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Archivio della ricerca – postprint

DC Shipboard Microgrids With Constant Power Loads: A Review of Advanced Nonlinear Control Strategies and Stabilization Techniques

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***Abstract*—In modern dc shipboard microgrid (SMG) systems, the propulsion motors and hotel loads are always supplied through tightly regulated point of load converters, which behave as constant power loads (CPLs). The negative incremental impedance due to CPL's characteristics destabilizes the dc bus voltage of dc SMGs. Due to uncertain operating conditions of maritime ships on the sea, the dc bus voltage robust control is a crucial matter. Therefore, this paper presents a cutting-edge systematic review on advanced nonlinear control strategies to stabilize and control the CPLs in dc SMGs, such as sliding mode control, synergetic control, backstepping control, model predictive control, and passivity-based control. The latest stabilization techniques and the future trends towards an adaptive nonlinear control have been presented throughout this review. Several feedforward control-based observation and estimation techniques have been highlighted. The stability analysis and stability challenges of dc SMGs are also discussed.**

***Index Terms*—DC shipboard microgrids, constant power load, adaptive nonlinear control, power electronic converters, system stabilization, nonlinear disturbance observer.**

I. Introduction

RECENTLY, dc microgrids (MGs) attracted great interest of many academic and industrial researchers, since it can efficiently integrate local groups of distributed generation (DG) units and energy storage systems (ESSs) directly to the dc loads with less conversion stages [1]–[3]. DC MGs based on local DG systems (renewable generation), combined with the capability to work dependently or independently of the main grid, makes the dc MGs technically a feasible option to address the concerns of substantiality, reliability, and energy efficiency [4]. Furthermore, the accelerated improvement in the performance of ESSs during the last decade makes dc MGs an economically viable option, which also helps to address the concerns of energy saving and balance [5], [6]. In addition to the application of dc MGs on land, it has also been successfully implemented in off-grid applications, such as electric vehicles, aircraft, and maritime ships [7], [8]. [9]–[11]. Thus, the dc shipboard microgrids (SMGs) emerged as a modern electrification network for maritime ships. Fig. 1 shows a typical structure of the dc SMGs for maritime ships, which is composed of the propulsion motors and hotel loads supplied by DG units; diesel generators, fuel cells, photovoltaic (PV) modules, and a pack of batteries. This structure can work in different operating modes with advanced energy management and control systems [9]. It can also be connected or disconnected from the shore power system. Since the 1990s, the controlled power electronic converters have created a breakthrough in the field of shipboard electric networks enabling electrification of the propulsion motors through drivers based on variable-voltage-variable-frequency control. To reduce fuel consumption, emission, and to increase the efficiency of maritime ships, the concept of all-electric ship (AES) has been presented as a modern electrification approach to supply the propulsion system electrically instead of the conventional mechanical one [12], [13]. In this regard, dc SMGs offer remarkable features as compared with ac MGs, which can efficiently reduce the fuel consumption, weight and space needed [8], [14]. The diesel generators in dc SMGs can work with optimum speed, whereas the speed in ac MGs can only be fixed at the frequency of the system. Therefore, dc SMGs allow the generators to work with a unity power factor with a faster and simpler parallel connection [14]. In view of the advantages of dc MGs, many practical dc maritime ships projects have been implemented around the world. Thanks to the Italian Navy project named Naval Package, the generation system for medium voltage dc (MVdc) integrated power systems (IPSs) has been implemented in [15]. ABB

Manuscript received 8 July 2021; revised 3 November 2021 and 28 February 2022; accepted 8 April 2022. Date of publication 19 April 2022; date of current version 23 August 2022. This work was supported in part by the Ministry of Science and Technology of Taiwan under Grant MOST 107-2221-E-992-073-MY3. Paper no. TSG-01042-2021. *(Corresponding author: Chun-Lien Su.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSG.2022.3168267.

Digital Object Identifier 10.1109/TSG.2022.3168267

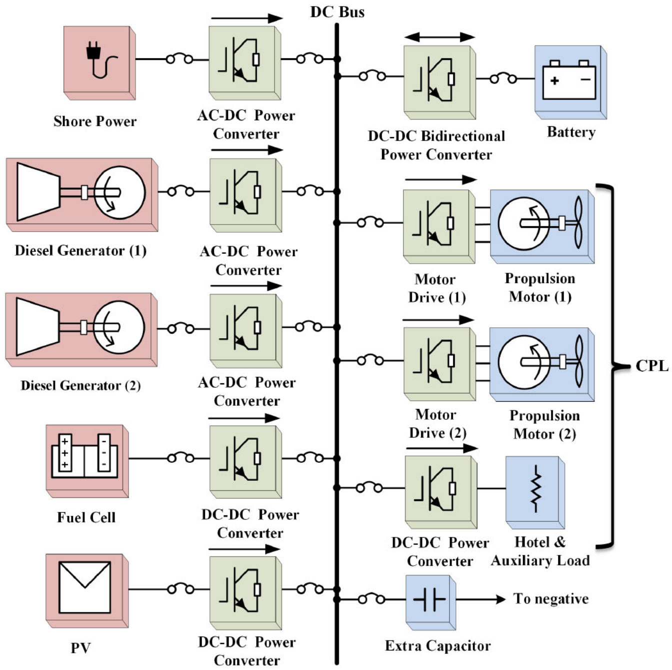

Fig. 1. Typical structure of dc SMGs.

has developed an onboard dc grid for ships, including power rectification, power protection, and safety [16], [17]. The dc vessel named BlueDrive PlusC was developed by Siemens to provide a comprehensive solution in cost reduction, where the diesel generators can run at an optimum speed to meet the load changes [18]. To further reduce cost, Siemens and Ostensjo Rederi in Norway have launched the Edda Ferd dc ship, which combines a set of batteries to work in one IPS with the available diesel generators [19]. In Norway, the Viking Lady vessel has also been developed by adding fuel cell generation to the available set of generators and batteries. The happiness hybrid-electric ferry is also developed in Taiwan based on a hybrid power source containing diesel generators with a set pack of batteries that are connected to dc and ac MGs [20].

However, due to uncertain operating conditions of maritime ships on the sea, dc bus voltage stabilization, regulation, and fast recovery during disturbances are the most important issues in the dc SMGs operation. Several disturbance dynamics could degrade the regulation of the dc bus voltages, such as oscillation dynamics due to the CPL [21], [22], pulsed load [22], [23], voltage mismatches between power converters [24]–[27], fault occurrences [28], and load rejection (sudden disconnection of entire propulsion loads). Due to off-grid working conditions of ships on the sea, the CPL is significantly impacting stability in dc SMGs compared to the dc MGs on the land. An effective three control levels for dc MGs were presented in [29], including primary control for dc bus voltage regulation, secondary control with voltage restoration, and tertiary control for energy management. This paper focuses on the CPL instability problem of dc SMGs at the primary control level, including the CPL's characteristics, definition, and problem solutions using advanced nonlinear control techniques.

The problem of CPL was originally defined by Middlebrook, 1976 in [30], when the tightly regulated point of load (POL) converter is supplied through an undamped input LC filter. The ideal infinite output impedance of the LC filter at the resonance frequency makes the system unstable. In order to regulate the propulsion motor's speed in dc SMGs, the motor driver absorbs constant power from the dc bus voltage. Likewise, to supply the hotel loads, the dc-dc buck power converter draws constant power to regulate the output voltage. The POL converters (either for speed or voltage regulation purposes) are the substantial causes of the CPL dynamic, which creates a negative incremental impedance (NII) [31]. Owing to this impedance, the system becomes unstable, poorly damped and has loss-less energy dissipation across the CPL's input terminals [21], [22]. The constant oscillation caused by the CPL is known as the limit-cycle dynamic, which is the origin of the dc bus voltage instability [21]. This dynamic not only degrades the stability of dc SMG, but also increases the stress across the switching components of power source converters. To stabilize the CPL in dc MGs, intensive research has been undertaken in the literature including linear or nonlinear control strategies. Numerous linear control strategies have been studied using either passive or active damping control techniques [21]. The passive damping is achieved by adding a real passive component to the converter's circuit such as real resistors or capacitors [32]–[34]. Whereas, the active damping is obtained by passivating the converter's circuit virtually through the control action [35]–[37]. For both linear control approaches, the main converter's circuit as well as the control feedback system must be linearized in a small vicinity near to a certain equilibrium point. Therefore, the linearization-based small-signal model can only provide an accurate control performance in a small neighborhood to this point. Given the nonlinear nature of the power electronic converters, a typical robust control dynamic away from this point cannot be obtained. Therefore, the majority of linear control techniques cannot maintain the global stability of the system at wide dynamic ranges.

A great effort was employed to cancel out the nonlinearity caused by the CPLs using; linearization via state feedback [38] or loop-cancellation control [39]. Although nonlinear feedback is added to capture the overall nonlinear dynamics owing to the CPLs, the baseline controller is still linear. For all these reasons, linear control strategies are considered as over conservative control methods which, may not be suitable in many industrial and power electronic applications [40], [41]. Therefore, the current research is attracted towards nonlinear control techniques. The main feature offered by nonlinear control techniques is that they can provide large-signal stability with globally asymptotically stable equilibrium points. Besides, all power electronic converters are nonlinear in nature, therefore, they are more efficiently controlled using nonlinear control strategies.

The main contribution of this article can be summarized as follows:

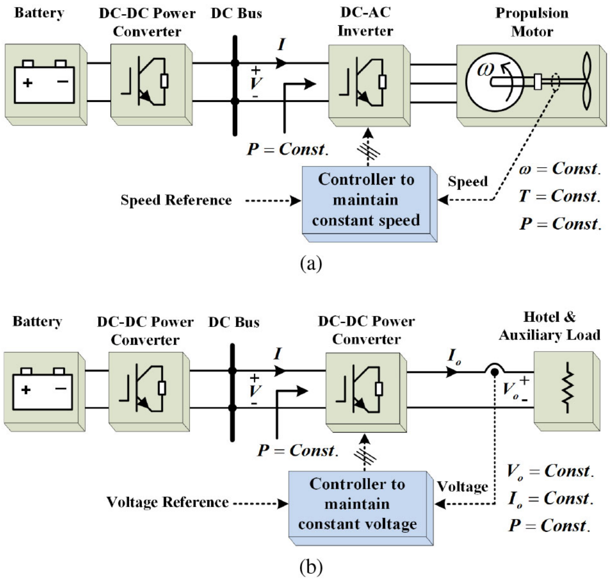

Fig. 2. Typical CPL characteristics due to the (a) speed regulation and (b) voltage regulation.

1) This paper reviews the latest nonlinear control techniques to stabilize the CPL in dc SMGs. The cutting-edge state-of-the-art literature for the most advanced nonlinear control strategies is presented and discussed. The instability problem of dc SMGs due to CPL limit-cycle dynamic has been introduced and defined. The recent stabilization techniques of dc SMGs with CPL have been reviewed.
2) It was noted that the majority of the nonlinear control strategies tend to use an adaptive control (using feedforward compensation control) to improve the control robustness against system disturbances, such as CPL changes. Therefore, this paper also fills the gap in the applications of feedforward control-based observation and estimation techniques. This review paves the road for further investigation on adaptive nonlinear control strategies and their application in dc SMGs.
3) Large-signal stability analysis and stability challenges of dc SMG have been presented. The future trends towards adaptive nonlinear control techniques have been covered and discussed. The upcoming work of this current version is also highlighted.

The paper is organized as follows. The CPL problem and its characteristics are defined in Section II. An overview of advanced nonlinear control technologies is presented in Section III. The main challenges and future trends for dc SMG CPL stability and control are presented in Section IV. The main conclusions of this work are summarized in Section V.

II. DC Shipboard Microgrid CPL Instability Definition and Characteristics

In dc SMGs, there are two types of CPLs, including the dc-ac inverter, which drives the propulsion motors of ships, and the dc-dc power converter that regulates the output voltage for the hotel and auxiliary loads (see Fig. 2). Both converters consume constant power from the dc bus. Fig. 2(a) depicts the dc-ac inverter, which drives the propulsion motor with tightly regulated speed. As the speed (ω) remains regulated at a fixed value, the torque (T) would remain constant too. Therefore, the power consumed ($P = T\omega$) is almost constant [31]. Similar to this one-to-one speed-torque characteristic of the propulsion loads, the power consumed by the hotel and auxiliary loads is also constant. As shown in Fig. 2(b), the dc-dc converter regulates the output voltage (V_o) at a constant value, the output current (I_o) is constant. Therefore, the power ($P = V_o I_o$) delivered to the load is also constant [31]. By neglecting the power converter's losses, the input power of CPL is equal to the output power. Fig. 3 shows the negative incremental impedance (NII) dynamic of CPL due to its input voltage-current curve characteristics. To maintain constant power at the CPL's input terminals, the feedback control system always enforces the input current (I) to increase (decrease) as the voltage (V) across the CPL decreases (increases). Although the instantaneous impedance of CPL is positive ($V/I > 0$), the incremental impedance is always negative ($dV/dI < 0$) [31], [33]. The incremental impedance can be determined as:

$$R_{inc} = \frac{\partial v}{\partial i} = \frac{\partial}{\partial i}\left(\frac{P}{i}\right) = -\frac{P}{I^2} = -\frac{V}{I} \quad (1)$$

This negative impedance always makes the system poorly damped, unstable, and has loss-less energy dissipation across the CPL's input terminals [21]. Besides, the NII dynamic is nonlinear in nature, and it is not stable when supplied by an open-loop control source power converter. Following an open-loop dynamic equation of dc-dc buck power converter supplying CPL. where L, C and E represent the circuit inductance, capacitance, and input voltage, respectively. μ, i_L and v are the duty-ratio, inductor current, and dc bus voltage, respectively.

$$\begin{cases} L\dot{i}_L = E\mu - v, \\ C\dot{v} = i_L - (P/v) \end{cases} \quad (2)$$

The output-to-input voltage transfer function $G(s)$ is given by [31], [42], [43]:

$$G(s) = \frac{\hat{v}(s)}{\hat{E}(s)} = \frac{\mu_e}{LCs^2 - L\left(\frac{P}{V^2}\right)s + 1} \quad (3)$$

where $\mu_e = V/E$ is the duty-ratio for the steady-state point (V, I_L). The poles of (3) have positive real parts, which means that the system is unstable owing to the effect of the CPL [31], [42], [43]. Therefore, without a robust feedback control system, the dc bus voltage oscillates, creating a limit-cycle dynamic. This dynamic also increases the stress across the switches of the source power converters.

III. Nonlinear Control Strategies and Stabilization Techniques for Constant Power Loads in DC Microgrids

Because all physical systems are nonlinear in nature, nonlinear control is more suitable [44]. Nonlinear control theory is one of the areas of control that deals with systems that are nonlinear, time-variant, or both. Nonlinear control strategies are a

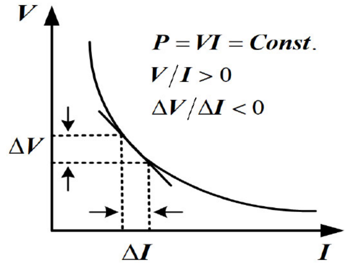

Fig. 3. An approximation voltage-current characteristics curve of the CPLs.

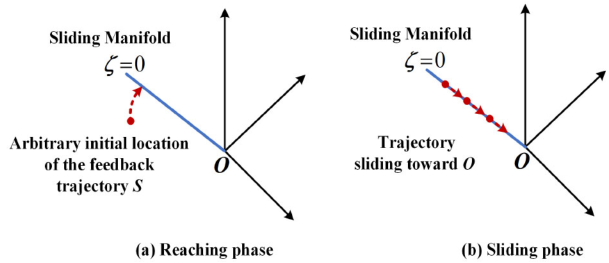

Fig. 5. Sliding phases toward the equilibrium point.

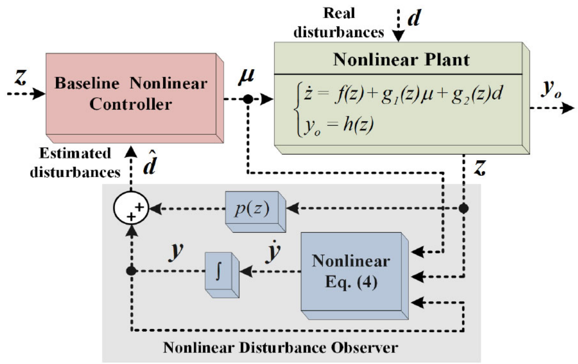

Fig. 4. Structure of the nonlinear disturbance observer.

class of closed-loop feedback control systems that can ensure a global solution for nonlinear systems with large-signal stability. Moreover, it also concurs with the nonlinear nature of the power electronic converters [45]–[47]. The majority of the nonlinear control strategies use Lyapunov's theorem as a general platform to analyze the system's stability. Since the power converters and the CPLs are nonlinear systems, it is more efficient to be controlled using nonlinear control schemes. Several advanced nonlinear control schemes have been presented in the previous literature to stabilize the CPL in dc SMGs, such as sliding mode control, synergetic control, backstepping control, model predictive control, and passivity-based control.

On the other hand, there have been great efforts to develop fast and robust control strategies for the nonlinear plants subjected to unknown disturbances/uncertainties. An adaptive nonlinear control (based observation and estimation) has been proved to be one of the most promising control systems, which can be applied to control power electronic converters subjected to large system disturbances [40]. In general, there are two stages to design adaptive nonlinear control schemes; (i) design baseline nonlinear controller to guarantee voltage regulation at steady-state operation, and (ii) adding an external control circuit to attenuate steady-state errors due to system disturbances [48]. In power electronic applications, two control techniques are usually used to eliminate the steady-state error caused by the system disturbances, including feedback or feedforward control. It is well-known that the linear proportional-integral-derivative (PID) control system always attenuates system disturbances through feedback control, which has slow performance, noise degradation due to derivative part, and stability margin reduction due to the integral control [40]. In contrast, the feedforward control-based observation and estimation technique ensures faster and robust dynamic response during system disturbances with less number of sensors [41], [47]. Although the PID control system is a successful mechanism that dates back to the 1920s, the author in [40], provided a sufficient justification to switch from the PID controller to the disturbance rejection control system based on extended state observer. Therefore, the majority of current research is focused towards adaptive control-based feedforward observation and compensation, such as nonlinear disturbance observer (NDO), sliding mode observer (SMO), immersion and invariance (I&I) observer, extended Kalman filter (EKF), artificial intelligence (AI)-based observer, etc. This paper will review all these observation techniques.

Recently, the NDO attracted substantial interest since it can work independently of the baseline nonlinear controllers, with less information dynamics [41], [48], [49]. Based on the observation mechanism, the NDO can estimate all disturbances/uncertainty of the system. The NDO can estimate the disturbances that are not easy to be sensed in some practical applications, thus reducing the number of required sensors. The general equation of the basic NDO is [41]:

$$\begin{cases} \dot{y} = -\ell(z)g_2(z)y - \ell(z)\big[f(z) + g_2(z)p(z) + g_1(z)\mu\big] \\ \hat{d} = y + p(z), \end{cases} \tag{4}$$

where $\hat{d}$, $y \in \mathbb{R}^l$, $\ell(z)$, and $p(z)$ are the estimated disturbances, observer's internal state vector, observer's nonlinear gain function, and the nonlinear function to be designed, respectively. $f(z)$, $g_1(z)$, $h(z)$, and $g_2(z)$ are smooth functions in terms of z. This observer can be connected to the nonlinear plant as depicted in Fig. 4, [41]. To reject system disturbances, the estimated disturbances $\hat{d}$ would be injected to the baseline nonlinear controller.

A. *Sliding Mode Control (SMC)*

SMC is one of the nonlinear control strategies categorized under the variable-structure system [46], [47], [50]. The main feature offered by the SMC is that it can operate at high-speed switching frequency control, which can drive the trajectory of the system state into a specified surface in the state space, named switching surface or sliding manifold. Thus, SMC has a fast recovery performance as well as robust control against system disturbances, such as CPL variations. In general, there are two important phases for SMC design, including (i) reaching phase, which enables the system trajectory S to be attracted towards the sliding manifold $\zeta = 0$, as shown in Fig. 5a, and (ii) sliding phase, which keeps the trajectory slides toward the steady-state equilibrium point $O = 0$, as shown in Fig. 5b [46], [47]. Following is the dynamic equation of the common power electronic converters, such as buck, boost, and buck-boost converters [46], [47]:

$$\dot{z} = Az + uBz \tag{5}$$

where $z \in \mathbb{R}^n$ is the vector state, $A, B \in \mathbb{R}^{n\times n}$ are the connection matrix, and u is the control law. The basic sliding surface can be written as:

$$S = z - z^* \tag{6}$$

where z^* is the desired reference vector. The discrete control law has been determined in the following form:

$$u = \frac{1}{2}(1 - sign(S)) \tag{7}$$

Owing to the fast switching performance, the nonlinear SMC has attracted great attention to enhancing the stability of dc bus voltage supplying CPLs in shipboard's electric networks [51]–[54]. Besides, there are great efforts to increase the robustness of the SMC using feedforward observers. To improve the control robustness of SMC strategy, an observers based on estimation techniques are introduced to work in parallel with SMC, as shown in Fig. 6, [51], [53]–[61]. i_{LN} are the N inductor currents, μ are the duty cycles and k are the control laws. The system states z are transformed into states representing the total energy stored x using the canonical form transformation, which is the input for the observers [58]. The proposed observers were designed as NDO in [57], [58]. It is also presented as an observer based on AI control algorithms in [53]–[56]. The AI algorithms are proposed using an interval type-2 fuzzy logic controller in [53], [54], and deep learning controller in [55], [56]. To reject the system disturbances, uncertainty and to enhance the stability of the dc-link voltage, the observer is also combined with working in parallel with a composite discretized quasi-sliding mode control scheme in [59] and SMC strategy (working as outer-loop) in [60]. It is worth mentioning that the observer-based estimation technique has gained great attention in all applications of nonlinear control strategies, including the SMC. The estimated disturbances $\hat{d}$ are injected into the SMC through feedforward compensation channels to ensure robust control dynamics. The feature offered by the feedforward control has an extremely fast response against system disturbances, such as CPL variations.

Rather than using observers, the SMC performance is also improved by introducing other techniques. In [62], the switching function-based SMC synthesizes CPL with a series inductor in the input port. The switching function is designed to represent the error difference between the input power and the desired power reference. In [31], a simple sliding surface has been proposed to control the dc-dc buck power converter feeding a CPL. The attraction region toward the equilibrium point is bounded by large-signal stability. However, the proposed sliding surface lacks to ensure voltage regulation during load changes. Authors in [63], [64], have proposed a robust nonlinear sliding surface to control different topologies of dc-dc power converters (buck, boost, and bidirectional) feeding a

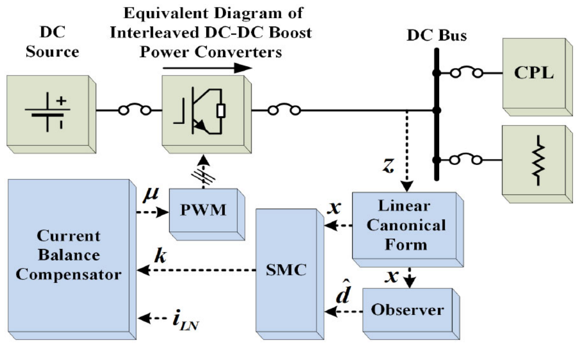

Fig. 6. Structure of sliding mode control strategy with the observer.

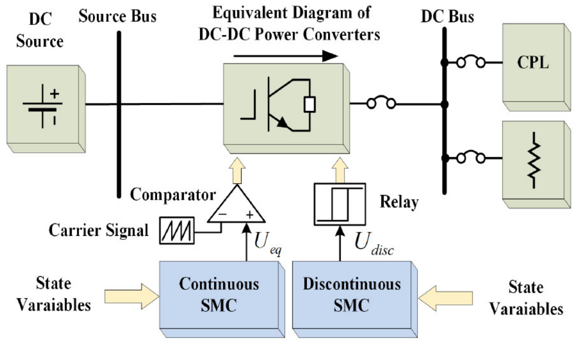

Fig. 7. Continuous and discontinuous SMC strategies.

CPL. In this work, the SMC was implemented based on two different control schemes; continuous or discontinuous control schemes (see Fig. 7). These controllers provide a robust voltage control against both input voltage and load variations.

Indeed, the common problem that faces the majority of SMC strategies is that ideal control performance can only be obtained at extremely high switching frequencies; which causes the well-known chattering problem. High switching frequencies lead to high switching losses in the power devices. It also increases the possibility of electromagnetic interference with neighboring devices. Recently, high-power high-frequency silicon carbide transistors can help SMC to achieve robust control performance. Therefore, the SMC is expected to be applied widely in the applications of dc SMGs in the future.

B. Synergetic Control (SC)

The synergetic control method is a nonlinear algorithm that can be designed based on the concept of the nonlinear dynamic dissipative system [65]. The synergetic control strategy and the SMC share a similar control scheme by designing a linear manifold that attracts the system states towards the desired equilibrium point. The following differential equation defines the nonlinear plant to be controlled:

$$\dot{z} = f(z, \mu, t) \tag{8}$$

where z is the state variable vector, μ is the control input for the plant, and t is time. The following steps have to be followed to design a synergetic control strategy:

1) Define a macro-variable ψ to be a function of z with considering all control system specifications and characteristics.

$$\psi = \psi(z) \quad (9)$$

The closed-loop control system forces the plant to work at switching surface $\psi = 0$. The derivative with respect to z is given by

$$\dot{\psi} = \frac{d\psi}{dz}\dot{z} \quad (10)$$

2) Determine the desired dynamic equation of macro-variable as.

$$\mathcal{T}\dot{\psi} + \psi = 0, \quad \mathcal{T} > 0 \quad (11)$$

$\mathcal{T}$ is the control parameter to ensure the convergence towards the desired manifold $\psi = 0$.

3) Synthesize the input control law μ, by invoking (8) and (10) in (12), obtaining

$$\mathcal{T}\frac{d\psi}{dz}f(z, \mu, t) + \psi = 0 \quad (12)$$

Numerous synergetic control strategies have been presented in the past literature to control the CPL in dc MG systems. In [66], the synergetic control strategy is used to stabilize parallel-connected dc-dc buck power converters feeding a CPL; the control performance of this strategy gives robust dynamics and faster response as compared with a linear control strategy. This work not only ensures voltage regulation but also provides equal current sharing among the parallel buck power converters. However, this article did not provide a detailed analysis for CPLs. In [67], [68], the same authors proposed synergetic control strategies to control the output voltage of the n number of paralleled dc-dc buck power converters supplying CPL in dc SMG. The condition of an equal current sharing is satisfied by introducing invariant manifolds into the state-space of the system, which significantly suppresses the error of the output voltages. The synergetic control strategy is also implemented in [69], [70] to stabilize the dc bus voltage supplying CPL in the MVdc distribution system. In both works, a detailed performance comparison has been presented to demonstrate the superiority of the synergetic control as compared with the linear feedback control.

A synergetic control strategy is a promising control method, which can generate fixed switching-frequency without chattering problem. However, it is sensitive to parameter uncertainty and load disturbances. The synergetic control is not yet combined with the NDO or other observers, which may open a new research direction to improve control robustness of synergetic strategy in terms of fast dynamic response against system disturbances. Since synergetic control requires a fairly low bandwidth for the control design, it is more suitable for digital control applications, such as digital signal processors. However, it requires more complex calculations.

C. Backstepping Control (BSC)

BSC is a nonlinear control approach that works according to a recursive Lyapunov-based scheme [71], [72]. The concept behind the BSC scheme is to design a controller that

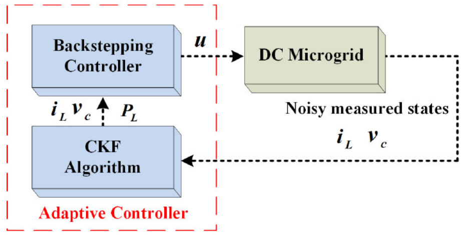

Fig. 8. Structure of BSC strategy with CKF.

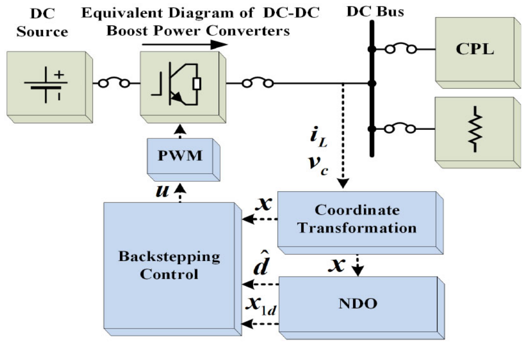

Fig. 9. Structure of BSC strategy with NDO.

works recursively by considering some of the state variables as virtual control and designing intermediate control laws for them. Following this criterion, the final control signal of the feedback system will be reached by systematically following a step-by-step backstepping algorithm [71]. In [73]–[75], the BSC performance of the dc-dc boost converter (classical or interleaved) feeding a CPL is improved by adding the NDO. Based on the standard backstepping design, the dynamic model of the dc-dc boost power converter with the CPL is converted into Brunovsky's canonical form. At the same time, the NDO is added to eliminate the regulation error during disturbances. This control strategy ensures global stability under large variations of the CPL and provides a fast dynamic response compared with the linear control. However, these papers did not present the control performance before and after adding the NDO. By transforming the model into Brunovsky's canonical form, an adaptive backstepping sliding mode control strategy is also presented in [76] to improve the control robustness of dc bus voltage supplying the CPL in the dc MG. In [77], an adaptive BSC strategy is proposed to stabilize the uncertain CPLs in dc MG. The CPLs are represented by electrical aircraft that comprise a vast amount of tightly regulated POL converters. A third-degree cubature Kalman filter (CKF) algorithm is developed to improve the control robustness of the backstepping controller by estimating not only the states of the dc MG, but also the total power of the load P_L (see Fig. 8). The estimated signals of load power are then sent to a backstepping controller to stabilize the dc MG, as well as to track the desired value of the dc bus voltage.

Based on the estimation technique (i.e., NDO), the BSC strategy has also been developed to control high voltage gain converters, such as floating dual boost converters (FDBCs) in [78], and multilevel boost converters (MBCs) in [79]. It is worthy to note that the NDO has been added to the majority of the above-mentioned BSC strategies [73]–[75], [78], [79]. Fig. 9 depicts the general structure of the BSC combined with the NDO. The NDO estimates the system disturbances $\hat{\boldsymbol{d}} = [\hat{d}_1 \quad \hat{d}_2]^T$ based on the input system's states $\boldsymbol{x} = [x_1 \quad x_2]^T$, using the following coordinate transformation, [73]–[75], [78], [79]:

$$\begin{cases} x_1 = \frac{1}{2}Cv_c^2 + \frac{1}{2}Li_L^2, \\ x_2 = \dot{x}_1 \end{cases} \tag{13}$$

where x_1 is the state of the total energy (potential plus kinetic), and x_2 describes the transient dynamics of x_1. Additional coordinates (z_1, z_2) have been added to enforce the state variables (x_1, x_2) to track the desired reference values (x_{1d}, x_{2d}), which can be written as:

$$\begin{cases} z_1 = x_1 - x_{1d}, \\ z_2 = x_2 - x_{2d} \end{cases} \tag{14}$$

Finally, the intermediated control law v of the BSC can be determined as follows:

$$v = -k_2 z_2 - \hat{d}_2 + \ddot{x}_1 \tag{15}$$

where k_2 is the control gain, and $\hat{d}_2$ is the estimated system disturbances provided by the NDO. We can conclude that the control dynamics of the BSC strategy is significantly improved by adding the NDO, which can open the window for using more advanced estimation techniques to enhance the stability of dc SMGs.

D. Model Predictive Control (MPC)

MPC is one of the nonlinear control strategies recently applied in power electronics converters [80]. This control strategy uses a discrete-time model to predict the changes in the system states (dependent variables) caused by variations in the independent variables, such as line and loads variation. The prediction process takes place at every single sample time to minimize a certain cost function. By comparing the system output with a reference value, this function works as an actuator to provide future information for the next sample time of each variable. Recently, the application of MPC in dc SMGs has also attracted much attention [81]–[85]. Generally, to stabilize the CPLs, the MPC can be categorized into two groups [86]; continuous control set (CCS) and finite control set (FCS). The CCS-PMC works based on the principles of continuous signals [87], [88], whereas the FCS-MPC considers the discrete nature of the nonlinear system [89]–[93]. To improve the control robustness of the MPC, both; extended [94] and pseudo-extended Kalman filters (EKFs) [95] are proposed to estimate the time-varying power of uncertain CPLs in dc SMG. The estimated power is then injected into the PMC circuits, which is considered an economical solution compared with using real sensors to measure the online CPL's power. Recently, observer-based control has also been applied to work in parallel with the MPC strategies to stabilize the CPLs [96]–[98]. This observer is designed either as NDO in [96], fuzzy-observer in [97], or higher-order sliding mode observer in [98]. Fig. 10 depicts the common structure of the MPC for dc-dc power converters supplying CPLs. The

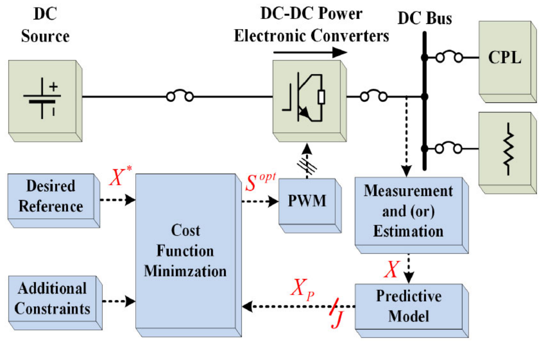

Fig. 10. Common structure of MPC strategies.

predictive model presents J different switching states. The control objective is obtained when the variables X converge with the desired values X^*. The common stages to implement the MPC strategies are shown as follows [80]:

1) Measure and (or) estimate (based observation) the controlled state variables X.
2) Based on the previous optimal switching state, predict the behavior of the state variable for the next sampling step X_P.
3) Evaluate and calculate the error $|X^* - X_P|$ to generate the switching state that minimizes the cost function S^{opt} to be the state for the next sampling interval.

Other new techniques also were presented to improve the control robustness of the MPC. By treating a multiparametric nonlinear programming problem, an offline optimal control law is designed in [99] to drive an explicit MPC for a dc-dc boost converter supplying CPL. In [100], parallel power converters are implemented to supply the CPL. The MPC is used to enhance the stability for equal current sharing and voltage regulation by replacing the conventional primary level of dc MGs (inner-loop and droop control) with a single optimal predictive model controller.

The main feature offered by MPC is that it can solve an online optimization problem for multi-input multi-output (MIMO) systems while handling all constraints of the system. However, it requires a powerful, fast processor with large memory. This increases the computational complexity and cost.

E. Passivity-Based Control (PBC)

PBC is one of the high-gain nonlinear control strategies that focus on the principle of energy conservation (i.e., energy supplied is equal to the sum of energy dissipated plus energy stored). The passivity property is presented as an alternative concept to describe and control nonlinear systems from an energy processing perspective. For physical systems that contain input ($u \in \mathbb{R}^m$) and output ($y \in \mathbb{R}^n$), the system is said to be passive if the energy stored $\dot{\mathcal{H}}(z)$ is always less than the energy supplied $u^T y$ with the difference being the energy dissipated $\mathcal{Z}^T \mathcal{R}_i(z) \mathcal{Z}$, which is represented by the following energy balance equation [101]:

$$\underbrace{\int_0^t u^T(t) y(t) dt}_{\textit{energy supplied}} = \underbrace{\int_0^t \mathcal{Z}^T \mathcal{R}_i(z) \mathcal{Z} dt}_{\textit{energy dissipated}} + \underbrace{\mathcal{H}(z(t)) - \mathcal{H}(z(0))}_{\textit{energy stored}} \tag{16}$$

The PBC strategy has been successfully applied in many power electronics and industrial applications. PBC strategy has been presented to stabilize the CPL in dc SMG and to control the dc bus voltage [102]. The passivity property almost concurs with the physical nature of power electronics architecture, which are composed of storing elements (inductances and capacitances) and dissipative loads. To damp the energy oscillation caused by the CPL, the PBC strategy reshapes the energy balance equation (16) by injecting the new desired storage energy and dissipation functions. This can be achieved virtually through the control action. Therefore, to implement the feedback PBC strategy, two stages have to be followed, including energy shaping stage by modifying the coordinates of the stored energy (potential or kinetic) with handling the new deviations, and the damping injection stage by injecting virtual damping resistance matrix. In general, the PBC strategy can be divided into two main groups including; (i) classical PBC, and (ii) interconnection and damping assignment (IDA-PBC), [103]. The classical PBC strategy was originally proposed by Ortega *et al.* [101], which is similar to standard Lyapunov methods successfully applied to control the physical systems described by Euler-Lagrange motion equations. The dynamic equations of the dc-dc power converter based on the classical PBC was determined as [101]:

$$\mathcal{H}\dot{\mathcal{Z}} + [\mathcal{G} + \mathcal{R}(z)]\mathcal{Z} = \mathcal{E} \tag{17}$$

$\mathcal{H}$ is a positive definite matrix of the storage system (inductance and capacitance), $\mathcal{Z}$ is the vector of the state variables, $\mathcal{G}$ is a skew-symmetric matrix, $\mathcal{R}(z)$ is the diagonal positive semi-definite matrix for heat dissipation, and $\mathcal{E}$ is the input vector matrix. The energy damping stage can be obtained by changing the coordinate of (17) using $\mathcal{Z} = \widetilde{\mathcal{Z}} + \mathcal{Z}_d$:

$$\mathcal{H}\dot{\widetilde{\mathcal{Z}}} + [\mathcal{G} + \mathcal{R}(z)]\widetilde{\mathcal{Z}} = \mathcal{E} - \left(\mathcal{H}\dot{\mathcal{Z}}_d + [\mathcal{G} + \mathcal{R}(z_d)]\mathcal{Z}_d\right) \tag{18}$$

where $\widetilde{\mathcal{Z}}$ is the new deviation from the reference point $\mathcal{Z}_d$. The damping injection stage can be determined by adding a virtual resistance matrix $\mathcal{R}_d\widetilde{\mathcal{Z}}$ to both sides of (18):

$$\begin{aligned} &\mathcal{H}\dot{\widetilde{\mathcal{Z}}} + [\mathcal{G} + \mathcal{R}_i(z)]\widetilde{\mathcal{Z}} \\ &\quad = \mathcal{E} - \left(\mathcal{H}\dot{\mathcal{Z}}_d + [\mathcal{G} + \mathcal{R}(z_d)]\mathcal{Z}_d - \mathcal{R}_d\widetilde{\mathcal{Z}}\right) \end{aligned} \tag{19}$$

where $\mathcal{R}_i(z) = \mathcal{R}(z) + \mathcal{R}_d$. In the classical PBC strategy, the feedback control system is usually designed by considering the system has well-defined input and output, and it tends to make the storage function nonincreasing. However, the classical PBC is considered as a particular case of the control by interconnections, which is the main property of the nascent IDA-PBC strategy [104]. In this sense, the IDA-PBC is effective for all physical systems that have an interconnection nature with other storage and dissipative elements where the input and output of the system are not easy to be assigned. Therefore, the port-controlled Hamiltonian (PCH) method is presented to characterize all assignable energy functions compatible with this structure, which is determined in the following form [103].

$$\dot{\mathcal{Z}} = [\mathcal{G} - \mathcal{R}(z)]\frac{\partial \mathcal{H}_d}{\partial z}(z) + g(z, u) \tag{20}$$

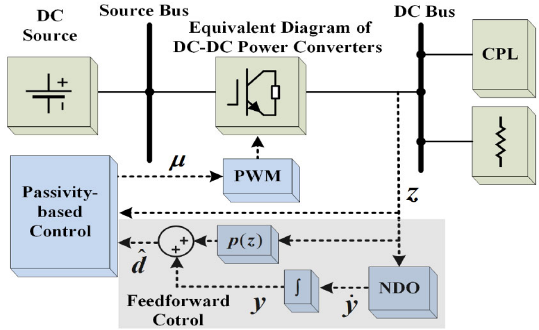

Fig. 11. Structure of PBC strategy with NDO.

where

$$\mathcal{H}_d(z) = \frac{1}{2}L{z_1}^2 + \frac{1}{2}C{z_2}^2. \tag{21}$$

This provides the IDA-PBC with robust dynamic and globally asymptotically solution. Both PBC strategies are presented and developed in several works to stabilize the CPL in dc MGs, including the classical PBC in [105]–[112], and IDA-PBC in [113]–[123]. However, each strategy has its own drawback. The main drawback of the classical PBC strategy is that it cannot eliminate the steady-state error caused by the wide variety of disturbances (such as input voltage or CPL variations) [108]–[111]. To eliminate this error, simple integral-controller-based feedback attenuation is added to classical PBC in [105], [106]. However, it has slow recovery performance during disturbances with high maximum overshoot. Therefore, the NDO is presented in [108]–[111] to work in parallel with the PBC strategy as feedforward compensation control. The NDO is added to observe and estimate the system disturbances ($\hat{d}$) online and inject it to the PBC through feedforward channels, as shown in Fig. 11. In this work, it is proved that the NDO-based feedforward control provides faster dynamic response during system disturbances with global trajectory tracking as compared to the integral-based feedback control [108]–[111]. Likewise, to improve the control performance of the IDA-PBC strategy, several observer techniques were also presented, such as immersion and invariance (I&I) in [115], [117]. I&I observer is added to estimate the power load online, which is difficult to be measured in some practical applications. An adaptive interconnection matrix is also developed in [118]–[121], by establishing internal links in the PCH model, which enables the generation of the desired control law for the cascaded power electronic system containing input filter and CPL. With the aid of an additional integrator, the IDA-PBC strategy has also been extended to control high-power multiphase interleaved boost power converters, suitable for transportation applications [116], [122]. Another drawback of the IDA-PBC is that the PCH used in the previous methods is not shifted passive. Therefore, the property of shifted passive has been enforced in [123] by adding state feedback, called shifted passivity via feedback. The results show accurate voltage control for the buck-boost converter supplying a CPL. However, the control robustness against CPL variation has not been examined. The instability issue of unknown nonlinear ZIP loads [i.e., constant

TABLE I

COMPARISONS OF BASELINE NONLINEAR CONTROL STRATEGIES WITH THEIR ADAPTIVE TECHNIQUES

Baseline Controller	**Advantages**	**Drawbacks**	**All Techniques**	**Adaptive Techniques**				
				NDO	**SMO**	**I&I**	**EKF**	**AI**
SMC	– Fast recovery performance. – Use continuous and discontinuous control schemes. – Robust control.	– Chattering problem. – Electromagnetic interference. – Complex for high-order power converters.	[31] [50]–[64]	[57], [58]	[59], [60]			[53]–[56]
SC	– Suitable for digital control. – Fixed switching-frequency. – Less power filtering.	– Sensitive to parameters uncertainty. – Less robustness against load disturbances. – Complex calculations.	[66]–[70]					
BSC	– Easy and simple design. – Systematic approach to construct the Lyapunov function. – Fast performance.	– Requires transformation to another canonical form. – Sensitive to parameters and disturbances uncertainty. – Requires adaptive technique.	[73]–[79]	[73]–[75] [78], [79]	[76]		[77]	
MPC	– Robust control dynamic. – Effective for MIMO systems. – Optimum with online problem solving. – Handling all constraints.	– Computational complexity. – Detailed model-based design. – Requires a powerful fast processor.	[85] [87]–[100]	[96]	[98]		[94], [95]	[97]
PBC	– Energy processing-based design. – Globally asymptotically stability. – Consistency with the physical nature of power electronics. – Systematic and easy design approach.	– Sensitive to system disturbances. – Detailed model-based design. – Requires adaptive technique.	[105]–[125]	[108]–[111]		[115], [117]		

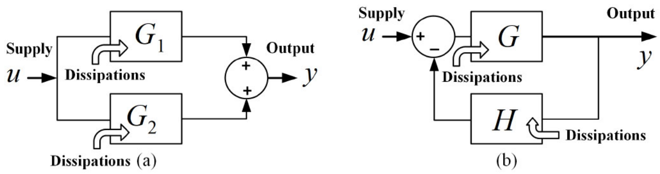

Fig. 12. Interconnected passive systems through (a) parallel and (b) feedback connection.

impedance (Z), current (I), and load (P)] was also addressed in [124], [125]. Based on the skew-symmetric interconnection properties between the individual local passive subsystems, stability of the entire dc SMG can be ensured using the PBC strategy.

It can be concluded that the adaptive PBC strategy could pave the road to better understand the dynamics of the dc SMG from the standpoint of energy processing (storage and dissipation elements) rather than signal processing. PBC offers the feature of local passivity for subsystems connected together through parallel connection or using passive feedback control (see Fig. 12) [126]. The transient energy can be dissipated locally in each subsystem owing to this feature, which facilitates the stability for the entire dc SMGs. In this sense, the overall energy balance of the dc SMG is always positive. Therefore, the PBC strategy is qualified to be pioneering in the applications of dc SMGs in the near future.

IV. CHALLENGES AND FUTURE PERSPECTIVE FOR DC SMG CPL STABILITY CONTROLS

It is obviously that dc SMG has been evolved rapidly as effective alternative network compared with ac SMG, which reduces the cost, size and makes the diesel generators working at optimum operating point with unity power factor. However, the control and stability of the dc bus in dc SMG is a crucial issue due to the presence of CPLs. Besides, the CPLs variations due to the uncertain operation condition of ships on the sea, such as torque and load changes of propulsion motors, increases the dc bus voltage control challenges. The aforementioned well-established nonlinear control methods, can be considered the backbone for more future control innovations and applications to regulate the dc bus voltage and ensure system stability for dc SMGs.

A. Stability Challenges of DC SMG With CPLs

Table I summarizes the comparison between advanced nonlinear control strategies and their adaptive techniques (type of observers) to stabilize CPLs. The comparison shows the advantages and drawbacks of each baseline nonlinear controller. Besides the estimation techniques used to improve their control performance. We can conclude that the stability analysis of dc SMGs requires more development for two levels of control, including local control level for each single power converter and system-level control for parallel-connected power converters.

1) Stability Challenges of Local Nonlinear Control: Several well-known frequency domain stability methods were successfully tested in the dc MGs linear control systems, such as Bode plot, Routh-hurwitz, root locus, Nyquist stability criteria, etc. [127]. On the other hand, a few techniques have been used for stability analysis of local nonlinear control systems, such as describing function, phase plane, Popov,

TABLE II
DIFFERENT COMPARISONS BETWEEN THE NONLINEAR CONTROL STRATEGIES

Control Method	Control-loop stability analysis criteria			Work without stability analysis	Work with only simulation results	Work with hardware-in-loop results		Work with hardware experimental results
	Lyapunov stability	Fixed-time stability	discrete stability			OPAL-RT simulation platform	dSPACE simulation platform	
SMC	[50], [52]–[54], [56]–[58], [61]–[63]	[51]	[59]	[55], [60]	[50]	[63], [64]	[51], [53]–[56], [59]–[61]	[52], [57]–[59], [61]–[64]
SC	[66]–[70]				[66]–[70]			
BSC	[73]–[79]				[75]		[73], [74]	[73], [74], [76]–[79]
MPC	[87], [93], [95]–[97]			[85], [88], [89], [91], [94], [99], [100]	[87]	[97], [100]	[88], [91], [93]–[96], [98], [99]	[85], [88]–[90], [92]–[94], [99]
PBC	[105]–[125]				[108], [123]–[125]	[108]–[111]	[113], [116], [118], [120]–[122]	[105]–[107], [109], [111]–[122]

and Lyapunov stability criteria, which require more complex equations and advanced analysis [44]. The problem of the nonlinear systems in the frequency domain is that there are always highly complex output frequencies, appearing as superharmonics, sub-harmonics, inter-modulation, chaos, limit-cycle, and bifurcation, which can produce output frequencies quite different from the input frequencies [44], [128]. This usually makes it rather difficult to analyze and design output frequency response of nonlinear systems than linear systems [128]. Table II shows that the majority of nonlinear control techniques used the Lyapunov stability criterion to analyze feedback closed-loop local control systems. It also shows the classification of works that have been implemented using simulation or hardware experiments. Besides, the hardware-in-loop simulation platforms were also classified. The advantage of nonlinear control systems is that they can handle many nonlinear dynamics, which can not be addressed using linear control, such as finite escape time, multiple isolated equilibria, limit cycles, chaos, etc. [44]. However, nonlinear control systems are complex and require complicated computational and programming modeling. Besides, the industry of nonlinear control systems has not yet become mature in the applications of dc MGs as compared to the linear PID controller. The cost of nonlinear control implementation is also high.

2) Stability Challenges of System-Level Control: Last decade, the system-level stability analysis of dc MGs have been presented using many effective linear criteria [129], including Middlebrook [30], gain margin and phase margin [130], opposing argument [131], energy source analysis consortium [132], three-step impedance [133], and passivity-based stability criterion [129], [134]. On the other hand, system-level nonlinear control stability of dc MGs, still limited to a few methods based on Lyapunov stability theorem, such as low-frequency bifurcation-based analysis [135], [136], Popov's absolute stability criterion [137], and mixed potential theory [138]–[142]. Thus, system-level stability analysis of dc SMGs based on nonlinear control needs more development. Other problems may also impact dc SMGs' system-level stability, such as bifurcation and chaos behavior due to system parameters changes [143]–[145]. Ships with high power weapons (pulse load) and motor drive probably experience high voltage fluctuation, which may lead to bifurcations and chaos dynamics. Therefore, the region of parameter space must be accurately justified to ensure the system is working within the allowed boundary of selected parameters [143]. Adaptive robust control techniques are also required to avoid bifurcation occurrence.

B. Stability Analysis of DC SMG With CPLs

Large-signal stability analysis of MGs, including all nonlinearities of the system and CPLs is a crucial matter. In [146], Lyapunov-based large-signal stability criteria have been intensively reviewed for MGs stabilization. Large-signal stability tools for dc power systems are also reviewed in [147]. The prime concerns of SMGs instability are the system disturbances due to intermittent nature of renewable energy resources, and MGs load pattern changes. Besides the uncertainty due to parameters variations. Therefore, Lyapunov large-signal stability criterion have been widely presented as the most effective methods for SMGs stability analysis to address all concerns, including CPLs [146]. Several stability criteria have been developed based Lyapunov's method for dc MGs [147]:

1) Mixed Potential Theory (MPT): MPT-based Lyapunov's method has been employed for many work as stability tool for dc MGs with CPLs [138]–[142], [148]. Which can be applied to analyze dc MG's stability from the level of single CPL to mutlti-CPLs. The MPT was originally proposed by Brayton and Moser [149], which has been recently applied in power electronics stability using region of attraction estimation [148]. The MPT is an energy-related function, which can contain the current and voltage potentials.

$$C(v)\frac{\partial v}{\partial t} = -\frac{\partial P(v,i)}{\partial v}, \quad L(i)\frac{\partial i}{\partial t} = \frac{\partial P(v,i)}{\partial i} \tag{22}$$

In [142], [148], MPT has been employed to analyze large-signal stability of parallel connected dc-dc power converters supplying CPL in dc MGs. Based on Lyapunov's equations,

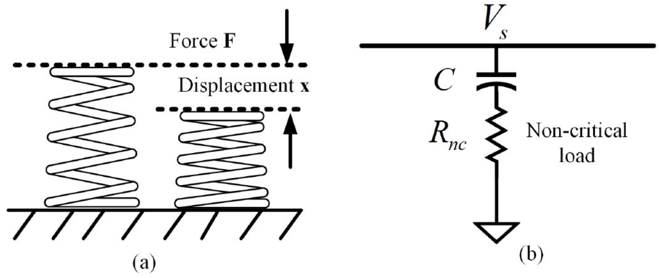

Fig. 13. Regulatory mechanisms, (a) mechanical spring and (b) dc electric spring.

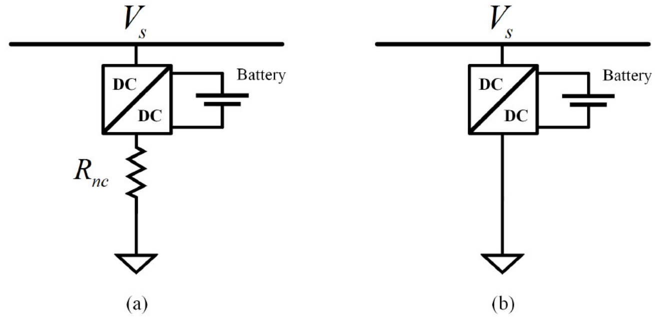

Fig. 14. DCES with battery, (a) with noncritical load and (b) without noncritical load.

the mixed potential function $P(v, i)$ have be constructed to analyze large-signal stability under certain conditions [142].

2) Bifurcation Theory: bifurcation occurs in power electronics, when a small smooth changing of the parameter values lead to a sudden qualitative variation in its behavior, such as high CPL changing and parameters uncertainty [150]–[152]. In [150], where MG supplying CPL, bifurcation boundaries before the MG become unstable can be predicted using bifurcation stability region analysis. In [151], a jacobian matrix has been developed to investigate the stability of limit cycles for dc power system with CPLs and LC filters. A simplified model was developed to understand the interaction dynamics between the inverters in ac MGs with CPLs using bifurcation theory [152]. The obtained results of simplified model with output power variation has been verified with the a full model of MG.

3) Popov Stability Criterion: Is a stability analysis tool to obtained the absolute stability for a class of nonlinear equations that satisfying an open-sector condition. In [137], the Popov's absolute stability method has been utilized to analyze system stability for an ac MG in presence of CPL. It was presented that the ac MGs becomes stable when the CPL changing satisfying certain conditions of Popov's criterion.

4) Recent Stability Analysis Techniques: In [153], a semidefinite programming (SDP) have been developed as a new stability tool to estimate the domain of attraction for dc MGs composed of multiple CPLs. In [154], the bifurcation analysis was used to study the fast-scale stability analysis for dc-dc boost power converter with CPL. A piecewise linear switched model can provide fast-scale stability for linear load and still providing the accuracy of the full model of CPL. In [155], using solving convex optimization problems (to check set of sufficient conditions), a robust stability framework has been developed for dc MGs for a given range of CPLs.

C. DC SMGs Stability Using DC Electric Springs (DCES)

DCES is an effective emerging method to ensure dc bus voltage stability of dc MGs against system disturbances, such as CPL oscillations, renewable power source fluctuation, system fault, voltage droop, etc. [156]–[159]. DCES behaves as mechanical spring to absorb the shock of the system subjected by external force. Similar dc regulatory mechanisms can be obtained using electric springs with capacitor and noncritical load [156] (see Fig. 13). With the development of energy storage system, such as lithium batteries, the DCES can be design combined with bidirectional dc-dc power converters, as shown in Fig. 14 [156]–[158]. The battery can be connected to the dc bus with and without noncritical load. The main function of DCES is to regulate the dc bus voltage within certain limits and to balance the power fluctuations by load boosting and shedding function [156].

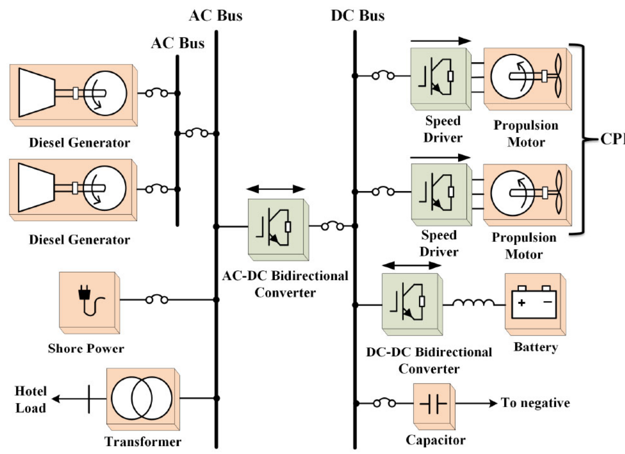

Fig. 15. Hybrid-electric ferry system structure.

D. Upcoming Work

The trade-off between the PBC strategy and other nonlinear control strategies is the strong relationship between stability and passivity, presented early by Youla *et al.* [160]. A passive system means a stable system. If all subsystems in dc SMG become strictly passive (dissipative), the entire dc SMG would be stable (as shown in Fig. 12) [126]. Therefore, the stability target of dc SMGs can be easily localized to each single power converter. Thus, the upcoming work of this current version focuses on dc SMG stabilization using the PBC strategy. The happiness hybrid-electric ferry (HEF) working in Taiwan has been taken as a study-case for practical application of dc SMGs [20]. Fig. 15 depicts system structure of the HEF, which contains propulsion motors (i.e., CPLs) supplied by hybrid power sources (diesel generators and set of batteries) through a common dc bus. Owing to the operation of HEF on the sea of Kaohsiung City, Taiwan, dc bus voltage stability and control is a crucial matter. The next work aims to ensure dc bus voltage control against CPL oscillation and its variations using PBC. Part of the next work have been published in [102].

V. Conclusion

This paper has provided a state-of-the-art literature review of adaptive nonlinear control strategies to stabilize the constant power loads (CPLs) in dc shipboard microgrids (SMGs). The tightly regulated point of load converters, such as the propulsion motors and hotel load, behave as CPLs. The negative incremental impedance due to CPL characteristics is the main cause of the dc bus voltage instability problem in dc SMGs. Besides, the CPL variations due to motor speed or torque changes on the sea increase the challenges of dc SMG stability and control. Therefore, a robust control design is a crucial matter. The CPL instability dynamics cannot be controlled effectively using simple PID linear control systems. Thus, this paper focuses on nonlinear control systems as well as adaptive techniques. Throughout this review, the most advanced adaptive nonlinear control technologies to enhance the stability for the dc SMGs have been presented, including sliding mode control, synergetic control, backstepping control, model predictive control, and passivity-based control. These techniques ensure large-signal stability, global tracking control to the reference voltage, and robust control dynamic against system disturbances, such as CPL variations. To this end, this manuscript has also provided an overview of the most popular observer-based estimation techniques to improve the control robustness of baseline nonlinear controllers, such as nonlinear disturbance observer, sliding mode observer, immersion and invariance observer, extended Kalman filter, and artificial intelligence-based observer.

This article also addresses the challenges of dc SMGs stability analysis based on nonlinear control techniques. Further development is required for dc SMGs stability analysis, including local and system-level control. Upcoming work of this current article contains the hybrid-electric ferry (HEF) as a case study for dc SMGs applications on maritime ships. An adaptive passivity-based control (PBC) strategy has been presented to stabilize the CPL. Simulation and experimental results of a practical dc shipboard microgrid are presented and used to ensure and demonstrate the performance of the proposed method.

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