Improving the Performance of DC Microgrids by Utilizing Adaptive Takagi-Sugeno Model Predictive Control

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***Abstract*—In naval direct current (DC) microgrids, pulsed power loads (PPLs) are becoming more prominent. A solar system, an energy storage system, and a pulse load coupled directly to the DC bus compose a DC microgrid in this study. For DC microgrids equipped with sonar, radar, and other sensors, pulse load research is crucial. Due to high pulse loads, there is a possibility of severe power pulsation and voltage loss. The original contribution of this paper is that we are able to address the nonlinear problem by applying the Takagi-Sugeno (TS) model formulation for naval DC microgrids. Additionally, we provide a nonlinear power observer for estimating major disturbances affecting DC microgrids. To demonstrate the TS-potential, we examine three approaches for mitigating their negative effects: instantaneous power control (IPC) control, model predictive control (MPC) formulation, and TS-MPC approach with compensated PPLs. The results reveal that the TS-MPC approach with adjusted PPLs effectively shares power and regulates bus voltage under a variety of load conditions, while greatly decreasing detrimental impacts of the pulse load. Additionally, the comparison confirmed the efficiency of this technique.**

***Index Terms*—DC microgrids (MG), model predictive control (MPC), pulsed power loads (PPLs), nonlinear power observer, Takagi–Sugeno (TS) fuzzy model.**

NOMENCLATURE

A. Abbreviations

IPC	Instantaneous power control.
MPC	Model predictive control.
PPLs	Pulsed power loads.
TS	Takagi–Sugeno.

B. Parameters

A_C, B_C, H_C, C_C	The parameter values of the model predictive controller are in the microgrid.
$\boldsymbol{B}_{ci}$	TS model matrices.
C_B	Filter capacitors of pulse load.
C_P	Filter capacitors of constant power load.
$h_i(\rho(k))$	Membership functions.
$\boldsymbol{L}$	The observer gain matrix.
L_{PV}	Photovoltaic inductance.
r_c	The number of scheduling variables..
$\boldsymbol{s}$	The observer gain matrix.
T_C	Time step.
X_k	Augmented state vector of the DC MG.
x_k	State Vector in a discrete-time respresentation.
y_k	Output Vector in a discrete-time respresentation.

C. Variables

I_{LB}	Battery output current.
I_{SC}	Input current of the ultracapacitor.
V_{PV}	PV voltage.
V_{bat}	Controlled voltage source.
V_{SC}	Controlled voltage source.
V_{DC}	DC-link voltage.
s_1, s_2, s_3	Duty cycle.
$\boldsymbol{z}$	State vector of power observer.
$\hat{d}$	Estimated power of the PPLs.

I. INTRODUCTION

WITH growing worry over rising carbon dioxide emissions, which contribute to climate change, worldwide population is concerned about the impacts of global warming. The Maritime Agreement on Oil Pollution (MARPOL) emphasizes the need of ships reducing greenhouse gas emissions [1]. Shipping, which accounts for 3.3% of global carbon dioxide emissions, was expected to emit more than 1,092.3 million tons in 2018 [2]. Both incremental renewable energy and efficient transmission are critical for reducing greenhouse gas emissions. On the one hand, solar energy has been integrated into a variety of ship types, ranging from small pleasure boats to enormous pelagic vessels, owing to rapid growth of renewable energy [3]. On the other hand, Madduri *et al.* [4] emphasized the significance of DC microgrids in integrating DC loads and current electronic loads more efficiently.

Manuscript received November 30, 2021; revised March 17, 2022; accepted April 11, 2022. Date of online publication May 6, 2022; date of current version February 15, 2023. This work was supported in part by the National Key Research and Development Program of China (Grant No. 2019YFE0118000), and in part by the research funding of Guangxi University (No. A3020051008).

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DOI: 10.17775/CSEEJPES.2021.08920

Additionally, Prabhakaran *et al*. [5] and Lakshmi *et al*. [6] contribute to reliability and stability of microgrids through their study on DC converters. Following that, microgrids will be key components of an intelligent power system that has been upgraded. The purpose of this study is to discuss unique DC microgrids that may require energy storage to be connected to loads that absorb large quantities of energy quickly, such as sonar, radar, and pulsed armament systems, for certain applications in ship power systems [7]. The phrase "pulse load" refers to this form of transient power load. In a DC microgrid system, pulse loads can cause voltage drops and instability, which can result in considerable damage in extreme instances.

The presence of an energy storage system contributes to overall system stability and reliability. Different storage components conceal each other's shortcomings, enhancing their overall efficiency. Mohamed *et al*. [8] previously demonstrated that combining batteries with ultracapacitors, as well as employing more advanced charging and discharging processes, can greatly lower a system's sensitivity to pulse loads. Similarly, some academics have suggested addressing intermittent demands using extra energy storage devices hybrid energy storage [9], such as a flywheel. Nonetheless, the approaches will entail additional expenditures. Due to economic considerations, hybrid energy storage has surpassed conventional energy storage as the principal area of research attention.

Numerous considerations are examined while analyzing the topology of ultracapacitors and batteries, including converter performance, battery prices, and component utilization. The most often used design for batteries and ultracapacitors is passive parallel connection mode. It is recommended that we use an active hybrid approach to address these challenges. Energy storage topology has received much attention and research recently. Akar *et al*. [10] proposed a non-isolated bidirectional converter. Although the converter includes multiple interfaces for loading various components, one disadvantage is it makes excessive use of power electronics. Sarvghadi *et al*. [11] proposed a converter that can reduce conduction loss, which can improve efficiency of the converter. Lu *et al*. [12] proposed a complementary topology for Switched-Capacitor DC-DC converter to improve dynamic response capability. The fundamental downside of this converter is its heavy usage of power electronics, which results in higher costs and more challenging control processes.

Developing a reliable control strategy is critical for regulating interaction of PPLs and DC power systems and mitigating the influence of the PPL in dc-link. Mohamed *et al*. [8] proposed instantaneous power control (IPC) approach. Although IPC technology performs well, it requires more sophisticated energy-management systems to coordinate loads. Alternatively, the adaptive energy calculator (AEC) technique can be used to mitigate the disruptive effects of the pulse load [13]. AEC determines the total amount of current that must to be injected by converters based on the loads power consumption and the supercapacitor bus voltage. However, this approach is not fast enough because bandwidth of each outer loop should be designed to be three times smaller than of the inner loop. This results in slow response of the external loop and the controller. According to Farhadi *et al*. [14], the proposed approach has the advantage of controlling both the voltage and current of the system while maintaining a relatively constant output current of the power converter. Though, these control approaches suffer primarily from the fact that real constraints on DC microgrid currents are not met; the instantaneous power value of the PPLs is not available or measured; and the nonlinear character of the PPLs is not considered.

Control strategies based on TS models are techniques for solving nonlinear problems by including nonlinearities inside model parameters that are dependent on certain scheduling variables. These techniques have gained widespread acceptance in the realm of autonomous vehicles, as demonstrated by [15] and [16]. Recent works such as [17], [18], and [7], [19] discuss the most recent developments in MPC control in the field of DC microgrids. Mardani *et al*. [17], proposed employing MPC to address the pulse load problem, and the experiment demonstrates that MPC has a higher research value than standard control approach. Vafamand *et al*. [18], proposed the method of using observer to optimize and stabilize the whole DC microgrid. Chen *et al*. [7], [19] expanded on the usage of MPC technology in microgrids operating at medium-voltage direct current. However, due to imprecision of the model, this strategy may prove unviable. This is why recent research into alternative methods has opened the door to concepts such as TS-MPC.

The unknown power of PPL is one of the external disturbances that have great influence on DC microgrids. Based on this, many techniques have been studied and discussed. One of these techniques is the Unknown Input Observer (UIO). This approach has been widely used for detection and isolation of faults [20]. Alcalá *et al*. [21] proposed employing Takagi–Sugeno estimator-Moving Horizon Estimator-Unknown Input Observer (TS-MHE-UIO) to estimate unknown disturbances. However, due to its excessive computing time, this technique may lead to infeasible results when dealing with systems with fast dynamics. In addition, recent works such as [22], [23] and [24] discuss developments in nonlinear power observer technique.

Only a few studies on the control of DC microgrids using an accurate dynamics model have been published. Compared with the most advanced methods to deal with pulse load, the proposed method reduces computation time and can show better dynamic and static performance. This paper proposes a unique Takagi-Sugeno-Model Predictive Control (TS-MPC) technique for managing voltage on the PPLs. The following outlines the important contributions of this study.

1) The contribution of this paper focuses on the use of Takagi Sugeno polytopic models for design of the control stages. The model predictive control (MPC) technique is designed with a Takagi Sugeno (TS) kinematic model that leads to a quadratic problem.

2) In this paper, the influence of model parameter inaccuracy on model predictive control is reduced by combining observer technology. A technique that utilizes an observer is the nonlinear power observer technique. The combination of observer

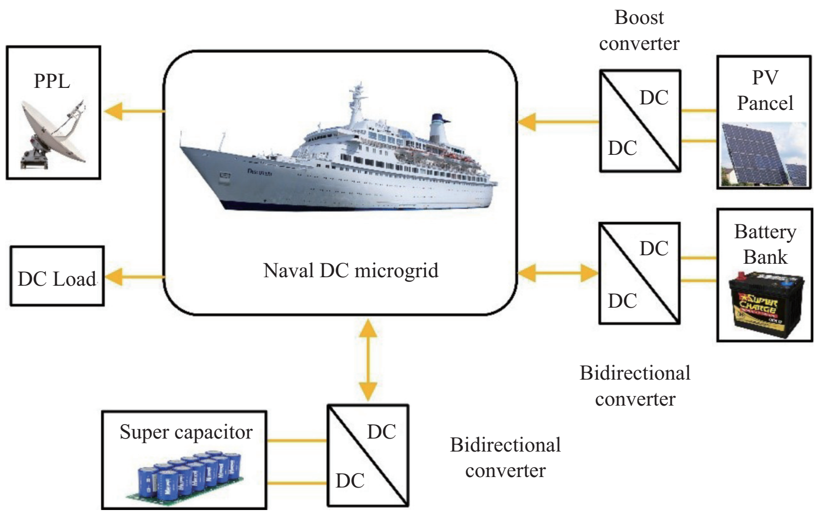


Fig. 1. A model of naval DC microgrids.

technology and model predictive control improves dynamic and static performance of the system under pulse load.

The remainder of the paper is structured in the following manner. The entire state-space model of DC microgrids analyzed is described in Section II. Section III details the TS-MPC controller's design. Section IV highlights the simulation's findings, and Section V concludes the article by discussing future directions.

II. DC MG Dynamics

A DC microgrid system is examined and modeled in this section. As seen in Fig. 1, the system is powered by a 320 V direct current bus. This system is comprised of a photovoltaic array, lithium-ion battery packs, supercapacitors, and a variety of load types. Additionally, it includes a control system and protective devices for microgrids; each component has a detailed introduction and description of its function:

1) The photovoltaic system, which has advanced fast, is the primary source of energy in DC microgrid. In this article, the photovoltaic system is connected to the DC bus via a boost converter, and the photovoltaic system is operated in constant voltage control mode.

2) The energy storage system (ESS) can charge and discharge rapidly and immediately, enabling dynamic management of the new generation system and mitigating external influences. The energy storage system described in this study is primarily intended to compensate for the numerous fluctuations in power and bus voltage caused by pulse loads. Active hybrid setup connects the ESSs to the DC-link.

3) Additionally, to steady current loads, pulse power loads, such as sonar, radar, and pulsed weapon systems, are evaluated for certain applications in ship power systems. The primary objective of this paper is to determine the effect of pulse loads on a DC microgrid.

4) The control layer is divided into two sections. TS-MPC controller solves for optimal output, while nonlinear power observer estimates PPL. By coordinating output current, the control layer maintains a steady bus voltage.

A. Dynamic Model of Photovoltaic (PV)

By harnessing the photo effect, a photoelectric turns light energy directly into electricity. It essentially consists of a photocurrent source, a diode, and an equivalent resistor, the latter of which is shown in Fig. 2(a) [25]. The photovoltaic system is connected to the DC bus through a boost converter. The corresponding circuit of the boost converter is depicted in Fig. 2(b). Equation (1) summarizes the size of photovoltaic current:

$$L_{\mathrm{PV}}\frac{\mathrm{d}I_{\mathrm{PV}}}{\mathrm{d}t} = V_{\mathrm{PV}} - (1-s_1)V_{\mathrm{DC}} \tag{1}$$

where I_{PV}, V_{PV}, and s_1 are the PV output current, PV voltage, and duty cycle, respectively.

B. Dynamic Model of the ESS and DC Voltage Source

As seen in Fig. 3, a battery-supercapacitor hybrid provides a straightforward solution to mitigate the influence of load variability on the provided voltage level. Active hybrid storage configurations not only provide increased power capabilities, but also ensure the ESSs have smaller volume, weight, and current ripple. The supercapacitor reduces duration of the short duration, high amplitude load spikes and creates a longer duration but lower amplitude load spike, resulting in increased energy efficiency due to the batteries' reduced rate capacity effect. As shown in Fig. 3(a), a bidirectional converter is used to connect the Rint lithium-iron phosphate battery to DC microgrids. Equation (2) can be used to determine the output voltage and current of a battery:

$$\begin{cases} C_E\dfrac{\mathrm{d}V_E}{\mathrm{d}t} = \dfrac{V_{\mathrm{bat}}}{Rb} - I_{\mathrm{LB}} \\ L_B\dfrac{\mathrm{d}I_{\mathrm{LB}}}{\mathrm{d}t} = V_E - V_{\mathrm{DC}}s_2 \end{cases} \tag{2}$$

where V_E, V_{bat}, I_{LB}, and s_2 are capacitor voltage of the battery, controlled voltage source, battery output current, and duty cycle, respectively.

The supercapacitor is connected to DC microgrids via a bidirectional converter in Fig. 3(b). Equation (3) can be used to determine the battery's output voltage and current:

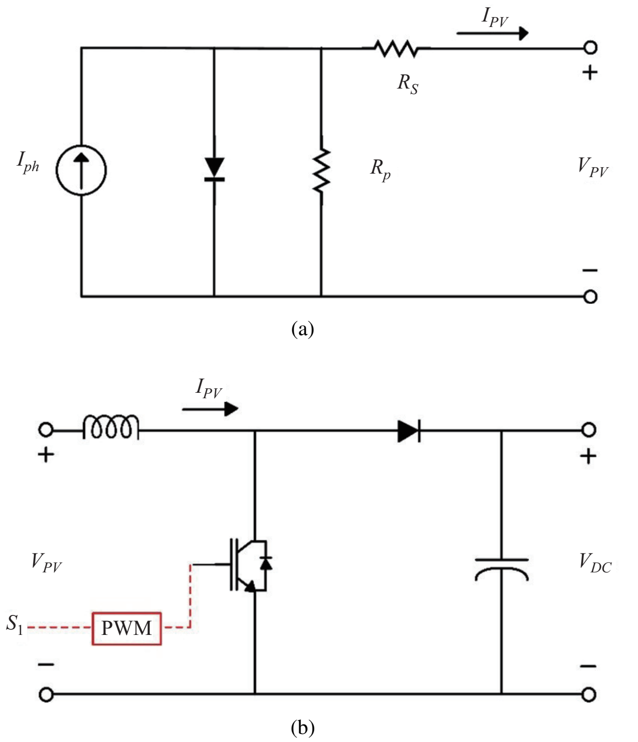


Fig. 2. PV panel model. (a) The equivalent circuit of a PV cell. (b) Connecting the PV panel to the grid.

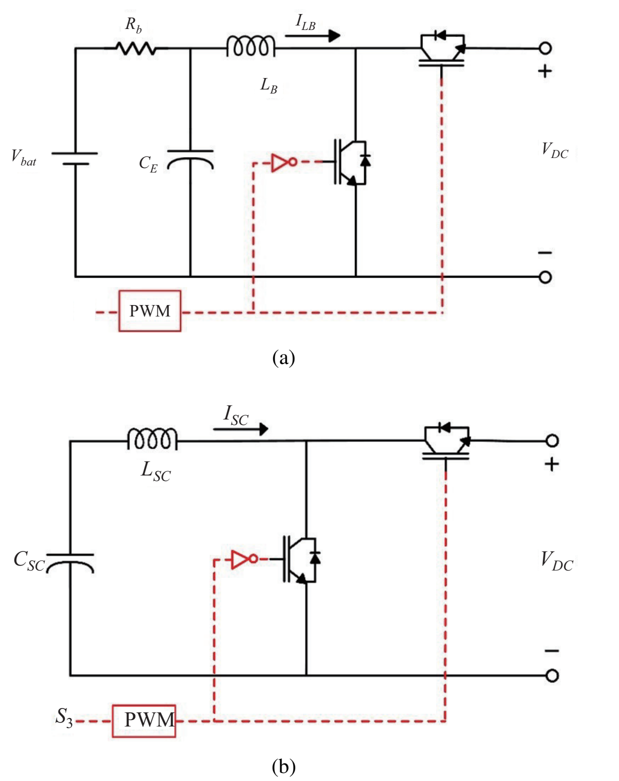


Fig. 3. ESS system equivalent circuit. (a) Connecting the battery to the grid. (b) Connecting the super capacitor to the grid.

$$\begin{cases} C_{\mathrm{SC}}\dfrac{\mathrm{d}V_{\mathrm{SC}}}{\mathrm{d}t} = -I_{\mathrm{SC}} \\ L_{\mathrm{SC}}\dfrac{\mathrm{d}I_{\mathrm{SC}}}{\mathrm{d}t} = V_{\mathrm{SC}} - V_{\mathrm{DC}}s_3 \end{cases} \tag{3}$$

where V_{SC} and I_{SC} are the input current and voltage of the ultracapacitor, respectively. s_3 is the duty cycle.

As illustrated in Fig. 1, the load on the DC bus is separated into two categories: constant power and pulse load. Constant power and pulse loads are both linked directly to the DC bus. By treating the PPL as an unknown perturbation, equation (4) can be used to explain DC voltage:

$$C_B\frac{\mathrm{d}V_{\mathrm{DC}}}{\mathrm{d}t} = I_{\mathrm{LB}}s_2 + I_{\mathrm{SC}}s_3 + I_{\mathrm{PV}}(1-s_1) - \frac{V_{\mathrm{DC}}}{R_L} - \frac{PPL(t)}{V_{\mathrm{DC}}} \tag{4}$$

where V_{DC}, I_{B}, $PPL(t)$ are DC-link voltage, load current, and power of the pulse load, respectively. C_P and C_B are filter capacitors of constant power load and pulse load respectively.

C. Dynamic Modeling of the Main Supplier of the DC Grid

Define $\boldsymbol{x} = [I_{\mathrm{PV}} \quad V_E \quad I_{\mathrm{LB}} \quad V_{\mathrm{SC}} \quad I_{\mathrm{SC}} \quad V_{\mathrm{DC}}]^{\mathrm{T}}$, $\boldsymbol{u} = [s_1 \quad s_2 \quad s_3]^{\mathrm{T}}$, $\boldsymbol{V}_{\mathrm{out}} = [V_{\mathrm{PV}} \quad V_{\mathrm{bat}}]^{\mathrm{T}}$. The overall state space model of the DC MG in Fig. 1 can be calculated by utilizing (1), until (4).

$$\begin{cases} \dot{x}(t) = \boldsymbol{A}x(t) + \boldsymbol{B}u(t) + \boldsymbol{H}V_{\mathrm{out}}t + \boldsymbol{D}d(t) \\ y(t) = \boldsymbol{C}x(t) \end{cases} \tag{5}$$

where $u(t)$, $x(t)$, and $y(t)$ are system input, state variables, and output vectors. $\boldsymbol{A} \in R^{6\times 6}$, $\boldsymbol{B} \in R^{6\times 3}$, $\boldsymbol{C} \in R^{6\times 3}$, $\boldsymbol{H} \in R^{6\times 2}$, and $\boldsymbol{D} \in R^{6}$.

$$\boldsymbol{A} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_{\mathrm{PV}}} \\ 0 & 0 & -\frac{1}{R_bC_E} & 0 & 0 & 0 \\ 0 & \frac{1}{L_B} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{C_{\mathrm{SC}}} & 0 \\ 0 & 0 & 0 & \frac{1}{L_{\mathrm{SC}}} & 0 & 0 \\ \frac{1}{C_B} & 0 & 0 & 0 & 0 & \frac{1}{R_LC_B} \end{bmatrix}$$

$$\boldsymbol{B} = \begin{bmatrix} \frac{V_{\mathrm{DC}}}{L_{\mathrm{PV}}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -\frac{V_{\mathrm{DC}}}{C_B} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{V_{\mathrm{DC}}}{L_{\mathrm{SC}}} \\ -\frac{I_{\mathrm{PV}}}{C_B} & \frac{I_{\mathrm{LB}}}{C_B} & \frac{I_{\mathrm{SC}}}{C_B} \end{bmatrix} \quad \boldsymbol{H} = \begin{bmatrix} \frac{1}{L_{\mathrm{PV}}} & 0 \\ 0 & \frac{1}{R_bC_E} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\boldsymbol{D} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{C_BV_{\mathrm{DC}}} \end{bmatrix} \quad \boldsymbol{C} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Section III discusses the usage of TS polytopic models in the control design process and proposes a systematic approach for estimating the PPL's unknown power (i.e., P).

III. TS-MPC DESIGN

We explore the power pulse load issue in a DC microgrid. Two essential tasks must be done to accomplish this: increasing the accuracy of the models and suppressing the influence of disturbances.

On one hand, the complexity of the model to be managed frequently dictates the degree of difficulty with which DC microgrids must be controlled (linear dynamic, non-linear simplified dynamic or non-linear dynamic). While approximate linearization is the simplest way for controlling nonlinear systems, it is difficult to fully characterize nonlinear systems with a single linearization model, and hence it is vital to consider employing numerous linearization models to approximate nonlinear systems.

On the other hand, grid-connected pulse loads generate interruptions. MPC is responsible for preserving the intended references, such as voltage and current shifts, as well as for generating smooth control actions necessary for device stability. The controller formulates the optimization issue using a TS model of DC microgrids, restrictions on states and control inputs, and an objective function. Additionally, ignorance of external disturbances may complicate the application of the specified control. As a result, an estimator is used to determine the instantaneous value of the PPLs powers.

A. Nonlinear Power Observer

On the one hand, the assumption that true states of the system are precisely understood is unrealistic in a large number of control scenarios. Multiple sensors, on the other hand, will result in a reverberation effect between the sensors, resulting in measurement mistakes. To address the aforementioned issues, it is vital to incorporate observation into the system.

The nonlinear power observer's fundamental strategy is to equalize all disparities between outputs of the actual model and the ideal model produced by external disturbances and parameter variation as control inputs. That is to detect a comparable disturbance and introduce equal compensation into the control so the disturbance is totally suppressed.

The improved disturbance observer can eliminate the differential term. For such a system, the following power observer structure can be expressed by utilizing (6).

$$\begin{cases} \hat{d} = \boldsymbol{z} + \boldsymbol{s} \\ \dot{z} = -LD(\boldsymbol{z} + \boldsymbol{s}) - \boldsymbol{L}(Ax + Bu + H) \end{cases} \tag{6}$$

where $\boldsymbol{z}$ is the state vector of power observer, $\hat{d}$ is estimated power of the PPLs, $\boldsymbol{L}$ is the observer gain matrix independent to system states. $\boldsymbol{s}$ is auxiliary vector and can be expressed by utilizing (7).

$$\boldsymbol{s} = Lx \tag{7}$$

The estimation error is defined as $e = d - \dot{d}$. Using (6) and (7) provides power estimation error.

$$\begin{aligned} \dot{e} &= \dot{\hat{}}d - \dot{d} \\ &= -\boldsymbol{L}(Ax + Bu + H + Dz + Ds) + \dot{s} - \dot{d} \\ &= -\boldsymbol{L}De - \dot{d} \end{aligned} \tag{8}$$

The gain matrix is defined as $\boldsymbol{L} = -\alpha(D^{\mathrm{T}}D)^{-1}D^{\mathrm{T}}$. Consider the following quadratic Lyapunov candidate:

$$\begin{aligned} \dot{V} &= \dot{e}^{\mathrm{T}}\dot{e} \\ &= -\alpha e^{\mathrm{T}}e - \dot{d}^{\mathrm{T}}e \\ &\le -2\alpha V + \|\dot{d}\|\|e\| \end{aligned} \tag{9}$$

Since PPLs possess constant values, it is assumed that after switching among these values [18], most general assumption here is that $\dot{d} = 0$, which leads to

$$-2\alpha e^{\mathrm{T}}e < 0 \tag{10}$$

According to the above analysis, when the condition $\alpha > 0$ is satisfied, the estimated value of the observer can be guaranteed to converge to the actual value.

B. Takagi-Sugeno Control Oriented Models

In the above paper, a complex microgrid system is modeled as a nonlinear state space model. Optimal results are obtained by using nonlinear systems. However, it may not be successfully applied in real-time control since the solution of a nonlinear model will need more time. In order to speed up solving speed, we use the Jacobian Linearization method for linearization processing, but at the same time, the loss of more model information will make the optimal solution result not meet the expectation. TS systems are a well-known technique for dealing with system nonlinearity and uncertainty in robust control methods [24]. The TS model is proposed in this paper to balance the needs of model information and computation speed. Therefore, we will adopt in the next subsections the TS fuzzy modeling approach for selecting local models.

By applying the Euler discretization approach and using Tc as the sample time, we can transform the continuous-time system in (7) to the following discrete model in (11):

$$\begin{cases} x(k+1) = A_c x(k) + B_c u(k) + H_c V_{\mathrm{out}}(k) + D_c d(k) \\ y(k+1) = C_c x(k) \end{cases} \tag{11}$$

where $A_c \in R^{6\times6}$, $B_c \in R^{6\times3}$, $C_c \in R^{6\times3}$, $H_c \in R^{6\times2}$, and $D_c \in R^{6}$. According to the converter circuit, vectors of scheduling variables are defined as $\rho(k) := [I_{\mathrm{PV}} \quad I_{\mathrm{bat}} \quad I_{\mathrm{SC}} \quad V_{\mathrm{DC}}]$. Next, calculate subsystem matrix under $I_{\mathrm{PV}} \in [5, 40]$, $I_{\mathrm{bat}} \in [0, 35]$, $I_{\mathrm{SC}} \in [-5, 30]$, and $V_{\mathrm{DC}} \in [300, 340]$. "If-then" rules are used to represent the relationship between different local models. Equation (14) can be used to explain "If-then" rules:

$$\begin{aligned} &\text{IF } \rho(k) \in Fi \qquad \text{then} \\ &x(k+1) = A_c x(k) + h_i(\rho(k))B_{ci}u(k) + H_c V_{\mathrm{out}}(k) \\ &\qquad + D_c d(k) \end{aligned} \tag{12}$$

where $i = 0, \ldots, r$, Fi is i^{th} fuzzy set, and the $h_i(\rho(k))$ is known as the membership functions. The membership functions can be calculated by utilizing (12).

$$hi(\rho(k)) = \prod_{j=1}^{r_c} \zeta ij(\eta_0^j, \eta_1^j),\ i = \{1, \cdots, 2^{r_c}\} \tag{13}$$

$$\begin{aligned} \eta_0^j &= \frac{\overline{\rho j} - \rho j(k)}{\overline{\rho j} - \underline{\rho j}} \\ \eta_1^j &= 1 - \eta_0^j,\ j = \{1, \cdots, r_c\} \end{aligned} \tag{14}$$

where $\zeta ij(\eta_0^j, \eta_1^j)$ corresponds to the weighted value of each membership function that depends on each rule i, and r_c is the number of scheduling variables.

The global model of the system is achieved by fuzzy combination of these linear models using nonlinear fuzzy membership functions. A polytopic representation for the control design is obtained in (15):

$$\begin{cases} x(k+1) = A_c x(k) + \sum_{i=1}^{2r_c} hi(\rho(k)) B_{ci} u(k) \\ \qquad\qquad +H_c V_{\text{out}}(k) + D_c dc(k) \\ y(k+1) = C_c x(k) \end{cases} \tag{15}$$

where B_{ci} represents each one of the polytopic vertex dynamic systems obtained as a combination of the extreme values of the scheduling variables.

C. TS-MPC Design

At this point, we present formulation of the TS Model Predictive Control approach, which is aimed at resolving the converter control problem in DC microgrids. To investigate the system's performance, a mathematical expression called a performance index or cost function must be defined. When goal function is minimized, the system is operating under specified conditions.The problem of minimizing J with regard to Δu is a quadratic problem. The reference signal is denoted by $r(k)$. At each time k, the values of xk and $\Delta uk-1$ are known, allowing for the solution of the following optimization problem.

$$\begin{aligned} \min Jk = & \sum_{i=0}^{H_P-1} (rk+i-yk+i)^{\mathrm{T}} Q(rk+i-yk+i) \\ & + \Delta uk + iR\Delta uk + i \end{aligned} \tag{16}$$

$$\begin{aligned} \textit{s.t. } x(k+i+1) &= A_c x(k+i) + \sum_{j=1}^{2r_c} h_j(\rho k+j) B_{cj} u(k+i) \\ &\quad + H_c V_{\text{out}}(k) + D_c d(k) \\ y(k+i) &= C_c x(k+i) \\ u(k+i) &= u(k+i-1) + \Delta u(k+i) \\ Uk &\in U_d \\ \Delta Uk &\in \Delta U_d \end{aligned} \tag{17}$$

where

$$\Delta Uk = \begin{bmatrix} \Delta uk \\ \Delta uk+1 \\ \vdots \\ \Delta uk+N-1 \end{bmatrix} \in R^m$$

$$Uk = \begin{bmatrix} uk \\ uk+1 \\ \vdots \\ uk+N-1 \end{bmatrix} \in R^m$$

H_P is the prediction. U_d and ΔU_d constraint the system inputs and their variations, respectively. The tuning matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$ are positive definitely in order to obtain a convex function.

Figure 4 illustrates the control-estimation diagram presented in this work. The nonlinear observer estimates the power

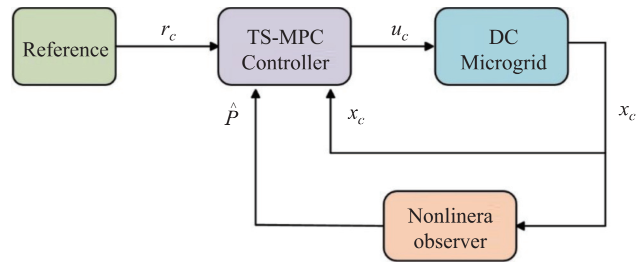


Fig. 4. DC microgrids control layer and a state estimation.

of the pulse load, and the MPC controller optimizes the control sequence. The nonlinear observer updates current state variable $x(k)$ at each k time steps, and the estimated value of the disturbance is calculated using (6). The MPC controller calculated the current control sequence by substituting current system's state quantity and disturbance value into (17). Modification of the control sequence alters the state of the system and completes the cycle in subsequent system sampling.

Remark 1 (Advantages of the TS-MPC)**.** In comparison to the previously discussed linear MPC [17], the suggested technique is more resistant to system uncertainties and increases the model's accuracy. When compared to the nonlinear model predictive control (NL-MPC) technique, the TS-MPC strategy improves computing time.

Remark 2 (Feedback correction)**.** Since Xk is measurable, the measured Xk at any point in time can be used directly to determine initial positioning for prediction and optimization at that point, which means that prediction and optimization are based on the system's real-time feedback information, and thus feedback correction occurs naturally without the need to introduce additional corrective measures.

Remark 3 (Satisfy a specified state constraint)**.** In accordance with IEEE recommendations for DC electrical power systems, the following constraints on state variables are proposed to be addressed during the design process [25].

Table I displays the design parameters for the adaptive Takagi-Sugeno (TS) model predictive control (MPC) used in this investigation. These parameters are essential for enhancing the efficacy of DC microgrids. The design parameters are meticulously chosen to optimise the control strategy and ensure the microgrid system's efficient operation. The table provides a thorough summary of the TS-MPC design parameters, including their empirical values, triad and errors and values. These parameters are necessary for comprehending the control algorithm and implementing it in a DC microgrid system.

IV. Simulation Result

To illustrate the effectiveness of the proposed TS-MPC for DC microgrids in mitigating disruptive effects of pulsed loads, suggested TS-performance MPC's was evaluated through simulation in MATLAB.

Then, the optimal control problem is solved using the solver quadprog. To verify real-time feasibility of the presented

TABLE I
TS-MPC DESIGN PARAMETERS

Empirical value	Value	Trial and error	Value
Q	$1 * \text{diag}(11150)$	I_{PV}	[5, 40]
R	$1 * \text{diag}(0.010.01)$	I_{bat}	[0, 35]
H_P	2	I_{SC}	[−5, 30]
r_c	4	V_{DC}	[300, 340]

strategies, we perform simulations on a DELL inspiron 15 (Intel(R) Core(TM) i5-6200U CPU @ 2.30 GHz).

The system's overall configuration is depicted in Fig. 1. The PV panel's open-circuit voltage and short-circuit current are 75 V and 10 A, respectively. The battery bank is comprised of 12 lead-acid battery cells rated at 120 V and 110 Ah in capacity. Additionally, the supercapacitor bank operates at 165 F. The components' specific parameters are summarized in Table II.

TABLE II
DC MICROGRID SYSTEM PARAMETER AND APPROACH

Component	Parameter	Specification
PV system	nominal power	2 kW
	Number of Parallel	4
	Number of Series	2
	Diode ideality factor	0.98
	Short-circuit current	7.84 A
	Open circuit voltage	36.3 V
Battery Bank	Rated Capacity	100Ah
	Bank nominal Voltage	120 V
	Internal Resistance	0.012 Ω
Supercapacitor Bank	Rated Capacity	165F
	Bank nominal Voltage	300 V
	Internal Resistance	6.50E-04 Ω
Bidirectional Converter	Switching frequency	10 k
	Series inductance	3 mH
	Parallel capacitance	1 mF
Boost Converter	Switching frequency	10 k
	Series inductance	2 mH
	Parallel capacitance	1 mF

Based on the selected parameter values, constraint $0 \leq u(t) \leq 1$ on the amplitude of control signals for PWM and constraint $314 \leq V_{\text{DC}} \leq 324$ on the amplitude of the Dc-link are considered [17].

Then, the weighting matrix is adjusted so the primary control target is satisfied first. Voltage stability must be the primary control target in the design.

Power balancing can be achieved in a DC microgrid with a voltage level of 320 V by establishing the reference value of current. We set PV output power to 1.5 kW and current reference value to 20.8 A in the case of a 2 kW load power. The battery produces 0.5 kW of power, whereas current reference value is 3.8 A. In our experiment, the PPL is set to a constant 4 kW with a duty cycle and frequency of 30% and 2 Hz, respectively.

Figure 5 illustrates power variation of the pulse load and the power estimated by the nonlinear observer. As a result, the observer accurately estimates disturbances caused by the changes. The observer's stability is deduced previously, and the value of is fixed to 0.5 in this paper.

To the effectiveness of the estimate scheme, we perform the comparison of adding the estimated PPL to TS-MPC control action against uncompensation of the PPL. The DC microgrid system performs under the influence of disturbance (Fig. 6).

Computation time of each optimization process should be highlighted to realize real-time feasibility when dealing with a

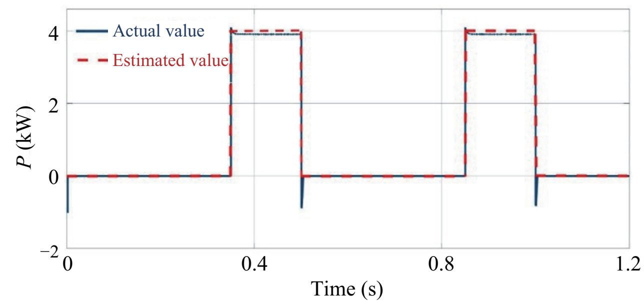
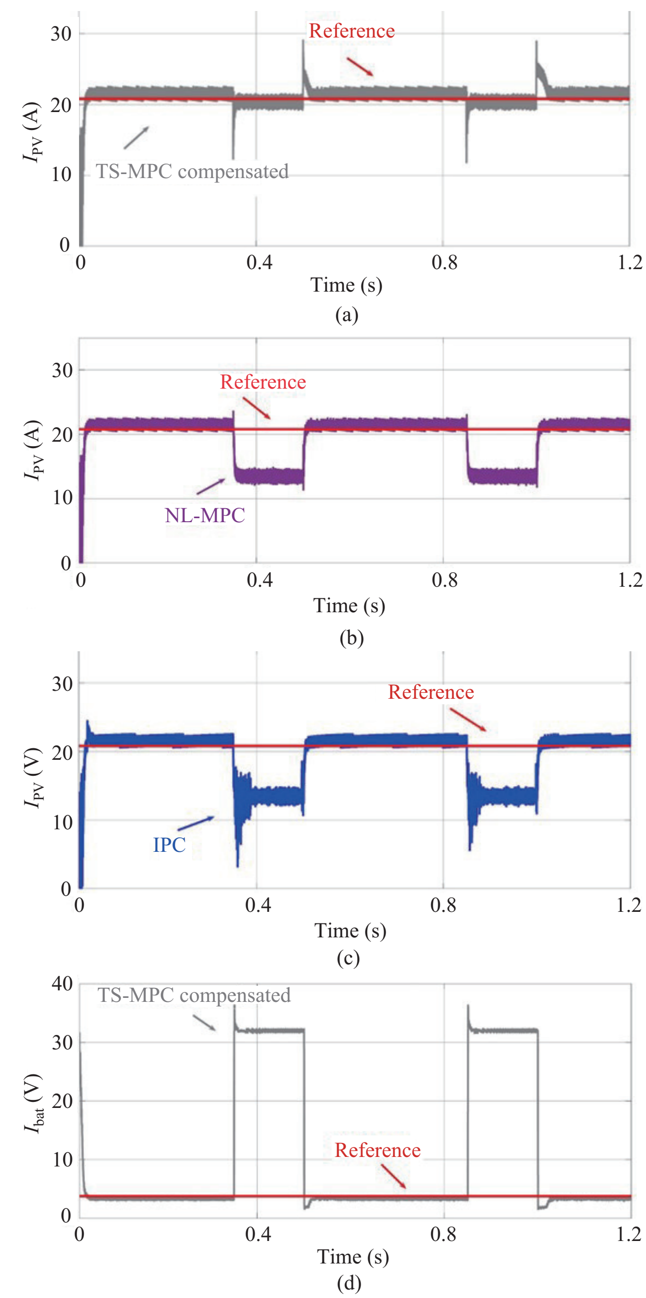


Fig. 5. DC microgrids control layer and a state estimation.



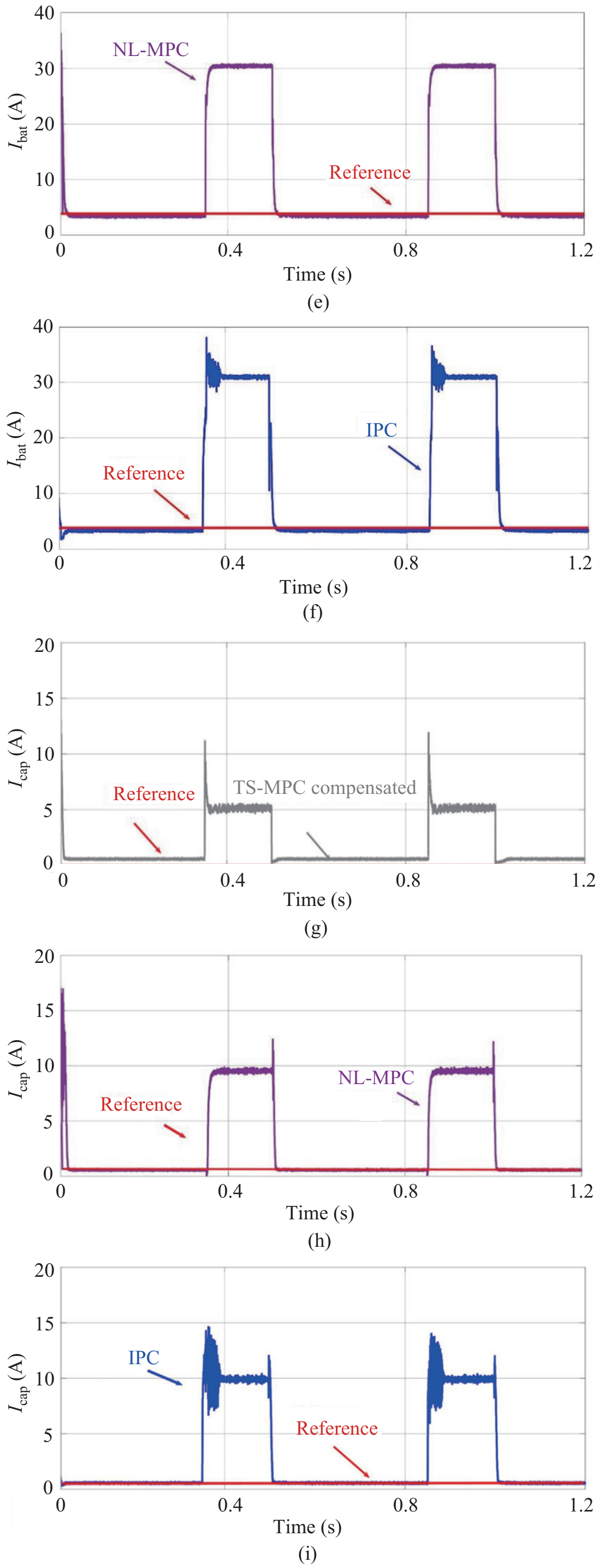


Fig. 6. Performance of DC microgrids using the TS-MPC, NL-MPC, and IPC control methods with a pulse load of 4 kW. (a) TS-MPC compensated. (b) NL-MPC. (c) IPC. (d) TS-MPC compensated. (e) NL-MPC. (f) IPC. (g) TS-MPC compensated. (h) NL-MPC. (i) IPC.

control strategy based on optimization. Fig. 7 shows running time of TS-MPC and NL-MPC methods for each sample

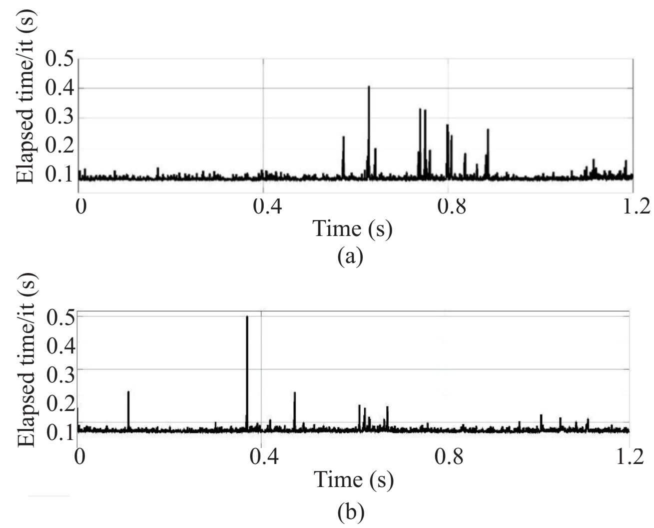


Fig. 7. Time spent on computation for each optimization process. (a) NL-MPC. (b) TS-MPC.

time solver. It can be concluded that calculation time of 0.03 seconds per cycle can be reduced by using TS approach. In addition, it is tested on an MG using the parameters listed in Table II and results are compared to MPC control [17] and IPC control [8].

In Fig. 6, we can see the differences between compensation and uncompensation situation. The effectiveness of the compensation mechanism can help the controller deal with coming external interference, thus helping reduce tracking error. When the system is connected to the pulse load, PV output power is required to remain constant, and the extra power is responsible for the ultracapacitor and the battery. PV output also becomes more stable when the disturbance is estimated. By comparing Fig. 6(a), (b), and (c), we can see that photovoltaics with compensation are capable of tracking maximum power. Fig. 6(d), (e), (f), (g), and (i) illustrate how the energy storage system adjusts the output power in response to load changes after compensating.

We find that the proposed method has better performance for pulse load in Fig. 8. Furthermore, voltage variation, settling time, and steady-state error of the DC link for each approach are in Table III. It can be seen that this method improves both transient and steady-state performances. Compared with NL-MPC, settling time of the proposed approach is improved about 0.04 s in respect to the IPC and the steady-state error is reduced by 4.3 V. It can be inferred that proposed strategy has a lower overshoot and a faster convergence rate. In addition, it can be seen the proposed technology can quickly stabilize DC microgrids and prevent system state oscillations.

TABLE III
PERFORMANCES OF DC LINK VOLTAGE FOR EACH APPROACH

Approach	Setting time	Steady-state error
Proposed MPC	0.016	0.7 v
NL -MPC	0.012	9 v
IPC	0.02 s	5 v

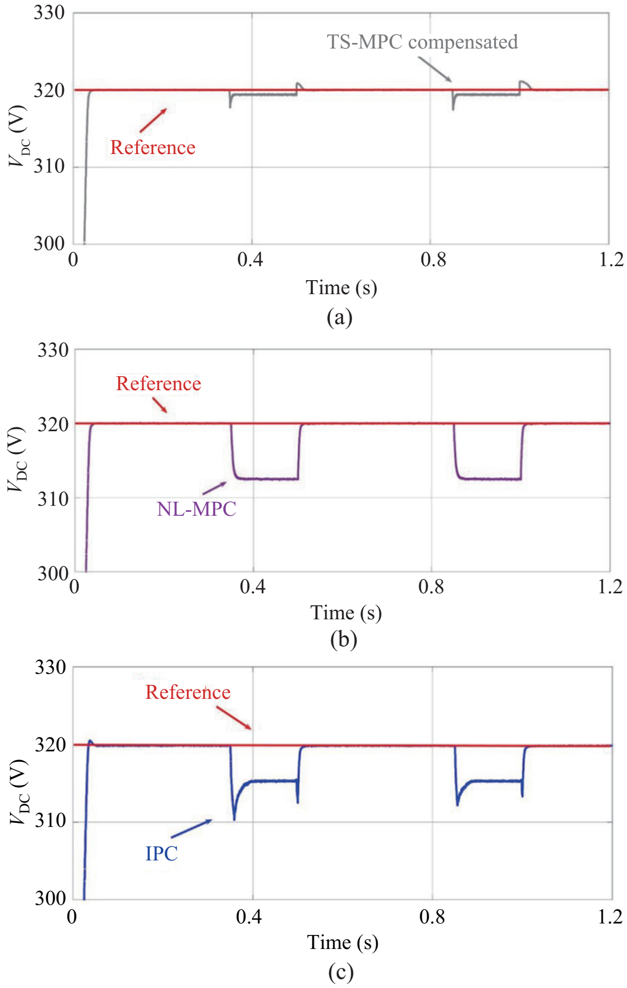


Fig. 8. Performances of DC link voltage for each approach. (a) NL-MPC. (b) TS-MPC. (c) IPC.

V. Conclusion

This paper presents a novel TS-MPC controller for reducing PPL impacts in DC Microgrids by resolving the converter control problem. The novel kinematic control was developed utilizing MPC with a prediction model expressed in the TS formulation without any linearisation. A comparison was made between two methods of solving the control problem: using the NL-MPC and using the TS-MPC approach being the TS model instanciated at each prediction step within the prediction stage.

The TS-MPC technique presents close performance to the non-linear control problem but in a much faster way. A non-linear power observer is introduced to estimate disturbances in DC microgrids. Compared with NL-MPC, the settling time of the proposed approach is improved about 0.04 s in respect to the IPC and the steady-state error is reduced by 4.3 V.

There are still some limitations in this paper, the operation process of this method is complicated, and it takes a certain amount of time for the program to run. The proposed technique will be evaluated in real-world DC microgrids as part of future research. Additionally, this article's findings should be extended to various topologies of DC Microgrids that supply linear and non-linear loads, such as resistive and pulse loads.

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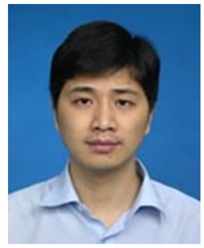

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