non-isolated [98,100,101,102,106,110-114], Isolated[128-130]
Passivity based control	-Passivity/stability guaranteed based on the physical structure -Plug and play stability -Accurate tracking with estimation based techniques	-Need to know detailed model	CPL[60-64]
Observer/estimation based techniques	-Fast and accurate tracking against disturbances and uncertainties -To be combined with other methods	-Need to transform the model into standard form	CPL[42,43,48-51,59,63,64], PPL[81,83,89-91], Non-isolated [99,109-112,105]
Intelligent control	-Fast dynamics -No need model information	-Complicated and not in a systematic way	CPL[65 -67], PPL [74,75,86-88], Non-isolated[107,108,117]

control in isolated DC-DC converters is rather scarce due to the more complicated models with high frequency transformers.

A sliding-mode input-output linearization controller is proposed for DC/DC zero voltage switching CLL-T resonant converter with significantly improved transient response, disturbance rejection and guaranteed closed-loop stability [128]. A deadbeat control was proposed for DAB converters in [129], [130]. They have used high bandwidth current sensors to accurately sample instant high frequency transformer current, therefore fast transition was obtained. Semi-predictive approaches were also investigated by researchers. Ref. [131] proposed a method with feedforward loop to improve the dynamic performance. The feedforward loop shared similarity to [129] with respect to the requirement in instant high frequency current sampling. Above methods [129]–[131] have limitations in DAB converters operating in high power/high switching frequency as the sampling of the instant transformer current becomes more challenging. No mature products are available in the market for current sensing with bandwidth above 2MHz and current rating higher than 100A. A virtual direct power control scheme for DAB converters that prescribed less current sensors was proposed by ref. [132]. This method calculated the control output from the expression of power. However, this method still relies on the PI controller and demonstrated limited load current disturbance rejection. Ref. [121] proposed a Moving-Discretized-Control-Set MPC (MDCS-MPC) for the DAB. It discretizes the only control variable – the outer phase shift into small elements to fit in the principle of the well-known Finite-Control-Set MPC (FCS-MPC). MDCS-MPC relies on the averaged model and features fast transition performance. The SMC has been applied to DAB which achieves not only the zero steady-state error without any chattering but also the fast transient response for load variations and reference changes [133]. In order to enhance the efficiency, burst mode control has been reported in the literature for DAB light load operation [134]. State plane analysis has been adopted to decide the optimal duty cycle for the use of burst mode. Ref. [135] proposed a cost function under the same concept of MDCS-MPC to achieve the transformer current online minimization when the terminal voltages vary from their nominal values. Additionally, MPC can be used to select the optimal modulation in real time to enhance the efficiency [136]. Fig. 13 illustrates the implementation of MPC in DAB in [121] based on the basic operation principle in Section III.A.

Though there are not many works about advanced control methods in isolated converter systems, the illustrations in Fig. 5-Fig. 10 in Section IV.A can provide a guideline for advanced control technologies to be applied to further enhance their performance.

Based on the concept introduced in Section III and the practical application works reviewed in Section IV and V, a comparison is summarized in Table I. It can be observed that all these methods provide good solutions to achieve fast dynamics and accurate tracking with large signal stability for the CPL issue. Moreover, MPC, backstepping, SMC, intelligent, estimation-based techniques can also deal with the PPL issue. The advanced control techniques can also be applied to various non-isolated and isolated converters to achieve high performance. To satisfy different application requirements, these methods can be selected based on their advantages and disadvantages, as listed in the table.

VI. Conclusion and future trend

This paper provides an overview on advanced control technologies and how they can be applied to DC/DC converters to address the problems of CPLs and PPLs. For CPLs, they may cause instability in DC microgrids due to the negative impedance characteristics; advanced control technologies, like MPC, backstepping, SMC, PBC, intelligent and disturbance estimation techniques can be applied to ensure the stability in a large signal sense. For PPLs, they may cause power imbalance in DC microgrids due to the pulse behavior with high power characteristics; advanced control technologies, like MPC, backstepping, SMC, intelligent and disturbance estimation based techniques can be applied for the coordination of ESS with the main power source to accommodate PPLs, and for fast dynamic response of the interface converters of the ESS. Except for the classical bidirectional DC/DC converters, the advanced control techniques can also be applied in high gain non-isolated converters (e.g., interleaved, multilevel, cascaded) and isolated converters (e.g., dual active bridge) for high power applications to improve system performances. Comparisons are made for various advanced control technologies with advantages and disadvantages; they can be selected based on different application requirements.

This work also provides a guideline about how the advanced controllers can be designed for DC/DC converters, which can also be extended to other non-isolated and isolated DC/DC converters and AC systems like voltage source converter, inverter, multilevel converter, etc. Based on the operation principles of the advanced control technologies described in Section III, the implementation of these advanced controllers can follow the examples given in Section IV.A. In the future, the advanced control technologies can be further explored in AC systems and high voltage DC systems to enhance the system performance, stability and robustness.

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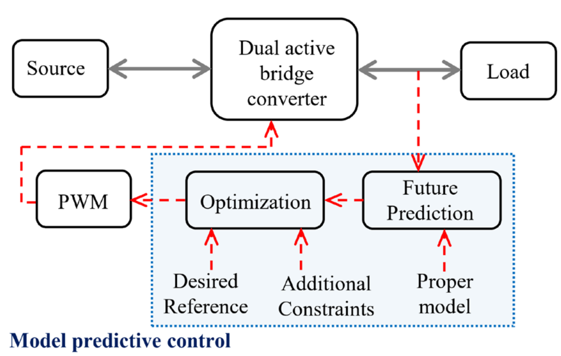

Fig.13. The model predictive control implementation for dual active bridge converter system with CPLs.

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