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A Repetitive Control–based Approach for Power Sharing Among Boost Converters in DC Microgrids

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Abstract- *In this paper a repetitive control (RC) approach to improve current sharing between parallel-connected boost converters in DC microgrids is presented. The impact of changes in line impedance on current sharing is investigated. A repetitive controller is designed and connected in series with current controller of the boost converters to control the switching signals such that by regulating of the output voltage of each converter, the circulating current is minimized. The performance of the proposed control strategy is validated through simulation.*

Keyword: DC microgrid, repetitive control, current sharing, boost converter.

1. INTRODUCTION

Nowadays, many efforts have been focused on the development of distributed generation (DG) technologies due to shortage in energy and the public concern about global warming and climate changes [1-4]. In this field, the concept of microgrid has been introduced to facilitate the integration of the DGs with utility [5]-[6]. A microgrid has been defined as a low voltage electrical network including DGs and related loads and can operate in grid-connected mode or islanded mode [7]. There are three types of microgrids: AC microgrids, DC microgrids, and hybrid microgrids. AC microgrids only contain AC resources and loads whereas DC microgrids include DC resources and loads. The hybrid microgrids comprise both AC and DC microgrids. DC microgrid is suitable when most of the loads are sensitive DC electronic equipment. The advantage of a DC microgrid is that loads, sources, and energy storage systems (ESSs) can be connected to the common DC bus with lowest power conversion stages. Moreover, it is not necessary to process AC power quality issues. So far, the DC microgrids have been used in telecom power systems, data centers systems, generating stations, traction power systems, and residential houses [8]–[10]. One of the common problems in microgrids is the circulating current between parallel-connected converters of DGs. This problem occurs due to the fact that the lines impedances, which connect the DGs to the loads, are not exactly the same. The circulating current may also occur because of different output voltages of converters. In practice, the rated voltage of parallel-connected converters is always the same. However, in a real microgrid, there is always differences in impedances of parallel-connected cables, and this results in a circulating current which deteriorates the overall system efficiency [12].

To counteract with this problem, various strategies have been proposed in the literature. In [13], a harmonic circulation current reduction method for parallel operation of uninterruptible power supplies (UPSs) with a three-phase PWM inverter has been presented. This method has used a PWM synchronizing technique to eliminate the harmonic circulation current in parallel operation of UPSs. A low-voltage DC distribution system for sensitive loads has been described in [14]. These works have focused on the hardware implementation of DC microgrids. A scenario-based operation strategy for a DC microgrid, based on detailed wind turbine and battery models, has been developed in [15]. A cooperative control paradigm has been proposed in [16] to establish a distributed secondary/primary control framework for DC microgrids. However, this method needed communication structure which reduces its reliability.

Distributed controllers have also been studied in the literature to regulate multi-terminal DC transmission systems which share similar problem aspects with DC microgrids. The controller which has been proposed in [17] achieved fair power sharing and has been able to asymptotically minimize the cost of the power injections. In [18] a unified port-Hamiltonian system model has been proposed, and the performance of decentralized proportional- integral (PI) control has been discussed for a multi-terminal DC transmission system. An adaptive

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droop control strategy for load sharing and circulating current minimization in low-voltage standalone DC microgrid has been proposed in [19]. A hierarchical control strategy for a droop-controlled DC microgrid has been proposed in [20], which fits the smart house infrastructure to adopt online renewable generation and load sharing.

The main objective of this work is to present a control scheme to improve current sharing between parallel-connected boost converters in a DC microgrid. The contributions of this paper are:

-A repetitive control-based scheme is proposed for parallel-connected boost converters. The proposed scheme is based on regulating the output of each converter such that the circulating current is minimized.

-The impact of changes in line impedance on current sharing for parallel-connected boost converters is investigated.

The rest of this work is organized as follows: Section 2 presents the dynamic modeling of boost converter. The formulation of circulating current in DC microgrids is also presented in this section. In Section 3, the proposed repetitive load sharing control strategy is described. The simulation results are provided in Section 4. Finally, the conclusion is drawn in Section 5.

2. BOOST CONVERTER MODEL AND CIRCULATING CURRENT

The structure of a typical DC microgrid is shown in Fig. 1. As shown, the sources in a DC microgrid are interfaced to a common DC bus through power converters. The control system of these power converters plays an important role in the power management performance and stability of the DC microgrid. The main power control objective in a microgrid is to ensure a proper load sharing among the sources.

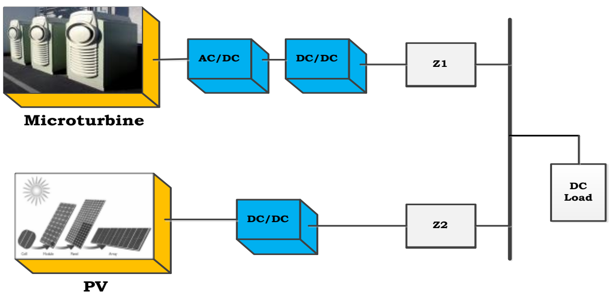


Fig. 1 A typical DC microgrid structure [6]

Fig. 2 shows the model of a single-phase boost converter. In this model, the AC input voltage v_{in} is rectified using the diode-bridge rectifier. The AC voltage v_{in} may be a representative for a diesel generator or even a wind turbine. The boost converter consists of an inductor, a diode, and a power electronic switch. Here, it is assumed that the inductor current always remains flowing (continuous conduction mode (CCM)). The average voltage across the inductor must be zero for the average current to remain in steady state [13]:

$$v_{in}t_{on} + (v_{in} - v_o)t_{off} = 0 \tag{1}$$

where, t_{on} , t_{off} are the on and off time durations of the switch, respectively.

This can be rearranged as follows [13]:

$$\frac{v_o}{v_{in}} = \frac{1}{1-d} \tag{2}$$

with

$$d = \frac{t_{on}}{T} \tag{3}$$

where, d is the duty cycle and $T = t_{on} + t_{off}$ is the switching period.

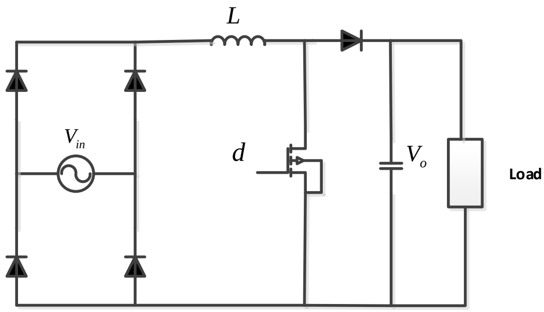


Fig. 2 Power circuit of a boost converter [1]

For load sharing analysis, one can consider an *n* single-phase parallel-connected converter system, as shown in Fig. 3. Suppose that the total current and total load power are I_{RT} and P_{RT}, respectively, and I_{Rk} and P_{Rk}, k = 1, 2…n are the current and power of each converter, respectively. Then, as shown in Fig. 3, when the load current is i_T, ideally, it is required to distribute the load current to each converter according to their assigned loadings as follows [23]:

$$i_k \triangleq h_k i_T \triangleq \frac{P_{Rk}}{P_{RT}} i_T \qquad \text{k=1, 2…n} \tag{4}$$

where, h_k is defined as the distribution factor of the k^{th} converter.

Normally, $\sum h_k = 1$. Therefore, under this condition, the circulating current of each converter is zero. One can now define the circulating current of k^{th} converter as the difference between the actual current and the assigned reference current as follows:

$$C_k \triangleq i_k - h_k i_T \triangleq i_k - I_k \triangleq C_{k1} + C_{k2} + C_{k3} \quad \text{, k=1, 2…n} \tag{5}$$

where, $C_{ki}, k \neq i$, is the circulating current component, as shown in Fig. 3, for k = 1 and self-circulating current C_{kk} = 0 [13]. More details can be found in [23].

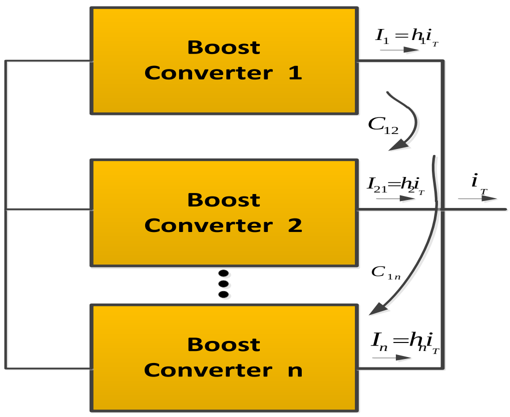


Fig. 3 Structure of n parallel–connected boost converters and circulating currents

3. PROPOSED REPETITIVE CONTROLLER DESIGN

Repetitive controllers (RC) are an effective solution for overcoming the complexity of multiple resonant controllers. The RC, which has originally been developed from the internal model principle, by using only a simple delay unit, is capable of achieving zero errors in tracking periodic signals, e.g. harmonic voltages [10]. In addition, since an RC can provide a similar behavior as that of a bank of resonant controllers, a large number of harmonic currents/voltages can be simultaneously compensated by using only one RC [13]. Due to this advantage, RCs have been applied to various applications such as uninterruptable power supplies (UPS) [10]-[13], and active power filters (APFs) [18]. In this study, a repetitive controller is designed to improve load sharing in DC microgrid.

3.1 Principle of repetitive control

As an internal model principal (IMP)-based [19] strategy, RC uses an IM which corresponds with the model of a periodic signal. In order to derive this model, recall that the trigonometric Fourier series expansion of a T_s-periodic signal $r(t)$ reads as follows:

$$r(t) = a_0 + \sum_{k=1}^{\infty} a_k \cos\left(\frac{2k\pi}{T_s}t\right) + b_k \sin\left(\frac{2k\pi}{T_s}t\right) \quad (6)$$

Any periodic signal, in form of (6), with period T_s can be generated by a time delay system. The block diagram of a time delay system including unity positive feedback is shown in Fig. 4. The resulting transfer function is [19]:

$$G_R(s) = \frac{Y(s)}{U(s)} = \frac{1}{s}\prod_{k=1}^{\infty} \frac{\left(\frac{2k\pi}{T_s}\right)^2}{s^2 + \left(\frac{2k\pi}{T_s}\right)^2} = \frac{T_s e^{-sT_s/2}}{1 - e^{-sT_s}} \quad (7)$$

where $Y(s)$ is the output and $U(s)$ is the input and $T_s e^{-sT_s/2}$ is a delay term with a gain T_s.

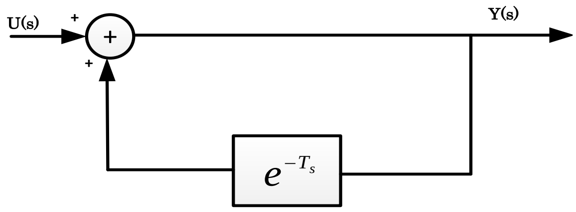


Fig. 4 Time delay system; generation of a periodic signal

A controller including the model in (7) is said to be a repetitive controller and a system with such controller is called a repetitive control system. As mentioned, the basic concept of the repetitive controller originates from the internal model principle [19]. This principle states that the controlled output tracks a set of reference inputs without steady state error if the model which generates these references is included in the stable closed loop system. For example, no steady state error occurs for step reference commands in type-1 stable feedback system that has an integrator ($1/s$) in the loop, i.e., the generator of step function. However, stand-alone repetitive controller cannot yield good transient performance; therefore, the repetitive controller is often used together with another controller such as PI controller to give quick transient response.

3.2 load sharing control scheme with repetitive controller

The block diagram of the DC microgrid including two parallel-connected boost converters, which has been equipped with the proposed control scheme, is shown in Fig. 5. The same reference voltage is used for each boost converter. The inductor current and AC input voltage of each converter are also measured and given to the controllers. The structure of the controller is shown in Fig. 6. Here, the DC output voltage of the boost converter V_o is compared to the reference V_{ref} and the error e_v is passed to the voltage controller $G_{cv}(s)$ which typically is a PI controller. A current command i_{ref} is obtained by multiplying the output signal of voltage controller I_{ref} with a rectified unity sine wave ($S(t)$) as follows:

$$S(t) = \frac{|v_{in}|}{\hat{v}_{in}} = |\sin(\omega t)| \quad (8)$$

where, $v_{in} = \hat{v}_{in} \sin(\omega t)$. The current command is compared with the inductor current i_L and the error e_i is given to the PI current controller $G_{ci}(s)$ to obtain V_{cont}. A pulse width modulation (PWM) control signal d, which has been obtained by comparing V_{cont} with the triangular wave V_{tri}, is applied to gate driver unit of power MOSFET transistor.

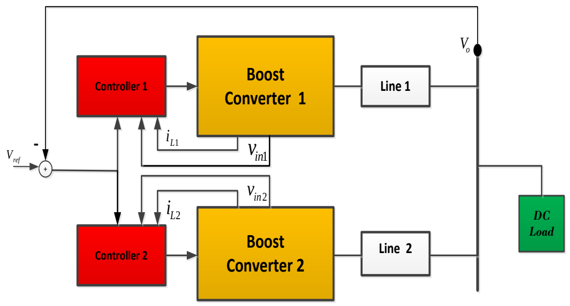


Fig. 5. DC microgrid with two parallel-connected boost converters equipped with the proposed control scheme.

The boost converter has an outer voltage loop and an inner current loop as shown in Fig. 6 (a). In this study, we focus on the inner current loop which has a controller $G_{ci}(s)$. The parameters of this PI controller of the current loop are chosen as K_p = 0.8 and K_i = 300. The repetitive controller is inserted in series with the PI controller. The converter system accompanied by the proposed repetitive controller is shown in Fig. 6 (b). The repetitive controller $C_{RP}(s)$ is located in series with conventional PI controller $G_{ci}(s)$ of current loop of boost converter. The transfer function of the repetitive controller is:

$$C_{RP}(s) = \frac{1}{1 - q(s)e^{-sT_s}} \tag{9}$$

where, $q(s)$ is a low pass filter in the form of $q(s) = \frac{\omega_c}{s+\omega_c}$ and should be appropriately chosen so that good tracking performance is obtained. The choice of $q(s)$ is based on the scientific approach described in [10]-[11]. The frequency response of this low pass filter is indicated in Fig. 7. In the repetitive control system shown in Fig. 6 the closed loop system without the repetitive controller (i.e. $\frac{G(s)}{1+G(s)}$) is stable and $|q(j\omega)| < |1 + G(j\omega), \forall\omega| > 0$ in which:

$$G(s) = \frac{V_{ref}(K_p s + K_i)}{s^2 \hat{V}_{tri} L} \tag{10}$$

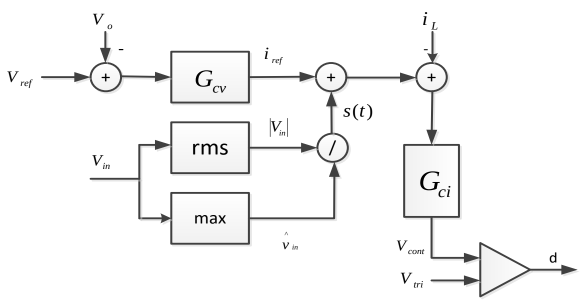
Then the system is exponentially stable. The system without repetitive controller is stable since G(s) has no unstable poles. The repetitive control system is therefore exponentially stable if the Nyquist plot of G(s) does not encircle the (–1, j0) point and lies outside of the circle of radius $|q(j\omega)|$ centered at the (-1, j0) point of complex plane [13]. The Nyquist plot of (10) is shown in Fig. 8. As shown, the plot does not encircle the (-1, j0) point of complex plane. To ensure the stability for all frequencies the value of $|q(j\omega)|$ must be less than unity to prevent any contact between the plot of $G(s)$ and the circle. The gain of low pass filter $q(s)$ is chosen as 0.98 to give stable system and good tracking performance. There is no systematic method to obtain cutoff frequency of $q(s)$ therefore simulation is required to find the best value from the point of view of good tracking and disturbances rejection. Accordingly, the cutoff frequency is chosen as 1100 HZ. It seems that, based on Figs. 7-8, 1100 HZ is a reasonable choice since most periodic disturbances are expected to lie within this band. Let the filter $q(s)$ is:

$$q(s) = \frac{0.98}{1 + s/2000\pi} \tag{11}$$

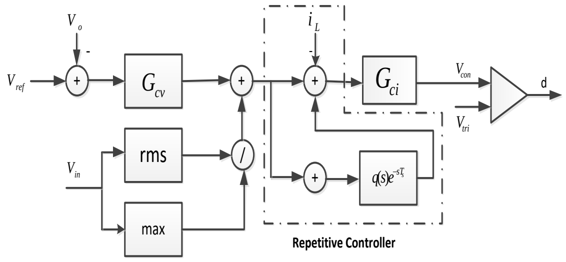
Here, a 10 ms delay is needed for compensation of harmonics of f_s = 100 Hz. Finally, the proposed repetitive controller for each converter is:

$$C_{RP}(s) = \frac{1}{1 + \frac{0.98}{1 + s/2000\pi} e^{-0.01s}} \tag{12}$$

This controller is inserted in series with the PI controller in current loop of boost converter which generates V_{cont}. The major characteristic of the repetitive controller is effective rejection of periodic disturbances. Note that adding repetitive controller increases the loop gain at particular frequencies, integral multiples of 100 Hz, maintaining a relatively unchanged gain at other frequencies.



(a)



(b)

Fig. 6 Inside the controller of Fig. 5: (a) Typical control of a boost converter (b) proposed control of converters for load sharing improvement

4. SIMULATION RESULTS

In this section, the performance of the proposed repetitive control scheme for load sharing in a typical DC microgrid is studied through simulation using MATLAB/SIMULINK [24]. The microgrid structure is the same as Fig. 5. The system parameters and values are given in Table 1. The load is a resistance of 100 Ω. Two case studies are considered. In the first case, the current control loop of converter is separately equipped with the proposed repetitive controller and the PI controller and the effect of changes in line parameters on the load sharing is investigated. In the second case, the effect of changes in the load parameters is studied. Each simulation result contains of two different plots; “PI controller” and “RC controller”.

Case I. Effect of changes in line parameters on the load sharing: In this case, to consider the effects of a disturbance on load sharing, during the simulation, the line resistance value of converter 1, R_1,is reduced from 0.8 Ω to 0 Ω in 0.08 Ω steps [26]. Here, a PI controller with parameters of K_p = 0.8 and K_i = 300 [7] is implemented in the current loop. The simulation results are shown in Figs. 9-14. The output voltage and current of the two converters are shown in Figs. 9-11. As can be observed from Fig. 9 and Fig. 10, when the proposed RC controller is implemented, the peak transient of the output current of the converters is reduced. The DC load voltage and current are shown in Figs. 12-13. As shown, the load current is 3 A for a resistance of 100Ω and output voltage of 300 V. Fig. 14 shows that the DC circulating current peak is 5.1 A by using the PI controller; however, this value is reduced to 0.72 A by using the RC controller.

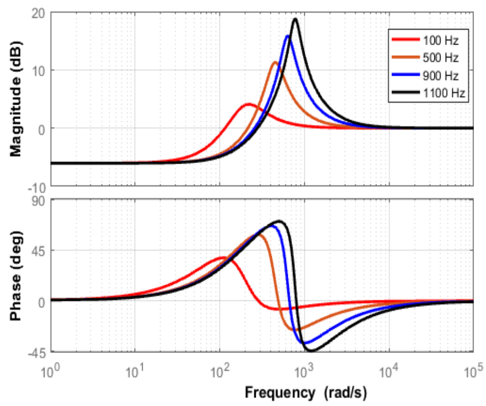


Fig. 7 Frequency response of the low pass filter q(s) for different values of cutoff frequency.

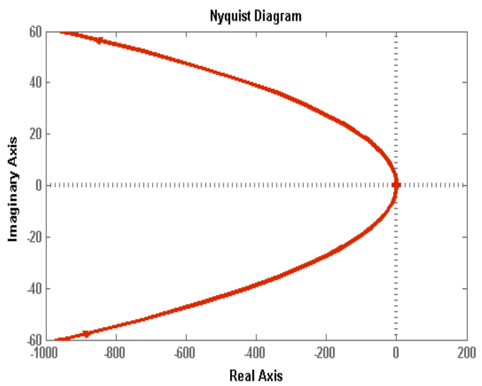


Fig. 8 The Nyquist plot of (10)

Comparing the results shows that, when the proposed repetitive controller (RC) is implemented, the circulating current is reduced by %85.88 which is a major improvement in the current sharing in a DC microgrid.

Case II. Effect of changes in load parameters on the load sharing: Here, the performance of the proposed repetitive controller (RC), described by Eq. (11), is verified during the changes in the load model. We have analyzed the effects of 50% changes in the resistance of the load on the load sharing. The simulation results are shown in Figs. 15-17. As shown, the performance of the proposed control scheme in reducing the circulating current is acceptable in this condition. The output currents of the two converters are shown in Figs. 15-16. These figures show the DC load current again is 3 A (the summation of the two output currents). However, as shown, the output currents tolerate lower transient when the RC controller is implemented. Fig. 17 shows that the circulating current peak is 4.3 A when the PI controller is used whereas it is reduced to 3.2 A when the RC controller is implemented.

Case III. Effects of simultaneous changes in load and line parameters on load sharing: The line resistance value of converter 1, R_1,is reduced from 0.8 Ω to 0 Ω in 0.08 Ω steps and at the same time, the effects of 50% changes in the resistance of the load on the load sharing based on the proposed strategy is studied. For the purpose of comparison, the simulation results, when the method of [25] is involved, are given. In [25], a modified droop method based on master current control for parallel-connected DC-DC boost converters have been proposed. The modified droop method has used an algorithm for parallel-connected DC-DC boost converters to adaptively adjust the reference voltage for each converter according to the load regulation characteristics of the droop method. The simulation results are shown in Figs. 18-20. As indicated in Fig. 18, when the proposed strategy is used, the output of each converter is stabilized at its nominal value, i.e. 300V, whereas the method of [25] impose about 12V voltage droop on each converter. The active power differences are shown in Fig. 19. As illustrated in Fig. 19(a), the average active power difference by using the proposed method is about 8.2W whereas this value increase to around 17W by using the method of [25]. The circulating current is also illustrated in Fig. 20. The circulating current peak is about 1.6A by implementation of the proposed scheme while it reaches to about 2.3A when using the method of [25].

5. CONCLUSIONS

The boost converters are widely used in DC microgrids. These converters, mostly, are connected in parallel to supply loads. In this work, a repetitive control strategy has been presented to improve the load sharing between parallel-connected boost converters. The proposed scheme regulates the output voltage of each boost converter such that the circulating current is minimized. The impact of changes in load parameters and line impedance on load sharing performance was considered. The repetitive controller has been designed which is connected in series with current controller of the boost converters to control the switching signals. Therefore, by regulating of the output voltage of each converter, the circulating current is minimized. The effectiveness of the proposed strategy has been verified through simulation using MATLAB/SIMULINK.

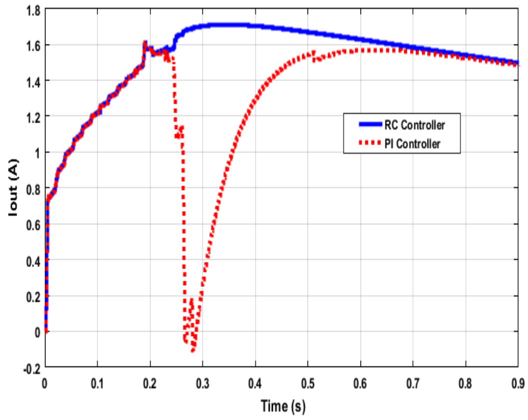


Fig. 9 Simulation results Case I. Converter 1 output current with proposed RC controller and conventional PI controller.

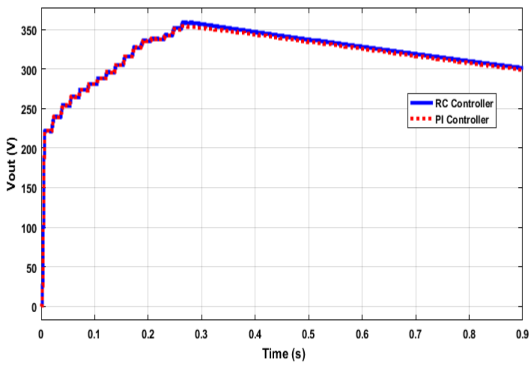


Fig. 10 Simulation results Case I. Converter 1 output voltage with proposed RC controller and conventional PI controller.

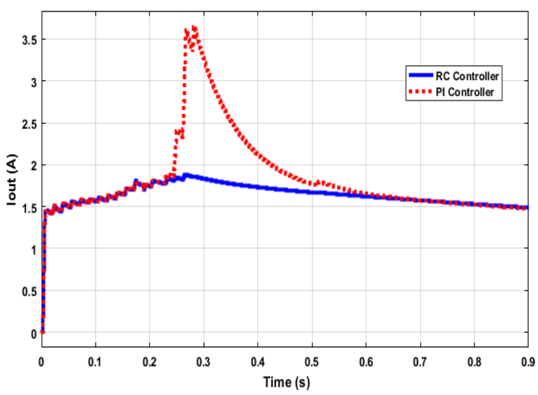


Fig. 11 Simulation results Case I. Converter 2 output current with proposed RC controller and conventional PI controller.

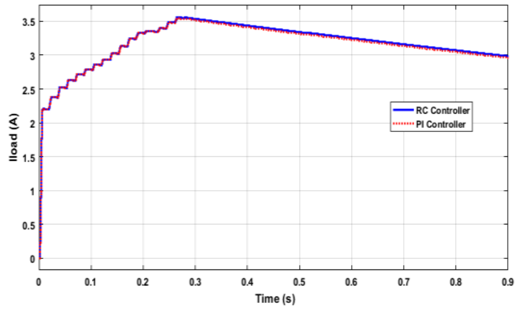


Fig. 12 Simulation results Case I. DC load current with proposed RC controller and conventional PI controller.

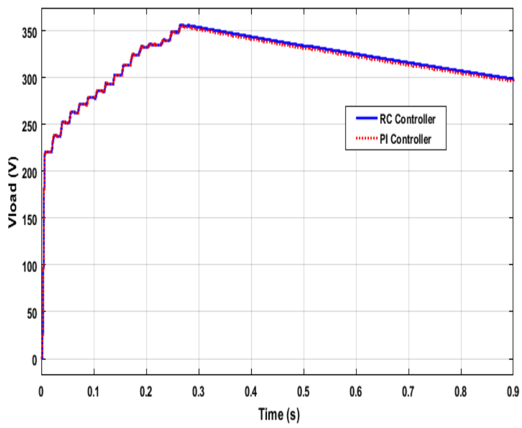


Fig. 13 Simulation results Case I. DC load voltage with proposed RC controller and conventional PI controller.

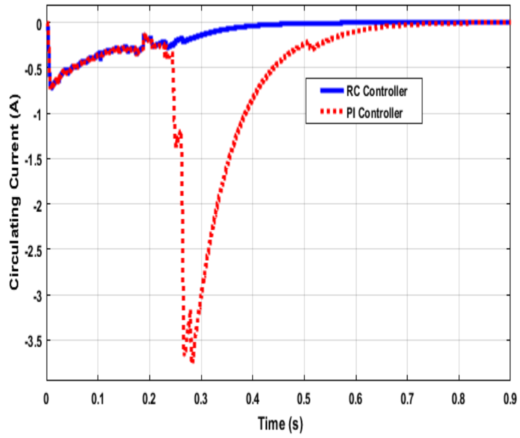


Fig. 14 Simulation results Case I. Circulating current with proposed RC controller and conventional PI controller

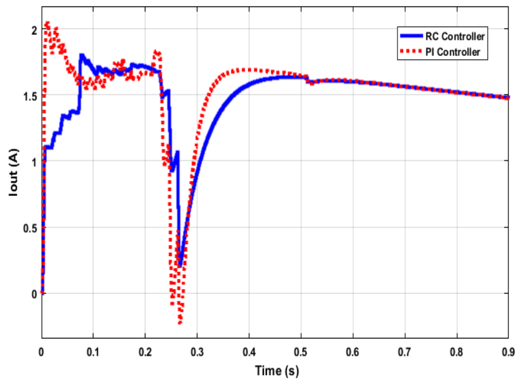


Fig. 15 Simulation results Case II. Converter 1 output current with proposed RC controller and conventional PI controller.

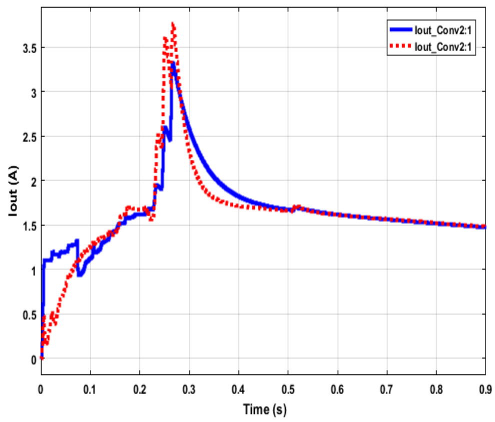


Fig. 16 Simulation results Case II. Converter 2 output current with proposed RC controller and conventional PI controller.

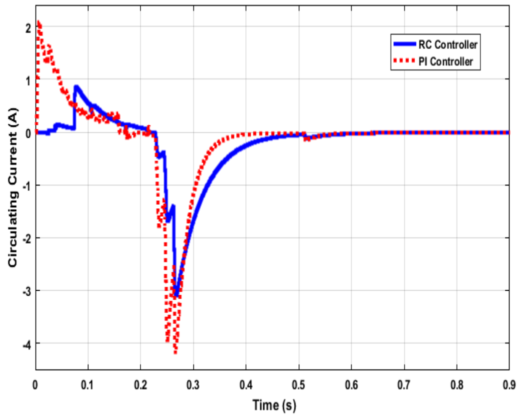


Fig. 17 Simulation results Case II. Circulating current with proposed RC controller and conventional PI controller.

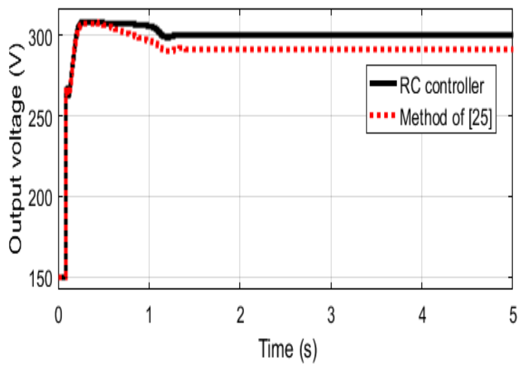
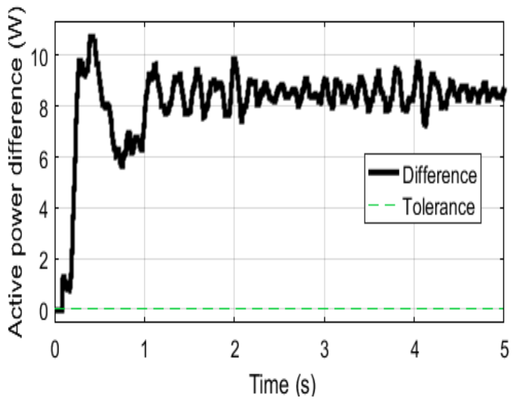
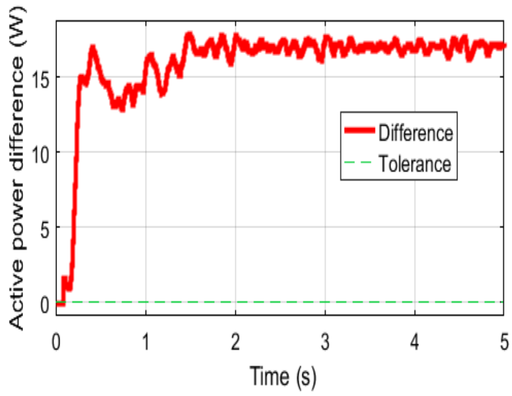


Fig. 18. Simulation results Case III: output voltages of each converter when the proposed method and method of [25] are implemented.

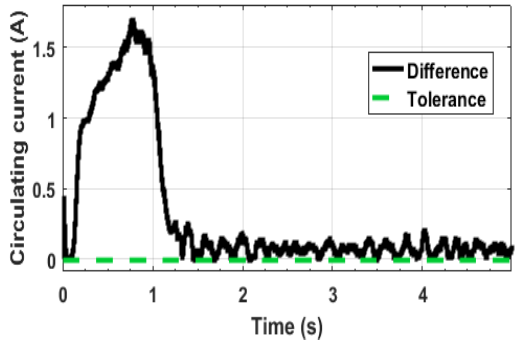


(a)



(b)

Fig. 19. Simulation results Case III: active power differences when (a) the proposed strategy and (b) the method of [25] are involved.



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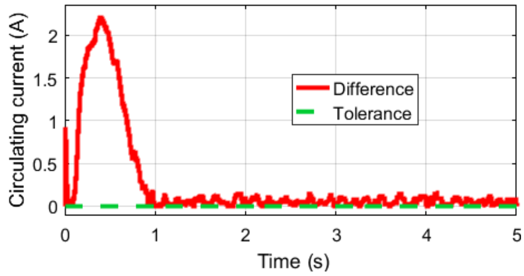

(b)

Fig. 20. Circulating current when (a) the proposed strategy and (b) the method of [25] are involved.

Table 1. Parameters values used in the simulation

Parameter	Value
Input line voltage (peak)	$110\sqrt{2}$
Input line frequency	60 Hz
Smoothing capacitance	3.414 μF
Smoothing inductance	50 mH
Rated power	300 W
Carrier frequency	25 kHz
Output voltage	300 V

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