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An Intelligent and Fast Controller for DC/DC Converter Feeding CPL in a DC Microgrid

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***Abstract*— The negative impedance characteristic of the constant power loads (CPLs) causes instability in DC/DC converters in the DC microgrids. To improve the stability of the DC/DC converter feeding CPLs, a robust and fast controller is required. This paper presents a robust pulse-width modulation-based type-II fuzzy controller for a DC/DC boost converter feeding the CPL in a DC microgrid. Theoretical analysis and real-time simulation are presented to demonstrate the effectiveness of the proposed non-integer intelligent controller. Finally, the experimental results demonstrate that the proposed intelligent controller for the DC/DC converter has a faster and more robust response in comparison to the previously suggested control techniques.**

***Index Terms*—DC Microgrid, Constant Power Load (CPL), Type-II Fuzzy System, Non-integer Controller, Modified Sine-Cosine Optimization Algorithm.**

I. Introduction

DC microgrids (MGs) provide an effective way to integrate renewable energy resources (RESs), energy storage systems (ESSs) and electronic loads to achieve high efficiency as well as simple control [1], [2]. Despite their advantages, DC microgrids suffer from certain shortcomings, such as the instability of the DC/DC converters feeding CPLs [3]. Since the power ratings of the loads in DC microgrids have different values, the cascaded distributed architecture is preferred for the power electronic converters to have proper power management [4], [5]. These power electronic converters feed the constant power loads, which have a nonlinear behavior and introduce destabilization effects on the DC microgrids. To overcome this problem, a proper intelligent control technique is necessary for the DC/DC converters [4]. So far, several controllers have been proposed to mitigate the negative impedance instability [6] in modern DC grids. In [7], a comprehensive comparison of the linear and boundary controllers was presented. Additionally, a sliding mode controller for the DC/DC converter in the DC microgrid was proposed in [8]. The authors of [9] proposed a control method based on the Lyapunov stability theory. Moreover, a control technique was presented in [10], which introduced an active compensator by using of the reshaping impedance in a voltage source converter.

In all the aforementioned studies, the proposed controllers are based on the integer order calculus. However, the fractional order controllers can be achieved by using fractional calculus, which combines fractional derivatives and fractional integrals in the controllers [11]. The basic theory of the fractional order integration and differentiation is well described in the literature [11]. In general, the fractional order controller can be used to guarantee both the fast-dynamic response and robustness of the system simultaneously.

Fuzzy logic controllers (FLCs) are often preferred as an alternative approach to solve the stated control problems in modern power grids [3], [12], [13]. Type-1 fuzzy logic controllers (T1FLC) are the most popular types of the FLCs, which can be easily adjusted by a non-expert [14]. The main drawback of the T1FLCs is that they cannot directly handle the uncertainties included in unstructured environments. Due to certain limitation in T1FLCs, the interval type-2 fuzzy logic controllers (IT2-FLCs), which are characterized by type-2 fuzzy sets (T2FSs), are considered as a very powerful control approach to overcome uncertainties and external disturbances [15], [16].

In this letter, a novel intelligent non-integer type-II fuzzy controller is proposed to stabilize the DC/DC boost converter connected to the CPLs. The proposed controller minimizes the instability effects of the CPLs in DC microgrids as fast as possible. To optimize the performance of the proposed method with respect to the changing parameters, a new optimization algorithm is proposed for tuning the controller's coefficients. Finally, the dSPACE-based real-time experimental results are presented, which illustrate the effective performance of the proposed controller for the DC/DC boost converter connected to the CPLs in the DC microgrids.

II. System Modeling of Boost Converter with CPL

Fig. 1 shows a DC/DC boost converter feeding a CPL [8]. RESs, such as solar PV, or fuel cells, are connected to CPLs through the DC/DC boost converter. The output voltage of renewable energy sources is defined as E and the total load is considered to be a CPL, which represents a worst-case scenario from the stability point of view [17], [18]. Moreover, it is assumed that the DC/DC boost converter operates in the continuous conduction mode (CCM). The DC/DC boost converter is responsible for the regulation and stabilization of the DC bus voltage as well as for supplying the demanded constant power of the CPL. To illustrate the behavior of the DC/DC boost converter when feeding a CPL, the mathematical modeling of the circuit diagram in Fig. 1 is presented. The CPL can be modeled as follows [4]

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$$i_{CPL}(t) = \frac{P}{v_{CPL}(t)}; \forall\, v_{CPL}(t) > \varepsilon \tag{1}$$

Here, P and i_{CPL} are the rated power and current of the CPL, respectively. v_{CPL} is the voltage of the CPL, which is equal to the capacitor voltage v_C of the boost converter, and ε is a small positive value.

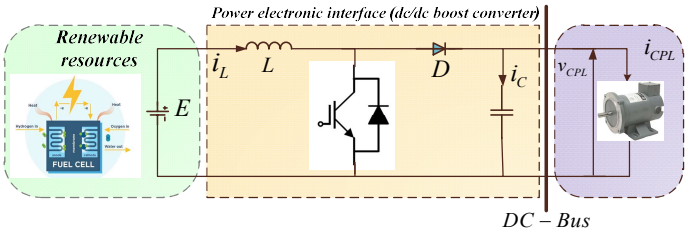

Fig. 1. DC/DC Converter Feeding CPL.

The state-space averaged model of the DC/DC boost converter is illustrated by:

$$\frac{dx_1}{dt} = \frac{E}{L} - \frac{(1-u)}{L}x_2 \tag{2}$$

$$\frac{dx_2}{dt} = \frac{(1-u)}{C}x_1 - \frac{P}{C}x_2 \tag{3}$$

where x_1 and x_2 are the average of the inductor current i_L and of the capacitor voltage v_C, respectively. L and C, are correspondingly the inductance and capacitance of the DC/DC boost converter. Moreover, $u \in \{0,1\}$ is the control input. In practical applications, $x_1$and x_2 are limited parameters; therefore, it is necessary to constrain their values. Furthermore, x_1 and $x_2 \in \phi$ where set ϕ is a subset of R^2 i.e.

$$x_1, x_2 \in \phi \subseteq R^2 \backslash \{0\} \tag{4}$$

It should be noted that to have a worst-case scenario from the stability point of view, the inductor, capacitor, diode, and power electronic switch in the DC/DC boost converter are assumed to be ideal. In this situation, the converter has a minimum of natural damping. Since most of the line regulation converters are efficient in the nominal operation condition, the validity of the ideal modeling of the boost converter is justified. Thus, by taking into account this situation, the designed controller would be exposed to the worst-case instability condition caused by the CPL.

III. Non-Integer Type-II Fuzzy P+ID Controller

In this section, by developing the fuzzy P+ID controller proposed by Li [19], a model-free fractional order fuzzy P+ID controller is discussed. In the suggested modified controller, the proportional term in the traditional PID controller is replaced by the two inputs of the fuzzy logic controller to modify the performance of the DC/DC boost converter in the transient and steady states, simultaneously. Since the proposed control scheme does not need any extra hardware adoption for real-time implementation, the simplicity of the PID controller remains unchanged. In the proposed novel type-II fuzzy P+ID controller, due to the smooth action of the derivative term, the effect of a derivative pick for a step change in the reference signal can be eliminated. Basically, for the control applications in the case of a sharp jump in the error rate, the controller tries to eliminate its destructive effects with a large amount of the derivative term. Therefore, for a sharp step change in the reference signal to have a proper control action in terms of regulating the derivative-pick, the fractional order derivative term in the feedback path and the fractional order integral term in the forward path are respectively adjusted by the rate of change in the plant variable and the time evolution of error. In this work, in order to overcome the instability effects of the CPL in the DC grids and to have more flexibility in the controller design, the proposed controller utilizes the benefits of the fractional order (FO) differ-integration and the type-II fuzzy logic theory [11], simultaneously.

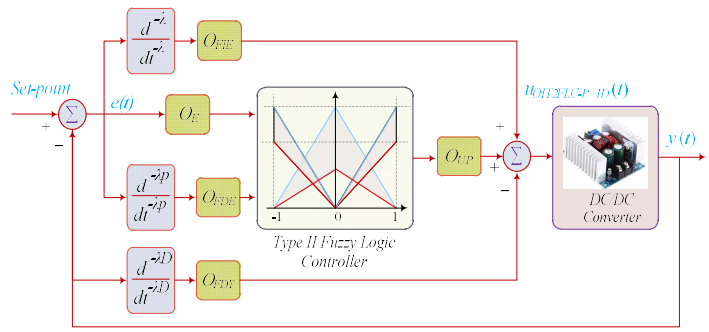

Fig. 2. The general structure of the nonlinear model-free controller.

Fig. 2 shows the overall structure of the proposed control method. As shown in Fig. 2, the output of the proposed control method can be written as:

$$u_{OIT2FLC-P+ID}(t) = O_{UP}(U_{IT2FLC}) + O_{FIE}\frac{d^{-\lambda}(e(t))}{dt^{-\lambda}} - O_{FDY}\frac{d^{-\lambda D}(y(t))}{dt^{-\lambda D}} \tag{5}$$

In the configured controller, O_E and O_{FDE} are the input scaling factors and O_{UP} is the output scaling factor. The integer order change of error in the input of the traditional integer order FLC has been replaced by its FO counterpart λp. Likewise, O_{FDY} and λD are respectively the FO derivative gain and the derivative order in the feedback path, and O_{FIE} and λ are correspondingly the FO integral gain and the integral order in the feed forward path.

As illustrated in Fig.2, the effectiveness and robustness of the proposed controller depend on the values of the controller's parameters. Therefore, it is essential to tune the intelligent fractional controller's parameters online. Moreover, to eliminate the effect of uncertainties and external disturbances, and to make an adaptive and robust controller, a hybrid Sine-Cosine algorithm is utilized, which is presented in the next section.

Generally, the DC/DC converters in the DC microgrids are controlled with the classical proportional-integral controllers. These controllers are adjusted base on some pre-defined operating conditions. In other words, if the operating point on the converter is changed, the traditional PID controller will not have a desirable efficiency and good performance.

Additionally, if the classical controller can always follow the variation, the desired performance can be achieved all the time. By utilizing the heuristic optimization algorithms, the online tuning parameters for the fractional order controllers are achieved. In the next section, a hybrid version of Sine-Cosine algorithm and Harmony Search entitled SCA-HS will be presented for the tuning of the proposed control method.

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IV. Overview of the Original Sine-Cosine Algorithm (SCA)

Based on the mathematical sine and cosine functions, the SCA algorithm is introduced as a stochastic optimization algorithm [20]. The SCA starts the optimization process with initial candidate solutions and ameliorates them through changing outwards and towards the targeted global solution using sine and cosine functions as follows:

$$X_{j,t+1} = \begin{cases} X_{j,t} + \omega \times \sin(rand) \times \left| rand\, P_{j,t} - X_{j,t} \right| & r_4 < 0.5 \\ X_{j,t} + \omega \times \cos(rand) \times \left| rand\, P_{j,t} - X_{j,t} \right| & r_4 \geq 0.5 \end{cases} \quad (6)$$

$$\omega = a - t\frac{a}{T_{max}} \quad (7)$$

Here, $X_{j,t}$ is the current solution at t^{th} iteration in j^{th} dimension; $P_{j,t}$ is the best solution; ω is a control parameter, which decreases linearly from a constant value a to 0 by each iteration and T_{max} is the total number of the iteration.

A. The proposed hybrid SCA and HS

In some cases, due to the heuristic algorithm's poor exploration of the optimal solution, the SCA suffers from the problem of the convergence to a local optimum point, which is referred to as the premature convergence. To overcome this problem, the improvisation approach established in the harmony search (HS) is added to the SCA. In this method, a candidate solution is improvised by three rules: memory consideration, pitch adjustment, and random selection. The SCA generates the component of each solution with a probability of the harmony memory consideration rate (*HMCR*). In this method, *LB* and *UP* are defined as the lower and upper bounds for the decision variables, respectively. A new component is randomly generated within the range of [*LB UP*] with the rate of (1-*HMCR*). Moreover, with a probability of the *HMCR* multiplying the pitch adjustment rate (*PAR*), the surrounding space of a candidate solution is explored by the parameter distance bandwidth (*bw*). In order to provide a tradeoff between the exploration and exploitation of the proposed SCA-HS, the parameters *PAR* and *bw* are dynamically adjusted as:

$$PAR_t = PAR_{min} + (PAR_{max} - PAR_{min}) \times t/T_{max} \quad (8)$$

$$bw_t = bw_{max} e^{\left(\frac{\ln\left(\frac{bw_{min}}{bw_{max}}\right)}{T_{max}} \times t\right)} \quad (9)$$

where PAR_t is the pitch adjustment rate in the iteration t, and PAR_{min} and PAR_{max} are the minimum and maximum pitch adjustment, respectively. bw_t is the distance bandwidth at iteration t. bw_{min} and bw_{max} are the minimum and maximum bandwidths, respectively. The computational process of a mixture of the SCA with HS is illustrated in Algorithm 1.

Since the heuristic evolutionary methods (e.g. Genetic, Firefly, cuckoo search, etc.) do not require any information about the particular system under operation, it is necessary to define a fitness function to guide the search of the population-based methods. Consequently, in this work, an objective function (eq. (10)) is used for the optimal setting of the coefficients embedded in the specific designed controller.

$$J = \int_0^{\infty} t \,.\, e_{set-point}^2(t) + \Delta u^2(t).\, dt \quad (10)$$

where $e_{set\text{-}point}$ is the error signal and Δu is the control signal.

Algorithm 1: The procedure computation of the SCA-HS

```
Generate initial population randomly
while t < T_max
Update the best solution P if there a better solution
Compute the parameters PAR(t), bw(t) and ω
for1 each solution
for2 j=1 to D
if1 rand < HMCR
if2 rand < 0.5
X_{j,t+1}=X_{j,t} + ω × sin (rand) × | rand P_{j,t} - X_{j,t}|
else2
X_{j,t+1}=X_{j,t} + ω × cos (rand) × | rand P_{j,t} - X_{j,t}|
end if2
if3 rand < PAR
X_{j,t+1}=X_{j,t+1} ± rand × bw
end if3
else if1
X_{j,t+1}=LB_j ± rand × (UB_j -LB_j)
end if1
end for1
end for2
t=t+1
end while
Return the best solution obtained so far
```

The DC/DC boost converter problem can be formulated as a constrained optimization problem by restricting the controller coefficients as: Minimize J

Subjected to:

$O_{E,min} \leq O_E \leq O_{E,max}$, $O_{FDE,min} \leq O_{FDE} \leq O_{FDE,max}$, $O_{UP,min} \leq O_{UP} \leq O_{UP,max}$, $O_{FDY,min} \leq O_{FDY} \leq O_{FDY,max}$, $O_{FIE,min} \leq O_{FIE} \leq O_{FIE,max}$, $\lambda p_{min} \leq \lambda p \leq \lambda p_{max}$, $\lambda D_{min} \leq \lambda D \leq \lambda D_{max}$, $\lambda_{min} \leq \lambda \leq \lambda_{max}$.

The approximation schemes are used in both simulations and hardware applications to approximate the non-integer transfer functions to their integer order form. CRONE [21] is one of the most powerful tools which can approximate the non-integer equations with a high accuracy. In this study, the CRONE is used to approximate the fractional order function s^{α}, which correspondingly employs a higher order filter by having an order of $2N + 1$, as given below:

$$s^{\alpha} \approx K \prod_{k=-N}^{N} \frac{1 + \omega_k'}{1 + \omega_k} \qquad q > 0 \quad (11)$$

Here, $K = \omega_h^{\alpha}$ α denotes the fractional order. The zeros and poles of the filter are obtained as:

$$\omega_k = \omega_l \left(\frac{\omega_h}{\omega_l}\right)^{\frac{k+N+\frac{1}{2}(1+\alpha)}{2N+1}}, \omega_k' = \omega_l \left(\frac{\omega_h}{\omega_l}\right)^{\frac{k+N+\frac{1}{2}(1-\alpha)}{2N+1}} \quad (12)$$

In this equation, N is the number of zeros and poles. Here, the frequency range is valid in $[\omega_l, \omega_h]$, where ω_l and ω_h represent the low and high frequency bands, respectively.

V. The Contributions Of This Study

This brief paper introduces a new population-based optimization approach for adjusting the parameters' value of non-integer model-free controllers in the modern DC grid. For designing the suggested control approach, some considerations have been made, which play a prominent role in its practical implementation.

1- The new intelligent-based DC/DC converter control is easy to implement and it is able to be applied in different power

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electronic devices.

2- The proposed robust non-integer control approach is a model-free controller. This entails that the intelligent control commands are based only on the accessible system input/output information, which can be obtained online.

3- The light computational burden of the intelligent non-integer control technique makes it very useful for the practical implementation and online control cases.

4- As presented below, the experimental results using the proposed technique confirmed the utility and applicability of the proposed control system, demonstrating that the conservatism of the conventional control approach was eliminated, and the performance criterion obtained was more accurate.

VI. Experimental Results

To validate the effectiveness and fast transient performance of the proposed method, a DC/DC boost converter in a DC microgrid is considered. The control method is executed in the dSPACE MicroLabBox with DS1202 PowerPC DualCore 2 GHz processor board and DS1302 I/O board. Table I shows the parameters of the system.

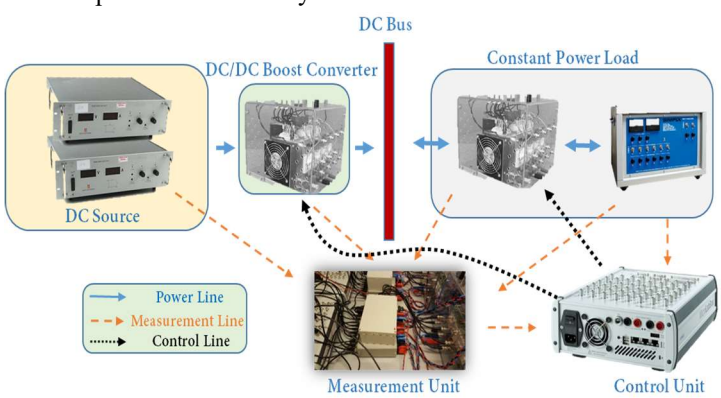

Fig. 3. The experimental DC/DC converter setup.

Moreover, to examine the robustness of the proposed method, the performance of the suggested control approach is compared to the model predictive control (MPC), optimal proportional–integral (OPI) controller, and the conventional PI (CPI) controller [22]. The prototype built is displayed in Fig. 3. The results of the real-time tests are given in Figs. 4–8. In the first step, the transient response of the DC grid has been investigated by assuming that the output power of the constant load is fixed.

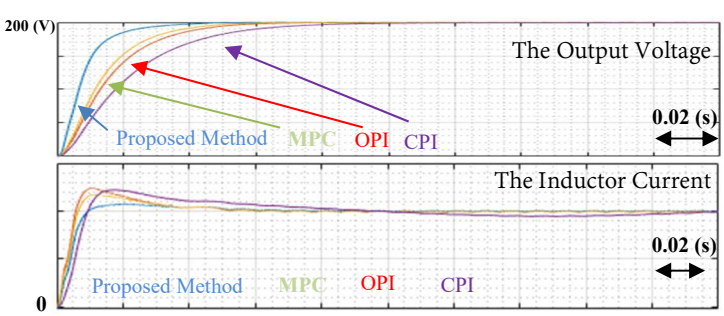

Fig. 4. The transient response of the DC grid: (a) the output voltage, (b) the inductor current.

Fig. 4 illustrates that the suggested optimal non-integer type-II fuzzy controller has a better transient response over the MPC, OPI, and CPI controllers. Besides, it can be seen that the proposed controller can track the voltage and current set-point as fast as possible. As shown in Fig. 4(a), the peak value of the voltage deviation is reduced, and the damping of the deviation is reached faster in comparison to other control methods.

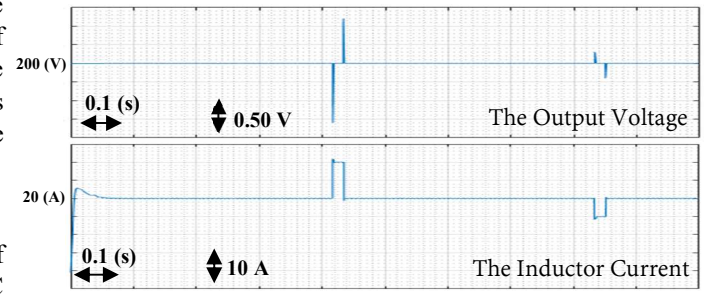

Fig. 5. The transient response of the proposed control approach corresponding to increasing the power of CPL: (a) the output voltage (b) the output Current.

Fig. 6. The transient response of the MPC controller corresponding to increasing the power of CPL: (a) The output voltage (b) the output Current.

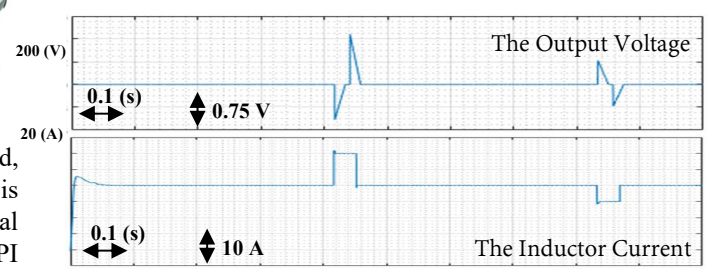

Fig. 7. The transient response of the optimal PI controller corresponding to increasing the power of CPL: (a) The output voltage (b) the output Current.

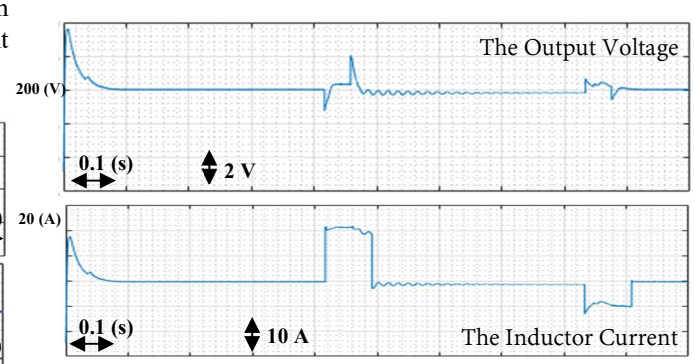

Fig. 8. The transient response of the conventional PI controller corresponding to increasing the power of CPL: (a) The output voltage (b) the output Current.

At this stage, we increase the power of the CPL by 50% at $t = 0.41$. Figs. 5 to 8 reveal that the proposed control

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technique has a better and faster response in restoring the voltage and current of the system to the set point. Moreover, as the stated figures illustrate, the proposed control approach has less overshoot over the conventional classic controllers. These experimental results confirm that the non-integer optimal type-II fuzzy P+ID controller can be very useful for controlling the of power electronic devices to make them more stable and flexible over uncertainties. Besides the stated advantages, the control technique proposed in this study is very easy to design and can be applied for a vast variety of other power electronic devices.

Table I
THE CASE-STUDY PARAMETERS

Parameter	Value
L	1 mH
C	1000 μf
E	50 V
V_{ref}	200V
P	1000 W

In the final stage, three different usual error measurement criteria (EMC) are applied to show the effectiveness and performance of the proposed intelligent non-integer controller over other control techniques. These EMCs include: 1) Sum of the Squared Errors (SSE), 2) Mean Absolute Error (MAE), and 3) Mean Square Error (MSE). According to these criteria, if the values of SSE, MAE, and MSE are close to zero, the control method will have an optimal performance. Table II presents the results of the evaluation made of the controller's performance based on the stated.

Table II.The controllers' performance analysis

Criteria	CPI	OPI	MPC	Suggested Approach
SSE	8.8510	4.9147	4.4019	1.9640
MAE	0.0751	0.0346	0.0299	0.0084
MSE	5.8491e-4	1.0275e-5	1.0179e-5	0.0679e-5

VII. Conclusion

This brief study presents a new approach to analytical performance validation of the optimal model-free fractional order type-2 fuzzy P+ID controller. The approach is mixed with the powerful population-based meta-heuristic algorithm from statistics and can be implemented to successfully validate the behavior of the control technique. The suggested fast and intelligent control method is robust over negative impedance instabilities, which is very usual in DC/DC converters dominated by DC modern grids and other similar power electronic devices. In order to evaluate the performance and superiority of the proposed control approach, the results are compared to those of the model predictive control (MPC), optimal proportional–integral (OPI) controller, and the conventional PI (CPI) controller. It was found that the suggested controller has fast and accurate performance over other control algorithms. Moreover, the proposed approach can be applied to other power electronic devices with different structures and uncertainties. Finally, the experimental results corroborated the effectiveness of the proposed approach in improving the performance of the control system in several operating conditions. Future research could apply the proposed controller to the voltage source converter in the hybrid AC/DC modern grid to have a more efficient performance.

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